Lattice 2024

Sunday 28 July 2024 through Saturday 3 August 2024

Book of Abstracts

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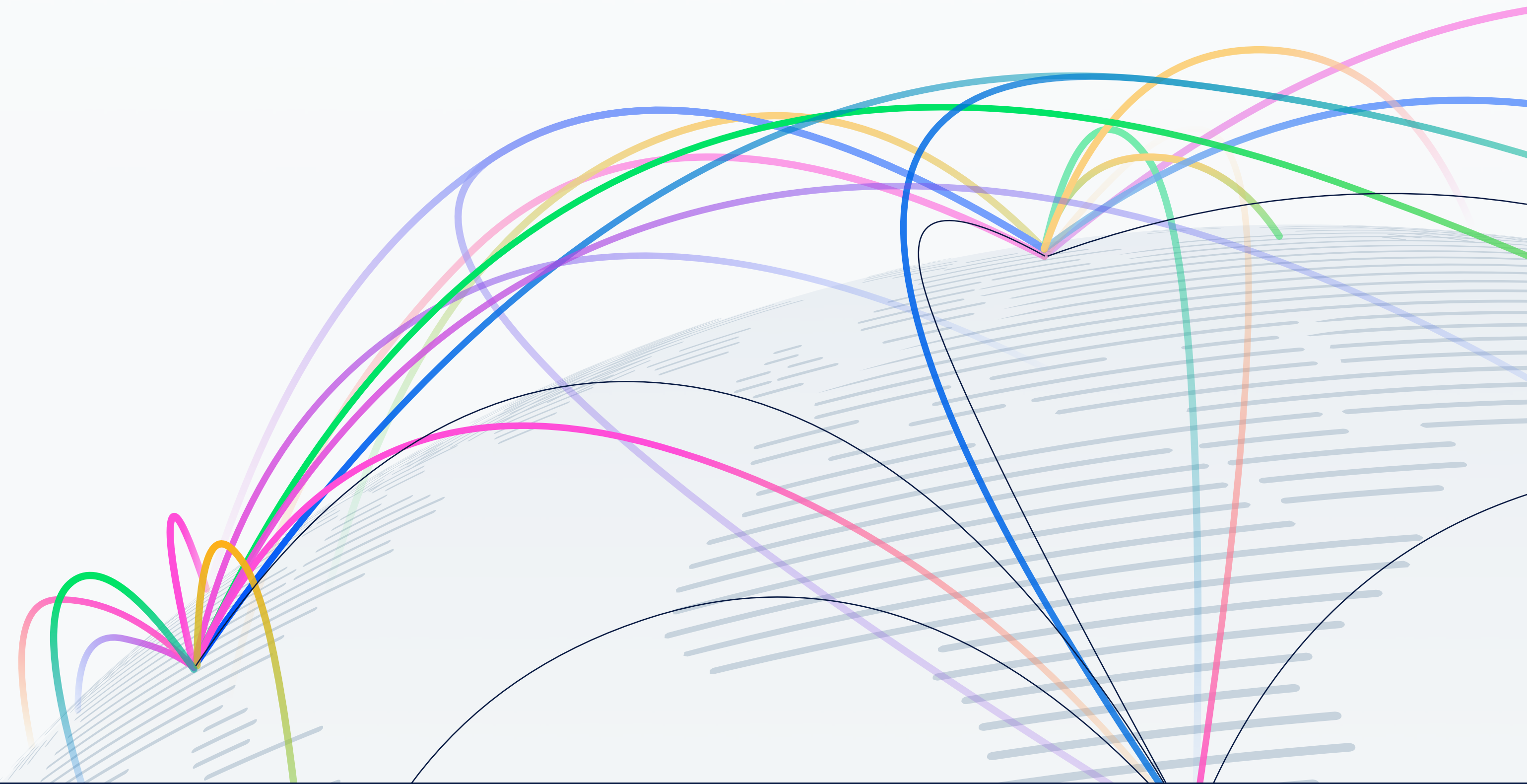

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Contents

Plenary / **411**

Opening

Corresponding Author: simon.hands@liverpool.ac.uk

Plenary / **493**

Status and outlook of quark flavour physics

Author: J. Tobias Tsang[1]

[1] *CERN*

Corresponding Author: j.t.tsang@cern.ch

In recent years there has been impressive progress in quark flavour physics, with current efforts tackling complicated quantities such as for example inclusive decays, decays to QCD-unstable final states and radiative decays. At the same time current lattice flavour physics results are receiving a lot of attention from outside the lattice community. This requires careful scrutiny, even for well explored quantities.

I will review the status of flavour physics observables and, in the context of heavy flavours, suggest possible benchmark quantities that could allow to better compare intermediate results. These can in turn be used to investigate the origin of existing (and possible future) tensions.

Plenary / **173**

Recent highlights from the LHCb experiment

Author: Mark Whitehead[1]

[1] *University of Glasgow*

Corresponding Author: mark.whitehead@glasgow.ac.uk

I will present a selection of recent results from the LHCb experiment, with a focus on topics that of interest at Lattice 2024. This will include highlights from the heavy flavour spectroscopy programme, with observations of new hadrons (both exotic and more standard in nature).

Plenary / **495**

Welcome

Algorithms and artificial intelligence / **118**

Machine Learning Estimation on the trace of inverse Dirac operator using the Gradient Boosting Decision Tree Regression

Authors: Benjamin J. Choi[1]; Hiroshi Ohno[1]; Takayuki Sumimoto[2]; Akio Tomiya[3]

[1] *University of Tsukuba*

[2] *FLECT Co., Ltd.*

[3] *TWCU*

Corresponding Authors: akio@yukawa.kyoto-u.ac.jp, benchoi@ccs.tsukuba.ac.jp, hohno@ccs.tsukuba.ac.jp

We present our preliminary results on the machine learning estimation of Tr M^{-n} from other observables with the gradient boosting decision tree regression, where M is the Dirac operator. Ordinarily, Tr M^{-n} is obtained by linear CG solver for stochastic sources which needs considerable computational cost. Hence, we explore the possibility of cost reduction on the trace estimation by the adoption of gradient boosting decision tree algorithm. We also discuss effects of bias and its correction.

Hadronic and nuclear spectrum and interactions / 14

Study of the pion-mass dependence of ρ -meson properties in lattice QCD

Author: Kang Yu[1]

Co-authors: Anthony W. Thomas [2]; Derek B. Leinweber [2]; Jiajun Wu [1]; Yan Li [3]

[1] *University of Chinese Academy of Sciences, Beijing*

[2] *Special Research Centre for the Subatomic Structure of Matter (CSSM), Department of Physics, University of Adelaide, Adelaide, South Australia 5005, Australia*

[3] *Department of Physics, University of Cyprus, 20537 Nicosia, Cyprus*

Corresponding Author: yukang21@mails.ucas.ac.cn

We collect spectra extracted in the $I = \ell = 1$ $\pi\pi$ sector provided by various lattice QCD collaborations and study the m_π dependence of ρ-meson properties using Hamiltonian Effective Field Theory (HEFT).In this unified analysis, the coupling constant and cutoff mass, characterizing the $\rho - \pi\pi$ vertex, are both found to be weakly dependent on m_π, while the mass of the bare ρ, associated with a simple quark-model state, shows a linear dependence on m_π^2. Both the lattice results and experimental data can be described well.

Drawing on HEFT's ability to describe the pion mass dependence of resonances in a single formalism, we map the dependence of the phase shift as a function of m_π, and expose interesting discrepancies in contemporary lattice QCD results.

Quark and lepton flavour physics / 390

Status of the ETMC calculation of a_μ^{HVP} in isoQCD

Authors: Marco Garofalo[1]; on behalf of the ETMC[None]

[1] *University of Bonn*

Corresponding Author: marcogarofalo31@gmail.com

We present the status of the ETMC computation of the leading-order hadronic vacuum polarization (HVP) contribution to the muon anomalous magnetic moment a_μ^{HVP-LO} employing $Nf = 2+1+1$

flavors of Wilson-clover twisted-mass quarks with physical pion mass. Here, we focus on the isospin symmetric QCD (isoQCD) contribution to a_μ^{HVP-LO}.

Structure of hadrons and nuclei / 132

Nucleon axial, tensor, and scalar charges and σ-terms from lattice QCD

Authors: Christos Iona[1]; Constantia Alexandrou[2]; Simone Bacchio[3]; Giannis Koutsou[3]; Yan Li[4]; Gregoris Spanoudes[1]

[1] *University of Cyprus*

[2] *University of Cyprus and The Cyprus Institute*

[3] *The Cyprus Institute*

[4] *Department of Physics, University of Cyprus, 20537 Nicosia, Cyprus*

Corresponding Authors: ciona001@ucy.ac.cy, g.koutsou@cyi.ac.cy, alexand@ucy.ac.cy, spanoudes.gregoris@ucy.ac.cy, s.bacchio@gmail.com

We determine the nucleon axial, scalar and tensor charges at the continuum limit including all contributions from valence and sea quarks by analyzing three $N_f = 2+1+1$ twisted mass fermion ensembles with all quark masses tuned to approximately their physical values. We use the Akaike Information Criterion to evaluate systematic errors due to excited states and the continuum extrapolation. For the nucleon isovector axial charge we find $g_A^{u-d} = 1.250(24)$, in agreement with the experimental value. We compute the axial, tensor and scalar charges for each quark flavor, offering crucial input for the intrinsic spin in the nucleon and experimental searches for physics beyond the standard model. Moreover, we extract the nucleon σ-terms and find for the light quark content $\sigma_{\pi N} = 41.0(7.6)$~MeV and for the strange $\sigma_s = 35(16)$~MeV.

QCD at non-zero temperature / 258

In- and out-of-equilibrium aspects of the Chiral Magnetic Effect

Authors: Bastian Brandt[1]; Gergely Endrodi[2]; Eduardo Garnacho-Velasco[2]; Gergely Marko[2]; Adeilton Dean Marques Valois[2]

[1] *University of Bielefeld*

[2] *Bielefeld University*

Corresponding Authors: dvalois@physik.uni-bielefeld.de, gmarko@physik.uni-bielefeld.de, egarnacho@physik.uni-bielefeld.de, brandt@physik.uni-bielefeld.de, endrodi@physik.uni-bielefeld.de

In this work, we study the Chiral Magnetic Effect (CME) from lattice QCD simulations considering two different scenarios, in particular focusing on the leading-order coefficient of the vector current in a chiral chemical potential expansion. In the first scenario, we consider continuum extrapolated QCD with 2+1 flavors of improved staggered fermions, a system in thermal equilibrium, with a non-uniform magnetic background. We show that local chiral magnetic currents appear in this setup, following non-trivially the magnetic field profile. We check that these currents average to zero in the full volume, confirming that the total CME conductivity vanishes in equilibrium. In the second case, we present the first steps towards studying the out-of-equilibrium aspects of CME on the lattice.

Vacuum structure and confinement / 112

The gluino condensate of large-N SUSY Yang–Mills

Authors: Claudio Bonanno[1]; Pietro Butti[2]; Margarita Garcia Perez[3]; Antonio Gonzalez-Arroyo[4]; Ken-Ichi Ishikawa[5]; Masanori Okawa[5]

[1] *IFT UAM/CSIC Madrid*

[2] *University of Zaragoza*

[3] *Instituto de Fisica Teorica UAM-CSIC*

[4] *Instituto de Fisica Teorica UAM/CSIC*

[5] *Hiroshima University*

Corresponding Authors: ishikawa@theo.phys.sci.hiroshima-u.ac.jp, antonio.gonzalez-arroyo@uam.es, margarita.garcia@uam.es, okawa@sci.hiroshima-u.ac.jp, pietro.butti.fl@gmail.com, claudio.bonanno@csic.es

We present the first lattice determination of the SUSY SU(N) Yang–Mills gluino condensate at large N. We exploit large-N twisted volume reduction, and present two determinations based on the Banks–Casher relation and on a Gell-Mann–Oakes–Renner-like formula, both giving perfectly compatible results. By expressing the lattice results in the Novikov–Shifman–Vainshtein–Zakharov (NSVZ) scheme, we are able for the first time to compare lattice and analytical computations, resolving a 40-year-long debate about the actual value and N-dependence of the gluino condensate.

Quantum computing and quantum information / 57

Quantum Hamiltonian Truncation

Authors: James Ingoldby[1]; Michael Spannowsky[1]; Simon Williams[2]; Timur Sypchenko[3]

[1] *IPPP, Durham University*

[2] *IPPP, Durham*

[3] *Durham (IPPP)*

Corresponding Authors: james.ingoldby@gmail.com, simon.j.williams@durham.ac.uk, michael.spannowsky@durham.ac.uk

We present ongoing work applying quantum computing techniques to investigate real-time evolution in the Schwinger model using the Hamiltonian Truncation approach - a general, numerical and fully nonperturbative method for solving Quantum Field Theories that is complementary to the lattice. We quantify and compare the quality of different approximations employed in the method, including consideration of Trotter and Hilbert space truncation errors, facilitating comparison with other approaches. Finally, we discuss the potential for exciting future applications.

Theoretical developments / 294

Effective mass-improvement of heavy valence Wilson quarks

Authors: Jochen Heitger[1]; Patrick Fritzsch[2]; Simon Kuberski[3]

[1] *University of Muenster, ITP*

[2] *Trinity College Dublin*

[3] *CERN*

Corresponding Authors: simon.kuberski@cern.ch, fritzscp@tcd.ie, heitger@uni-muenster.de

We extend an established strategy to non-perturbatively determine mass-improvement coefficients for heavy valence Wilson fermions in $N_f = 3$ massless QCD to effectively cancel higher-order mass-dependent cutoff effects. Using Schrödinger functional simulations in physical volumes of $L \simeq 0.25, 0.5\,\mathrm{fm}$ we test our strategy by simulating relativistic b-quarks at lattice spacings of $0.008 \leq a/\mathrm{fm} \leq 0.021$, and compare it to results obtained with the traditional method for tuning the b-quark hopping parameter. The new strategy significantly enhances the window for which a predominantly $O(a^2)$ scaling behaviour of physical quantities is observed, comparable to that of massless sea quarks.

Algorithms and artificial intelligence / 165

Applying the Triad network representation to four-dimensional ATRG method

Author: Yuto Sugimoto[1]

Co-author: Shoichi Sasaki [2]

[1] *Tohoku University*

[2] *Department of Physics, Tohoku University*

Corresponding Authors: yuto.sugimoto.q5@dc.tohoku.ac.jp, ssasaki@nucl.phys.tohoku.ac.jp

Anisotropic Tensor Renormalization Group (ATRG) is a powerful algorithm for four-dimensional tensor network calculations. However, the larger bond dimensions are known to be difficult to achieve in practice due to the higher computational cost. Adopting the methods of the minimally-decomposed TRG and its Triad prescriptions, we construct a Triad representation of the 4D ATRG by decomposing the unit cell tensor. We observe that this combining approach can significantly improve the computational cost even with maintaining the convergence accuracy of the free energy in the 4D Ising model. In addition, we also show that a further improvement can be achieved in terms of the computational cost when our proposed approach is implemented in parallel on GPUs.

Hadronic and nuclear spectrum and interactions / 136

Physical-mass calculation of $\rho(770)$ and $K^*(892)$ resonance parameters via $\pi\pi$ and $K\pi$ scattering amplitudes from lattice QCD

Authors: Antonin Portelli[1]; Fabian Joswig[2]; Felix Erben[3]; Maxwell T. Hansen[2]; Michael Marshall[2]; Nelson Pitanga Lachini[4]; Peter Boyle[5]; Vera Guelpers[1]

[1] *The University of Edinburgh*

[2] *University of Edinburgh*

[3] *CERN*

[4] *University of Cambridge*

[5] *Brookhaven National Laboratory*

Corresponding Authors: paboyle@ph.ed.ac.uk, np612@cam.ac.uk, felix.erben@cern.ch, antonin.portelli@ed.ac.uk, vera.guelpers@ed.ac.uk, maxwell.hansen@ed.ac.uk

We present our study of the $\rho(770)$ and $K^*(892)$ resonances from lattice QCD employing domain-wall fermions at physical quark masses. We determine the finite-volume energy spectrum in various momentum frames and obtain phase-shift parameterizations via the Lüscher formalism, and as a final

step the complex resonance poles of the $\pi\pi$ and $K\pi$ elastic scattering amplitudes via an analytical continuation of the models. By sampling a large number of representative sets of underlying energy-level fits, we also assign a systematic uncertainty to our final results. This is a significant extension to data-driven analysis methods that have been used in lattice QCD to date, due to the two-step nature of the formalism.

Quark and lepton flavour physics / 123

$\pi^0 \to \gamma^*\gamma^*$ transition form factor and the pion pole contribution to a_μ on CLS ensembles

Authors: Antoine Gerardin[1]; Georg von Hippel[2]; Harvey B. Meyer[2]; Jonna Koponen[3]; Konstantin Ottnad[2]

[1] *Centre de Physique Théorique de Marseille*

[2] *University of Mainz*

[3] *JGU Mainz*

Corresponding Authors: meyerh@uni-mainz.de, kottnad@uni-mainz.de, hippel@uni-mainz.de, antoine.gerardin@univ-amu.fr, jkoponen@uni-mainz.de

We present the status of the Mainz group's lattice QCD calculation of the pion transition form factor $\mathcal{F}_{\pi^0\gamma^*\gamma^*}$, which describes the interaction of an on-shell pion with two off-shell photons. This form factor is the main ingredient in the calculation of the pion-pole contribution to hadronic light-by-light scattering in the muon $g-2$.

We use the $N_f = 2+1$ CLS gauge ensembles, and we update our previous work by including a physical pion mass ensemble (E250). We compute the transition form factor in the pion rest frame as well as in a moving frame in order to have access to a wider range of photon virtualities. In addition to the quark-line connected correlator we also compute the quark-line disconnected diagrams that contribute to the form factor.

In this final stage of the analysis, we combine the result on E250 with the previous work published in 2019 to extrapolate the form factor to the continuum and to physical quark masses. Testing different Ans\"atze for the fit, we explore the systematic uncertainties of the extrapolation. The contribution from the disconnected diagrams is also scrutinized.

Structure of hadrons and nuclei / 368

Flavor diagonal charges of the nucleon and the sigma term

Author: Rajan Gupta[1]

Co-authors: Sungwoo Park [2]; Tanmoy Bhattacharya [3]

[1] *Los Alamos National Lab*

[2] *Lawrence Livermore National Laboratory*

[3] *Los Alamos National Laboratory*

Corresponding Authors: park49@llnl.gov, tanmoy@lanl.gov, rg@lanl.gov

This talk will summarize the calculations of the axial, scalar and tensor charges of the nucleons using lattice QCD. These charges quantify the pion-nucleon sigma term, the coupling to dark matter and Higgs-like interactions, the contribution of quark spin to the nucleon spin, the contribution of quark electric dipole moment to the neutron dipole moment and to the transversity moment. The implications of these results for the standard model and BSM physics will be discussed.

QCD at non-zero temperature / 169

Baryon electric charge correlation as a magnetometer of QCD

Authors: Arpith Kumar[1]; Heng-Tong Ding[1]; Jin-Biao Gu[1]; Sheng-Tai Li[1]; junhong liu[1]

[1] *Central China Normal University*

Corresponding Authors: jinbiaogu@mails.ccnu.edu.cn, junhongliu@mail.ccnu.edu.cn, hengtong.ding@ccnu.edu.cn, lishengtai@ccnu.edu.cn, arpithk@ccnu.edu.cn

We present the first lattice QCD results of quadratic fluctuations and correlations of conserved charges in (2+1)-flavor lattice QCD in the presence of a background magnetic field. The simulations were performed using the Highly Improved Staggered Quarks with physical pion mass m_π = 135 MeV on $N_\tau = 8$ and 12 lattices. We find that the correlation between net baryon number and electric charge, denoted as $\chi_{11}^{\rm BQ}$, can serve as a magnetometer of QCD. At pseudocritical temperatures the $\chi_{11}^{\rm BQ}$ starts to increase rapidly with magnetic field strength eB
$gtrsim2M_\pi^2$ and by a factor 2 at $eB \simeq 8M_\pi^2$.

By comparing with the hadron resonance gas model, we find that the eB dependence of $\chi_{11}^{\rm BQ}$ is mainly due to the doubly charged Δ(1232) baryon. Although the doubly charged Δ(1232) could not be detected experimentally, its decay products, protons and pions, retain the eB dependence of Δ(1232)'s contribution to $\chi_{11}^{\rm BQ}$.
Furthermore, the ratio of electric charge chemical potential to baryon chemical potential, $\mu_{\rm Q}/\mu_{\rm B}$, shows significant dependence on the magnetic field strength and varies with the ratio of electric charge to baryon number in the colliding nuclei in heavy ion collisions. These results provide baselines for effective theory and model studies, and both $\chi_{11}^{\rm BQ}$ and $\mu_{\rm Q}/\mu_{\rm B}$ could be useful probes for the detection of magnetic fields in relativistic heavy ion collision experiments as compared with corresponding results from the hadron resonance gas model.

Vacuum structure and confinement / 224

Beyond Nambu-Goto corrections for the Effective String Theory of SU(N) lattice gauge theories

Authors: Alessandro Nada[1]; Dario Panfalone[2]; Lorenzo Verzichelli[3]; Marco Panero[4]; Michele Caselle[1]; Nicodemo Magnoli[5]

[1] *Università di Torino*

[2] *Univesita' di Torino*

[3] *Università di Torino, INFN sezione di Torino*

[4] *University of Turin and INFN Turin*

[5] *Università di Genova*

Corresponding Authors: magnoli@ge.infn.it, dario.panfalone@unito.it, alessandro.nada@unito.it, caselle@to.infn.it, lorenzo.verzichelli@unito.it, panero@to.infn.it

We study the Effective String Theory corrections beyond the Nambu-Got{\=o} action in SU(N) lattice gauge theories in 2 + 1 dimensions, for $N = 3$ and $N = 6$. We extract these corrections from a set of high-precision Monte Carlo simulations of Polyakov loop correlators at
finite temperatures close to the deconfinement transition. We also report an estimate for the SU(2) theory obtained from a reanalysis of
published data. We show that these corrections are in general very small, they increase with N and are always compatible with the bounds derived from the S-matrix Bootstrap analysis. Moreover, since in 2+1 dimensions the deconfinement transition of the $N = 3$ theory is of second order, our results allow for a non-trivial test of the Svetitsky-Yaffe conjecture which, in the neighbourhood of the critical point, maps the 2+1 dimensional SU(3) gauge theory into the two dimensional three-state

Potts model. In particular we show that our
results for the correlator of Polyakov loops perfectly agree with an expression for the short distance spin-spin correlator in the Potts model
obtained using a conformal perturbation approach.

Quantum computing and quantum information / 243

Quantum Error Correction and Z(2) Lattice Gauge Theories

Author: Seyong Kim[1]

[1] *Sejong University*

Corresponding Author: skim@sejong.ac.kr

A threshold probability in Quantum Error Correction (QEC) is maximally allowed quantum error rate below which QEC can be implemented for a given quantum code. Usually one can find a mapping of QEC problem into a statistical mechanics model under certain assumptions on the quantum error pattern in physical quantum circuits. Then this threshold probability can be studied by Monte Carlo simulation of mapped statistical mechanics model. Here, we show how this mappings work for toric/surface code in 2 dimension together with measurement errors with different assumptions and discuss results from Monte Carlo simulation of various classes of Z(2) lattice theories.

Theoretical developments / 30

Exact space-time symmetry conservation and automatic mesh refinement for classical lattice field theory

Author: Alexander Rothkopf[1]

Co-authors: Jan Nordström ; Will Horowitz

[1] *University of Stavanger*

Corresponding Author: alexander.rothkopf@uis.no

The breaking of space-time symmetries and the non-conservation of the associated Noether charges constitutes a central artifact in lattice field theory. In [1] we have shown how to overcome this limitation for classical actions describing point particle motion, using the world-line formalism of general relativity. The key is to treat coordinate maps (from an abstract parameter space into space-time) as dynamical and dependent degrees of freedom, which remain continuous after discretization of the underlying parameter space. Here we present latest results [2] where we construct a reparameterization invariant classical action for scalar fields, which features dynamical coordinate maps. We achieve the following: 1) global space-time symmetries remain intact after discretization and the associated Noether charges remain exactly preserved 2) coordinate maps adapt to the dynamics of the scalar field leading to adaptive grid resolution guided by the symmetries 3) dynamic coordinate maps contribute to boundary terms, offering new freedom in constructing boundary conditions.

[1] A.R. and J. Nordström "A symmetry and Noether charge preserving discretization of initial value problems" J.Comput.Phys. 498 (2024) 112652 (https://arxiv.org/abs/2307.04490)

[2] A.R., W.A. Horowitz and J. Nordström "Exact symmetry conservation and automatic mesh refinement in discrete initial boundary value problems" (https://arxiv.org/abs/2404.18676)

Algorithms and artificial intelligence / 78

Gauge symmetric transformer for lattice gauge theory

Authors: Akio Tomiya[1]; Hiroshi Ohno[2]; Yuki Nagai[3]

[1] *Tokyo Woman's Christian University*

[2] *University of Tsukuba*

[3] *University of Tokyo*

Corresponding Author: akio@yukawa.kyoto-u.ac.jp

In this talk, we will discuss transformers that preserve gauge symmetry and their applications. Gauge symmetry is crucial in lattice QCD. There has been significant progress in accelerating lattice calculations using machine learning, particularly neural networks. Meanwhile, in the field of machine learning, transformers such as GPT have rapidly advanced and transformed society. Transformers excel at capturing long-range correlations in data and handling data with local causal structures, such as language. In this study, we have formulated a transformer that preserves gauge symmetry. This presentation will cover the fundamental aspects of this research and the results of practical calculations.

Hadronic and nuclear spectrum and interactions / 20

Implementing the relativistic-field-theory finite-volume formalism across all three-pion isospins

Authors: Athari Alotaibi[1]; Maxwell Hansen[1]

[1] *University of Edinburgh*

Corresponding Authors: maxwell.hansen@ed.ac.uk, s1889602@ed.ac.uk

In this talk, we present a numerical exploration of the relativistic field theory (RFT) formalism for three pions with all possible values of non-maximal isospin, $I_{\pi\pi\pi} = 2, 1,$ and 0. Using the published generic-isospin extension of the RFT formalism and applying our open-source Python library to implement the formalism, we predict an array of three-pion energies for realistic values of the two-to-two scattering amplitudes. Considering all possible finite-volume irreps with three values of total momentum, we demonstrate how complicated spectra emerge, in particular from the mixing of all allowed two-pion isospins in a given sector of definite $I_{\pi\pi\pi}$. The present results restrict attention to the case of a vanishing intrinsic three-body interaction so that the spectra can be understood as a baseline. In future lattice QCD calculations, deviations from these values will translate to evidence of intrinsic three-particle effects.

Quark and lepton flavour physics / 115

Status of the RBC/UKQCD HVP program

Author: Christoph Lehner[1]

[1] *University of Regensburg*

Corresponding Author: christoph.lehner@ur.de

I will present the current status and future prospects of the RBC/UKQCD HVP program. The talk will include new results for the long-distance window contribution.

Structure of hadrons and nuclei / 381

The isoscalar non-singlet axial form factor of the nucleon from lattice QCD

Authors: Alessandro Barone[1]; Dalibor Djukanovic[2]; Georg von Hippel[3]; Hartmut Wittig[3]; Harvey B. Meyer[3]; Jonna Koponen[4]; Konstantin Ottnad[3]

[1] *Johannes Gutenberg University Mainz*

[2] *Helmholtz Institute Mainz*

[3] *University of Mainz*

[4] *JGU Mainz*

Corresponding Authors: kottnad@uni-mainz.de, d.djukanovic@him.uni-mainz.de, abarone@uni-mainz.de, hippel@uni-mainz.de, hartmut.wittig@uni-mainz.de, meyerh@uni-mainz.de, jkoponen@uni-mainz.de

We present our progress on the computation of the axial form factor of the nucleon with flavour structure $u + d - 2s$ from lattice QCD. We employ a set of $N_f = 2 + 1$ CLS ensembles with O(a)-improved Wilson fermions and the Lüscher-Weisz gauge action, with lattice spacings ranging from 0.05 fm to 0.086 fm and pion masses spanning between 130 MeV and 350 MeV.
We employ multiple source-sink separations and use the summation method to suppress the contamination from excited states. We use a z-expansion on each ensemble to parametrize the Q^2-dependence of the form factor and simultaneously fit the available source-sink separation for all $Q^2 <= 0.7\,\mathrm{GeV}^2$. We outline our analysis of the stability of the fits under different ansätze and different estimations of the covariance matrix and report on our strategy for a comprehensive determination of the physical form factor.

QCD at non-zero temperature / 300

Shear viscosity from quenched to full lattice QCD

Authors: Christian Schmidt[1]; Guy Moore[2]; Hai-Tao Shu[3]; Luis Altenkort[4]; Olaf Kaczmarek[5]; Pavan Pavan[4]

[1] *Universitaet Bielefeld*

[2] *TU Darmstadt*

[3] *Brookhaven National Laboratory*

[4] *Bielefeld University*

[5] *University of Bielefeld*

Corresponding Authors: altenkort@physik.uni-bielefeld.de, hshu@bnl.gov, okacz@physik.uni-bielefeld.de, pavan@physik.uni-bielefeld.de, schmidt@physik.uni-bielefeld.de, guy.moore@physik.tu-darmstadt.de

The shear viscosity of the quark-gluon plasma (QGP) plays a crucial role in interpreting current measurements from heavy-ion collisions and are key inputs to hydro-dynamical models. The interest in shear viscosity also lies in the fact that QGP is the most ideal fluid ever observed and has the shear viscosity to entropy ratio (η/s) close to the theoretical bound $\eta/s \geq 1/4\pi$ in the strong coupling region within AdS/CFT formalism. We utilize the gradient flow method to renormalize the Energy-Momentum Tensor (EMT) and to suppress UV fluctuations in correlators on a lattice SU(3) gauge theory. After taking the continuum and zero flow-time limits, we extract shear viscosity in the pure-gauge theory by modeling the spectral function with a combination of the perturbative UV part and the hydro-motivated infrared part. We also present the extension of quenched findings to full QCD, specifically the renormalization of EMT and progress update on determining the relevant coefficients for shear viscosity with $m_s/m_l = 20$ on the lattice.

Vacuum structure and confinement / 242

SU(6) model revisited

Author: Tatsuya Yamaoka[1]

[1] *Osaka University*

Corresponding Author: t_yamaoka@het.phys.sci.osaka-u.ac.jp

We present our study on the 't Hooft anomalies for generalized symmetry of a chiral SU(6) gauge theory with selfconjugate representation.
This theory is interesting since it is found to realize chiral symmetry breaking without bilinear condensate having three-fold generate vacua, based on previous study of the mixed anomaly between the center symmetry and discrete chiral symmetry
by S. Yamaguchi. However, the computation of full 't Hooft anomalies for all the symmetries of this model based on the UV theory is still missing.
We revisit this model and study all possible 't Hooft anomalies for generalized symmetry including pure discrete chiral anomaly and gravitational mixed anomaly, which can be obtained using eta invariant method. Based on this 't Hooft anomalies, we try to construct an effective theory in the low-energy regime that reproduces all these anomalies.
We showed that all anomalies except the self-anomaly can be reproduced by extending the WZW term, accounting for the threefold degenerate vacua.Finally, we demonstrated that the self-anomaly can be understood through the degrees of freedom on the domain wall inserted between these vacua, using Symmetric Topological Field Theory (SymTFT).

Quantum computing and quantum information / 265

Noise-aware mixed state quantum computation and its applications

Author: Giuseppe Clemente[1]

Co-author: Kevin Zambello [2]

[1] *University of Pisa and INFN*

[2] *University of Pisa and INFN - Sezione di Pisa*

Corresponding Authors: giuseppe.clemente@unipi.it, kevin.zambello@pi.infn.it

We introduce a framework for noise-aware optimization of mixed-state quantum computation, showing the advantages for NISQ era and some lattice applications.

Theoretical developments / 354

The constraint potential for fermionic order parameters

Author: Gergely Marko[1]

Co-authors: Gergely Endrodi [1]; Laurin Pannullo [2]; Tamas G. Kovacs [3]

[1] *Bielefeld University*

[2] *University of Bielefeld*

[3] *Department of Physics and Astronomy, Eotvos University, Budapest*

Corresponding Authors: endrodi@physik.uni-bielefeld.de, tamas.gyorgy.kovacs@ttk.elte.hu, lpannullo@physik.uni-bielefeld.de, gmarko@physik.uni-bielefeld.de

The quantum effective potential is an object, often central in the discussion of spontaneous symmetry breaking, however, it is not directly accessible in lattice simulations. Therefore here we concentrate on the closely related constraint potential. It is defined by a path integral, where all local fluctuations are taken into account but the volume averaged order parameter is fixed. This ensures that in the thermodynamic limit one recovers the effective potential. The Grassmanian nature of fermionic fields complicates the definition of such a construction, and so we discuss the arising problems and possible solutions. Most prominently we introduce an approximation scheme with numerical feasability for Monte Carlo lattice QCD simulations in mind.

Theoretical developments / 183

The constraint potential in the chiral Gross-Neveu model

Authors: Gergely Endrodi[1]; Tamas G. Kovacs[2]; Gergely Marko[1]; Laurin Pannullo[3]

[1] *Bielefeld University*

[2] *Department of Physics and Astronomy, Eotvos University, Budapest*

[3] *University of Bielefeld*

Corresponding Authors: endrodi@physik.uni-bielefeld.de, gmarko@physik.uni-bielefeld.de, tamas.gyorgy.kovacs@ttk.elte.hu, lpannullo@physik.uni-bielefeld.de

We present results using a novel method for constraining fermionic condensates in a fermionic path integral. This approach enables us to obtain the quantum effective potential in the infinite volume limit, which is typically inaccessible using the standard technique of taking the double limit of infinite volume and zero explicit symmetry breaking. By constraining the relevant order parameter such as the chiral condensate, we can explore the flat region of the potential and determine the physically realized value of the order parameter. We apply our method to the chiral Gross-Neveu model in the large-N limit, where the continuous chiral symmetry is spontaneously broken, and demonstrate that in the infinite volume limit, the potential becomes flat, dominated by inhomogeneous field configurations. Beyond this test-case setup, the method is fully applicable in full Monte Carlo simulations of other theories such as QCD.

Algorithms and artificial intelligence / 207

Exploring Generative Networks for Manifolds with Non-Trivial Topology

Author: Shiyang Chen[1]

Co-authors: Biagio Lucini [2]; Gert Aarts [2]

[1] *Swansea university*

[2] *Swansea University*

Corresponding Authors: 2222895@swansea.ac.uk, g.aarts@swansea.ac.uk, b.lucini@swansea.ac.uk

The expressive power of neural networks in modeling complex distributions is desirable to bypass topological freezing and critical slowing down in simulations of lattice field theory. Some approaches suffer from problems with topology, which may lead to some classes of configurations not being generated. In this talk, I will present a novel generative approach inspired by a model previously introduced in the ML community (GFlowNets) and simulate triple ring models and lattice ϕ^4 model to demonstrate the capabilities of the method to solve issues connected with ergodicity.

Hadronic and nuclear spectrum and interactions / 44

Three-particle formalism for multiple channels: the ηππ + KKπ system in isosymmetric QCD

Author: Stephen Sharpe[1]

[1] *University of Washington*

Corresponding Author: srsharpe@uw.edu

We generalize the three-particle finite-volume formalism to allow for multiple three-particle channels, focussing on the two-channel ηππ and (positive G-parity sector of the) KKπ system in isosymmetric QCD. The formalism we obtain is thus appropriate to study the b1(1235) and η(1295) resonances. The derivation is made in the generic relativistic field theory approach using the time-ordered perturbation theory method. We study how the resulting quantization condition reduces to that for a single three-particle channel when one drops below the upper (KKπ) threshold. This work was done in collaboration with Zachary T. Draper.

Quark and lepton flavour physics / 439

Analysis of g-2 long distance two-pion correlators for the reconstruction of light vector correlators

Author: Joe Mckeon[1]

Co-authors: Bipasha Chakraborty [1]; Christoph Lehner [2]; Felix Erben [3]; J. Tobias Tsang [3]; Nils Hermansson-Truedsson [4]; Ryan Hill [4]; Vera Guelpers [5]

[1] *University of Southampton*

[2] *University of Regensburg*

[3] *CERN*

[4] *University of Edinburgh*

[5] *The University of Edinburgh*

Corresponding Authors: jm1n22@soton.ac.uk, nils.hermansson-truedsson@ed.ac.uk, christoph.lehner@ur.de, b.chakraborty@soton.ac.uk, vera.guelpers@ed.ac.uk, felix.erben@cern.ch, ryan.hill@ed.ac.uk, j.t.tsang@cern.ch

The largest uncertainty in the Standard Model (SM) prediction of the anomalous magnetic moment of the Muon (a_μ) is due to strong interactions, particularly the Hadronic Vacuum Polarisation (HVP). To make the SM predictions comparable in precision to the new experimental results we need to compute the HVP from first principles lattice QCD with proper handling of all possible uncertainties. One major source of large statistical uncertainties is the long-distance signal-to-noise problem in the light-quark vector-vector correlator. Since, in the long-distance regime, the light-connected vector channel is dominated by two-pion states, the signal-to-noise problem can be handled with the reconstruction of the two-pion states. In this talk, I will describe our approach to handle these two-pion states, specifically focusing on the spectrum analysis using the Generalised Eigenvalue Problem (GEVP) using various two-pion operators. I will show detailed results for one of the analysis groups for the new RBC/UKQCD long-distance data on physical point ensembles with large volumes.

Structure of hadrons and nuclei / 16

How much strangeness is needed for the axial-vector form factor of the nucleon?

Authors: David Thoma[None]; Felix Hermsen[None]; Matthias F.M. Lutz[None]; Tobias Isken[None]

Corresponding Author: felixundsandra@posteo.de

We consider the axial-vector together with its induced pseudo-scalar form factor of the nucleon as computed from the chiral Lagrangian with nucleon and isobar degrees of freedom. The form factors are evaluated at the one-loop level, where particular emphasis is put on the use of on-shell masses in the loop expressions. Our results are presented in terms of a novel set of basis functions that generalize the Passarino–Veltman scheme to the case where power-counting violating structures are to be subtracted. The particularly important role of the isobar degrees of freedom is emphasized. We obtain a significant and simultaneous fit to the available Lattice QCD results based on flavour SU(2) ensembles for the baryon masses and form factors up to pion masses of about 500 MeV. Our fits includes sizeable finite volume effects that are implied by using in-box values for the hadron masses entering our one-loop expressions. We conclude that from flavour SU(2) ensembles it appears not possible to predict the empirical formfactor at the desired precision. Effects from strange quarks are expected to remedy the situation.

QCD at non-zero temperature / 327

Thermal photon production rate from lattice QCD

Authors: Anthony Francis[1]; Dibyendu Bala[2]; Greg Jackson[None]; Jonas Turnwald[None]; Nicolas Wink[None]; Olaf Kaczmarek[3]; Sajid Ali[2]; Tristan Ueding[2]

[1] *National Yang Ming Chiao Tung University*

[2] *Bielefeld University*

[3] *University of Bielefeld*

Corresponding Authors: dibyendu.bala@physik.uni-bielefeld.de, sajid.ali@physik.uni-bielefeld.de, afrancis@nycu.edu.tw, tueding@physik.uni-bielefeld.de, okacz@physik.uni-bielefeld.de

Thermal photon production in heavy-ion collisions is a crucial tool for studying quark-gluon plasma (QGP), as photons carry information about the local environment from the point of creation. The thermal photon production rate from an equilibrated plasma is proportional to the spectral function in the vector channel. We estimate the photon rate from the difference between the transverse and longitudinal spectral functions (T-L) in 2+1 flavor lattice QCD with a pion mass of 320 MeV and quenched QCD. The advantage of this T-L spectral function is that the UV part of the spectral function is much suppressed compared to the spectral function in other channels, yet both give identical photon rates. As a result, the lattice correlator from this T-L spectral function is dominated by the important IR part of the spectral function, which is advantageous for the spectral reconstruction process. Since extracting the spectral function from the lattice correlator is an ill-posed problem, we have used various techniques for the spectral reconstruction process. These include modeling the spectral function constrained by its asymptotic behavior at high energies along with the sum rule. We have used a polynomial model of the spectral function and the Padé ansatz for this purpose. Additionally, we have attempted the Backus-Gilbert method and Gaussian process regression to estimate the photon rate. We show that, within systematic uncertainties, all the methods provide a consistent photon production rate.

Vacuum structure and confinement / 454

Test of a two-level algorithm for the glueball spectrum in $SU(N_c)$ Yang-Mills theory.

Authors: Andrea Falzetti[1]; Francesco Scardino[2]; Mauro Lucio Papinutto[3]

[1] *Università "La Sapienza" di Roma*

[2] *University of Rome "La Sapienza"*

[3] *Sapienza Università di Roma*

Corresponding Authors: mauro.papinutto@uniroma1.it, andrea.falzetti@uniroma1.it, fs.91@live.it

We present preliminary results obtained using a new code for $SU(N_c)$ Yang-Mills theory which performs a 2-level sampling of glueball correlators obtained from a suitably chosen basis of (APE) smeared and unsmeared operators. The code builds loop operators of any shape and length and classifies them according to the irreducible representations of the cubic group. We report on the performances of the algorithm and on the computation of the first low-lying glueball states choosing $N_c = 3$ as a reference to compare our results with the literature.

Quantum computing and quantum information / 357

Gauge field digitization in the Hamiltonian limit

Authors: Attila Pasztor[1]; Dávid Pesznyák[2]

[1] *University of Wuppertal*

[2] *Eötvös Loránd University, HUN-REN Wigner Research Centre for Physics*

Corresponding Authors: apasztor@bodri.elte.hu, david.pesznyak@gmail.com

The use of quantum computers could circumvent the complex action problem hampering first-principles studies of gauge theories in real time or at finite density. One of the main bottlenecks of quantum computers is the limited number of available qubits. One approach to mitigate this bottleneck is the discretization of continuous gauge groups to their discrete subgroups, which introduces systematic uncertainties. Previously, discrete subgroups and dense subsets of gauge groups had been investigated, but only with isotropic Euclidean lattices. In this work, we take the first steps in studying the systematics associated with digitization by performing anisotropic Euclidean simulations and taking the Hamiltonian limit, where the temporal lattice spacing approaches zero while the spatial lattice spacing is kept fixed.

Quark and lepton flavour physics / 314

Hadronic vacuum polarization contribution to the muon g-2 at short and long distances

Authors: Simon Kuberski[1]; Dalibor Djukanovic[2]; Georg von Hippel[3]; Harvey B. Meyer[3]; Nolan Miller[4]; Konstantin Ottnad[3]; Andreas Risch[5]; Hartmut Wittig[3]

[1] *CERN*

[2] *Helmholtz Institute Mainz*

[3] *University of Mainz*

[4] *Helmholtz-Institut Mainz*

[5] *Bergische Universität Wuppertal*

Corresponding Authors: nmiller@uni-mainz.de, d.djukanovic@him.uni-mainz.de, hartmut.wittig@uni-mainz.de, kottnad@uni-mainz.de, meyerh@uni-mainz.de, hippel@uni-mainz.de, simon.kuberski@cern.ch, andreas.risch@uni-wuppertal.de

We present an update on our ongoing computation of the hadronic vacuum polarization contribution to the anomalous magnetic moment of the muon, focusing on short and long distance contributions in the time-momentum representation. By combining lattice QCD and perturbation theory at short

distances and utilizing a broad range of lattice spacings, we achieve a controlled continuum extrapolation. The quark mass dependence, critical for the long-distance contribution, is constrained using several ensembles that are either at or near physical quark masses. Advanced noise reduction techniques allow for a precise evaluation of the long-distance regime for both isovector and isoscalar contributions.

Algorithms and artificial intelligence / 142

Improvement of Heatbath Algorithm in Lattice Field Theory using Generative AI

Authors: Ankur Singha[1]; Ali Faraz[None]

Co-authors: Vipul Arora [2]; Dipankar Chakrabarti [2]; Shinichi Nakajima [1]

[1] *TU Berlin*

[2] *IIT Kanpur*

Corresponding Authors: vipular@iitk.ac.in, dipankar@iitk.ac.in, ali21579@gmail.com, shinnkj23@gmail.com, ankurrrssingha@gmail.com

The Heatbath Algorithm is popular for sampling local lattice field theories. However, exact updates or sampling from the local density are challenging due to the continuous nature of the variables. Rejection methods can have low acceptance rates if the proposal is not correctly chosen, which is a non-trivial task. In this talk, I will propose a new and simple method for making proposals at each site of the lattice for the phi-4 and XY models using generative AI models. Additionally, I will explain how these ideas can be applied to improve the sampling of pure gauge theory via the Heatbath and Generative AI.

Hadronic and nuclear spectrum and interactions / 97

Three-meson scattering amplitudes with physical quark masses

Authors: Andrew Hanlon[1]; Ben Hörz[2]; Colin Morningstar[1]; Fernando Romero-Lopez[3]; Sarah Skinner[1]; Sebastian Dawid[4]; Stephen Sharpe[4]; Zack Draper[4]

[1] *Carnegie Mellon University*

[2] *Intel*

[3] *MIT / Uni Bern*

[4] *University of Washington*

Corresponding Authors: cmorning@andrew.cmu.edu, ben.hoerz@intel.com, srsharpe@uw.edu, dawids@uw.edu, ztd@uw.edu, ddhanlon@gmail.com, fernando.romero-lopez@unibe.ch

We study systems of two and three mesons composed of pions and kaons at maximal isospin using the E250 CLS ensemble with physical quark masses. Using the stochastic LapH method, we determine the energy spectrum of these systems including many levels in different momentum frames. Using the two- and three-body finite-volume formalism, we constrain the two and three-meson K matrix, including not only the leading s wave, but also p and d waves. By solving the three-body integral equation, we determine the physical-point scattering amplitudes of $3\pi^+$, $3K^+$, $\pi^+\pi^+K^+$ and $K^+K^+\pi^+$ systems.

Structure of hadrons and nuclei / 353

Proton and neutron electromagnetic form factors using Nf=2+1+1 twisted-mass fermions with physical values of the quark masses

Authors: Bhavna Prasad[1]; Constantia Alexandrou[2]; Giannis Koutsou[1]; Gregoris Spanoudes[3]; Simone Bacchio[1]

[1] *The Cyprus Institute*

[2] *University of Cyprus and The Cyprus Institute*

[3] *University of Cyprus*

Corresponding Authors: alexand@ucy.ac.cy, spanoudes.gregoris@ucy.ac.cy, b.prasad@cyi.ac.cy, s.bacchio@gmail.com, g.koutsou@cyi.ac.cy

We compute the electromagnetic form factors of the proton and neutron using lattice QCD with $N_f = 2+1+1$ twisted mass clover-improved fermions and quark masses tuned to their physical values. Three ensembles with lattice spacings of a=0.080 fm, 0.068 fm, and 0.057 fm, and approximately the same physical volume allow us obtain the continuum limit directly at the physical pion mass. Several values of the source-sink time separation ranging from 0.5 fm to 1.5 fm are used, enabling a thorough analysis of excited state effects via multi-state fits. The disconnected contributions are analyzed using high statistics for the two-point functions combined with low-mode deflation and hierarchical probing for the fermion loop estimation. We study the momentum dependence of the form factors using the z-expansion and dipole Ansaetze, thereby enabling the extraction of the electric and magnetic radii, as well as the magnetic moments in the continuum limit.

QCD at non-zero temperature / 481

Adjoint chromoelectric correlators for heavy quarkonium diffusion

Author: Julian Mayer-Steudte[1]

Co-authors: Marc Janer [2]; Nora Brambilla [3]; Peter Petreczky [4]; Saumen Datta [5]; Viljami Leino [6]

[1] *Technical University of Munich (TUM)*

[2] *Technical University of Munich*

[3] *Technical University München*

[4] *BNL*

[5] *Tata Institute of Fundamental Research*

[6] *Johannes Gutenberg University Mainz*

Corresponding Authors: nora.brambilla@ph.tum.de, julian.mayer-steudte@tum.de, saumdatt@gmail.com, petreczk@bnl.gov, viljami.leino@uni-mainz.de, m.janer@tum.de

The real time evolution of a heavy particle in a strongly coupled plasma is determined by transport coefficients, such as the diffusion coefficient κ and γ. While, in the fundamental representation, the heavy quark diffusion is well studied, the diffusion of adjoint quarks or quarkonium has not yet been fully explored on the lattice. In a suitable NREFT description of QCD, κ can be related to the chromoelectric correlator and the first mass-suppressed correction can be extracted from the chromomagnetic correlator. γ is related to an integral over the chromoelectric correlator after subtracting the zero temperature correlator contribution, which is also related to gluelump masses and P-wave decay of heavy quarkonium.

We present results of the adjoint chromoelectric correlators at finite T under gradient flow and compare them to results from multilevel calculations.

Vacuum structure and confinement / 216

The imaginary-theta dependence of the SU(N) spectrum

Authors: Claudio Bonanno[1]; Claudio Bonati[2]; Davide Vadacchino[3]; Mario Papace[4]

[1] *IFT UAM/CSIC Madrid*

[2] *Università di Pisa*

[3] *University of Plymouth*

[4] *University of Wuppertal*

Corresponding Authors: davide.vadacchino@plymouth.ac.uk, claudio.bonanno@csic.es, mario.papace@uni-wuppertal.de, claudio.bonati@df.unipi.it

In this talk we will report on a study of the θ-dependence of the string tension and of the mass gap of four-dimensional SU(N) Yang-Mills theories. The spectrum at N=3 and N=6 was obtained on the lattice at various imaginary values of the θ parameter, using Parallel Tempering on Boundary Conditions to avoid topological freezing at fine lattice spacings. The coefficient of the O(θ^2) term in the Taylor expansion of the spectrum around θ=0 could be obtained in the continuum limit for N=3, and on two fairly fine lattices for N=6.

Quantum computing and quantum information / 234

Euclidean Monte Carlo informed ground state preparation for quantum simulation

Authors: Christopher David White[1]; Navya Gupta[1]; Zohreh Davoudi[1]

[1] *University of Maryland, College Park*

Corresponding Authors: cdwhite@umd.edu, navyag@umd.edu, davoudi@umd.edu

Quantum simulators offer great potential for investigating the dynamical properties of quantum field theories. However, a key challenge is the preparation of high-fidelity initial states for these simulations. In this study, we focus on ground states and explore how information about their static properties, which can be efficiently obtained using lattice-based path-integral Monte Carlo performed on classical computers, can help identify suitable initial states. For the scalar field theory in 1+1 dimensions, we demonstrate variational ansatz families that yield comparable ground state energy estimates but exhibit distinct correlations and local non-Gaussianity. The simulation of quantum dynamics is expected to be highly sensitive to such initial state moments beyond the energy. We show that it is possible to optimize the behavior of selected ansatz moments using known ground state moments to address specific simulation needs. Drawing inspiration from the scalar field theory, our ultimate goal is to utilize existing lattice quantum chromodynamics (QCD) data to inform the preparation of the QCD ground state on quantum simulators.

Theoretical developments / 64

Symplectic quantization: a new deterministic approach to the dynamics of quantum fields inspired by statistical mechanics

Authors: Giacomo Gradenigo[1]; Martina Giachello[1]

[1] *Gran Sasso Science Institute*

Corresponding Authors: giacomo.gradenigo@gssi.it, martina.giachello@gssi.it

The present work is about a new method to sample the quantum fluctuations of relativistic fields by means of a pseudo-Hamiltonian dynamics in an enlarge space of variables. The proposed approach promotes the fictitious time of Parisi-Wu stochastic quantisation to a true physical parameter controlling a deterministic dynamics. The sampling of quantum fluctuations is guaranteed by the presence of new additionational conjugated momenta, which reprents the rate of variation of ordinary fields with respect to the newly added time variable. The main goal of this approach is to provide a numerical method to sample quantum fluctuations of fields directly in Minkowski space, whereas all existent methods allowed one so far to do this only in Euclidean space, therefore loosing important physics. From the pseudo-Hamiltonian dynanamics one is then able, assuming ergodicity, to retrieve the Feynman path integral as the Fourier transform of a pseudo-microcanonical partition function. The whole framework proposed is not only the source of a new numerical approach to study quantum fields but also and most importantly reveals important connections between quantum field theory, statistical mechanics and Hamiltonian dynamics. Here we will discuss the main ideas behind the formalism and the first successful results of numerical tests, as well as the difficulties we encountered. (Preprint: https://arxiv.org/abs/2403.17149)

Theoretical developments / 9

Weyl Fermions on a Finite Lattice

Authors: Srimoyee Sen[1]; David Kaplan[2]

[1] *Iowa State University*

[2] *Institute for Nuclear Theory*

Corresponding Authors: dbkaplan@uw.edu, srimoyee@iastate.edu

The phenomenon of unpaired Weyl fermions appearing on the sole 2n dimensional boundary of a (2n+1)-dimensional manifold with massive Dirac fermions was recently analyzed. Similar unpaired Weyl edge states can be seen on a finite lattice. In particular, we consider the discretized Hamiltonian for a Wilson fermion in (2+1) dimensions with a 1+1 dimensional boundary and continuous time. We demonstrate that the low-lying boundary spectrum is indeed Weyl-like: it has a linear dispersion relation and definite chirality and circulates in only one direction around the boundary. We comment on how these results are consistent with Nielsen-Ninomiya theorem. This work removes one potential obstacle facing the program for regulating chiral gauge theories.

QCD at non-zero temperature / 264

An update on the determination of the sphaleron rate in finite temperature QCD

Authors: Nicolò Bellini[1]; Claudio Bonanno[2]; Francesco D'Angelo[1]; Massimo D'Elia[1]; Andrea Giorgieri[3]; Lorenzo Maio[4]

[1] *Università di Pisa & INFN Pisa*

[2] *IFT UAM/CSIC Madrid*

[3] *University of Pisa*

[4] *CPT, Marseille*

Corresponding Authors: massimo.delia@unipi.it, andrea.giorgieri@phd.unipi.it, lorenzo.maio@cpt.univ-mrs.fr, claudio.bonanno@csic.es, n.bellini1@studenti.unipi.it, francesco.dangelo@phd.unipi.it

The sphaleron rate is a key phenomenological quantity both for the axion thermal production in the early Universe and the Chiral Magnetic Effect occurring in the Quark-Gluon Plasma in presence of

a background magnetic field. In this talk we present an extension of our recent determination of the sphaleron rate, both in pure gauge and full QCD, based on the determination of the two-point function of the topological charge density at finite temperature.

Hadronic and nuclear spectrum and interactions / 474

$\pi\pi\pi$ scattering

Author: Haobo Yan[1]

[1] *Peking University*

Corresponding Author: haobo@stu.pku.edu.cn

The three-body problem, renowned for its unsolvable nature in celestial mechanics and homonymous science fiction, is not only solvable in the quantum realm regarding spectra but also offers profound insights into QCD. Many hadronic resonances, such as the Roper resonance, T_{cc}, and ω, can be thoroughly understood only by studying the underlying three-body dynamics. As a step toward analyzing more complex systems, we have performed lattice calculations of the $\pi\pi\pi$ finite-volume spectra, implemented the corresponding quantization conditions, and solved the integral equations. The resulting infinite-volume scattering information will be presented.

Quark and lepton flavour physics / 487

Hadronic τ data and Lattice QCD+QED simulations for the muon $g-2$

Author: Mattia Bruno[1]

[1] *Universita' di Milano-Bicocca*

Corresponding Author: mattia.bruno@unimib.it

Present tensions within data-driven estimates of the Hadronic-Vacuum-Polarization contribution to the muon anomalous magnetic moment, and additional tensions in the so-called intermediate window between dispersive and lattice calculations, are severely limiting our ability to test the Standard Model, with high precision. Investigating the role of hadronic τ decays as a different input to the dispersive approach is therefore becoming extremely timely. Using available experimental data, we present the current status of our determination of the intermediate window a_μ^W from τ data, and report our progress on the calculation of various sources of isospin-breaking effects, including radiative corrections.

Structure of hadrons and nuclei / 444

Nucleon electromagnetic form factors at large momentum from Lattice QCD

Author: Sergey Syritsyn[1]

[1] *Stony Brook University*

Corresponding Author: syritsyn@gmail.com

Proton and neutron electromagnetic form factors are some the primary characteristics of their spatial structure. At large momentum transfer Q^2, their behavior probes transition from nonperturbative to perturbative QCD dynamics, diquark correlations, quark orbital angular momenta, as well as other phenomenological assumptions about nucleon structure. Recently at JLab, data on the proton form factors up to $Q^2 = 18$ GeV^2 and the neutron form factors up to 14 GeV^2 have been collected. We will report progress in our lattice calculations of these form factors, including G_E and G_M nucleon form factors with momenta up to $Q^2 = 12$ GeV^2, pion masses down to the almost-physical m_π=170 MeV, several lattice spacings down to $a = 0.073$ fm, high $O(10^5)$ statistics, and disconnected diagrams. We study asymptotic behaviors of the G_E/G_M and F_2/F_1 ratios and separate light-flavor contributions to the form factors, which are both relevant to phenomenology and experiment. Comparison of our calculations and upcoming JLab experimental results will be an important test of nonperturbative QCD methods close to the perturbative regime.

Vacuum structure and confinement / 309

Numerical evidence for a CP broken deconfined phase at $\theta = \pi$ in 4D SU(2) Yang-Mills through simulations at imaginary θ

Authors: Mitsuaki Hirasawa[1]; Kohta Hatakeyama[2]; Masazumi Honda[3]; Akira Matsumoto[4]; Jun Nishimura[5]; Atis Yosprakob[6]

[1] *University of Milano-Bicocca*

[2] *Kyoto University*

[3] *RIKEN iTHEMS*

[4] *Yukawa Institute for Theoretical Physics, Kyoto University*

[5] *KEK, SOKENDAI*

[6] *Niigata University*

Corresponding Authors: mitsuaki.hirasawa@mib.infn.it, akira.matsumoto@yukawa.kyoto-u.ac.jp, yosprakob2@gmail.com

We investigate the possibility of the spontaneous breaking of CP symmetry in 4D SU(2) Yang-Mills at $\theta = \pi$, which has recently attracted much attention in the context of the higher-form symmetry and the 't Hooft anomaly matching condition. Here we provide a numerical evidence that the CP symmetry is indeed spontaneously broken at low temperature and it gets restored above the deconfining temperature at $\theta = \pi$, which is consistent with the anomaly matching condition and yet differs from the situation predicted in the large-N limit. We avoid the severe sign problem by performing simulations at imaginary θ. Then we estimate the relation between the critical temperature of the CP restoration and that of deconfinement at $\theta = \pi$ by analytic continuation.

Quantum computing and quantum information / 398

Quantum Many-Body Scars in 2+1D Gauge Theories

Authors: Joao Pinto Barros[1]; Marina Krstic Marinkovic[2]; Thea Budde[1]

[1] *ETH Zürich*

[2] *ETH Zurich*

Corresponding Authors: jpinto@phys.ethz.ch, tbudde@phys.ethz.ch, marinama@phys.ethz.ch

The real-time dynamics of Quantum Chromodynamics and other strongly coupled gauge theories present significant challenges for standard Monte Carlo methods due to severe sign problems. This limitation makes these problems ideal candidates for quantum simulation techniques. Identifying

phenomena that can be tackled using near-term quantum simulators is crucial for understanding of real-time dynamics in strongly coupled gauge theories.

Quantum many-body scars have recently garnered attention for challenging
the Eigenstate Thermalization Hypothesis (ETH). I will discuss the
emergence of quantum many-body scarring in $U(1)$ gauge theories in (2+1)-d and arbitrary dimension (spin) of the gauge links. Benchmarking against the exact diagonalization for small spin systems, we uncover the analytical structure that facilitates the construction of scar states in gauge links with arbitrarily large Hilbert space dimensions. This allows us to explore potential imprint of quantum many-body scars as we approach the continuum limit and sheds light on how many-body systems may fail to thermalize.

Theoretical developments / 156

Testing nucleation calculations for strong phase transitions

Authors: Anna Kormu[1]; David Weir[1]; Oliver Gould[2]

[1] *University of Helsinki*

[2] *University of Nottingham*

Corresponding Authors: david.weir@helsinki.fi, anna.kormu@helsinki.fi, oliver.gould@nottingham.ac.uk

Accurate calculations of the nucleation rate Γ for first order phase transitions are important for determining their observable consequences in particle physics and cosmology. Perturbative calculations are often used, but they are incomplete and should be tested against fully nonperturbative lattice simulations. We simulate nucleation on the lattice in a scalar field theory with a tree-level barrier, a scenario which should be well described by perturbation theory. Our computation of the nucleation rate, however, only shows qualitative agreement with the perturbative result. This motivates further study of nucleation on the lattice and to higher orders in perturbation theory.

Hadronic and nuclear spectrum and interactions / 35

Quark mass dependence of doubly heavy tetraquark binding

Authors: Anthony Francis[1]; Brian Colquhoun[2]; Kim Maltman[3]; Randy Lewis[3]; Renwick Hudspith[3]; William Parrott[3]

[1] *National Yang Ming Chiao Tung University*

[2] *University of Glasgow*

[3] *York University*

Corresponding Authors: randy.lewis@yorku.ca, brian.colquhoun@glasgow.ac.uk, afrancis@nycu.edu.tw, parrott@yorku.ca, renwick.james.hudspith@gmail.com, kmaltman@yorku.ca

The existence of bound doubly heavy tetraquark states was confirmed by the recent LHCb discovery of the doubly charmed T_{cc}, less than 1MeV below the meson pair threshold. Other states with two heavy (bottom or charm) quarks could also be bound, perhaps more deeply. Here we discuss our previous work, and the improvements in our current, updated analysis of various heavy-heavy-light-light tetraquark candidates, including the light and heavy quark mass dependence of the binding.

Quark and lepton flavour physics / 105

Status report on the hadronic light-by-light contribution to the muon g-2 using twisted-mass fermions.

Authors: Gurtej Kanwar[1]; Marcus Petschlies[2]; Nikolaos Kalntis[1]; Simone Romiti[1]; Urs Wenger[1]

[1] *University of Bern*

[2] *U. Bonn*

Corresponding Authors: nikos.kalntis@gmail.com, simone.romiti.1994@gmail.com, gurtejkanwar@gmail.com, wenger@itp.unibe.ch

We report on our preliminary results on the lattice computation of the hadronic light-by-light contribution to the anomalous magnetic moment of the muon. We use twisted-mass fermions on $N_f = 2 + 1 + 1$ gauge ensembles at the physical point generated by the Extended Twisted Mass Collaboration (ETMC).

Structure of hadrons and nuclei / 73

A proposal for removing πN-state contamination from the nucleon induced pseudoscalar form factor in lattice QCD

Author: Shoichi Sasaki[1]

Co-authors: Yasumichi Aoki [2]; Ken-Ichi Ishikawa [3]; Yoshinobu Kuramashi [4]; Kohei Sato [5]; Eigo Shintani [5]; Ryutaro Tsuji [6]; Hiromasa Watanabe [7]; Takeshi Yamazaki [8]

[1] *Department of Physics, Tohoku University*

[2] *RIKEN*

[3] *Hiroshima University*

[4] *University of Tsukuba/RIKEN AICS*

[5] *University of Tsukuba*

[6] *KEK*

[7] *YITP, Kyoto Univerisity*

[8] *Univ. of Tsukuba*

Corresponding Authors: ssasaki@nucl.phys.tohoku.ac.jp, eigo.shintani@gmail.com, yasumichi.aoki@riken.jp, rtsuji@post.kek.jp, yamazaki@het.ph.tsukuba.ac.jp, ksatoh@het.ph.tsukuba.ac.jp, kuramasi@het.ph.tsukuba.ac.jp, ishikawa@theo.phys.sci.hiroshima-u.ac.jp

In the PACS10 project, the PACS collaboration have generated three sets of the PACS10 gauge configurations at the physical point with lattice volume larger than $(10 \text{ fm})^4$ and three different lattice spacings. The isovector nucleon form factors had been already calculated by using two sets of the PACS10 gauge configurations. In our strategy, the smearing parameters of the nucleon interpolation operator were highly optimized to eliminate as much as possible the contribution of excited states in the nucleon two-point function. This strategy was quite successful in calculations of the electric (G_E), magnetic (G_M) and axial-vector (F_A) form factors, while the induced pseudoscalar (F_P) and pseudoscalar (G_P) form factors remained strongly affected by residual contamination of πN-state contribution. In this talk, we propose a simple method to remove the πN-state contamination from the F_P form factor, and then evaluate the induced pseudoscalar charge g_P^* and the pion-nucleon coupling $g_{\pi NN}$ from existing data in a new analysis. Applying this method to the G_P form factor will also be considered.

QCD at non-zero temperature / 135

Constraints on the Dirac spectrum from chiral symmetry restoration and the fate of $\mathrm{U}(1)_A$ symmetry

Author: Matteo Giordano[1]

[1] *Eotvos University, Budapest*

Corresponding Author: giordano@bodri.elte.hu

I discuss chiral symmetry restoration in the chiral limit of QCD with two quark flavours of mass m, focussing on its consequences for scalar and pseudoscalar susceptibilities, and on the resulting constraints on the Dirac spectrum. I show that $\mathrm{U}(1)_A$ symmetry remains broken in the $\mathrm{SU}(2)_A$ symmetric phase if the spectral density $\rho(\lambda; m)$ develops a singular near-zero peak, tending to m^4/λ in the chiral limit. Moreover, $\mathrm{SU}(2)_A$ restoration requires that the number of modes in the peak be proportional to the topological susceptibility, indicating that such a peak must be of topological origin.

Vacuum structure and confinement / 149

Absence of CP violation in the strong interaction

Author: Gerrit Schierholz[1]

[1] *DESY*

Corresponding Author: gerrit.schierholz@desy.de

Quantum Chromodynamics admits a CP-violating contribution to the action, the θ term, which is expected to give rise to a nonvanishing electric dipole moment of the neutron. Despite intensive search, no CP violations have been found. This puzzle is referred to as the strong CP problem. In this talk I will show, on a dynamical basis, that CP is conserved in the strong interaction.

Quantum computing and quantum information / 6

Quantum Simulation of Large N Lattice Gauge Theories

Authors: Anthony Ciavarella[1]; Christian Bauer[1]

[1] *Lawrence Berkeley National Lab*

Corresponding Authors: anciavarella@lbl.gov, cwbauer@lbl.gov

A Hamiltonian lattice formulation of lattice gauge theories opens the possibility for quantum simulations of the non-perturbative dynamics of QCD. By parametrizing the gauge invariant Hilbert space in terms of plaquette degrees of freedom, we show how the Hilbert space and interactions can be expanded in inverse powers of Nc. At leading order in this expansion, the Hamiltonian simplifies dramatically, both in the required size of the Hilbert space as well as the type of interactions involved. Adding a truncation of the resulting Hilbert space in terms of local energy states we give explicit constructions that allow simple representations of SU(3) gauge fields on qubits and qutrits to leading order in large N. This enabled a simulation of the real time dynamics of a SU(3) lattice gauge theory on a 8x8 lattice with a superconducting quantum processor.

Algorithms and artificial intelligence / 370

Kernels and integration cycles in complex Langevin simulations

Authors: Denes Sexty[1]; Michael Mandl[1]; Michael Westh Hansen[1]

[1] *University of Graz*

Corresponding Authors: denes.sexty@uni-graz.at, michael.hansen@uni-graz.at, mi.mandl@gmx.at

The study of Quantum Chromodynamics (QCD) at non-zero baryonic density from first principles is notoriously hard due to the infamous sign problem. One way to potentially by-pass the sign problem is the complex Langevin approach, which is based on a complexification of the underlying field manifold. While this method does not suffer from a sign problem, it is plagued by its own set of shortcomings, which will be the main topic of this talk. In particular, we will discuss the problem that complex Langevin simulations sometimes produce incorrect results despite apparently converging correctly. Using simple toy models, we outline how correct results may be recovered by introducing a so-called kernel into the complex Langevin equations. Moreover, we elaborate on the origin of wrong convergence in the "absence of boundary terms" (which is sometimes viewed as a criterion for correctness) and trace it back to an interplay of different competing so-called integration cycles.

Theoretical developments / 11

Exact lattice chiral symmetry in 2d gauge theory

Author: Aleksey Cherman[1]

Co-author: Evan Berkowitz [2]

[1] *University of Minnesota*

[2] *Forschungszentrum Jülich*

Corresponding Authors: e.berkowitz@fz-juelich.de, acherman@umn.edu

I'll explain how to construct symmetry-preserving lattice regularizations of 2d QED, as well as the '3450' chiral gauge theory. The basic idea is to leverage bosonization and recently-proposed modifications of Villain-type lattice actions. The internal global symmetries act just as locally on the lattice as they do in the continuum, the anomalies are reproduced at finite lattice spacing. We also find methods to evade the sign problems that would naively occur in our construction.

Hadronic and nuclear spectrum and interactions / 59

Strong decay of double charm tetra quark T_cc

Author: Subhasish Basak[1]

Co-authors: Protick Mohanta ; Srijit Paul [2]

[1] *National Institute of Science Education and Research (NISER)*

[2] *University of Maryland*

Corresponding Authors: spaul137@umd.edu, sbasak@niser.ac.in, protick.mohanta@gmail.com

We report our ongoing study of the pole structure of doubly charmed tetraquark T_{cc}. In this work we considered diquark-antidiquark, molecular and scattering operators in our analysis. Relativistic Heavy Quark action and clover improved Wilson action have been employed

for charm and light quarks respectively. We varied the light quark mass to determine the region where three body effects becomes important. We present our preliminary results obtained at eight κ values on MILC $N_f = 2+1$ asqtad lattices with $a \sim 0.15$ and 0.09 fm.

Quark and lepton flavour physics / 213

The hadronic light-by-light contribution to the muon $g{-}2$ using staggered fermions at the physical point

Authors: Antoine Gerardin[1]; Christian Zimmermann[2]

[1] *Centre de Physique Théorique de Marseille*

[2] *Centre de Physique Théorique, Marseille*

Corresponding Authors: christian.zimmermann@univ-amu.fr, antoine.gerardin@univ-amu.fr

Hadronic contributions dominate the uncertainty of the Standard Model prediction for the anomalous magnetic moment of the muon. In this work, we present results on the hadronic light-by-light contribution obtained from the evaluation of the hadronic four-point function of electromagnetic currents using the position-space formalism developed by the Mainz group. The simulations are performed with staggered fermions directly at the physical point. Our results include continuum extrapolations for connected and leading disconnected diagrams for light, strange and charm quark contributions. Several physical volumes are used to estimate finite volume effects. This direct lattice study is supplemented by considering the contribution of the light pseudoscalar pole in both finite and infinite volumes, where we reuse the transition form factors that have been evaluated in previous simulations on the same ensembles.

Structure of hadrons and nuclei / 252

$\gamma^* N \to \pi N$ on Lattice

Author: Yusheng Gao[1]

Co-authors: Jin Luchang [2]; Xu Feng [1]; Zhaolong Zhang [1]

[1] *Peking University*

[2] *Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA*

Corresponding Authors: xu.feng@pku.edu.cn, 2101110096@stu.pku.edu.cn

In this talk, I will report on the lattice QCD calculation of pion electroproduction on the nucleon. This process describes how pions are produced when nucleons are struck by electrons and provides insights into the internal structure of nucleon. At pion-production threshold, we extract the multipole amplitudes E_{0+} and L_{0+} from the $N + \gamma^* \to N\pi$ matrix element. The rescattering effects between the nucleon and the pion are also evaluated, and the Lellouch-Luscher factor is properly included to convert the $N\pi$ state in the finite volume to that in the infinite volume. processes involving pions.

QCD at non-zero temperature / 208

QCD topology, axions and electromagnetic fields

Authors: Bastian Brandt[1]; Gergely Endrodi[2]; Gergely Marko[2]; José Javier Hernández Hernández[1]; Laurin Pannullo[1]

[1] *University of Bielefeld*

[2] *Bielefeld University*

Corresponding Authors: lpannullo@physik.uni-bielefeld.de, hernandez@physik.uni-bielefeld.de, gmarko@physik.uni-bielefeld.de, brandt@physik.uni-bielefeld.de, endrodi@physik.uni-bielefeld.de

We present the first non-perturbative determination of the magnetic field dependence of the QCD topological susceptibility for temperatures in the crossover region. We use 2+1 flavours of improved staggered quarks at the physical point. In our study we employ a reweighting of the fermion determinant to reduce the discretisation effects and obtain a controlled continuum limit. The identification of the topological modes at low temperatures, necessary for the correct implementation of the reweighting, is complicated due to the mixing of the topological would-be zero modes and the modes building up the chiral condensate. We will show that the ratios of reweighted susceptibilities are unaffected to the possible misidentification of the topological zero modes. Furthermore we will also discuss our recent progress regarding the non-perturbative determination of the QCD contributions to the axion-photon coupling.

Vacuum structure and confinement / 281

Scale setting of $\mathrm{SU}(N)$ Yang–Mills theories via Twisted Gradient Flow

Authors: Andrea Giorgieri[1]; Claudio Bonanno[2]; Jorge Luis Dasilva Golán[3]; Margarita Garcia-Perez[4]; Massimo D'Elia[5]

[1] *University of Pisa*

[2] *IFT UAM/CSIC Madrid*

[3] *Physics Deparment, Brookhaven National Laboratory*

[4] *Instituto de Fisica Teorica UAM-CSIC*

[5] *University of Pisa and INFN*

Corresponding Authors: jgolandas@bnl.gov, margarita.garcia@uam.es, claudio.bonanno@csic.es, massimo.delia@unipi.it, andrea.giorgieri@phd.unipi.it

We present preliminary results for the scale setting of $\mathrm{SU}(N)$ Yang–Mills theories using twisted boundary conditions and the gradient-flow scale $\sqrt{t_0}$. The end goal of this study is to determine the SU(N) Λ-parameter through the step-scaling method. The scale $\sqrt{t_0}$, being defined from the flowed action density of the gauge fields, is correlated with their topological charge and thus could be affected by topological freezing. We deal with this problem with the Parallel Tempering on Boundary Conditions algorithm, which we found to be effective for the same numerical setup in previous work.

Quantum computing and quantum information / 32

Duality and entanglement in lattice gauge theories

Authors: Andrea Bulgarelli[1]; Marco Panero[1]

[1] *University of Turin and INFN Turin*

Corresponding Authors: andrea.bulgarelli@unito.it, panero@to.infn.it

The study of entanglement in quantum field theories provides insight into universal properties which are typically challenging to extract by means of local observables. However, calculations of quantities related to entanglement in gauge theories are limited by ambiguities that stem from the non-factorizability of the Hilbert space. On the other hand, Abelian lattice gauge theories are known to admit a dual description in terms of spin models, for which the replica trick and Rényi entropies are well defined. In the first part of the talk, I will discuss how duality transformations can be used to unambiguously derive the lattice geometry of the replica space for Abelian gauge theories. In the second part, I will present a numerical study of the entropic c-function of the (2+1)-dimensional $\mathbb{Z}_2$ gauge theory in the continuum limit, and compare it with analytical predictions from holographic models.

Algorithms and artificial intelligence / 41

Designing weight regularizations based on Lefschetz thimbles to stabilize complex Langevin

Authors: Kirill Boguslavski[1]; Paul Hotzy[1]; David Müller[1]

[1] *TU Wien*

Corresponding Authors: paul.hotzy@tuwien.ac.at, dmueller@hep.itp.tuwien.ac.at, kirill.boguslavski@tuwien.ac.at

The complex Langevin (CL) method shows significant potential in addressing the numerical sign problem. Nonetheless, it often produces incorrect results when used without any stabilization techniques. Leveraging insights from previous research that links Lefschetz thimbles and CL, we explore a strategy to regularize the CL method to address this issue of incorrect convergence. Specifically, we implement weight regularizations inspired by the associated Lefschetz thimble structure. We demonstrate the effectiveness of this approach by solving the SU(N) Polyakov chain model and various scalar models, including the cosine model and the one-link model, across a broad range of couplings where the CL method previously failed. We also discuss the potential application of these insights to gauge theories in practical scenarios.

Theoretical developments / 329

Generalized BKT Transitions and Persistent Order on the Lattice

Author: Evan Berkowitz[1]

Co-authors: Aleksey Cherman [2]; Srimoyee Sen [3]

[1] *Forschungszentrum Jülich*

[2] *University of Minnesota*

[3] *Iowa State University*

Corresponding Authors: acherman@umn.edu, srimoyee@iastate.edu, e.berkowitz@fz-juelich.de

The BKT transition in low-dimensional systems with a U(1) global symmetry separates a trivially gapped, disordered phase, and is driven by vortex proliferation. Recent developments in modified Villain actions provide a class of lattice models which have an extra $\mathbb{Z}_W$ global symmetry that counts vortices mod W, mixed ‘t Hooft anomalies, and persistent order even at finite lattice spacing. While there is no fully-disordered phase (except in the original BKT case) there is still a phase boundary which separates gapped ordered phases from gapless phases. I'll describe a numerical Monte Carlo exploration of these phenomena.

Hadronic and nuclear spectrum and interactions / 95

Towards quark mass dependence of Tcc

Author: Sasa Prelovsek[1]

Co-authors: Alexey Nefediev [2]; Padmanath Madanagopalan [3]; Sara Collins [4]

[1] *University of Ljubljana*

[2] *Jozef Stefan Institute*

[3] *The Institute of mathematical Sciences, Chennai*

[4] *University of Regensburg*

Corresponding Authors: padmanath@imsc.res.in, anelxey.nefediev@ijs.si, sasa.prelovsek@ijs.si, sara.collins@ur.de

I will present how the DD*scattering amplitude and the pole positions in Tcc channel vary with the charm and the light-quark masses. This will be based on our lattice results for five charm quark masses and results by other groups for various light-quark mass. Effective Field Theory for DD* interaction mediated by pions implies attraction at short range and a slight repulsion at long range mediated by one-pion exchange for mpi > mD*-mD. The pion exchange manifests as a left-hand cut in the partial wave projected scattering amplitude, which is accounted for in our analysis. Tcc pole transitions between a resonance, virtual and bound state as charm and light quark masses are varied.

Quark and lepton flavour physics / 247

Lattice QCD calculation of pion pole's contribution to HLbL

Author: Tian Lin[1]

[1] *School of Physics, Peking University*

Corresponding Author: tlin@stu.pku.edu.cn

In this study we develop a novel method for computing the pion pole's contribution to hadronic light-by-light in the absence of a parametrization of the pion transition form factor. By introducing a pion structure function and performing the gegenbauer expansion, we demonstrate that the majority of the pion pole's contribution can be extracted in a model-independent manner.
The calculation is carried out using five ensembles generated with 2+1 flavor domain wall fermions at the physical pion mass. After performing a continuum extrapolation and analyzing systematic effects, we obtain the final result $a_\mu^{\pi^0\text{-pole}} = (58.3 \pm 2.3) \times 10^{-11}$.

Structure of hadrons and nuclei / 210

Update on pion scalar radii with $N_f = 2 + 1$ Clover-improved Wilson fermions

Author: Konstantin Ottnad[1]

Co-author: Georg von Hippel [1]

[1] *University of Mainz*

Corresponding Authors: hippel@uni-mainz.de, kottnad@uni-mainz.de

We give a status update on our analysis of the pion scalar form factors $F_S^{\pi,f}$, $f = l, 0, 8$ and the associated radii $\langle r_S \rangle_\pi^{l,0,8}$. Our lattice results are computed on a large set of 18 CLS gauge ensembles with $N_f = 2+1$ Wilson Clover-improved sea quarks. These ensembles cover four values of the lattice spacing $a = 0.049\mathrm{fm} \dots 0.086\mathrm{fm}$, a pion mass range of $130\mathrm{MeV}$ to $350\mathrm{MeV}$ and many different physical volumes. The precise determination of the notorious quark disconnected contributions together with large and fine ensembles in the vicinity of physical quark masses allow us to achieve an unprecedented momentum resolution for $F_S^{\pi,f}$.
In addition to ensembles on the $\mathrm{tr}[M] = \mathrm{const}$ trajectory ensembles on a trajectory with constant strange quark mass $m_s \approx \mathrm{phys}$ have now been included as well. Further improvements compared to what has been presented at the previous Lattice conference include, but are not limited to: Increased gauge statistics on our most chiral ensembles by a factor 2 to 3, a factor ~ 4 increase in the number of measurements for the two-point functions used in the computation of the $2+1$ quark-disconnected diagrams, and an enhanced method for the subtraction of the vacuum expectation value on ensembles with open boundary conditions.

The ground state matrix elements are extracted with controlled systematics using several ansätze and the radii are obtained from a z-expansion fitted to the $Q^2-dependence of the resulting form factors. The physical extrapolation of these results is carried out using NLO chiral perturbation theory to parametrize the quark mass dependence.

QCD at non-zero temperature / 147

QCD Anderson transition with overlap valence quarks on a twisted-mass sea

Authors: Dominik Smith[1]; Lorenz von Smekal[2]; Robin Kehr[3]

[1] *Justus Liebig University Giessen, Facility for Antiproton and Ion Research in Europe GmbH*

[2] *Justus Liebig University Giessen, Helmholtz Forschungsakademie Hessen für FAIR*

[3] *Justus Liebig University Giessen*

Corresponding Authors: robin.kehr@physik.uni-giessen.de, dominik.d.smith@theo.physik.uni-giessen.de, lorenz.smekal@physik.uni-giessen.de

In this work we probe the QCD Anderson transition by studying spectral distributions of the massless overlap operator on gauge configurations created by the *twisted mass at finite temperature collaboration* (tmfT) with 2+1+1 flavors of dynamical quarks and the Iwasaki gauge action. We assess finite-size and discretization effects by considering two different lattice spacings and several physical volumes, and mimic the approach to the continuum limit through stereographic projection. Fitting the inflection points of the participation ratios of the overlap Dirac eigenmodes, we obtain estimates of the temperature dependence of the mobility edge, below which quark modes are localized. We observe that it is well described by a quadratic polynomial and systematically vanishes at temperatures below the pseudocritical one of the chiral transition. In fact, our best estimates within errors overlap with that of the chiral phase transition temperature of QCD in the chiral limit.
In addition to the published version of this work, more recent results on lower temperatures and gauge configurations smoothed with gradient flow will be presented.

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Vacuum structure and confinement / 308

The confined-deconfined surface tension in SU(N) gauge theories at large N

Authors: Ahmed Salami[None]; Kari Rummukainen[1]; Tobias Rindlisbacher[2]

[1] *University of Helsinki*

[2] *University of Bern*

Corresponding Author: ahmed.salami@helsinki.fi

We present results from an investigation of the N-dependency of the confined-deconfined interface tension in pure $SU(N)$ gauge theories at large N. By measuring the transverse fluctuations of the surface on large lattices, we determine the surface tension up to $N = 16$ and observe unambiguously that it scales as N^2. Our results show that in the continuum limit the surface tension can be described by $\sigma/T_c^3 = -0.16(4) + 0.0173(11)N^2(N \geq 4)$.

Quantum computing and quantum information / 268

Towards quantum simulation of lower-dimensional supersymmetric lattice models

Author: Emanuele Mendicelli[1]

Co-author: David Schaich [1]

[1] *University of Liverpool*

Corresponding Authors: david.schaich@liverpool.ac.uk, emanuelemendicelli@hotmail.it

Supersymmetric models are built upon a hypothetical symmetry between bosonic and fermionic particles. Lattice studies of their non-perturbative features such as spontaneous supersymmetry breaking and real-time evolution are limited by the sign-problem. The sign-problem can be avoided by working in the Hamiltonian formalism, but it requires an amount of classical resources that grows exponentially with the number of lattice sites and bosonic modes. The use of a quantum hardware instead makes the study feasible because it requires a polynomial growing amount of quantum resources. In this talk, we discuss how to encode supersymmetric models on qubits and briefly present ongoing efforts and challenges of running some lower-dimensional systems on noisy IBM gate-based quantum hardware.

Algorithms and artificial intelligence / 146

Diffusion models and stochastic quantisation in lattice field theory

Author: Gert Aarts[1]

Co-authors: Lingxiao Wang [2]; Kai Zhou [3]

[1] *Swansea University*

[2] *RIKEN*

[3] *Chinese University of Hong Kong (CUHK)*

Corresponding Authors: lingxiao.wang@riken.jp, g.aarts@swansea.ac.uk, zhoukai@cuhk.edu.cn

Diffusion models are currently the leading generative AI approach used for image generation in e.g. DALL-E and Stable Diffusion. In this talk we relate diffusion models to stochastic quantisation in field theory and employ it to generate configurations for scalar fields on a two-dimensional lattice. We end with some speculations on possible applications.

Theoretical developments / 34

Scaling results for charged sectors of near conformal QCD

Authors: Alessandra D'Alise[1]; Clelia Gambardella[2]; Francesco Sannino[3]; Jahmall Bersini[4]

[1] *Università degli studi di Napoli "Federico II" & INFN sezione di Napoli, Napoli, Italy*

[2] *Scuola Superiore Meridionale & INFN sezione di Napoli, Napoli, Italy*

[3] *Quantum Theory Center at IMADA and D-IAS, Odense, Denmark & Università degli studi di Napoli "Federico II" & INFN sezione di Napoli & Scuola Superiore Meridionale, Napoli, Italia*

[4] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Japan*

Corresponding Authors: sannino@qtc.sdu.dk, c.gambardella@ssmeridionale.it, jahmall.bersini@ipmu.jp, alessandra.dalise@unina.it

We provide the leading near conformal corrections on a cylinder to the scaling dimension of the lowest-lying fixed isospin charge Q operators defined at the lower boundary of the Quantum Chromodynamics conformal window:
\begin{equation}
\tilde{\Delta}Q = \tilde{\Delta}_Q^\ast +\left(\frac{m{\sigma}}{4 \pi \nu}\right)^2 \, Q^{\frac{\Delta}{3}} B_1 + \left(\frac{m_\pi(\theta)}{4\pi \nu} \right)^4\ Q^{\frac{2}{3}(1-\gamma)} B_2 + \mathcal{O}\left (m_\sigma^4 , m_\pi^8, m_\sigma^2 m_\pi^4\right) \ . \nonumber
\end{equation}
Here $\tilde{\Delta}_Q/r$ is the classical ground state energy of the theory on $\mathbb{R}\times S^3_r$ at fixed isospin charge while $\tilde{\Delta}^*_Q$ is the scaling dimension at the leading order in the large charge expansion. In the conformal limit $m_\sigma = m_\pi = 0$ the state-operator correspondence implies $\tilde{\Delta}_Q = \tilde{\Delta}^*_Q$.
The near-conformal corrections are expressed in powers of the dilaton and pion masses in units of the chiral symmetry breaking scale $4\pi\nu$ with the θ-angle dependence encoded directly in the pion mass. The characteristic Q-scaling is dictated by the quark mass operator anomalous dimension γ and the one characterizing the dilaton potential Δ. The coefficients B_i with $i = 1, 2$ depend on the geometry of the cylinder and properties of the nearby conformal field theory.

Hadronic and nuclear spectrum and interactions / 272

T_{cc} via plane wave approach and including diquark-antidiquark operators

Authors: Ivan Vujmilović[1]; Sasa Prelovsek[2]; Emmanuel Ortiz Pacheco[3]; Luka Leskovec[2]; Padmanath Madanagopalan[4]; Sara Collins[5]

[1] *Jožef Stefan Institute*

[2] *University of Ljubljana*

[3] *Michigan State University*

[4] *The Institute of mathematical Sciences, Chennai*

[5] *University of Regensburg*

Corresponding Authors: sasa.prelovsek@ijs.si, ivan.vujmilovic@ijs.si, ortizpac@msu.edu, sara.collins@ur.de, padmanath@imsc.res.in, luka.leskovec@ijs.si

The analysis of DD^* scattering, where the exotic state T_{cc} was discovered in 2021, in lattice QCD is complicated by long-range interactions, which make the extraction of the scattering amplitude via the Lüscher method dubious. We tackle this problem with a multifaceted approach: first, in addition to the relevant scattering operators, we incorporate a diquark-antidiquark interpolator in order to get the full picture of the energy spectrum. The inclusion of the latter has some impact at physical charm quark mass, although it is more significant for larger heavy quark masses, in line with expectations. Second, we adopt the plane-wave and effective-field-theoretic methods to address the left-hand cut problem and partial wave mixing.

Quark and lepton flavour physics / 227

Progress on the Hadronic vacuum polarization contribution to muon g-2 from lattice QCD

Authors: Christopher Aubin[1]; Luchang Jin[2]; Maarten Golterman[3]; Santiago Peris[4]; Thomas Blum[5]; Vaishakhi Moningi[2]

[1] *Fordham University*

[2] *University of Connecticut*

[3] *San Francisco State University*

[4] *univ. autonoma de barcelona*

[5] *UConn*

Corresponding Authors: maarten@sfsu.edu, vaishakhi.moningi@uconn.edu, luchang.jin@uconn.edu, peris@ifae.es, thomas.blum@uconn.edu, caubin@fordham.edu

We give an update of our calculation of the light-quark, connected hadronic vacuum polarization contribution to the muon anomalous magnetic moment. The update includes preliminary results on a $2 + 1 + 1$ highly-improved staggered quark (HISQ) ensemble from the MILC collaboration with physical pion mass, 0.042 fm lattice spacing, and size $144^3 \times 288$ sites. We discuss code and algorithm improvements for these calculations to compute the vector-vector correlation function more efficiently.

Structure of hadrons and nuclei / 219

Calculation of meson charge radii using model-independent method in the PACS10 configuration

Author: Kohei Sato[1]

Co-authors: Hiromasa Watanabe [2]; Takeshi Yamazaki [3]

[1] *University of Tsukuba*

[2] *YITP, Kyoto U.*

[3] *Univ. of Tsukuba*

Corresponding Authors: yamazaki@het.ph.tsukuba.ac.jp, ksatoh@het.ph.tsukuba.ac.jp

We report our preliminary results for the charge radii of π^+ and K^+ mesons with the PACS10 configuration generated at the physical point using the Iwasaki gauge action and $N_f = 2{+}1$ stout-smeared nonperturbatively $\mathcal{O}(a)$ improved Wilson quark action, especially at $a = 0.085$ fm corresponding lattice size 128^4. The charge radii are obtained from a model-independent method that directly calculates the first-order differential coefficient of the electromagnetic form factor and also from a traditional method that analyzes the form factor using a fit ansatz. We compare our preliminary results obtained by these various methods with previous lattice calculations and experiments.

QCD at non-zero temperature / 152

Localization of Dirac modes in the finite temperature SU(2)-Higgs model

Authors: György Baranka[1]; Matteo Giordano[2]

[1] *ELTE*

[2] *Eotvos University, Budapest*

Corresponding Authors: giordano@bodri.elte.hu, barankagy@gmail.com

Low-lying Dirac modes become localized at the finite-temperature transition in QCD and other gauge theories, indicating a connection between localization and deconfinement. This phenomenon can be understood through the "sea/islands" picture: in the deconfined phase, modes become trapped on "islands" of Polyakov loop fluctuations within a "sea" of ordered Polyakov loops.

To test the universality of the "sea/islands" mechanism, we investigate whether changes in the localization properties of low modes occur across other thermal transitions where the Polyakov loop becomes ordered, beyond the usual deconfinement transition. The fixed-length SU(2)-Higgs model is appropriate for this study. After mapping out the phase diagram, we find that low Dirac modes become localized in the deconfined and Higgs phases, where the Polyakov loop is ordered. However, localization is absent in the confined phase. These findings confirm the "sea/islands" picture.

Vacuum structure and confinement / 238

Fractional instantons and Confinement: a T2XR2 roadmap

Authors: Antonio Gonzalez-Arroyo[1]; Georg Bergner[2]; Ivan Soler[3]

[1] *Instituto de Fisica Teorica UAM/CSIC*

[2] *University of Jena*

[3] *University of Pisa*

Corresponding Authors: antonio.gonzalez-arroyo@uam.es, georg.bergner@uni-jena.de, ivan.soler@df.unipi.it

We report results obtained for SU(2) Yang-Mills theory on a 4d torus with two directions much smaller than the other two. The small 2-torus is equipped with twisted boundary conditions. This construction provides a way to interpolate from a region in which semiclassical methods can be applied (for small 2-torus size) to the standard infinite volume case. Our simulations at small torus sizes show how the topological charge and the string tension result from a gas of vortex-like fractional instantons. As the size becomes larger the density increases in agreement with fractional instanton liquid model picture of the Yang-Mills vacuum.

Quantum computing and quantum information / 425

Dynamics of the Sachdev-Ye-Kitaev model

Author: Muhammad Asaduzzaman[1]

Co-authors: Bharath Sambasivam ; Raghav Govind Jha

[1] *University of Iowa*

Corresponding Authors: masaduzzaman@uiowa.edu, raghav.govind.jha@gmail.com, bsambasi@syr.edu

We study the dynamics of the SYK model, an important toy model for quantum gravity, on IBM's superconducting qubit quantum computers. Using a graph coloring algorithm for construction with the Jordan-Wigner transformation, we find an implementation for the Trotter evolution with a complexity of $\mathcal{O}(N^5J^2t^2/\epsilon)$, where N represents the number of Majorana fermions, J is the dimensionful coupling parameter, t is the evolution time, and ϵ is the desired precision. With IBM's Eagle r3 processor, we performed simulations of quantum circuits with different error mitigation techniques. In particular, we compute the vacuum return probability and out-of-time-order correlators (OTOC), which are standard observables for quantifying the chaotic nature of quantum systems.

Algorithms and artificial intelligence / 176

Diffusion models learn distributions generated by complex Langevin dynamics

Author: Diaa Eddin Habibi[1]

Co-authors: Gert Aarts [1]; Kai Zhou [2]; Lingxiao Wang [3]

[1] *Swansea University*

[2] *Chinese University of Hong Kong (CUHK)*

[3] *RIKEN*

Corresponding Authors: zhoukai@cuhk.edu.cn, lingxiao.wang@riken.jp, g.aarts@swansea.ac.uk, diaaeddinh@gmail.com

The probability distribution effectively sampled by a complex Langevin process for theories with a sign problem is not known a priori and notoriously hard to understand. Diffusion models, a class of generative AI, can learn distributions from data. In this contribution, we explore the ability of diffusion models to learn the distributions created by a complex Langevin process.

QCD at non-zero temperature / 107

Pseudoscalar Screening Mass at Finite Temperature and Magnetic Field

Authors: Heng-Tong Ding[1]; rishabh thakkar[2]

[1] *Central China Normal University*

[2] *Central China normal University*

Corresponding Authors: hengtong.ding@ccnu.edu.cn, rishabh@ccnu.edu.cn

Understanding the screening mass of pseudoscalar mesons at finite temperature and magnetic field is crucial for comprehending the behavior of strongly interacting matter under extreme conditions, such as those found in the early universe or inside neutron stars. Additionally, in heavy ion collisions, strong magnetic fields are generated, which could significantly influence the properties of the quark-gluon plasma. The study of these screening masses provides insight into the modifications of mesonic properties in such environments, which is essential for the theoretical understanding of Quantum Chromodynamics (QCD) phase transitions and the properties of the quark-gluon plasma.

Here, we present continuum-extrapolated lattice QCD results on the screening mass of pseudoscalar mesons at finite temperatures and nonzero magnetic fields. The simulations used (2+1)-flavor lattice QCD simulations using physical quark masses employing the HISQ/tree action. The continuum extrapolation was carried using lattices having temporal extents $N_\tau = 8$, 12 and 16, all having aspect ratio $N_\sigma/N_\tau = 4$. The investigated temperature range is near the pseudocritical temperature, and the magnetic field ranges from 0 to 1 GeV². We discuss the dependence of the screening masses of various pseudoscalar mesons on temperature, magnetic field strength, and quark mass.

Hadronic and nuclear spectrum and interactions / 442

Three-body analysis of the tetraquark $T_{cc}^+(3875)$

Authors: Sebastian Dawid[1]; Fernando Romero-Lopez[2]; Stephen Sharpe[1]

[1] *University of Washington*

[2] *MIT / Uni Bern*

Corresponding Authors: dawids@uw.edu, fernando.romero-lopez@unibe.ch, srsharpe@uw.edu

We present a strategy for applying the relativistic three-particle scattering formalism to reactions of non-degenerate mesons of arbitrary angular momenta. For concreteness, we focus on the $DD\pi$ system in the charm $C = 2$ and isospin $I = 0$ sectors, where the T_{cc}^+ tetraquark appears as a pole in the elastic $DD\pi \to DD\pi$ scattering amplitude. We solve integral equations for a model describing this three-body process and access the DD^* phase shifts at heavier-than-physical pion mass via the LSZ reduction. We compare our results to available lattice data at $J^P = 1^+, 0^-$. Finally, we apply two- and three-body quantization conditions to the same model and discuss the effect of the left-hand cuts associated with one-pion exchanges on the predicted finite-volume energy levels.

Quark and lepton flavour physics / 447

Structure-dependent electromagnetic finite-volume effects to the hadronic vacuum polarisation

Author: Nils Hermansson-Truedsson[1]

[1] *University of Edinburgh*

Corresponding Author: nils.hermansson-truedsson@ed.ac.uk

The current precision goal of the hadronic vacuum polarisation requires the inclusion of electromagnetic corrections as well as strong isospin-breaking effects. In finite-volume QED prescriptions such as $\mathrm{QED_L}$, finite-volume effects scale as inverse powers of the volume, L. For the hadronic vacuum polarisation in $\mathrm{QED_L}$ the volume effects enter at $1/L^3$ and are known analytically in a point-like approximation of pions. For actual predictions, these effects would have to be derived including also dependence on internal structure of the pions. In this talk, I will discuss on-going work and prospects to determine the structure-dependent finite-volume effects for the hadronic vacuum polarisation in $\mathrm{QED_L}$.

Structure of hadrons and nuclei / 316

Isovector axial and pseudoscalar form factors from twisted mass lattice QCD at the physical point

Authors: Constantia Alexandrou[1]; Simone Bacchio[2]; Martha Constantinou[3]; Jacob Finkenrath[4]; Roberto Frezzotti[5]; Bartosz Kostrzewa[6]; Giannis Koutsou[2]; Gregoris Spanoudes[7]; Carsten Urbach[8]

[1] *University of Cyprus and The Cyprus Institute*

[2] *The Cyprus Institute*

[3] *Temple University*

[4] *CERN*

[5] *University of Rome Tor Vergata, Physics Department and INFN - Sezione di Roma Tor Vergata*

[6] *High Performance Computing & Analytics Lab, University of Bonn*

[7] *University of Cyprus*

[8] *University of Bonn*

Corresponding Authors: spanoudes.gregoris@ucy.ac.cy, bkostrze@uni-bonn.de, g.koutsou@cyi.ac.cy, marthac@temple.edu, s.bacchio@gmail.com, alexand@ucy.ac.cy, urbach@hiskp.uni-bonn.de, roberto.frezzotti@roma2.infn.it

We present the isovector axial, induced pseudoscalar, and pseudoscalar form factors of the nucleon using three twisted-mass fermion ensembles with degenerate up- and down-, strange-, and charm-quarks with masses tuned to their physical values (physical point). The three ensembles have lattice spacing a=0.08, 0.068, and 0.057 fm and approximately equal physical volume allowing for the continuum limit to be taken at the physical point. Excited-state contributions to the matrix elements are evaluated using several sink-source separations from 0.5 fm to 1.5 fm and multistate fits. We check the partially conserved axial-vector current (PCAC) hypothesis and the pion pole dominance (PPD) and show that in the continuum limit both relations are satisfied. We provide results at the continuum limit for the isovector nucleon axial charge, axial radius, pion-nucleon coupling constant, and for the induced pseudoscalar form factor at the muon capture point.

Vacuum structure and confinement / 338

Fractional instantons and Confinement: first results for T^2xR^2

Authors: Antonio Gonzalez-Arroyo[1]; Georg Bergner[2]; Ivan Soler[3]

[1] *Instituto de Fisica Teorica UAM/CSIC*

[2] *University of Jena*

[3] *University of Pisa*

Corresponding Authors: antonio.gonzalez-arroyo@uam.es, georg.bergner@uni-jena.de, ivan.soler@df.unipi.it

In this talk, we provide results for our first studies of Yang-Mills theory on a 4d torus with twisted boundary conditions. We show how information of the semiclassical confinement at small T^2 size is extracted. Different strategies to apply gradient flow techniques and instanton identifications are presented and discussed. We show how the identification becomes increasingly challenging once the small circle regime is left. We discuss possible implications for an instanton liquid model.

Quantum computing and quantum information / 486

Determining entanglement measures in SU(N) lattice gauge theory for N>4: difficulties and solutions

Authors: Niko Jokela[1]; Tobias Rindlisbacher[2]; Kari Rummukainen[1]; Ahmed Salami[1]

[1] *University of Helsinki*

[2] *University of Bern*

Corresponding Authors: ahmed.salami@helsinki.fi, trindlis@itp.unibe.ch, niko.jokela@helsinki.fi, kari.rummukainen@helsinki.fi

Despite recent progress, the accurate determination of entanglement measures in SU(N) lattice gauge theory remains a challenging task; in particular as the number of colors, N, is increased.
Considering entanglement entropy (EE) for slab-shaped entangling regions in (3+1)-dimensional pure SU(N) gauge theory, we discuss the difficulties that arise for N>4 and present our approaches to overcome them.

Algorithms and artificial intelligence / 113

Sparse modeling study to extract spectral functions from lattice QCD data

Author: Junichi Takahashi[1]

Co-authors: Hiroshi Ohno [2]; Akio Tomiya [3]

[1] *Meteorological College, Japan Meteorological Agency*

[2] *University of Tsukuba*

[3] *TWCU*

Corresponding Authors: akio@yukawa.kyoto-u.ac.jp, hohno@ccs.tsukuba.ac.jp, mhjkk-takahashi@met.kishou.go.jp

We present spectral functions extracted from Euclidean-time correlation functions by using sparse modeling. Sparse modeling is a method that solves inverse problems by considering only the sparseness of the solution we seek, without a default model. To check applicability of the method, we firstly test it with mock data which imitate charmonium correlation functions on a fine lattice. We show that the method can reconstruct the resonance peaks in the spectral functions. Then, we extract charmonium spectral functions from correlation functions obtained from lattice QCD at temperatures below and above the critical temperature. We show that this method yields results like those obtained with MEM and other methods.

QCD at non-zero temperature / 98

Pseudo-scalar meson spectral properties from spatial hadron correlators

Author: Tristan Ueding[1]

Co-authors: Dibyendu Bala [1]; Olaf Kaczmarek [2]; Owe Philipsen [3]; Peter Lowdon [3]

[1] *Bielefeld University*

[2] *University of Bielefeld*

[3] *Goethe-University Frankfurt am Main*

Corresponding Authors: dibyendu.bala@physik.uni-bielefeld.de, tueding@physik.uni-bielefeld.de, okacz@physik.uni-bielefeld.de, lowdon@itp.uni-frankfurt.de, philipsen@itp.uni-frankfurt.de

At extreme temperatures the behavior of hadronic matter depends on the type of excitations that can exist in a thermal medium. This information is encoded within the spectral functions of hadronic correlators. Using lattice data for correlators of pseudo-scalar meson operators in $2+1$ flavour QCD we investigate the presence of particle-like excitations, so-called thermoparticles. In particular, we extract the spectral contribution of these potential excitations from spatial correlators at two temperatures close to the pseudo-critical temperature, and test the robustness of these components by comparing their temporal correlator predictions with the corresponding data. Our findings suggest that pseudo-scalar mesons have a bound-state-like structure within the chiral crossover region, and this is influenced by the vacuum states of the theory.

Hadronic and nuclear spectrum and interactions / 266

Lattice QCD study of Ξ_{cc}-Ξ_{cc} interactions on the physical point

Author: Takumi Doi[1]

Co-authors: YAN LYU [2]; Kotaro Murakami [3]; Liang Zhang [4]

[1] *RIKEN*

[2] *RIKEN iTHMES*

[3] *Tokyo Institute of Technology*

[4] *RIKEN iTHEMS; SINAP, CAS*

Corresponding Authors: doi@ribf.riken.jp, zhangliang@sinap.ac.cn, kotaro.murakami@yukawa.kyoto-u.ac.jp, helvetia@pku.edu.cn

The discoveries of exotic hadrons with heavy quark degrees of freedom are stimulating theoretical studies to understand their physical mechanism, and lattice QCD calculations of relevant hadron-hadron interactions are expected to play a crucial role.
In this talk, we present lattice QCD studies of hadron interactions with charm quark degrees of freedom by the HAL QCD method. In particular, we study the Ξ_{cc}-Ξ_{cc} system which is a candidate of a superflavor partner of the exotic tetraquark state, $T_{cc}(3875)$. The calculation is performed with $N_f = 2+1$ Wilson-clover fermion at the physical point, $m_\pi = 137$ MeV, on the lattice box of $(8.1\mathrm{fm})^4$, using the configurations generated by HAL QCD Collaboration, "HAL-conf-2023". The comparison with their strange quark counterpart, Ξ-Ξ interactions, will be presented as well.

Quark and lepton flavour physics / 449

finite-volume effects on the LO-HVP contribution to the muon g-2

Author: Alessandro Lupo on behalf of the BMW and DMZ collaborations[1]

[1] *Aix-Marseille Université*

Corresponding Author: alessandro.lupo@cpt.univ-mrs.fr

We discuss the finite-volume corrections to the LO-HVP contribution to the muon g-2, computed in the latest BMW update for the dominant I=1 channel by using a combination of Meyer-Lellouch-Lüscher and Hansen-Patella methods as well as dedicated lattice simulations. Particular attention is given to estimating the various systematics of the calculation.

Quantum computing and quantum information / 256

Symmetries of the Loop-string-hadron Framework: Towards Quantum Simulating Gauge Theories

Author: Indrakshi Raychowdhury[1]

Co-authors: Emil Mathew [2]; Saurabh Kadam [3]

[1] *Department of Physics, BITS Pilani, KK Birla Goa Campus*

[2] *BITS Pilani, KK Birla Goa Campus*

[3] *IQuS, University of Washington*

Corresponding Authors: ksaurabh@uw.edu, indrakshir@goa.bits-pilani.ac.in, p20210036@goa.bits-pilani.ac.in

Reformulating the Hamiltonian formulation of non-Abelian lattice gauge theories entirely in terms of gauge invariant loop-string-hadron degrees of freedom provides a set of advantages for simulating the theory on quantum hardware and in turn is expected to address a series of physics quests. The framework is manifestly (non-Abelian) gauge invariant, yet possesses a set of remnant Abelian gauge symmetries along with its global symmetry properties. In this talk, we describe all the symmetries of this framework and discuss the advantages/ challenges of the symmetry structure being

present/preserved in a Hamiltonian simulation towards understanding real-time dynamics of non-Abelian gauge theories.

Plenary / **335**

Machine-learning approaches to accelerating lattice simulations

Author: Scott Lawrence[1]

[1] *Los Alamos National Laboratory*

Corresponding Author: srlawrence@lanl.gov

The last decade has seen an explosive growth of interest in exploiting developments in machine learning to accelerate lattice QCD calculations. On the sampling side, generative models are a promising approach to mitigating critical slowing down and topological freezing. Meanwhile, signal-to-noise problems have been shown to be improvable by the use of optimized improved observables. Both techniques can be made free of bias, resulting in trustworthy but reduced statistical errors. This talk reviews recent developments in this field.

Plenary / **103**

Approaches to the Inverse Problem

Author: William Jay[1]

[1] *MIT*

Corresponding Author: willjay@mit.edu

In this talk, I will review the physics context for and recent approaches to the inverse problem of spectral reconstruction.

Plenary / **383**

The International Particle Physics Outreach Group (IPPOG) - Engaging the world with science

Author: Despina Hatzifotiadou[1]

[1] *INFN Bologna*

Corresponding Author: despina.hatzifotiadou@cern.ch

The pillar for outreach in particle physics, which is nowadays an integral part of our work as researchers, is IPPOG, the International Particle Physics Outreach Group. IPPOG is a network of scientists, science educators and communication specialists working across the globe in informal science education and public engagement for particle physics. The flagship activity of IPPOG is the International Particle Physics Masterclasses programme, to which other activities such as the Worldwide Data Day, the International Muon Week and International Cosmic Day organisation have been added. IPPOG members also participate in a wide range of events: public talks, festivals, exhibitions, teacher training, student competitions, and open days at local institutes. A resource database has

also been developed containing a wealth of material for the dissemination of particle physics. In this talk the history and evolution of IPPOG will be presented briefly, and its various activities will be discussed, with emphasis on the masterclasses, which have been expanding both geographically and in scope during the years.

Plenary / 492

From scattering towards multi-hadron weak decays

Author: Felix Erben[1]

[1] *CERN*

Corresponding Author: felix.erben@cern.ch

Hadron spectroscopy and the study of QCD resonances on the lattice has seen rapid advancements in recent years. This is thanks to new and refined analytical formalisms, improved computational strategies and last but not least a substantial community effort in pushing the boundaries to more complicated resonant channels and simulations at physical quark masses. In this talk I present a selection of recent lattice QCD scattering computations and give an outlook on how a fundamental understanding of resonances in lattice QCD is a key component in a wide range of computations that can be compared to experimental results and as such serve as crucial tests of the Standard Model.

Plenary / 404

Muon g-2

Author: Christine Davies[1]

[1] *University of Glasgow*

Corresponding Author: christine.davies@glasgow.ac.uk

QCD at non-zero density / 162

First-order phase transitions in the heavy quark region of lattice QCD at high temperatures and high densities

Author: Shinji Ejiri[1]

Co-authors: Kazuyuki Kanaya [2]; Masakiyo Kitazawa [3]

[1] *Niigata University*

[2] *Tomonaga Center for the History of the Universe, Univ. Tsukuba*

[3] *Yukawa Institute for Theoretical Physics*

Corresponding Authors: kitazawa@yukawa.kyoto-u.ac.jp, ejiri@muse.sc.niigata-u.ac.jp, kanaya@ccs.tsukuba.ac.jp

If there is a first-order phase transition in the light quark region of 2+1 flavor finite temperature and density QCD and if the region of the first-order phase transition expands with increasing density as suggested by several lattice studies, then, at very high densities, we may expect that the first-order phase transition region expands into the heavy quark region of QCD, where we can perform efficient

large scale simulations by adopting an effective theory of heavy quark QCD based on the hopping parameter expansion.
In the heavy quark region of QCD, we have another first-order phase transition region around the heavy quark limit at zero density. By numerical simulations of effective heavy quark QCD, we found that, the first-order transition at zero density turns into a crossover as the chemical potential is increased, but, when we increase the chemical potential further, the change in the plaquette value near the crossover point becomes much steeper. This may be suggesting reappearance of the first-order phase transition.
In this talk, we first show the nature of the phase transition of phase-quenched finite-density QCD in the heavy quark region, and then study the effect of the complex phase to discuss whether the QCD phase transition changes again to a first-order phase transition at very high densities.

Hadronic and nuclear spectrum and interactions / 43

Predicting the spectrum and decay constants of positive-parity heavy-strange mesons using domain-wall fermions

Authors: Forrest Guyton[1]; Stefan Meinel[2]

[1] *University of Arizona*

[2] *University of Arizona / RIKEN BNL Research Center*

Corresponding Authors: smeinel@email.arizona.edu, forrestguyton@arizona.edu

We determine the energies and decay constants of the lowest-lying positive-parity bottom-strange and charm-strange mesons using lattice QCD. The calculations are performed with domain-wall up, down, and strange quarks and with an anisotropic clover action for the heavy quarks, on seven different RBC/UKQCD ensembles with pion masses ranging from a near physical $m_\pi \approx 139 MeV$ up to $m_\pi \approx 431 MeV$. On all of these ensembles, our preliminary results for the ground-state energies of the B^*_{s0}, B_{s1}, D^*_{s0}, and D_{s1} are below the BK, B^*K, DK, and D^*K thresholds, respectively.

Quark and lepton flavour physics / 355

Virtual radiative Leptonic decays of charged Kaons

Author: Roberto Di Palma (On behalf of the RM123 Collaboration)[1]

[1] *Università Roma Tre*

Corresponding Author: roberto.dipalma@uniroma3.it

We present preliminary results for $K \to l\nu_l l'^+ l'^-$ decays, which are mediated by an off-shell W boson and a virtual photon. These decays are suppressed in the Standard Model since their rates start at $\mathcal{O}(\alpha_{em}^2)$, making them very interesting in the search for new physics.
We compute the four form factors needed to describe the structure-dependent part of the decay amplitudes using the $N_f = 2+1+1$ gauge ensembles generated by the Extended Twisted Mass Collaboration (ETMC) at the pion physical point.
We choose several values of both the momentum and the virtuality of the photon k^2 to cover all the allowed kinematic range. In the region above the two-pion threshold ($k^2 > 4m_\pi^2$), where issues related to the analytic continuation are present, we reconstruct the form factors employing the so-called HLT method.
As a byproduct of our analysis, we reassess the form factors entering $K \to l\nu_l\gamma$.

Structure of hadrons and nuclei / 28

Phase shift in doubly Charmed H-like dibaryon $\Lambda_c \Lambda_c$ scattering at $M_\pi \approx 303 MeV$

Author: Yiqi（乙淇）Geng（耿）[1]

Co-authors: Liuming Liu [2]; peng sun [2]; Jia-jun Wu [3]; Hanyang Xing [2]; Ruilin Zhu [4]

[1] 南京师范大学，中国科学院近代物理所

[2] *IMP*

[3] *GUCAS*

[4] *Nanjing Normal U.*

Corresponding Authors: liuming@impcas.ac.cn, pengsun@impcas.ac.cn, rlzhu@njnu.edu.cn, wujiajun@ucas.ac.cn, hanyang@impcas.ac.cn, 251848737@qq.com

To explore the possibility of H-like dibaryon $\Lambda_c \Lambda_c(0^+)$, we proceed calculation on lattice. Two Wilson-Clover ensembles are used which were generated by CLQCD collaboration with similar settings that $m_\pi \approx 303$ MeV, $m_D \approx 1.966$ GeV, $m_{D^*} \approx 2.077$ GeV. In this work, finite-volume scattering with single channel Luscher's formula is adopted because the coupling between $\Lambda_c \Lambda_c$ and $\Xi_{cc} N$ is quite small according to our calculation. There is a sign of the CDD zero pole here. By parameterizing the Luscher's scattering matrix, S and D wave phase shift can be given then. However, we find no bound state within a single channel $\Sigma_c \Sigma_c$. Further, the coupling between $\Lambda_c \Lambda_c$ and $\Sigma_c \Sigma_c$ is a little strong.

QCD at non-zero temperature / 119

Towards a parameter-free determination of critical exponents and chiral phase transition temperature in QCD

Authors: Frithjof Karsch[1]; Sabarnya Mitra[1]; Sipaz Sharma[1]

[1] *Bielefeld University*

Corresponding Authors: smitra@physik.uni-bielefeld.de, sipaz@physik.uni-bielefeld.de

The chiral phase transition in QCD is frequently studied by either locating the inflection point of a suitably renormalized order parameter or the extrema of chiral susceptibilities as function of the light quark masses. In the limit of vanishing light quark masses their scaling behaviour is dominated by scaling functions and critical exponents that are unique for a given universality class.
Generally properties of the relevant universality class, $i.e.$ the 3-d, $O(2)$ or $O(4)$ universality classes are used to extract the chiral phase transition temperature at vanishing values of the chemical potentials. No serious attempt exists so far, to extract the relevant universal critical exponents directly from lattice QCD calculations.

In this talk, we will use properties of a renormalized chiral order parameter M, obtained as a suitable difference of the 2-flavor light quark chiral condensate M_b and its susceptibility χ_b and given by $M = M_b - H\,\chi_b$ [1,2].
Similar to the related observable $H\,\chi_b/M_b$, the improved order parameter M also is directly proportional to a scaling function. In addition the latter has the advantage of eliminating additive UV divergences as well as $calO(H)$ regular contributions.
In the scaling region the logarithm of the ratio of this order parameter, evaluated for two different light quark masses, has a unique

crossing point as function of temperature. This crossing-point arises at the chiral phase transition temperature T_c and directly gives the value of the critical exponent δ without any prior information regarding the associated universality class of the phase transition.
We present first results from our numerical study of this order parameter ratio on lattices with fixed temporal extent $N_\tau = 8$. We discuss the prospects for a parameter free determination of T_c and δ in the chiral limit of (2+1)-flavor QCD.

References:

1 L. Dini et al, Phys.Rev.D 105 (2022) 034510, arXiv:2111.12599
2 H.-T. Ding et al, arXiv:2403.09390

Quantum computing and quantum information / 429

Handling challenges for robust and reliable quantum simulation of gauge theories on 1+1D and 2+1D

Author: Bipasha Chakraborty[1]

Co-authors: Alex Tomlinson [1]; Balint Koczor [2]; Debasish Banerjee [3]; Emilie Huffman [4]; Graham Van Goffrier [1]; Sandip Maiti [3]; Zenyu Cai [2]

[1] *University of Southampton*

[2] *University of Oxford*

[3] *Saha Institute of Nuclear Physics*

[4] *Perimeter Institute for Theoretical Physics*

Corresponding Authors: debasish.banerjee@saha.ac.in, ehuffman@perimeterinstitute.ca, zhenyu.cai@sjc.ox.ac.uk, koczor@maths.ox.ac.uk, gwvg1e23@soton.ac.uk, a.tomlinson@soton.ac.uk, sandipmaiti73@gmail.com, b.chakraborty@soton.ac.uk

Quantum simulation of gauge theories has already crossed its initial phase and is rapidly becoming a solid testing ground for novel quantum algorithms. However, the challenges are numerous for robust and reliable quantum simulation of gauge theories, and in this talk I will discuss our ongoing work to address a few challenges. I will describe ground state preparation for gauge theory Hamiltonians on 1+1D and 2+1D using Variational algorithms and Quantum Approximate Optimisation Algorithm. Specifically, on 2+1D we work with a matter-free non-Abelian SO(3) lattice gauge theory in a phase where the global charge conjugation symmetry is spontaneously broken. In this context, we demonstrate how the exact imposition of the non-Abelian Gauss Law in the rishon representation of the quantum link operator, significantly reduces the degrees of freedom, and thus alleviates the challenge dealing with a large Hilbert space for gauge theories in contrast to quantum spins. We also provide experimental results from the quantum hardware, IonQ. A major challenge to the reliability and robustness of practical quantum computing is its sensitivity to errors and noise. In the context of quantum simulation of gauge theories, I will describe an effective scheme for quantum error mitigation by identifying errors that break the symmetries of the ideal quantum state and removing them via post-selection.

Theoretical developments / 221

Generalized Ginsparg-Wilson relations: Fermionic anomalies and topological phases on the lattice

Authors: David Kaplan[1]; Hersh Singh[2]; Michael Clancy[None]

[1] *Institute for Nuclear Theory*

[2] *Fermilab*

Corresponding Authors: hershs@fnal.gov, dbkaplan@uw.edu

A lattice formulation of non-Abelian chiral gauge theories has long been an open problem. One of the most important developments motivated by this question is the Ginsparg-Wilson (GW) relation, which encodes how the anomalous chiral symmetry "optimally" manifests on the lattice. Developments in condensed-matter physics have uncovered a deep connection between anomalies and topological insulators/superconductors. Domain-wall fermions used in lattice QCD simulations can be understood as a special case of this. Since domain-wall fermions are also a solution to the GW relation, we may ask: can the GW relation be generalized to other topological phases? We show that it is possible to write down such generalized GW relations, as well as corresponding overlap operators. Interestingly, perturbative and even some global anomalies (à la Witten) show up in this formalism in an elementary fashion from the Jacobian of the fermionic measure.

Particle physics beyond the Standard Model / 7

Electroweak correction to parity violating ep scattering

Authors: Lu-Chang Jin[None]; Xu Feng[1]; Zhaolong Zhang[1]

[1] *Peking University*

Corresponding Authors: 2301110116@pku.edu.cn, xu.feng@pku.edu.cn

We present a first-principle lattice QCD calculation of the axial γZ box correction, which is necessary to be taken into account to determine the weak charge in low energy parity violating ep scattering. We calculate the electron energy dependence of axial γZ box up to 155MeV, which perfectly matches the beam energy range of the upcoming PVES experiment at Mainz $E < 155\text{MeV}$. Combining the axial γZ correction given by this work and latest vector γZ contribution calculated by phenomenological method, we update the value of full γZ box correction at $E = 155\text{MeV}$, illustrating that the vector contribution now dominates the uncertainty of total γZ box correction. We also update SM prediction of weak charge using our result at $E = 0\text{MeV}$, and our preliminary result shows that it probably shows a small deviation from the original value in 2022 PDG.

QCD at non-zero density / 48

Chiral and deconfinement properties of the QCD crossover have a different volume and baryochemical potential dependence

Authors: Szabolcs Borsanyi[1]; Zoltan Fodor[2]; Jana N. Guenther[1]; Ruben Kara[1]; Paolo Parotto[3]; Attila Pasztor[1]; Ludovica Pirelli[4]; Chik Him Wong[1]

[1] *University of Wuppertal*

[2] *University of Wuppertal, Penn State University, Eotvos University, IAS Jülich, UC San Diego*

[3] *Università di Torino*

[4] *Bergische Universität Wuppertal*

Corresponding Authors: cwong@uni-wuppertal.de, jguenther@uni-wuppertal.de, apasztor@bodri.elte.hu, pirelli@uni-wuppertal.de, borsanyi@uni-wuppertal.de

The crossover from hadronic to quark matter is understood to be both a deconfinement as well as a chiral symmetry restoring transition. Here, we study observables related to both aspects using lattice simulations: the Polyakov loop and its derivatives and the chiral condensate and its derivatives. At zero baryochemical potential, and infinite volume, the chiral and deconfinement crossover temperatures almost agree. However, chiral and deconfinement related observables have a qualitatively different chemical potential and volume dependence. In general, deconfinement related observables have a milder volume dependence. Furthermore, while the deconfinement transition

appears to get broader with increasing μ_B, the width as well as the strength of the chiral transition is approximately constant. Our results are based on simulations at zero and imaginary chemical potentials using 4stout-improved staggered fermions with $N_\tau = 12$ time-slices and physical quark masses.

Hadronic and nuclear spectrum and interactions / 190

Static-light meson spectroscopy with optimal distillation profiles

Authors: Francesco Knechtli[1]; Juan Andres Urrea Nino[2]; Laura Struckmeier[2]; Michael Peardon[3]; Roman Höllwieser[1]; Tomasz Korzec[2]

[1] *University of Wuppertal*

[2] *Bergische Universität Wuppertal*

[3] *Trinity College Dublin*

Corresponding Authors: korzec@uni-wuppertal.de, knechtli@physik.uni-wuppertal.de, hoellwieser@uni-wuppertal.de, mjp@maths.tcd.ie, lstruckmeier@uni-wuppertal.de, urreanino@uni-wuppertal.de

The spectrum of static-light and static-charm mesons is studied using optimized distillation in two different $N_f = 3 + 1$ QCD ensembles with pion masses of $m_\pi \approx 800\,\mathrm{MeV}$ and $m_\pi \approx 420\,\mathrm{MeV}$. Local and derivative-based operators are used to access states of multiple quantum numbers. The use of optimal profiles is shown to improve the overlap with the energy states compared to standard distillation.

Quark and lepton flavour physics / 274

Form factor curves consistent with unitarity for semileptonic decays

Author: Callum Radley-Scott[1]

Co-authors: Jonathan Flynn [1]; Nikolai Husung [2]

[1] *University of Southampton*

[2] *IFT UAM/CSIC*

Corresponding Authors: j.m.flynn@soton.ac.uk, nikolai.husung@uam.es, c.j.radley-scott@soton.ac.uk

We discuss a method to generate form factor curves across the entire kinematic range for semileptonic (SL) pseudoscalar to pseudoscalar decays, for example $B \to \pi\mu\nu$ and $B_s \to K\mu\nu$.

The work builds upon the Dispersive Matrix (DM) method. Using known form factor information at specific discrete q^2 points as input, the DM method allows model-independent extrapolation to any desired q^2 value in the SL physical region. Here q is the outgoing lepton-pair 4-momentum. The main obstacle in using DM results to determine phenomenological predictions, such as forward-backward asymmetry, is that it is not obvious how to exploit the bounds over continuous ranges of q^2 when integrating, for example, the differential decay rate over the physical q^2 range or over bins in q^2.

Using this method, we can generate a family of curves, each consistent with unitarity constraints, that can be used in the same way as a set generated from a parametrized fit (e.g. a z-fit). This allows integration over any desired bins. We further show some techniques to increase the computational efficiency of the method.

We demonstrate the application to determining V_{ub}.

Structure of hadrons and nuclei / 99

Three Neutrons in a Finite Volume

Authors: Stephen Sharpe[1]; Wilder Schaaf[1]

[1] *University of Washington*

Corresponding Authors: wilderschaaf@gmail.com, srsharpe@uw.edu

We present an implementation of the three-neutron quantization condition (QC) derived in previous work. We construct the QC computationally and numerically determine the solutions. The symmetry of the QC means that it can be projected onto representations of the appropriate little group (depending on frame momentum $\vec{P}$), restricting the size of the matrices and reducing computational complexity. Two-neutron interactions are modelled using experimental data for scattering amplitudes. We obtain results for the volume-dependent energy shifts for the case of three neutrons in a finite energy range.

QCD at non-zero temperature / 203

Three-flavour QCD phase transition with Mobius domain-wall fermions

Author: Yu Zhang[1]

Co-authors: Issaku Kanamori [2]; Shoji Hashimoto [3]; Takashi Kaneko [3]; Yasumichi Aoki [2]; Yoshifumi Nakamura [2]

[1] *Bielefeld University*

[2] *RIKEN*

[3] *KEK*

Corresponding Authors: shoji.hashimoto@kek.jp, takashi.kaneko@kek.jp, yasumichi.aoki@riken.jp, nakamura@riken.jp, yzhang@physik.uni-bielefeld.de, kanamori-i@riken.jp

We update the study of three-flavour QCD phase transition with Mobius domain-wall fermions at zero chemical potential. The simulations are performed on Nt=12 lattices with aspect ratio between 2 and 4 for a variety of quark masses at a lattice spacing 0.13 fm. A large volume lattice of 48^3x12 is added to clarify the nature of transition by measuring the volume dependence of chiral susceptibility and Binder cumulants.

Quantum computing and quantum information / 448

Simulating an SO(3) Quantum Link Model with Dynamical Fermions in 2+1 Dimensions

Author: Graham Van Goffrier[1]

Co-authors: Bipasha Chakraborty [2]; Debasish Banerjee [3]; Emilie Huffman [4]; Sandip Maiti [3]

[1] *University College London*

[2] *University of Southampton*

[3] *Saha Institute of Nuclear Physics*

[4] *Perimeter Institute for Theoretical Physics*

Corresponding Authors: b.chakraborty@soton.ac.uk, sandipmaiti73@gmail.com, ehuffman@perimeterinstitute.ca, debasish.banerjee@saha.ac.in, vangoffrier@gmail.com

Quantum link models (QLMs) are generalizations of Wilsonian lattice gauge theory which can be formulated with finite-dimensional link Hilbert spaces, and which can be embedded onto local spin Hamiltonians for efficient quantum simulation by exact imposition of the Gauss Law constraint. Previously, SO(3) QLMs have been studied in 1+1d and shown to reflect key properties of QCD and nuclear physics, including distinct confining/deconfining phases and hadronic bound states. We have conducted one of the first simulations of SO(3) QLMs with dynamical in 2+1d, and here report our results. In this talk, we review the construction of a gauge-invariant state space for 1+1d and 2+1d SO(3) QLMs, and show how knowledge of discrete symmetries facilitates exact diagonalisation of the spin-Hamiltonian. We also briefly discuss how the quantum simulation of the SO(3) QLM in 1+1d and 2+1d may be efficiently performed by variational methods.

Theoretical developments / 161

η invariant of massive Wilson Dirac operator and the index

Authors: Shoto Aoki[1]; Hidenori Fukaya[2]; Mikio Furuta[3]; Shinichiroh Matsuo[4]; Tetsuya Onogi[5]; Satoshi Yamaguchi[2]

[1] *The University of Tokyo*

[2] *Osaka Univ.*

[3] *U. of Tokyo*

[4] *Nagoya Univ.*

[5] *Osaka University*

Corresponding Authors: shotoaoki@g.ecc.u-tokyo.ac.jp, onogi@phys.sci.osaka-u.ac.jp, hfukaya@het.phys.sci.osaka-u.ac.jp

We mathematically show an equality between the index of a Dirac operator on a flat continuum torus and the η invariant of the Wilson Dirac operator with a negative mass when the lattice spacing is sufficiently small. Unlike the standard approach, our formulation using the K-theory does not require the Ginsparg-Wilson relation or the modified chiral symmetry on the lattice. We prove that a one-parameter family of continuum massive Dirac operators and the corresponding Wilson Dirac operators belong to the same equivalence class of the K^1 group at a finite lattice spacing. Their indices, which are evaluated by the spectral flow or equivalently by the η invariant at finite masses, are proved to be equal.

Particle physics beyond the Standard Model / 29

Flavour singlet mixing in Sp(4) gauge theory with fermions in multiple representations

Authors: Biagio Lucini[1]; C.-J David Lin[2]; Davide Vadacchino[3]; Deog Ki Hong[4]; Ed Bennett[1]; Fabian Zierler[1]; Ho Hsiao[2]; Jong-Wan Lee[5]; Maurizio Piai[1]; Niccolo Forzano[1]

[1] *Swansea University*

[2] *National Yang Ming Chiao Tung University*

[3] *University of Plymouth*

[4] *Pusan National University*

[5] *Institute for Basic Science (IBS)*

Corresponding Authors: m.piai@swansea.ac.uk, dlin@nycu.edu.tw, nic.forz@gmail.com, dkhong@pusan.ac.kr, fabian.zierler@swansea.ac.uk, j.w.lee@ibs.re.kr

We study the pseudoscalar flavour-singlet mesons of $Sp(4)$ gauge theory with two distinct fermion representations. The model contains two fundamental and three anti-symmetric Dirac fermion. It is a minimal realization of a composite Higgs scenario with partial top compositeness. We determine both the masses and the mixing angles of the states associated with the global U(1) symmetries, one of which, is expected to be broken by the axial anomaly. These states complete the sector of pseudo-Nambu-Goldstone bosons present in this theory.

QCD at non-zero density / 286

The temperature of the chiral phase transition in LQCD at its tri-critical point

Author: Jan Philipp Klinger[1]

Co-authors: Owe Philipsen [2]; Reinhold Kaiser [1]

[1] *Goethe University Frankfurt*

[2] *Goethe-University Frankfurt am Main*

Corresponding Authors: klinger@itp.uni-frankfurt.de, philipsen@itp.uni-frankfurt.de, kaiser@itp.uni-frankfurt.de

The nature of the QCD phase transition in the chiral limit constitutes a challenging problem for lattice QCD as it is not directly simulable. Its study, however, provides constraints on the phase diagram at the physical point. Recently, the thermal transition for massless fermions was shown to be of second order for all numbers of flavours N_f
$lesssim 7$. For this, the lattice chiral limit was approached by mapping out the chiral critical surface separating the first-order region from the crossover region in an enlarged parameter space which consists of the gauge coupling, a variable number of quark flavours, their masses, and the lattice spacing. Based on simulations of lattice QCD with standard staggered quarks, it was found that for all N_f
$lesssim 7$ there exists a tricritical lattice spacing $a^{tric}(N_f)$, where the chiral transition changes from first order (above) to second order (below). The first-order region thus constitutes a cutoff effect and the transition in the continuum chiral limit is of second order for all N_f
$lesssim 7$. In the current work we determine the associated temperatures $T(N_f^{tric}, a^{tric})$ at these tricritical points. We confirm an expected decrease in the temperature for increasing number of flavours. Running simulations on finer lattices and for larger N_f will allow us to determine the location of the tricritical point in the continuum limit and let us resolve the question whether the conformal window is approached by a first or second order phase transition.

Hadronic and nuclear spectrum and interactions / 278

Precision charmonium spectroscopy on CLS ensembles

Authors: Gunnar Bali[1]; Sara Collins[1]; Sebastian Spiegel[2]; Wolfgang Soeldner[3]

[1] *University of Regensburg*

[2] *Universität Regensburg*

[3] *Regensburg University*

Corresponding Authors: wolfgang.soeldner@ur.de, gunnar.bali@ur.de, sebastian.spiegel@physik.uni-regensburg.de, sara.collins@ur.de

The masses of the lowest charmonium states are determined on a large set of coordinated lattice simulations (CLS) gauge ensembles with $N_f = 2 + 1$ sea quark flavours of non-perturbatively improved Wilson fermions. The inverse lattice spacing is varied from about 2 GeV up to more than 5 GeV, enabling a controlled continuum limit extrapolation. This allows the impact of the neglected charm quark annihilation diagrams and the electromagnetic interaction to be assessed.

Quark and lepton flavour physics / 197

Gradient Flow Renormalisation for Meson Mixing and Lifetimes

Author: Matthew Black[1]

[1] *University of Siegen*

Corresponding Author: matthew.black@uni-siegen.de

Fermionic gradient flow in combination with the short flow time expansion provides a renormalisation scheme where hadronic matrix elements on the lattice are evolved along the flow time gradually removing UV divergences.
In this renormalisation scheme certain challenges such as mixing with operators of lower mass dimension are suppressed or shifted to the perturbative part of the procedure, matching e.g. to the $\overline{\mathrm{MS}}$ scheme.

We demonstrate our gradient flow renormalisation procedure determining matrix elements of four-quark operators describing neutral meson mixing or meson lifetimes.
While meson mixing calculations are well-established on the lattice and serve to validate our procedure, a lattice calculation of matrix elements for heavy meson lifetimes is still outstanding.
Preliminary results for mesons formed of a charm and strange quark are presented and prospects towards determinations for B mesons are given.

Structure of hadrons and nuclei / 154

Investigation of πN contributions to nucleon matrix elements

Authors: Constantia Alexandrou[1]; Ferenc Pittler[2]; Giannis Koutsou[2]; Marcus Petschlies[3]; Yan Li[4]

[1] *University of Cyprus and The Cyprus Institute*

[2] *The Cyprus Institute*

[3] *U. Bonn*

[4] *University of cyprus*

Corresponding Authors: f.pittler@cyi.ac.cy, g.koutsou@cyi.ac.cy, alexand@ucy.ac.cy, li.yan@ucy.ac.cy

We investigate an improved method to extract nucleon matrix elements from lattice 3-point functions and generalized eigenvalue problem with nucleon and pion-nucleon interpolating fields. Our method avoids the costly three-point functions with 2-hadron interpolators at both source and sink. We demonstrate minimization of excited state contamination in matrix elements of the scalar, vector,

pseudoscalar, axial, and tensor currents and discuss our results based on two twisted mass gauge field ensembles and 131 MeV and 346 MeV.

QCD at non-zero temperature / 191

Charm thermodynamics near chiral crossover

Author: Sipaz Sharma[1]

[1] *Bielefeld University*

Corresponding Author: sipaz@physik.uni-bielefeld.de

I will talk about our recent results on the nature of charm degrees of freedom in hot strong interaction matter based on lattice QCD calculations of the second and fourth-order cumulants of charm fluctuations, and their correlations with net baryon number, electric charge, and strangeness fluctuations. I will begin by showing that below the chiral crossover temperature, T_{pc}, thermodynamics of charm can be very well understood in terms of charmed hadrons. Above T_{pc}, however, charm quark-like excitations emerge as new degrees of freedom contributing to the partial charm pressure. Nonetheless, up to temperatures as high as 175 MeV, charmed hadron-like excitations significantly contribute to the partial charm pressure. I will discuss the implications of these findings for understanding the nature of interactions inside the Quark-Gluon Plasma.

I will also discuss technical details related to the lattice QCD calculations of charm fluctuations. I will show that in open-charm physics, the major source of cutoff effects is the lightest charmed hadron mass, which in turn depends upon the input bare charm quark mass. I will discuss different approaches that we employed to take the continuum limit. These approaches were based on three different lines of constant physics used to tune the charm quark mass on the lattice.

Quantum computing and quantum information / 93

Computing theta-dependent mass spectrum of the 2-flavor Schwinger model in the Hamiltonian formalism

Authors: Akira Matsumoto[1]; Etsuko Itou[2]; Yuya Tanizaki[2]

[1] *Yukawa Institute for Theoretical Physics, Kyoto University*

[2] *YITP, Kyoto U.*

Corresponding Authors: yuya.tanizaki@yukawa.kyoto-u.ac.jp, akira.matsumoto@yukawa.kyoto-u.ac.jp, itou@yukawa.kyoto-u.ac.jp

We compute the θ-dependent mass spectrum of the 2-flavor Schwingr model using the tensor network (DMRG) in the Hamiltonian formalism. The pion and the sigma meson are identified as stable particles of the model for nonzero θ whereas the eta meson becomes unstable. The meson masses are obtained from the one-point functions, using the meson operators defined by diagonalizing the correlation matrix to deal with the operator mixing. We also compute the dispersion relation directly by measuring the energy and momentum of the excited states, where the mesons are distinguished by the isospin quantum number. We confirmed that the meson masses computed by these methods agree with each other and are consistent with the calculation by the bosonized model. Furthermore, at the critical point $\theta = \pi$, the mesons become almost massless, and the one-point functions reproduce the expected CFT-like behavior.

Theoretical developments / 52

Axion QED as a Lattice Gauge Theory and Non-Invertible Symmetry

Author: Yamato Honda[1]

Co-authors: Soma Onoda [2]; Hiroshi Suzuki [2]

[1] *Kyushu university*

[2] *Kyushu University*

Corresponding Authors: hsuzuki@phys.kyushu-u.ac.jp, onoda.soma@phys.kyushu-u.ac.jp, honda.yamato@phys.kyushu-u.ac.jp

We formulated axion QED on a lattice using a modified Villain formalism. While the axion-photon coupling in the continuum theory is straightforward, we found that the corresponding coupling in the lattice gauge theory using the modified Villain formalism is more complex. As a result, we discovered that the gauge-invariant 't Hooft loop requires a surface inside it. Additionally, we discussed the non-invertible symmetry related to the axion's 0-form shift symmetry, namely the axial transformation. In the continuum theory, it has been reported that a membrane is stretched inside the 't Hooft loop under the action of the non-invertible symmetry operator. However, starting from our formulation, we demonstrated that no nontrivial change occurs to the 't Hooft loop under such an action.

Particle physics beyond the Standard Model / 53

Supersymmetric QCD on the lattice: Fine-tuning and counterterms for the Yukawa and quartic couplings

Author: Marios Costa[1]

Co-authors: Herodotos Herodotou [1]; Haralambos Panagopoulos [1]

[1] *University of Cyprus*

Corresponding Authors: kosta.marios@ucy.ac.cy, panagopoulos.haris@ucy.ac.cy, hherod01@ucy.ac.cy

In this study, we determine the fine-tuning of parameters in $\mathcal{N} = 1$ Supersymmetric QCD, discretized on a Euclidean lattice. Our focus is on the renormalization of Yukawa (gluino-quark-squark interactions) and quartic (four-squark interactions) couplings. Given that SUSY is broken on the lattice, non-supersymmetric counterterms must be added to the discretized Lagrangian, with coefficients which must be appropriately fine-tuned in order to recover SUSY in the continuum limit. To deduce the renormalization factors and the coefficients of the counterterms, we compute the relevant three-point (for the Yukawa couplings) and four-point Green's functions (for the quartic couplings) perturbatively to one-loop and to the lowest order in lattice spacing. Both dimensional and lattice regularizations are used to implement the Modified Minimal Subtraction scheme. Our lattice formulation employs the Wilson discretization for gluino and quark fields, the Wilson gauge action for gluons, and naive discretization for squark fields. The sheer difficulties of this study lie in the fact that different components of squark fields mix among themselves at the quantum level. Consequently, for an appropriate fine-tuning of the aforementioned couplings, these mixings must be taken into account in the renormalization conditions. All Green's functions and renormalization factors are analytic expressions depending on the number of colors, N_c, the number of flavors, N_f, and the gauge parameter, α, which are left unspecified. This work follows previous investigations on SQCD and finalizes the one-loop fine-tuning of the SQCD action on the lattice, paving the way for numerical simulations of SQCD.

QCD at non-zero density / 194

Novel first-order phase transition and critical points on SU(3) Yang-Mills theory on $T^2 \times R^2$

Authors: Masakiyo Kitazawa[1]; Daisuke Fujii[2]; Akihiro Iwanaka[3]; Daiki Suenaga[4]

[1] *Yukawa Institute for Theoretical Physics*

[2] *JAEA*

[3] *RCNP, Osaka*

[4] *Nagoya University*

Corresponding Authors: kitazawa@yukawa.kyoto-u.ac.jp, suenaga.daiki.j1@f.mail.nagoya-u.ac.jp, fujii.daisuke@jaea.go.jp, iwanaka@rcnp.osaka-u.ac.jp

We investigate the thermodynamics and phase structure of SU(3) Yang-Mills theory on $T^2 \times R^2$ with anisotropic spatial volumes in Euclidean spacetime in lattice numerical simulations and an effective model. In lattice simulations, the energy-momentum tensor defined through the gradient flow is used for the analysis of the stress tensor on the lattice. It is found that a clear pressure anisotropy is observed only at a significantly shorter spatial extent compared with the free scalar theory. We then study the thermodynamics obtained on the lattice in an effective model that incorporates two Polyakov loops along two compactified directions as dynamical variables. The model is constructed to reproduce thermodynamics measured on the lattice. The model analysis indicates the existence of a novel first-order phase transition and critical points as its endpoints. We argue that the interplay of the Polyakov loops induces the first-order transition.

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D. Fujii, A. Iwanaka, M. Kitazawa and D. Suenaga, arXiv:2404.07899 [hep-ph].

Hadronic and nuclear spectrum and interactions / 19

Flavor mixing in charmonium and light mesons with optimal distillation profiles

Authors: Francesco Knechtli[1]; Juan Andres Urrea Nino[2]; Tomasz Korzec[2]; Jacob Finkenrath[2]; Roman Höllwieser[2]; Michael Peardon[3]

[1] *University of Wuppertal*

[2] *Bergische Universität Wuppertal*

[3] *Trinity College Dublin*

Corresponding Authors: finkenrath@uni-wuppertal.de, hoellwieser@uni-wuppertal.de, mjp@maths.tcd.ie, knechtli@physik.uni-wuppertal.de, korzec@uni-wuppertal.de, urreanino@uni-wuppertal.de

We study the light meson - charmonium - glueball mixing using flavor-singlet meson operators built from optimal distillation profiles together with purely gluonic operators in different J^{PC} channels at two different pion masses ($m_\pi \approx 420,\ 800$ MeV) in two $N_f = 3+1$ ensembles at almost physical charm quark mass. We observe non-zero mixing correlations between the different types of operators and quantify the overlaps between states created by them and the energy eigenstates by means of a GEVP formulation. We are particularly interested in the scalar glueball and its possible decay into two pions so we also include two-pion operators in our calculation.

Quark and lepton flavour physics / 483

$B^*\pi$ excited-state contamination in B-physics observables

Authors: Antoine Gerardin[1]; Gregorio Herdoiza[2]; Oliver Bär[3]; Rainer Sommer[4]; Simon Kuberski[5]

[1] *Centre de Physique Théorique de Marseille*

[2] *IFT UAM-CSIC*

[3] *Humboldt Universität*

[4] *NIC @ DESY*

[5] *CERN*

Corresponding Authors: antoine.gerardin@univ-amu.fr, gregorio.herdoiza@uam.es, simon.kuberski@cern.ch, rainer.sommer@desy.de

B decays are important for flavor physics. One of the difficulties of these calculations is to control excited states. A standard approach to overcome this issue is to use smeared interpolators to optimize B-meson ground state overlap. However, the ability of such interpolators to effectively suppress multi-hadronic state contributions remains an open question.
In this context, using Heavy Meson Chiral Perturbation Theory (HMChPT), a recent work emphasized the potentially large $B^*\pi$ excited-state contamination of the $B \to \pi$ vector form factors that could lead to a severe underestimation of $h_\perp$. The findings are expressed in terms of a few low-energy constants (LECs) that are accessible on the lattice.
In this talk, we present a lattice calculation of the relevant LECs for smeared interpolators, in particular for Gaussian smearing. The LECs can be determined well and it turns out that the investigated smearings do not suppress excited states significantly. Still, their knowledge will help to analyse the lattice results at finite Euclidean times.

Structure of hadrons and nuclei / 450

Lattice EFT test of the finite-volume formalism for two-body matrix elements

Authors: Amy Nicholson[1]; Andrew Jackura[2]; Charles Kacir[1]; Joseph Moscoso[1]; Raul Briceno[3]

[1] *University of North Carolina, Chapel Hill*

[2] *William and Mary*

[3] *Thomas Jefferson National Accelerator Facillity*

Corresponding Authors: awjackura@wm.edu, ckacir@unc.edu, rbriceno@jlab.org, annichol@unc.edu, jomo101@email.unc.edu

The study of two-hadron matrix elements and form factors is critical for the success of several planned experimental searches for new physics which utilize low-energy nuclear environments. Lattice QCD calculations of, e.g., short-distance nn->pp transitions relevant for neutrinoless double beta decay experiments, rely on a recently derived finite-volume formalism for computing 2+J->2 amplitudes. In this work, I will discuss consistency checks on the formalism to confirm its validity and provide quantitative predictions for lattice QCD calculations using lattice calculations of a low-energy non-relativistic EFT. Numerical calculations of the scattering system with a tunable interaction allows us to test the application of the formalism to bound and unbound systems. I will discuss preliminary results for the electromagnetic form factors of two-nucleon systems, including the case of deuteron break up.

QCD at non-zero temperature / 246

QCD thermodynamics on the physical point with 2+1 flavor Möbius domain wall fermions

Author: Yasumichi Aoki[1]

Co-authors: Hidenori Fukaya [2]; Jishnu Goswami [3]; Shoji Hashimoto [4]; Issaku Kanamori [1]; Takashi Kaneko [4]; Yoshifumi Nakamura [1]; Yu Zhang [5]

[1] *RIKEN*

[2] *Osaka Univ.*

[3] *RIKEN Center for Computational Science*

[4] *KEK*

[5] *Bielefeld University*

Corresponding Authors: jishnu.goswami@riken.jp, yzhang@physik.uni-bielefeld.de, nakamura@riken.jp, takashi.kaneko@kek.jp, kanamori-i@riken.jp, yasumichi.aoki@riken.jp, shoji.hashimoto@kek.jp, hfukaya@het.phys.sci.osaka-u.ac.jp

We report on the investigation of the thermodynamics of 2+1 flavor QCD along the lines of constant physics (LCP) tuned on and near the physical point with Möbius domain wall fermions. The study is aiming to explore the temperature range covering (pseudo-) criticality for two lattice spacings with $N_t = 12$ and 16. In our simulations the lattice spacing covers 1.4 $> a >$ 0.6 fm, where the residual chiral symmetry breaking changes two-orders of magnitude: $3m_{ud}^{phys} > m_{res} > 0.03m_{ud}^{phys}$ compared with the physical average ud quark mass. We discuss how one can control the effect of m_{res}. It is crucial for the chiral condensate, which is used for the demonstration.

Quantum computing and quantum information / 54

Phase Diagram of the Schwinger Model by Adiabatic Preparation of States on a Quantum Simulator

Author: Oleg Kaikov[1]

Co-authors: Mohamed Tamaazousti [2]; Theo Saporiti [3]; Vasily Sazonov [2]

[1] *University Paris-Saclay, CEA-List*

[2] *University Paris-Saclay, CEA, List*

[3] *Université Paris-Saclay / CEA*

Corresponding Authors: theosaporiti@gmail.com, vasily.sazonov@cea.fr, oikaikov@gmail.com, mohamed.tamaazousti@cea.fr

We argue the feasibility to study the phase structure of a quantum physical system on quantum devices via adiabatic preparation of states. We introduce a novel method and successfully test it in application to the Schwinger model in the presence of a topological θ-term. We explore the first-order-phase-transition and the no-transition regions of the corresponding phase diagram. The core idea of the method is to separately evolve the ground and the first excited states with a time-dependent Hamiltonian, the time-dependence of which interpolates between different values of θ. Despite our approach being a direct application of the adiabatic theorem, we are able to demonstrate its advantages in comparison to a different method from the literature that also employs adiabatic state preparation.

Theoretical developments / 250

Discrete symmetry and 't Hooft anomalies for 3450 model

Author: Tetsuya Onogi[1]

Co-authors: Hiroki Wada [1]; Tatsuya Yamaoka [1]

[1] *Osaka University*

Corresponding Authors: onogi@het.phys.sci.osaka-u.ac.jp, hwada@het.phys.sci.osaka-u.ac.jp, t_yamaoka@hetmail.phys.sci.osaka-u.ac.jp

We report our study of the discrete symmetry for lattice 3450 model
proposed by Wang and Wen. .

Lattice 3450 model is expected to describe the anomaly free chiral U(1) gauge theory in 1+1 dimension using 2+1 dimensional domain-wall fermion with gapping interactions for the mirror sector.

We find that the lattice model has exact discrete symmetry in addition to U(1) x U(1) symmetry.

Asuuming the Zumino-Stora procedure works also for discrete symmetry, we compute the full 't Hooft anomaly for the target continuum U(1) chiral gauge theory with the same discrete symmetry. We show that the mixed and self anomalies involving the discrete symmetry are absent, which is consistent with the expectation that the lattice 3450 produces chiral U(1) gauge theory in the continuum limit.

Particle physics beyond the Standard Model / 473

Dilaton effective theory and soft theorems

Author: Roman Zwicky[1]

[1] *Edinburgh University*

Corresponding Author: roman.zwicky@ed.ac.uk

I will first discuss model-independent properties of dilaton effective theory. Using soft theorems a constraint on the operator generating a potential dilaton mass will be derived. As the operator is relevant this indicates that the dilaton can only acquire a mass through explicit symmetry breaking. The results will derived alternatively from the Lagrangian and linked to the improvement term necessary to reproduced the defining
Goldstone current matrix element. I will further show how an infrared fixed point interpretation of gauge theories is compatible with the end of the conformal window. I will show how this interpretation is related and supported by N=1
supersymmetric gauge theories.

Outreach Masterclass / 498

Particle Physics Masterclasses interactive demo

Corresponding Authors: jonivar@thphys.nuim.ie, despina.hatzifotiadou@cern.ch

Algorithms and artificial intelligence / 333

Using Machine Learning based Unfolding to reduce error on lattice QCD observables

Authors: Christian Schmidt[1]; Simran Singh[2]

[1] *Universitaet Bielefeld*

[2] *University of Bielefeld*

Corresponding Authors: schmidt@physik.uni-bielefeld.de, ssingh@physik.uni-bielefeld.de

In lattice QCD studies, physical observables like the chiral condensate or baryon number density are computed as the trace of a combination of products of the inverse fermion matrix, typically estimated stochastically using the random noise method. The accuracy of this method depends on the number of random sources used; ideally, an infinite number of sources would yield true physical results. However, practical limitations introduce systematic errors due to the finite number of sources. We propose using an unfolding algorithm based on a sequential neural network to learn the inverse transformation from a "true"distribution (obtained with a large number of random sources) to a "measured" distribution (obtained with fewer sources). Applying this learned transformation to observables measured with fewer sources can improve accuracy. We demonstrate that this method's effectiveness is strongly dependent on the distribution of the random noise vectors and only weakly dependent on the matrix structure of the observable, making it a viable approach for lattice studies.

Hadronic and nuclear spectrum and interactions / 456

Beautiful exotics in a non-perturbatively tuned Lattice NRQCD setup

Authors: Daniel Mohler[1]; Renwick Hudspith[2]

[1] *TU Darmstadt*

[2] *York University*

Corresponding Authors: daniel.mohler@tu-darmstadt.de, renwick.james.hudspith@gmail.com

We present a calculation of exotic tetraquark states with two $\bar{b}$-quarks and of the lowest-energy $J^P = 0^+$ and 1^+ B_s-mesons using Lattice NRQCD. The calculations have been performed on the $N_f = 2 + 1$ Wilson-Clover gauge-field configurations from the CLS consortium. For the $ud\bar{b}\bar{b}$ and $us\bar{b}\bar{b}$ tetraquarks we obtain bound states below the respective BB^* and B_sB^* thresholds, which we compare to other Lattice QCD determinations. For the b-quark cousins of the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ we obtain predictions with a better precision and better controlled systematic uncertainty than previous lattice QCD calculations. Overall our uncertainties are dominated by systematics and we outline future steps to remedy this.

Quark and lepton flavour physics / 131

Lattice QCD calculation of the semileptonic decay $J/\psi \to D/D_s l\nu_l$

Author: Yu Meng[1]

Co-authors: Chuan Liu [2]; Haobo Yan [2]; Jin-Long Dang [2]; Xin-Yu Tuo [3]; Yi-Bo Yang [4]; Ke-Long Zhang [5]

[1] *Zhengzhou University*

[2] *Peking University*

[3] *Brookhaven National Laboratory*

[4] *University of Chinese Academy of Sciences*

[5] *Computer Network Information Center, Chinese Academy of Sciences*

Corresponding Authors: yu_meng@zzu.edu.cn, liuchuan@pku.edu.cn, klzhang@cnic.cn

We perform the first lattice calculation on the semileptonic decay of J/ψ using the (2+1)-flavor Wilson-clover gauge ensembles generated by CLQCD collaboration. After a continuum extrapolation using three lattice spacings, we obtain the final branching fraction of $J/\psi \to D/D_s e\nu_e$. The ratios of the branching fractions between lepton μ and e are also calculated and given by $R_{J/\psi}(D)$ and $R_{J/\psi}(D_s)$, which provide necessary theoretical supports for the experimental test of lepton flavour universality in the future.

Structure of hadrons and nuclei / 24

Measurement of the TMD soft function on the lattice using the auxiliary field representation of the Wilson line

Authors: Anthony Francis[1]; C.-J David Lin[1]; Issaku Kanamori[2]; Wayne Morris[1]; Yong Zhao[3]

[1] *National Yang Ming Chiao Tung University*

[2] *RIKEN*

[3] *Argonne National Lab*

Corresponding Authors: dlin@nycu.edu.tw, afrancis@nycu.edu.tw, waynemorris@nycu.edu.tw, kanamori-i@riken.jp, yong.zhao@anl.gov

The TMD soft function may be obtained by formulating the Wilson line in terms of auxiliary 1-dimensional fermion fields on the lattice. We take inspiration from heavy quark effective theory (HQET) in order to define the auxiliary field. Our computation takes place in the region of the lattice that corresponds to the "spacelike"region in Minkowski space in order to obtain the Collins soft function. The matching of our result to the Collins soft function is achieved through the mapping of the auxiliary field directional vector to the Wilson line rapidity. I present some exploratory numerical results of our lattice calculation, and discuss the methodology employed.

QCD at non-zero density / 82

First-order phase transition in dynamical 3-flavor QCD at imaginary isospin

Authors: Alessandro Sciarra[1]; Gergely Endrodi[2]; Guy Moore[3]

[1] *Goethe Universität*

[2] *Bielefeld University*

[3] *TU Darmstadt*

Corresponding Authors: guy.moore@physik.tu-darmstadt.de, endrodi@physik.uni-bielefeld.de, sciarra@th.physik.uni-frankfurt.de

We revisit QCD with three mass-degenerate quark flavors at an imaginary isospin chemical potential set to 4pi/3. This choice corresponds to a special point in the parameter space, where the theory possesses an exact Z(3) center symmetry. Through a finite-size scaling analysis, we demonstrate that in this case the finite temperature QCD transition is of first order and entails singular behavior both in the Polyakov loop and in the quark condensate. Our results are based on simulations with stout-smeared staggered quarks and a dedicated multi-histogram analysis.

Software development and machines - parallel / 150

Lattice QCD on the NVIDIA Grace-Hopper architecture

Author: Mathias Wagner[1]

[1] *NVIDIA*

Corresponding Author: mathiasw@nvidia.com

The NVIDIA Grace Hopper Superchip architecture, powering upcoming supercomputers like Alps at CSCS, Jupyter in Juelich, Isambard-AI in the UK, and Venado at Los Alamos National Laboratory, offers significant advancements for Lattice QCD applications. Integrating the ARM-based Grace CPU with the Hopper GPU via NVLink-C2C, it provides 7x the bandwidth of PCIe Gen5, enabling coherent memory and efficient data transfer. This architecture's high system memory bandwidth (up to 500 GB/s) and NVLink-C2C bandwidth (900 GB/s) and high GPU memory bandwidth (4TB/s) enhance performance for Lattice QCD. Its balance also helps legacy applications with significant CPU components. This talk will present performance results for QUDA-accelerated workloads like MILC and Chroma, discuss how specific features of Grace Hopper can benefit Lattice QCD and show performance of Lattice QCD applications on the NVIDIA Grace CPU. Furthermore, extracting more science can be achieved by co-scheduling different parts of the workflow on CPU and GPU concurrently.

Theoretical developments / 88

The perturbative computation of the gradient flow coupling for the twisted Eguchi–Kawai model with the numerical stochastic perturbation theory

Authors: Hironori Takei[1]; Ken-Ichi Ishikawa[1]; Masanori Okawa[1]

[1] *Hiroshima University*

Corresponding Authors: okawa@sci.hiroshima-u.ac.jp, t-hironori@hiroshima-u.ac.jp, ishikawa@theo.phys.sci.hiroshima-u.ac.jp

The gradient flow method has become an important tool which enables us to efficiently extract the nonperturbative low energy physics from lattice simulations. In this study we perturbatively compute the gradient flow scheme coupling for the SU(N) twisted Eguchi—Kawai (TEK) model using the numerical stochastic perturbation theory (NSPT) in the large-N limit. We evaluate the perturbative coefficients of the gradient flow coupling in terms of the lattice bare 't Hooft coupling up to three-loop and successfully extract the universal one-loop beta function using the NSPT combined with the Lüscher—Weisz formula relating the $\overline{\mathrm{MS}}$ and lattice bare couplings. The feasibility of extracting the higher order beta function coefficients for the gradient flow scheme with the NSPT will be discussed.

Applications outside particle physics - parallel / 134

Lattice field theory of organic semiconductors

Author: Pavel Buividovich[1]

Co-author: Johann Ostmeyer [2]

[1] *University of Liverpool*

[2] *Bonn University*

Corresponding Authors: ostmeyer@hiskp.uni-bonn.de, pavel.buividovich@liverpool.ac.uk

Organic semiconductors such as rubrene or pentacene feature an unconventional charge transport mechanism that is entirely driven by dynamical disorder created by thermal bath of soft phonons, and that is very nontrivial to simulate from first principles. We report on Hybrid Monte-Carlo simulations of charge transport in organic semiconductors, and discuss physical similarities with finite-temperature QCD. In particular, we introduce reduced-variance observables for current-current correlators and the corresponding spectral functions which might also be useful in lattice QCD at finite temperature.

Algorithms and artificial intelligence / 310

Control variates with neural networks

Author: Hyunwoo Oh[None]

Corresponding Author: hyunwooh@umd.edu

In lattice QCD, the precision of results is often hampered by the inherent uncertainty of stochastic methods. Recently, control variates methods have emerged as a promising solution for such noise. Traditional control variates have been used to mitigate this issue, but they rely on educated guesses, which can be limiting. In this talk, I will introduce a neural network approach to parametrize control variates, eliminating the need for guesswork. Using 1+1 dimensional scalar field theory as a testbed, I will demonstrate significant variance reduction, particularly in the strong coupling regime. Also, I will discuss applications of neural control variates on gauge theories.

Hadronic and nuclear spectrum and interactions / 377

Antistatic-antistatic-light-light tetraquark potentials with u, d and s quarks from lattice QCD

Authors: Pedro Bicudo[1]; Marina Krstic Marinkovic[2]; Lasse Müller[3]; Marc Wagner[4]

[1] *IST - LISBOA*

[2] *ETH Zurich*

[3] *Goethe University, Frankfurt am Main*

[4] *Goethe University Frankfurt*

Corresponding Authors: marinama@phys.ethz.ch, mwagner@itp.uni-frankfurt.de, bicudo@tecnico.ulisboa.pt, lmueller@itp.uni-frankfurt.de

We report on our lattice QCD computation of the static-light $\bar{Q}\bar{Q}qq$ potentials, using the CLS configurations and the OpenQ*D codebase. We utilize a set of 24 creation operators, corresponding to 12 sectors characterized by isospin, angular momentum and parity quantum numbers for uu, ud or dd light quarks and 6 sectors for us or ds light quarks. We include off-axis separations of the static antiquarks and use tree-level improvement. The resulting potentials provide some indication for one-pion exchange at intermediate $\bar Q \bar Q" separations.

Quark and lepton flavour physics / 257

Form factors for semi-leptonic $B_{(s)} \to D^*_{(s)} \ell \nu_\ell$ decays

Author: Anastasia Boushmelev[1]

Co-authors: Matthew Black [1]; Oliver Witzel [1]

[1] *University of Siegen*

Corresponding Authors: matthew.black@uni-siegen.de, anastasia.boushmelev@uni-siegen.de, oliver.witzel@uni-siegen.de

Semileptonic $B_{(s)}$ decays are of great phenomenological interest because they allow to extract CKM matrix elements or test lepton flavor universality. Taking advantage of existing data, we explore extracting form factors for vector final states using the narrow width approximation. Based on RBC-UKQCD's set of 2+1 flavor gauge field ensembles with Shamir domain-wall fermion and Iwasaki gauge field action, we study semileptonic $B_{(s)}$ decays using domain-wall fermions for light, strange and charm quarks, whereas bottom quarks are simulated with the relativistic heavy quark (RHQ) action. Exploratory results for $B_s \to D_s^* \ell \nu_\ell$ are presented.

Structure of hadrons and nuclei / 302

Lattice Boer-Mulders TMDPDF with LaMET

Author: Lingquan Ma[1]

[1] *Beijing Normal University*

Corresponding Author: 202031140013@mail.bnu.edu.cn

Transverse-momentum-dependent parton distribution functions (TMDPDFs) are important in revealing the 3D structure of hadrons. Among these distributions, the T-odd Boer-Mulders TMDPDF describes the transversely polarized quark distribution in an unpolarized hadron. Within large-momentum effective theory, we perfromed a lattice calculation of the nucleon Boer-Mulders function. The calculation was done on the X650 ensemble generated by CLS collaboration with Clover fermion and HYP-smeared gauge links.

QCD at non-zero density / 280

Progress on the QCD chiral phase transition for various numbers of flavors and imaginary chemical potential

Authors: Alfredo D'Ambrosio[1]; Michael Fromm[None]; Reinhold Kaiser[1]; Owe Philipsen[2]

[1] *Goethe University Frankfurt*

[2] *Goethe-University Frankfurt am Main*

Corresponding Authors: ambrosio@itp.uni-frankfurt.de, mfromm@itp.uni-frankfurt.de, philipsen@itp.uni-frankfurt.de, kaiser@itp.uni-frankfurt.de

The order of the thermal chiral phase transition in lattice QCD is strongly cutoff-dependent. A recent study from our group using mass-degenerate, unimproved staggered quarks on $N_\tau = \{4, 6, 8\}$ lattices found that the first-order regions shrink to zero for $N_\mathrm{f} \in [2, 6]$ as the continuum limit is approached for zero chemical potential. Here we present the progress of an analogous study at a fixed value of imaginary baryon chemical potential of $\mu_i = 0.81 \frac{\pi T}{3}$. The same qualitative behavior as for zero chemical potential is found: The first-order regions disappear with decreasing lattice

spacing in tricritical points and they are bounded by Z_2-critical lines which exhibit tricritical scaling for sufficiently small quark masses. The results predict a second order chiral phase transition in the continuum limit for $N_\mathrm{f} \in [2,6]$ for both cases, at zero and imaginary chemical potential. Additionally an effective Ginzburg-Landau theory is developed around the tricritical point in the chiral limit. The possibility to encode the dependence of the Landau potential on the parameters of the lattice theory is explored.

Software development and machines - parallel / 337

Implementing automatic testing of Lattice QCD Software on Supercomputing Clusters

Authors: Antonin Portelli[1]; Simon Bürger[2]

[1] *The University of Edinburgh*

[2] *University of Edinburgh*

Corresponding Authors: antonin.portelli@ed.ac.uk, sburger@ed.ac.uk

The advancement of lattice Quantum Chromodynamics (QCD) simulations demands robust and efficient computational infrastructure. This presentation details the implementation of Continuous Integration and Continuous Development (CI/CD) within our research group, specifically tailored to enhance the development and deployment of scientific software on a supercomputing cluster.

Our *TeamCity*-based CI/CD setup automates the testing and performance monitoring of the *Grid* and *Hadrons* software packages, ensuring consistent code quality and system reliability. By integrating automated unit tests and performance benchmarks, we can promptly identify and address issues, thereby accelerating the development cycle and maintaining high-performance standards. This talk aims to share our experiences and insights, providing a potential blueprint for other research teams looking to enhance their computational infrastructure.

Theoretical developments / 168

Smoothing Properties of the Wilson Flow and Topological Charge

Author: Benjamin Jaeger[1]

Co-authors: J. Tobias Tsang [2]; Michele Della Morte [1]; Sofie Martins [1]

[1] *University of Southern Denmark*

[2] *CERN*

Corresponding Authors: jaeger@imada.sdu.dk, martinss@imada.sdu.dk, j.t.tsang@cern.ch

We explore the smoothing properties induced by Wilson flow and their implications on the topological charge. Our study examines the smoothness of the flowed energy density and the topological charge within the framework of orientifold theories. We find that jumps in these quantities can appear even at very large flow times. These jumps in smoothness coincide with changes in the topological charge and seem to be completely dominated by large spatial fluctuations at the lattice scale.

Applications outside particle physics - parallel / 275

Overcoming Ergodicity Problems of the HMC Method using Radial Updates

Author: Finn Temmen[1]

Co-authors: Anthony Kennedy [2]; Evan Berkowitz [1]; Johann Ostmeyer [3]; Thomas Luu [4]; Xinhao Yu [2]

[1] *Forschungszentrum Jülich*

[2] *University of Edinburgh*

[3] *Bonn University*

[4] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: t.luu@fz-juelich.de, e.berkowitz@fz-juelich.de, s1871834@ed.ac.uk, adk@ph.ed.ac.uk, ostmeyer@hiskp.uni-bonn.de, f.temmen@fz-juelich.de

Despite its many advantages, the sensible application of the Hybrid Monte Carlo (HMC) method is often hindered by the presence of large - or even infinite - potential barriers. These potential barriers partition the configuration space into distinct sectors, which leads to ergodicity violations and biased measurements of observables.
In this work, we address this problem by augmenting the HMC method with a multiplicative Metropolis-Hastings update in a so-called "radial direction" of the fields, which enables jumps over the aforementioned potential barriers at comparably low computational cost. The effectiveness of this approach is demonstrated for the Hubbard model, formulated in a non-compact space by means of a continuous Hubbard-Stratonovich transformation. Our numerical results show that the radial updates successfully resolve the ergodicity violation, while simultaneously reducing autocorrelations.

Algorithms and artificial intelligence / 31

Parton Distribution Functions in the Schwinger Model with Tensor Networks

Authors: C.-J David Lin[1]; Krzysztof Cichy[2]; Manuel Schneider[3]; Mari Carmen Bañuls[4]

[1] *National Yang Ming Chiao Tung University*

[2] *Adam Mickiewicz University of Poznan*

[3] *National Yang Ming Chiao Tung University (NYCU), Taiwan*

[4] *Max Planck institute of Quantum Optics*

Corresponding Authors: mari.banuls@mpq.mpg.de, manuel.schneider@nycu.edu.tw, dlin@nycu.edu.tw, krzysztof.cichy@gmail.com

Parton Distribution Functions (PDFs) describe universal properties of bound states and allow to calculate scattering amplitudes in processes with large momentum transfer. Calculating PDFs involves the evaluation of correlators with a Wilson line in lightcone-direction. In contrast to Monte Carlo methods in euclidean spacetime, these correlation functions can be directly calculated in the Hamiltonian formalism. The necessary spatial- and time-evolution can be efficiently applied using established tensor network methods. We study PDFs in the Schwinger model using matrix product states.

Hadronic and nuclear spectrum and interactions / 74

Tetraquarks $\bar{b}\bar{b}ud$, $I(J^P) = 0(1^-)$ and $\bar{b}\bar{c}ud$ with $I(J^P) = 0(0^+), 0(1^+)$ from Lattice QCD Static Potentials

Author: Jakob Hoffmann[1]

Co-authors: Lasse Müller [1]; Marc Wagner [1]

[1] *Goethe University, Frankfurt am Mian*

Corresponding Authors: jhoffmann@itp.uni-frankfurt.de, lmueller@itp.uni-frankfurt.de

We use existing antistatic-antistatic potentials computed with two flavors of twisted mass fermions to study antiheavy-antiheavy-light-light four-quark systems in the Born-Oppenheimer approximation. We do not only compute masses of bound states, but also search for poles in the scattering amplitude above the lowest meson-meson threshold, to detect resonances and determine their parameters. We include effects due to the heavy quark spins, by considering coupled channel Schroedinger equations and using the experimentally measured mass splittings of the B and B^* meson as input. We present indications for a $\bar{b}\bar{b}ud$ tetraquark resonance with quantum numbers $I(J^P) = 0(1^-)$ close to the B^*B^* threshold. We also discuss first results for $\bar{b}\bar{c}ud$ systems with $I(J^P) = 0(0^+)$ and $I(J^P) = 0(1^+)$.

Quark and lepton flavour physics / 326

$B \to D^{(*)}$ decays from $N_f = 2+1+1$ highly improved staggered quarks and clover b-quark in the Fermilab interpretation.

Authors: Pietro Butti[1]; Andrew Lytle[2]; Elvira Gamiz[3]; Carleton DeTar[4]; Steven Gottlieb[5]; Andreas Kronfeld[6]; Aida El-Khadra[7]; Hwancheol Jeong[8]; Jack Laiho[9]; William Jay[10]; Alejandro Vaquero[4]

[1] *University of Zaragoza*

[2] *University of Glasgow*

[3] *University of Granada*

[4] *University of Utah*

[5] *Indiana University*

[6] *Fermilab*

[7] *University of Illinois Urbana-CHampaign*

[8] *Seoul National University*

[9] *Syracuse University*

[10] *MIT*

Corresponding Authors: alexvaq@physics.utah.edu, pietro.butti.fl@gmail.com, megamiz@ugr.es, detar@physics.utah.edu, willjay@mit.edu, axk@illinois.edu, sg@indiana.edu, sonchac@gmail.com, ask@fnal.gov, andrew.lytle@glasgow.ac.uk

We present an update on the analysis of semileptonic $B \to D^{(*)}$ decays at non-zero recoil. Our computation employs 2+1+1 FNAL-MILC ensembles with highly improved staggered quark (HISQ) action for sea and light valence quarks, while the bottom quark is treated using the clover action in the Fermilab interpretation. Simulations are performed across several lattice spacings, ranging approximately from ~ 0.15 fm to ~ 0.06 fm, and for various quark masses. We will present an overview of the analysis and show some preliminary results for the form factors.

Structure of hadrons and nuclei / 391

Nucleon TMDPDFs within the twisted mass fermion formulation of lattice QCD

Authors: Aniket Sen[1]; Constantia Alexandrou[2]; Martha Constantinou[3]; Krzysztof Cichy[4]; Fernanda Steffens[5]; Simone Bacchio[6]; Gregoris Spanoudes[7]; Jacopo Tarello[7]

[1] *HISKP, University of Bonn*

[2] *University of Cyprus and The Cyprus Institute*

[3] *Temple University*

[4] *Goethe-University Frankfurt am Main*

[5] *U. Bonn*

[6] *The Cyprus Institute*

[7] *University of Cyprus*

Corresponding Authors: marthac@temple.edu, spanoudes.gregoris@ucy.ac.cy, sen@hiskp.uni-bonn.de, alexand@ucy.ac.cy, s.bacchio@gmail.com, krzysztof.cichy@gmail.com

Using large momentum effective theory it is possible to calculate transverse momentum dependent parton distribution functions (TMDPDFs) from first principle in lattice QCD. In this work, we present results for the 3 main constituents of the TMD Parton distribution functions, namely the quasi-TMDPDF, the Collins-Soper kernel and the reduced soft function. We construct the physical TMD-PDF using a twisted fermion mass ensemble of size $24^3 \times 48$ with a pion mass of 350 MeV.

QCD at non-zero density / 367

Dense, magnetized, and strangeness-neutral QCD from imaginary chemical potential

Authors: Adeilton Dean Marques Valois[1]; Bastian Brandt[2]; Gergely Endrodi[1]; Jana N. Guenther[3]; Marc-André Petri[3]; Szabolcs Borsanyi[3]

[1] *Bielefeld University*

[2] *University of Bielefeld*

[3] *University of Wuppertal*

Corresponding Authors: dvalois@physik.uni-bielefeld.de, brandt@physik.uni-bielefeld.de, borsanyi@uni-wuppertal.de, jguenther@uni-wuppertal.de, endrodi@physik.uni-bielefeld.de, petri@uni-wuppertal.de

Finite density and strong magnetic fields are expected in peripheral heavy-ion collision experiments. Moreover, global strangeness-neutrality is an important condition satisfied by the system. Therefore, in this work, we study the impact of magnetic fields on the equation of state of dense QCD in the line of strangeness-neutrality and isospin asymmetry from lattice QCD simulations at imaginary baryon chemical potential. Our simulations include 2+1+1 flavors of stout-smeared staggered fermions with masses at the physical point. To ensure strangeness neutrality, we expand in strange and charge chemical potentials around our previously tuned simulation points and extrapolate to the point of vanishing strangeness density. We study the dependence of strangeness-neutrality on the magnetic field using three values of the field strength, namely, $B = 0.3\,, 0.5\,, 0.8$ GeV^2. Our results can be used by future works to benchmark the equation of state of dense and magnetized QCD for heavy-ion phenomenology.

Software development and machines - parallel / 402

O(a)-improved QCD+QED Wilson Dirac operator on GPUs

Author: Roman Gruber[1]

[1] *ETH Zürich*

Corresponding Author: rgruber@ethz.ch

Heterogeneous clusters of GPU-accelerated nodes offer large total memory bandwidth which can be used to speed-up our application, openQxD-1.1. In this work we investigate offloading solves of the Dirac equation from our framework openQxD-1.1 to GPU using the lattice-QCD library QUDA, and our early results demonstrate a significant potential speed-up in the time-to-solution for state-of-the-art problem sizes.
Minimal extensions to the existing QUDA library are required for our specific physics programme (mainly implementing C* boundary conditions) while greatly enhancing the performance portability of our code and retaining the reliability and robustness of existing applications in openQxD-1.1.
Our new interface will enable us to utilize pre-exascale infrastructure and reduce the systematic uncertainty in our physics predictions by incorporating the effects of quantum electromagnetism in our simulations.

Theoretical developments / 212

Energy-momentum tensor in the 2D Ising CFT in full modular space

Authors: Richard Richard Brower[1]; George Fleming[2]; Jin-Yun Lin[3]; Nobuyuki Matsumoto[1]

[1] *Boston University*

[2] *Yale University*

[3] *Carnegie Mellon University*

Corresponding Authors: gfleming@fnal.gov, jinyunl@andrew.cmu.edu, nmatsum@bu.edu, brower@bu.edu

The energy-momentum tensor in the 2D Ising CFT is constructed on the lattice in both spin and fermionic variables. The expression is confirmed by conformal Ward identities on the torus. We work in hexagonal lattice (and by taking the dual, triangular lattice), which enables us to study it in the full range of the modular parameter τ 1 and further its role of deforming τ. In relation to that it is conjugate to the metric, it is more sensitive to the lattice geometry than the primaries. In fact, operator mixing in the components of the Symanzik-type operator, which happens on the non-regular lattices and remains as we approach the continuum limit, can be understood by a shift in the staggered structure of the lattice. For this nature of the operator, it can be a fundamental concept in defining lattice field theories on a curved manifold with a simplicial lattice, which is our ultimate goal 2.

1 R. C. Brower and E. K. Owen, "Ising model on the affine plane," Phys. Rev. D **108**, no.1, 014511 (2023) [arXiv:2209.15546 [hep-th]].
2 For pioneering work, see, for example: R. C. Brower, M. Cheng, G. T. Fleming, A. D. Gasbarro, T. G. Raben, C. I. Tan and E. S. Weinberg, "Lattice ϕ^4 field theory on Riemann manifolds: Numerical tests for the 2-d Ising CFT on $\mathbb{S}^2$," Phys. Rev. D **98**, no.1, 014502 (2018) [arXiv:1803.08512 [hep-lat]]; see also contributions by R. C. Brower and G. T. Fleming in this conference.

Applications outside particle physics - parallel / 293

Hamiltonian Lattice Formulation of Compact Maxwell-Chern-Simons Theory

Authors: Changnan Peng[1]; Cristina Diamantini[2]; Lena Funcke[3]; Syed Muhammad Ali Hassan[4]; Karl Jansen[5]; Stefan Kühn[5]; Di Luo[1]; Maxim Metlitski[1]; Pranay Naredi[4]; Emil Otis Rosanowski[6]

[1] *MIT*

[2] *University of Perugia*

[3] *University of Bonn*

[4] *Cyprus Institute*

[5] *DESY*

[6] *HISKP, University of Bonn*

Corresponding Authors: cristina.diamantini@pg.infn.it, rosanowski@hiskp.uni-bonn.de, cnpeng@mit.edu, p.naredi@cyi.ac.cy, mmetlits@mit.edu, lfuncke@uni-bonn.de, stefan.kuehn@desy.de, diluo@mit.edu, karl.jansen@desy.de, s.m.hassan@cyi.ac.cy

Chern-Simons theory is a topological quantum field theory with numerous applications in condensed matter and high-energy physics, including the study of anomalies, fermion/boson dualities, and the fractional quantum Hall effect. The lattice formulation of pure Chern-Simons theory faces a doubling problem, which can be resolved by incorporating a Maxwell term, resulting in Maxwell-Chern-Simons theory. While the Lagrangian formulation for Euclidean spacetime lattices has been recently derived, a Hamiltonian formulation remains absent.

In this work, we address this gap by deriving a Hamiltonian lattice formulation of compact Maxwell-Chern-Simons theory using the Villain approximation. We analytically solve this theory and show that the mass gap in the continuum limit matches the well-known continuum formula. The inclusion of fermions necessitates numerical methods, but standard Monte Carlo simulations cannot simulate the theory due to the sign problem. Our Hamiltonian formulation of Maxwell-Chern-Simons theory lays the groundwork for future Hamiltonian-based simulations of the theory on classical and quantum computers.

Quark and lepton flavour physics / 396

Towards more accurate $B_{(s)} \to \pi(K)$ and $D_{(s)} \to \pi(K)$ form factors

Author: Logan Roberts[1]

Co-authors: Chris Bouchard [2]; Olmo Francesconi [2]; William Parrott [3]

[1] *Univeristy of Glasgow - Particle Physics Theory Group*

[2] *University of Glasgow*

[3] *York University*

Corresponding Authors: l.roberts.1@research.gla.ac.uk, olmo.francesconi@glasgow.ac.uk, parrott@yorku.ca, chris.bouchard@glasgow.ac.uk

I present progress on the calculation of scalar, vector, and tensor form factors for the following meson decays: $B \to \pi$, $B_s \to K$, $D \to \pi$, and $D_s \to K$. The calculation uses the MILC $N_f = 2 + 1 + 1$ HISQ gluon field ensembles and HISQ valence quarks. We generate ensembles of correlator data with varying lattice spacings, as small as 0.044 fm. Some ensembles have a strange-to-light quark mass ratio of 5:1 and others use the physical light quark mass. The fully-relativistic, heavy-HISQ approach is used for the heavy quark, with simulation masses ranging from the charm to near the bottom. The heavy-HISQ approach provides nearly full coverage of the kinematic range. Preliminary correlator fits and next steps are discussed.

Algorithms and artificial intelligence / 67

Toward tensor renormalization group study of lattice QCD

Author: Atis Yosprakob[1]

[1] *Niigata University*

Corresponding Author: yosprakob2@gmail.com

The tensor renormalization group (TRG) method is a powerful tool for studying lattice field theories and quantum many-body systems that is free from the sign problem. In this talk, I discuss two of the recent developments toward the TRG study of lattice QCD. The first is the proposal for incorporating multiple fermion flavors for 2D Abelian gauge theory, using the Grassmann tensor network. The second is the proposal for the reduced tensor network formulation for non-Abelian pure gauge theories in arbitrary dimensions. These two techniques are essential for the efficient computations of non-Abelian gauge theories with multiple flavors, including quantum chromodynamics.

Hadronic and nuclear spectrum and interactions / 178

Hybrid static potentials and gluelumps on $N_f = 3 + 1$ ensembles

Authors: Francesco Knechtli[1]; Juan Andres Urrea Nino[2]; Laura Struckmeier[None]; Michael Peardon[3]; Roman Höllwieser[1]; Tomasz Korzec[2]

[1] *University of Wuppertal*

[2] *Bergische Universität Wuppertal*

[3] *Trinity College Dublin*

Corresponding Authors: urreanino@uni-wuppertal.de, hoellwieser@uni-wuppertal.de, korzec@uni-wuppertal.de, lstruckmeier@uni-wuppertal.de, mjp@maths.tcd.ie, knechtli@physik.uni-wuppertal.de

QCD permits the existence of hybrid mesons that are made up of both quarks and gluons, including exotic states, i.e., quantum numbers prohibited for pure quark-antiquark states, with possible candidates found in experiments. We present static hybrid potentials measured via Laplace trial states together with static-light meson thresholds on $N_f = 3 + 1$ dynamical fermion ensembles with 420 MeV pions. Furthermore, we measure corresponding gluelump masses which refer to the $R \to 0$ limit of the hybrid potentials and are essential input parameters for effective models to describe hybrid mesons.

Structure of hadrons and nuclei / 91

Forward-limit generalized parton distributions of the η_c-meson

Author: Jose Manuel Morgado Chávez[1]

Co-authors: Benoît Blossier [2]; Cédric Mezrag [3]; Miguel Teseo San José Pérez [2]

[1] *LSN/DPhN/Irfu CEA-Saclay*

[2] *IJCLab*

[3] *Irfu/CEA-Saclay*

Corresponding Authors: jose-manuel.morgadochavez@cea.fr, cedric.mezrag@cea.fr, blossier@ijclab.in2p3.fr, san-jose-perez@ijclab.in2p3.fr

The formalism of short-distance factorization allows to connect light-cone correlators with spacelike ones. The later being directly accessible in Euclidean lattices, and the former being the key objects for all of parton physics, the possibility of studying hadron structure in the framework of lattice QCD is opened. In this work we take advantage of this formalism −conveyed through the pseudo-distribution approach− to compute, for the first time, the generalized parton distributions (GPDs) of the η_c-meson. To this end we use CLS ($n_f = 2$) ensembles of gauge configurations to evaluate the η_c-meson's pseudo-GPD for a number of t-values. We study the continuum− and light-cone−limit

of our results. Finally, relying on analytic properties of Ioffe-time distributions, we achieve a model-independent extraction of the η_c-GPD. The η_c being a heavy pseudo−scalar meson, direct comparison with similar results available for lighter ones −say, pions− allows for a pioneering analysis of the effect of quark masses on the structure of hadrons.

QCD at non-zero density / 360

QCD EoS in strong magnetic fields and nonzero baryon density

Authors: Arpith Kumar[1]; Heng-Tong Ding[1]; Jin-Biao Gu[1]; Sheng-Tai Li[1]

[1] *Central China Normal University*

Corresponding Authors: jinbiaogu@mails.ccnu.edu.cn, arpithk.phy@gmail.com, hengtong.ding@ccnu.edu.cn, lishengtai@ccnu.edu.cn

Equilibrium properties of strongly interacting matter are typically characterized by the quantum chromodynamics (QCD) equation of state (EoS). External factors, especially magnetic fields that reach the order of the QCD scale, can significantly influence this characterization. Strong magnetic fields can be produced in the relativistic heavy-ion collisions where baryon chemical potentials can be nonzero. Therefore, understanding the QCD EoS under nonzero magnetic fields and baryon chemical potential is indispensable. To this end, we have carried out lattice simulations of $(2+1)$-flavor QCD using highly improved staggered quarks at the physical pion mass on $32^3 \times 8$ and $48^3 \times 12$ lattices, with magnetic field strengths ranging up to 0.8 GeV^2 and nonzero baryon chemical potentials employing the Taylor expansion framework. We present a comprehensive lattice QCD analysis, along with the hadron resonance gas comparison, for the leading order and next-to-leading order Taylor expansion coefficients for bulk thermodynamic quantities such as pressure, number density, energy density, and entropy density, focussing on the significant impact of strong magnetic fields.

Software development and machines - parallel / 440

A Julia Code for Lattice QCD on GPUs

Authors: Alberto Ramos[1]; Carlos Pena[2]; Fernando Pérez Panadero[3]; Guilherme Catumba[4]

[1] *CERN*

[2] *IFT UAM-CSIC*

[3] *IFT-UAM/CSIC*

[4] *IFIC*

Corresponding Authors: gtelo@ific.uv.es, carlos.pena@uam.es, alberto.ramos@cern.ch, fernando.p@csic.es

We present a new GPU-based open source package to perform Lattice simulations developed in Julia. The Code currently supports generation of SU(2) and SU(3) (pure gauge) configurations with different actions and boundary conditions. The code can be used to measure different flow observables (both gluonic and fermionic) as well as different fermionic two point functions. In the talk we will show the capabilities of the code, and provide information of some measurement codes built on top of this framework.

Theoretical developments / 331

Lattice Field Theory On Curved Manifolds – The Affine Conjecture

Author: Richard Brower[1]

Co-authors: George Fleming [2]; Jin-Yun Lin [3]; Nobuyuki Matsumoto [1]

[1] *Boston University*

[2] *Fermi National Accelerator Laboratory*

[3] *Carnegie Mellon University*

Corresponding Authors: nmatsum@bu.edu, brower@bu.edu, jinyunl@andrew.cmu.edu, gfleming@fnal.gov

Lattice radial quantization on cylinders ($\mathbb{R} \times \mathbb{S}^{d-1}$), potentially offers a powerful new approach for strong coupling conformal or near conformal field theories, including gauge theories under considerations for Beyond the Standard Model (BSM) composite Higgs and Dark Matter physics. A general solution for any triangulated (or simplicial) lattice manifold was formulated by Regge in 1960 for the Einstein Hilbert action or any classical field theory. However the lattice spacing (edge length) introduces a noisy UV cut-off that obstructs quantization. Our solution for the 2d Ising CFT on a 2 sphere using an analytic local affine map to the tangent planes on geometrically smoothed Regge manifold suggests a general strategy or Affine Conjecture. A sequence of geometrical investigations and numerical tests are proposed for non-integrable systems such as phi 4th theories and gauge and fermionic theories on 3d spherical, 4d cylindrical and dual Anti de Sitter manifolds.

Applications outside particle physics - parallel / 334

Low-Lying Spectrum of Two-Dimensional Adjoint QCD from the Lattice

Authors: Manki Kim[1]; Neill Warrington[1]; Patrick Oare[1]; Phiala Shanahan[1]; William Jay[2]

[1] *Massachusetts Institute of Technology*

[2] *MIT*

Corresponding Authors: mk2427@mit.edu, ncwarrin@mit.edu, willjay@mit.edu, pshana@mit.edu, poare@mit.edu

Two-dimensional adjoint QCD is the theory of a single Majorana fermion coupled to an SU(N) gauge field in the adjoint representation in (1+1) spacetime dimensions. The theory has been studied as a toy model of confinement in gauge theories: it confines test charges when the adjoint fermion is massive but deconfines when the adjoint fermion is massless. We present a preliminary calculation of the low-lying spectrum of two-dimensional adjoint QCD for $N = 2$ colors using a Wilson discretization of the fermion action. The Wilson term radiatively generates a four-fermion coupling that is not present in the standard adjoint QCD action, which flows to zero in the continuum. The presence of this term and its implications for future lattice Monte Carlo simulations of adjoint QCD are discussed.

Quark and lepton flavour physics / 387

Inclusive semileptonic $D_s \mapsto X\ell\nu$ decay from lattice QCD

Author: Alessandro De Santis[1]

Co-authors: Antonio Evangelista [2]; Aurora Melis [3]; Antonio Smecca [4]; Carsten Urbach [5]; Christiane Groß [6]; Francesca Margari [7]; Francesco Sanfilippo [8]; Giuseppe Gagliardi [8]; Marco Garofalo [5]; Marco Panero [9]; Nazario Tantalo [10]; Paolo Gambino ; Roberto Frezzotti [11]; Silvano Simula [12]; Vittorio Lubicz [13]

[1] *University of Roma Tor Vergata and INFN*

[2] *University and INFN of Rome Tor Vergata*

[3] *RomaTre University*

[4] *Swansea University*

[5] *University of Bonn*

[6] *HISKP, Bonn University*

[7] *Univ. of Roma Tor Vergata and INFN - Roma Tor Vergata*

[8] *Infn, sezione di Roma Tre*

[9] *University of Turin and INFN Turin*

[10] *Rome University Tor Vergata and INFN sez. of Rome Tor Vergata*

[11] *University of Rome Tor Vergata, Physics Department and INFN - Sezione di Roma Tor Vergata*

[12] *INFN Roma Tre*

[13] *Università Roma Tre and INFN*

Corresponding Authors: giuseppe.gagliardi@roma3.infn.it, antonio.smecca@swansea.ac.uk, francesco.sanfilippo@roma3.infn.it, simula@roma3.infn.it, nazario.tantalo@gmail.com, alessandro.desantis@roma2.infn.it, urbach@hiskp.uni-bonn.de, panero@to.infn.it, margari@roma2.infn.it, vittorio.lubicz@uniroma3.it, gross@hiskp.uni-bonn.de, marcogarofalo31@gmail.com, me.aurora.16@gmail.com, roberto.frezzotti@roma2.infn.it, gambino@to.infn.it, antonio.evangelista@roma2.infn.it

We present a fully non-perturbative computation of the inclusive semileptonic $D_s \mapsto X\ell\nu$ decay and its leptonic moments from lattice QCD. A first principles computation of such observable has a phenomenological relevance since its comparison with experimental data allows for stringent Standard Model tests in the sector of Flavour physics. Additionally, this work sets the stage to a future project involving the B meson(s). The computation, performed employing state-of-the-art ETMC ensembles at the physical point with four lattice spacings and three volumes, is carried out by extracting smeared spectral densities from Euclidean four-point correlation functions. In this talk we focus on the theoretical background and the methodology, which implies solving an ill-posed inverse Laplace transform. This can currently be achieved with controlled statistical and systematic uncertainties by using the Hansen-Lupo-Tantalo method.

Algorithms and artificial intelligence / 217

Initial tensor construction and dependence for tensor renormalization group

Author: Katsumasa Nakayama[1]

Co-author: Manuel Schneider [2]

[1] *Riken*

[2] *National Yang Ming Chiao Tung University (NYCU), Taiwan*

Corresponding Authors: manuel.schneider@nycu.edu.tw, katsumasa.nakayama@riken.jp

We propose a method for the construction of the initial tensor representation and its dependence on the tensor renormalization group (TRG). The TRG method is a numerical calculation technique that utilizes tensor network representations of physical quantities to investigate physical properties without encountering the sign problem.
To apply the TRG method, it is essential to make a typical (locally connected) tensor network suitable for recursive coarse-graining. In this talk, we present a systematic approach for translating a general tensor network into this typical tensor network. Additionally, we discuss the dependence on the details of the initial tensor network.

Hadronic and nuclear spectrum and interactions / 349

A scheme for studying the heavy pentaquark spectrum in lattice QCD

Author: Abdullah Shams Bin Tariq[1]

Co-authors: Mahmud Ashraf Shamim [2]; Md. Rounak Jahan Raj [1]; Md. Taufiqul Islam [1]; Rubya Akter Badhon [1]

[1] *University of Rajshahi, Bangladesh*

[2] *University of Rajshahi, Bangladesh and University of Alabama*

Corresponding Authors: mashamim@crimson.ua.edu, s1912022102@ru.ac.bd, rounakjahanraj@gmail.com, asb-tariq@ru.ac.bd

It is now clear that bound multiquark states are possible with heavy quarks. Several tetraquark and a handful of pentaquark states have been observed in experiments. However, most of these are molecular states just below threshold. Lattice QCD holds an advantage over experiment in studying possible states with more heavy quarks. Apart from measuring the mass, it is now interesting to understand the nature of these states –differentiating between loosely bound hadronic molecules and any prospect for tightly bound hadrons. A scheme is presented for the spectroscopy of prospective pentaquark states with varying numbers of heavy quarks as well as the differentiation between molecular and tightly bound ones in lattice QCD.

Structure of hadrons and nuclei / 230

Gluon Collins-Soper kernel from lattice QCD

Authors: Artur Avkhadiev[1]; Michael Wagman[2]; Phiala Shanahan[3]; Yang Fu[1]; Yong Zhao[4]

[1] *MIT*

[2] *Fermilab*

[3] *Massachusetts Institute of Technology*

[4] *Argonne National Lab*

Corresponding Authors: aavkhadi@mit.edu, yangfu@mit.edu, mwagman@fnal.gov, yong.zhao@anl.gov, pshana@mit.edu

We will present a first lattice QCD calculation of gluon Collins-Soper kernel, which relates the transverse momentum-dependent gluon parton distribution functions at different energy scales.

QCD at non-zero density / 262

The Roberge-Weiss endpoint in (2+1)-flavor QCD with background magnetic fields

Authors: Kevin Zambello[1]; Massimo D'Elia[2]; Lorenzo Maio[3]; Giuseppe Zanichelli[4]

[1] *University of Pisa and INFN - Sezione di Pisa*

[2] *University of Pisa and INFN*

[3] *CPT, Marseille*

[4] *University of Pisa*

Corresponding Authors: lorenzo.maio@cpt.univ-mrs.fr, massimo.delia@unipi.it, kevin.zambello@pi.infn.it

In this work we discuss our results on the Roberge-Weiss (RW) transition at imaginary chemical potentials and in the presence of background magnetic fields. We perform lattice QCD simulations

on $N_t = 6, 8$ lattices with 2+1 flavors of stout-staggered fermions at physical quark masses and the tree-level Symanzik improved gauge action. We determine the location the RW endpoint at finite magnetic fields and we study the order of the transition.

Software development and machines - parallel / 463

Rearchitecting QUDA for Multi-RHS Computation

Author: Kate Clark[1]

Co-authors: Bálint Joó [1]; Evan Weinberg [1]; Jiqun Tu [1]; Mathias Wagner [1]

[1] *NVIDIA*

Corresponding Authors: mathiasw@nvidia.com, eweinberg@nvidia.com, bjoo@nvidia.com, mclark@nvidia.com

It is well-known that computers are no longer getting faster, and only more parallel and hierarchical. Moreover, computations are increasingly bandwidth limited; and with the advent of the end of Moore's Law, often power limited as well. This requires us to rethink how we deploy LQCD computations to maximize science throughput. In this talk we discuss the rearchitecting of QUDA for batch computation to expose more parallelism and locality. Performance results are shown for a variety of workloads, including linear solves, multigrid, and contractions.

Theoretical developments / 8

Lattice study of RG fixed point based on gradient flow in 3D $O(N)$ sigma model

Author: Okuto Morikawa[1]

Co-authors: Mizuki Tanaka [2]; Masakiyo Kitazawa [3]; Hiroshi Suzuki [4]

[1] *RIKEN*

[2] *Osaka University*

[3] *Yukawa Institute for Theoretical Physics*

[4] *Kyushu University*

Corresponding Authors: okuto.morikawa@riken.jp, hsuzuki@phys.kyushu-u.ac.jp, kitazawa@yukawa.kyoto-u.ac.jp

We present the lattice simulation of the renormalization group flow in the 3-dimensional $O(N)$ linear sigma model. This model possesses a nontrivial infrared fixed point, called Wilson-Fisher fixed point. Arguing that the parameter space of running coupling constants can be spanned by expectation values of operators evolved by the gradient flow, we exemplify a scaling behavior analysis based on the gradient flow in the large N approximation at criticality. Then, we work out the numerical simulation of the theory with finite N. Depicting the renormalization group flow along the gradient flow, we confirm the existence of the Wilson-Fisher fixed point non-perturbatively.

Applications outside particle physics - parallel / 340

Real time simulations of scalar fields with kernelled complex Langevin equation

Author: Denes Sexty[1]

Co-authors: Alexander Rothkopf [2]; Daniel Alvestad [3]

[1] *Uni Wuppertal*

[2] *University of Stavanger*

[3] *Stavanger University*

Corresponding Authors: daniel.alvestad@uis.no, sexty.denes@gmail.com, alexander.rothkopf@uis.no

Real time evolution of a scalar field theory is investigated. The severe sign problem is circumvented using the Complex Langevin equation. The naive application of the method breaks down for extended real times due to the appearance of boundary terms. We use the kernel freedom of the complex Langevin equation to push the breakdown to larger real-times. We search for the optimal kernel using machine learning methods. Thus, we extend the available range for 1+1d scalar simulations beyond the state of the art simulations.

QCD at non-zero density / 76

B dependence of the QED chiral condensate induced by an external magnetic field.

Author: Donald Sinclair[1]

Co-author: John Kogut [2]

[1] *Argonne National Laboratory*

[2] *USDOE and University of Maryland*

Corresponding Authors: jbkogut@umd.edu, dks@anl.gov

We have shown by lattice QED simulations that an external magnetic field induces chiral symmetry breaking with a non-zero chiral condensate, as predicted by Schwinger-Dyson methods, using a single large external magnetic field (see J.B.Kogut and D.K.Sinclair, Phys. Rev. D 109, 034511 (2024)). We are now extending these simulations to a weaker magnetic field to test that the chiral condensate is $\propto (eB)^{3/2}$ as expected.

Quark and lepton flavour physics / 140

Semileptonic Inclusive Decay of the D_s Meson

Author: Christiane Groß[1]

[1] *Extended Twisted Mass Collaboration*

Corresponding Author: gross@hiskp.uni-bonn.de

We analyse the semileptonic decay of the D_s meson, focusing on the $D_s \to X\ell\nu$ channel based on an Extended Twisted mass ensembles at the physical pion mass value.
On the basis of four-point correlation functions, we use the HLT reconstruction method to calculate the differential decay rate, allowing us to analyse the inclusive decay.
The analysis is performed at four different lattice spacings, and three different volumes to address the associated systematic uncertainties.

Algorithms and artificial intelligence / 292

Machine Learning Enhanced Optimization of Variational Quantum Eigensolvers

Authors: Kim A. Nicoli[1]; Luca Wagner[1]; Lena Funcke[1]

[1] *University of Bonn*

Corresponding Authors: knicoli@uni-bonn.de, s6lawagn@uni-bonn.de, lfuncke@uni-bonn.de

Variational Quantum Eigensolvers (VQEs) are a powerful class of hybrid quantum-classical algorithms designed to approximate the ground state of a quantum system described by its Hamiltonian. VQEs hold promise for various applications, including lattice field theory and quantum chemistry. However, the inherent noise present in Noisy Intermediate-Scale Quantum (NISQ) devices poses a significant challenge for running VQEs. These algorithms are particularly susceptible to noise, such as measurement shot noise and hardware noise.
Within this work, we propose to enhance VQEs using Gaussian Processes and Bayesian Optimization. These established machine-learning techniques excel at learning from noisy data, making them ideal candidates for improving VQEs. The contributions of this work are twofold. First, we introduce a "VQE-kernel", a custom kernel function specifically designed to incorporate valuable prior physics information in the Gaussian Process by design. Second, we propose a physics-informed acquisition function for Bayesian Optimization termed "Expected Maximum Improvement over Confident Regions" (EMICoRe). Extensive numerical experiments demonstrate that our approach outperforms state-of-the-art baselines.

Hadronic and nuclear spectrum and interactions / 15

Exotic T_{bc} tetraquarks from Lattice QCD

Authors: Archana Radhakrishnan[1]; Nilmani Mathur[1]; Padmanath M[2]

[1] *Tata Institute of Fundamental Research*

[2] *The Institute of Mathematical Sciences, India*

Corresponding Authors: padmanath@imsc.res.in, arcradhakrishnan07@gmail.com, nilmani@theory.tifr.res.in

Research into doubly heavy tetraquarks has become highly relevant, especially with the recent discovery of the doubly charmed tetraquark T_{cc}. In this study, we present a lattice investigation of S-wave $D\bar{B}^{(*)}$ scattering within the isoscalar axial-vector and scalar channels. Both the processes feature the flavor combination $bc\bar{u}\bar{d}$, which could potentially host T_{bc} tetraquarks.

Our calculations were conducted on four different $N_f = 2 + 1 + 1$ MILC gauge ensembles, each with varying lattice spacings and volumes. Utilizing the amplitude analysis method la Lüscher, we extracted the $D\bar{B}^{(*)}$ scattering amplitudes from the finite-volume spectra. By examining the light quark mass ($m_{u/d}$) dependence of these amplitudes and extrapolating to the continuum, we explored the behavior of the $bc\bar{u}\bar{d}$ tetraquarks at the physical $m_{u/d}$.Our findings provide evidence for a bound state of the $bc\bar{u}\bar{d}$ tetraquark at the physical $m_{u/d}$ within both the scalar and the axial-vector channels.

Structure of hadrons and nuclei / 426

Refining Gluon Distributions in Nucleons via Lattice QCD

Authors: Christopher Chamness[1]; Hervé Dutrieux[1]; Robert Edwards[2]; Joseph Karpie[2]; Lorenzo Maio[3]; Christopher Monahan[1]; Kostas Orginos[4]; Anatoli Radyushkin[2]; David Richards[2]; Eloy Romero Alcalde[2]; Alexandru Sturzu[1]; Savvas Zafeiropoulos[5]

[1] *William-Mary Coll.*

[2] *Jefferson Lab*

[3] *CPT, Marseille*

[4] *College of William and Mary/JLAB*

[5] *Aix Marseille University*

Corresponding Authors: kostas@wm.edu, eromero@jlab.org, lorenzo.maio@cpt.univ-mrs.fr

In this talk, we present updates on the measurement of the unpolarized gluon distribution in the nucleon from $N_f = 2 + 1$ QCD on the lattice, extending the work published in PRD 104 (2021) 9, 094516, where the estimation is performed with a 358 MeV pion mass and 0.094 fm lattice spacing. Utilizing larger statistical datasets and refining the sGEVP determination through a projection of the two-point function onto the most relevant subspace, we aim to enhance the precision of our results. This work represents the first step of a forthcoming project that aims to achieve continuum results for physical masses.

Software development and machines - parallel / 465

openQCD on GPU

Author: Antonio Rago[1]

Co-author: Stefan Schaefer [2]

[1] *QTC & IMADA, University of Southern Denmark*

[2] *NIC, DESY*

Corresponding Authors: rago@qtc.sdu.dk, stefan.schaefer@desy.de

openQCD is a simulation suite for lattice QCD, featuring an efficient implementation of the $\mathcal{O}(a^2)$ Wilson-Dirac fermion operator. Pivotal to the scaling properties of the code is the locally deflated solver. In this presentation, I will report on the status of porting openQCD to the GPU architecture and its scaling performance, specifically for the SAP Deflated solver.

Applications outside particle physics - parallel / 346

Exploring Group Convolutional Networks for Sign Problem Mitigation via Contour Deformation

Author: Christoph Gäntgen[1]

Co-authors: Marcel Rodekamp [2]; Thomas Luu [3]

[1] *Forschungszentrum Jülich, University Bonn*

[2] *Forschungszentrum Jülich*

[3] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: m.rodekamp@fz-juelich.de, c.gaentgen@fz-juelich.de, t.luu@fz-juelich.de

The sign problem that arises in Hybrid Monte Carlo calculations can be mitigated by deforming the integration manifold. While simple transformations are highly efficient, they reach a limit with decreasing temperature and increasing interaction. Machine learning models have demonstrated the

ability to push further, but require additional computational effort and upfront training.
We examine the Hubbard model on select low-dimensional systems.
While all networks possess the capacity to learn physical symmetries through proper training, there are anticipated advantages associated with encoding them into the network's structure. These include enhanced accuracy, accelerated training, and improved stability. The objective of the present study is twofold. First, we investigate the benefits of group convolutional models in comparison to fully connected networks, with a specific focus on the effects on the sign problem and on computational aspects. Second, we examine their capabilities for transfer learning, demonstrating the ability to further reduce training cost.

Standard Model parameters / 202

Leptonic decays of charmed mesons with Wilson quarks on $N_\mathrm{f} = 2+1$ CLS ensembles

Authors: Simon Kuberski[1]; Fabian Joswig[2]; Sara Collins[3]; Jochen Heitger[4]; Wolfgang Soeldner[5]

[1] *CERN*

[2] *University of Edinburgh*

[3] *University of Regensburg*

[4] *University of Muenster, ITP*

[5] *Regensburg University*

Corresponding Authors: simon.kuberski@cern.ch, wolfgang.soeldner@ur.de, sara.collins@ur.de, heitger@uni-muenster.de

We present results for the pseudoscalar decay constants $f_{\mathrm{D}_{(\mathrm{s})}}$ from the RQCD and ALPHA collaboration's joint effort. Our calculations are based on the $N_\mathrm{f} = 2+1$ CLS ensembles at six values of the lattice spacing in the range from a = 0.098 fm down to a = 0.039 fm, with pion masses spanning from approximately 420 MeV to below the physical mass. The ensembles lie on three trajectories in the quark mass plane enabling tight control of the light and strange quark mass dependence. The overall uncertainty of the results achieved for the decay constants and their ratio is significantly less than 1 percent. We also outline our effort on the analysis of charm vector and tensor decay constants.

Quark and lepton flavour physics / 415

Bs -> mu+mu- gamma & Bs -> phi gamma decay rates from Nf=2+1+1 twisted mass simulations

Author: Francesco Sanfilippo[1]

[1] *INFN Roma Tre*

Corresponding Author: francesco.sanfilippo@roma3.infn.it

We present our recent estimate of the $B_s \to \mu^+\mu^-\gamma$ decay rate at large q^2, computed on four lattice spacing of $N_f = 2+1+1$ twisted mass simulations. The relevant form factors are extrapolated to physical B_s meson mass from simulations carried out up to $2M_{D_s}$, covering the region of $\sqrt{q^2} > 4.16\,\mathrm{GeV}$, and adopting a novel strategy to circumvent the problem of analytic continuation of electroweak amplitude.
We will also present preliminary results of the $B_s \to \phi\gamma$ decay rate.

Quantum computing and quantum information / 317

Simulating (1+1)d Abelian Gauge Theories with Cluster Algorithms

Authors: Thea Budde[1]; Marina Krstic Marinkovic[2]; Joao Pinto Barros[1]

[1] *ETH Zürich*

[2] *CERN*

Corresponding Authors: tbudde@phys.ethz.ch, marina.marinkovic@cern.ch, jpinto@phys.ethz.ch

The Hamiltonian formulation of lattice gauge theories offers a pathway to new quantum and classical simulation techniques. Given the finite number of degrees of freedom in quantum simulators, it is necessary to make the Hilbert space for each link finite. In this talk, we discuss common approaches to achieve finite Hilbert spaces per link for (1+1)d Abelian gauge theories.
By adding constraints to a Meron cluster algorithm, we solve Gauss'law exactly for $\mathbb{Z}_n$, truncated link, and quantum link models. For the first two theories, we observe fast convergence when increasing the size of the Hilbert space, even for small couplings and moderate temperatures. However, quantum link models require larger Hilbert spaces per link. This provides insights for resource-efficient quantum simulations. Additionally, it facilitates taking a continuum limit through Monte Carlo simulations at finite theta without encountering a sign problem.

Hadronic and nuclear spectrum and interactions / 325

The timelike pion form factor and other applications of $I = 1$ $\pi\pi$ scattering

Authors: Ben Hörz[1]; Dalibor Djukanovic[2]; Hartmut Wittig[3]; Harvey B. Meyer[3]; Nolan Miller[4]; Simon Kuberski[5]; Srijit Paul[6]

[1] *Intel*

[2] *Helmholtz Institute Mainz*

[3] *University of Mainz*

[4] *Helmholtz-Institut Mainz*

[5] *CERN*

[6] *University of Edinburgh*

Corresponding Authors: meyerh@uni-mainz.de, hartmut.wittig@uni-mainz.de, d.djukanovic@him.uni-mainz.de, nmiller@uni-mainz.de, ben.hoerz@intel.com, simon.kuberski@cern.ch, spaul137@umd.edu

The timelike pion form factor is a rare example of a form factor that can be measured on the lattice in the timelike region without analytic continuation from the spacelike region. The most precise experimental results disagree near the ρ resonance, leading to diverging estimates of hadronic vacuum polarization. We will present a calculation of the timelike pion form factor using a physical pion mass ensemble, carefully controlling for systematic uncertainties in the generalized eigenvalue problem following the strategy described by Blossier et al (2009). Along the way, we will also show results for the resonance mass m_ρ, the coupling $g_{\rho\pi\pi}$, and the reconstructed vector-vector correlator, the latter of which can be used to improve the estimate of the hadronic vacuum polarization contribution to the muon's anomalous magnetic moment, a_μ^{hvp}.

Software development and machines - parallel / 3

Autotuning multigrid parameters in the HMC on different architectures

Author: Bartosz Kostrzewa[1]

Co-authors: Aniket Sen [2]; Marco Garofalo [3]; Simone Romiti [4]

[1] *High Performance Computing & Analytics Lab, University of Bonn*

[2] *HISKP, University of Bonn*

[3] *University of Bonn*

[4] *University of Bern*

Corresponding Authors: sen@hiskp.uni-bonn.de, bkostrze@uni-bonn.de, simone.romiti.1994@gmail.com, marcogarofalo31@gmail.com

Multigrid-preconditioned solvers have proven crucial for the efficient generation of ensembles of gauge configurations at physical quark mass parameters. A highly efficient implementation of such a solver for GPUs by different vendors and for different types of Wilson fermions is provided in the QUDA library. It includes functionality for updating and evolving the multigrid setup in the Hybrid Monte Carlo algorithm together with the gauge field. In the force calculation for the most poorly conditioned systems in simulations with Wilson-clover twisted mass fermions the solver outperforms mixed-precision CG by up to two orders of magnitude at the physical light quark mass, leading also to a large overall speedup of the HMC as a whole.

QUDA provides an autotuner which selects optimal launch parameters and communication policies for each kernel, problem size and domain decomposition, ensuring optimal performance of the underlying kernels. The multigrid solver, however, depends on a large number of choices such as block sizes, numbers of vectors, maximum iterations as well as thresholds and, in the case of twisted mass fermions, a scaling of the twisted quark mass on the coarse grids. As these parameters are generally defined on a per-level basis the search space is large, making exhaustive scans expensive. In addition, even if a good parameter set for a particular situation is found, in general it will fail to be optimal on a different machine or for a different domain decomposition.

We present an autotuner for these solver parameters implemented in tmLQCD which finds good parameter sets relatively quickly, requiring only some intution on the order in which parameters are to be tuned and on the step sizes to be used in the tuning procedure. By comparing the performance of the resulting setups on machines based on NVIDIA and AMD GPUs we further demonstrate its practical applicability.

Theoretical developments / **245**

Tensor renormalization group study of (1+1)-dimensional O(3) nonlinear sigma model w/ and w/o finite chemical potential

Author: Yoshinobu Kuramashi[1]

Co-author: Xiao Luo [1]

[1] *University of Tsukuba*

Corresponding Authors: luo@het.ph.tsukuba.ac.jp, kuramasi@het.ph.tsukuba.ac.jp

We study the (1+1)-dimensional O(3) nonlinear sigma model using the tensor renormalization group method. At zero density we investigate the von Neumann and R\'enyi types of entanglement entropies. The central charge is determined from the asymptotic scaling properties of the entropies. We examine the consistency between two entropies. In the finite density region, where this model suffers from the sign problem, we investigate the properties of the quantum phase transition. We determine the transition point μ_{c} and the critical exponent ν from the μ dependence of the number density in the thermodynamic limit. The dynamical critical exponent z is also extracted from the scaling behavior of the temporal correlation length as a function of μ.

Algorithms and artificial intelligence / 128

Effects of FTHMC with 2+1 Domain Wall Fermions on Autocorrelation Times via Master-Field Technique

Author: Shuhei Yamamoto[1]

Co-authors: Lu-Chang Jin ; Peter Boyle [2]; Taku Izubuchi [1]

[1] *Brookhaven National Laboratory*

[2] *University of Edinburgh*

Corresponding Authors: izubuchi@bnl.gov, paboyle@ph.ed.ac.uk, shuhei.yamamoto.2011@gmail.com

Field-Transformed Hybrid Monte-Carlo (FTHMC) algorithm potentially mitigates the issue of critical slowing down by combining HMC with a field transformation, originally proposed by Luscher and motivated
as trivializing the theory. For the transformation, we use an invertible discrete smearing step modelled on the Wilson flow and applied it to the system with Iwasaki gauge fields and 2+1 Domain-Wall fermions. We have studied its effect of different smearing parameter values on autocorrelation times of Wilson-flowed energies with different flow time. We have found a reduction of exponential autocorrelation times for infra-red observables
such as Wilson flowed energy densities and topological charge densities when larger value of the smearing parameter is used. In determination of autocorrelation times, autocorrelation times of local observables are computed using a new approach akin to master-field technique, allowing us to estimate the effect of FT with different parameters based on a small number of configurations.

Applications outside particle physics - parallel / 291

Simulating the Hubbard Model with Normalizing Flows

Authors: Dominic Schuh[None]; Janik Kreit[None]; Evan Berkowitz[1]; Lena Funcke[2]; Thomas Luu[3]; Kim A. Nicoli[4]; Marcel Rodekamp[1]

[1] *Forschungszentrum Jülich*

[2] *University of Bonn*

[3] *Forschungszentrum Jülich / University of Bonn*

[4] *knicoli@uni-bonn.de*

Corresponding Authors: knicoli@uni-bonn.de, t.luu@fz-juelich.de, e.berkowitz@fz-juelich.de, schuh@hiskp.uni-bonn.de, m.rodekamp@fz-juelich.de, lfuncke@uni-bonn.de, kreit@hiskp.uni-bonn.de

Generative models, in particular normalizing flows, have demonstrated exceptional performance in learning probability distributions across various domains of physics, including statistical mechanics, collider physics, and lattice field theory. In lattice field theory, using normalizing flows for accurately learning the Boltzmann distribution has been applied to a wide range of tasks, such as the direct estimation of thermodynamic observables and the sampling of independent and identically distributed (i.i.d.) configurations.

In this work, for the first time, we provide a proof-of-concept demonstration that normalizing flows can be used to learn the Boltzmann distribution for the Hubbard model. This model is extensively used to study the electronic structure of graphene and other carbon nanomaterials. State-of-the-art numerical simulations of the Hubbard model, such as obtained with Hamiltonian Monte Carlo (HMC) methods, often suffer from ergodicity issues and thus lead to biased estimates of physical observables. Leveraging i.i.d. sampling from the normalizing flow, our numerical experiments demonstrate that generative models successfully overcome these issues.

Standard Model parameters / 322

Form factor in semileptonic decay of D meson

Author: Tinghong Shen[1]

[1] *WHU, IHEP*

Corresponding Author: thshen@ihep.ac.cn

We report our progress in determining the form factors in semileptonic decays of D mesons. We work with overlap valence fermions on 2+1-flavor domain wall fermion configurations. The lattice is of size 32^3*64 and with an inverse lattice spaicng 1/a=2.383(9) GeV. Renormalizations of current operators are done nonperturbatively.

Quark and lepton flavour physics / 358

Update of HPQCD $B_c \to J/\psi$ Form Factors

Author: Judd Harrison[1]

[1] *University of Glasgow*

Corresponding Author: judd.harrison@glasgow.ac.uk

I will present an update of the currently available $B_c \to J/\psi$ form factors from HPQCD, computed using the heavy-HISQ method. This calculation uses our recent $\bar{b}c$ susceptibilities to perform a fully model-independent physical-continuum extrapolation, including unitarity bounds at all values of m_h.

Quantum computing and quantum information / 254

Quantum computational resources for lattice QCD in the strong-coupling limit

Authors: Michael Fromm[None]; Lucas Katschke[None]; Owe Philipsen[1]; Wolfgang Unger[2]

[1] *Goethe-University Frankfurt am Main*

[2] *Bielefeld University*

Corresponding Authors: wunger@physik.uni-bielefeld.de, mfromm@itp.uni-frankfurt.de, katschke@itp.uni-frankfurt.de, philipsen@itp.uni-frankfurt.de

We consider the strong coupling limit of Lattice QCD with massless staggered quarks and study the resource requirements for quantum simulating the theory in its Hamiltonian formulation. The bosonic Hilbert space of the color-singlet degrees of freedom grows quickly with the number of quark flavors, making it a suitable testing ground for resource considerations across different platforms. In particular, in addition to the standard model of computation with qubits, we consider mapping the theory to qudits (d > 2) and qumodes, as used on trapped-ion systems and photonic devices, respectively.

Hadronic and nuclear spectrum and interactions / 343

Timelike pseudoscalar form factors in a coupled channel from lattice QCD

Author: Felipe Ortega Gama[1]

[1] *William & Mary*

Corresponding Author: felipeortegagama@gmail.com

Transition amplitudes to two-hadron states arise in the interactions between hadrons and electromagnetic and weak currents.
From these transitions, we can study internal charge distributions or rare weak decays of hadrons.
In this talk, we present the first calculation of a transition amplitude to a coupled-channel of two-meson states from first principles.
We extract the timelike form factor of the pion beyond the elastic energy region above the $K\overline{K}$ threshold.
This allows us to compute both the pion and the kaon isovector-vector timelike form factor.
We verify that the extraction of the ρ-meson decay constant, from the timelike form factor at the resonance pole, is consistent in both the elastic analysis and the coupled-channel case.
This work lays the foundation to study the internal structure and potentially the nature of resonances that decay into multiple channels, e.g., the exotic π_1 meson.

Software development and machines - parallel / 350

Multigrid Multilevel Monte Carlo for Efficient Trace Estimation in Lattice QCD Simulations

Authors: Jose Jimenez-Merchan[1]; Juan Andres Urrea-Nino[1]; Gustavo Ramirez-Hidalgo[1]

Co-authors: Andreas Frommer [1]; Francesco Knechtli [2]

[1] *Bergische Universität Wuppertal*

[2] *University of Wuppertal*

Corresponding Authors: ramirezhidalgo@uni-wuppertal.de, urreanino@uni-wuppertal.de, frommer@uni-wuppertal.de, knechtli@physik.uni-wuppertal.de, jimenezmerchan@uni-wuppertal.de

Trace estimation poses a significant challenge in lattice QCD simulations. The Hutchinson method's accuracy scales with the square root of the sample size, resulting in high costs for achieving precise estimates. To alleviate this issue, variance reduction techniques are employed, such as deflating the lowest eigen or singular vectors of the matrix.

This study explores Multigrid Multilevel Monte Carlo (MGMLMC) to reduce the computational cost of constructing the deflation subspace while maintaining an efficient application of the deflation projectors and improving variance reduction. In MGMLMC, spectral deflation is accomplished using a projector derived from the multigrid prolongator P employed in solving linear systems involving the Wilson-Dirac operator D. By utilizing the low-mode spectral information inherent in P, this approach significantly lowers memory requirements while achieving up to a three-fold variance reduction compared to inexact deflation which relies on a few iterations of the inverse block power method to derive the deflation subspace.

We investigate the efficacy of MGMLMC for computing $\mathrm{tr}(B(t)D^{-1}(t,t))$, where $B(t)$ is an operator which acts on spin, color and space indices, for example a combination of gamma matrices and gauge covariant spatial derivatives.

Theoretical developments / 167

Grassmann Tensor Renormalization Group for two-flavor massive Schwinger model with a theta term

Authors: Hayato Kanno[1]; Shinichiro Akiyama[2]; Kotaro Murakami[3]; Shinji Takeda[4]

[1] *RIKEN BNL Research Center, RIKEN*

[2] *University of Tsukuba*

[3] *Tokyo Institute of Technology*

[4] *Kanazawa University*

Corresponding Authors: takeda@hep.s.kanazawa-u.ac.jp, hayato.kanno@yukawa.kyoto-u.ac.jp, kotaro.murakami@yukawa.kyoto-u.ac.jp, akiyama@ccs.tsukuba.ac.jp

We use the Grassmann tensor renormalization group method to calculate the free energy of the $N_f = 2$ Schwinger model with a 2π periodic θ term in a broad range of mass. We confirm the numerical results agree with the analytical ones in the large mass limit, and check the qualitative consistency in the small mass limit. We also calculate the vacuum degeneracy, which is consistent in the large mass regime. The θ dependence is then examined in the finite mass region, which is inaccessible in analytical calculations. Our numerical study suggests that the finite mass effects lead to a different result than analytic values in both large and small mass regimes.

Algorithms and artificial intelligence / 63

Minimal Autocorrelation in HMC simulations using Exact Fourier Acceleration

Author: Johann Ostmeyer[1]

Co-author: Pavel Buividovich [2]

[1] *Bonn University*

[2] *University of Liverpool*

Corresponding Authors: ostmeyer@hiskp.uni-bonn.de, pavel.buividovich@liverpool.ac.uk

Hybrid Monte Carlo (HMC) simulations often suffer from long autocorrelation times, severely reducing their efficiency. In this talk two of the main sources of autocorrelations are identified and eliminated. The first source is the sampling of the canonical momenta from a sub-optimal normal distribution, the second is a badly chosen trajectory length. Analytic solutions to both problems are presented and implemented in the exact Fourier acceleration (EFA) method. EFA completely removes autocorrelations for near-harmonic potentials and consistently yields (close-to-) optimal results for numerical simulations of various physical systems. Some examples will be presented.

Applications outside particle physics - parallel / 303

The Hubbard interaction at finite temperature on a Hexagonal lattice

Author: Lado Razmadze[1]

Co-authors: Evan Berkowitz [2]; Johann Ostmeyer [3]; Thomas Luu [4]

[1] *Forschungszentrum Juelich*

[2] *Forschungszentrum Jülich*

[3] *Bonn University*

[4] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: l.razmadze@fz-juelich.de, ostmeyer@hiskp.uni-bonn.de, e.berkowitz@fz-juelich.de, t.luu@fz-juelich.de

The temporal finite volume induces significant effects in Monte Carlo simulations of systems in low dimensions. An example is graphene, a 2-D hexagonal system known for its unique electronic properties and numerous potential applications.

In this work, we explore the behavior of fermions on a graphene sheet with a Hubbard-type interaction characterized by coupling U. This system exhibits zero or near zero-energy excitations that are highly sensitive to finite temperature effects. Therefore, accounting for this dependence is essential to obtaining reliable zero-temperature extrapolations. We compute corrections to the self-energy and the effective mass of low-energy excitations, as well as the shift in ground state energy. These analyses are conducted for both zero and finite temperatures. Our findings reveal that the first-order $\mathcal{O}(U)$ contributions are absent, leading to non-trivial corrections starting at $\mathcal{O}(U^2)$. We validate our calculations against numerical results from Hybrid Monte Carlo simulations on small lattices and extrapolate the behavior at low temperatures.

Hadronic and nuclear spectrum and interactions / 497

The 3-pion K-matrix at NLO in ChPT

Author: Mattias Sjö[1]

[1] *CPT, Aix-Marseille University*

Corresponding Author: mattias.sjo@cpt.univ-mrs.fr

The finite-volume spectrum of 3-hadron systems on the lattice can be captured by the so-called K-matrix. This scheme-dependent object can be related to the corresponding 3-to-3 scattering amplitude in infinite volume, which can in turn be calculated using a low-energy effective field theory such as chiral perturbation theory (ChPT). We present the next-to-leading-order calculation of the K-matrix for three pions in all isospin channels, generalizing the maximum-isospin case presented at Lattice 2023. Our results are qualitatively similar to those at maximum isospin, but the technical aspects serve as a stepping stone toward further generalization to cases including kaons and other hadrons.

Standard Model parameters / 433

The Cabibbo Angle from Inclusive τ Decays

Author: Giuseppe Gagliardi (On behalf of the ETM Collaboration)[1]

[1] *Università di Roma Tre*

Corresponding Author: giuseppe.gagliardi@roma3.infn.it

The inclusive hadronic decays of the τ lepton are of great interest as they provide an alternative method for determining the CKM matrix elements $V_{\rm ud}$ and $V_{\rm us}$. In this talk, I will present the results of the ETM Collaboration on the inclusive hadronic decay rate of the τ. Our results have been obtained in $N_f = 2+1+1$ QCD using the novel HLT method, which circumvents the well-known inverse Laplace transform problem that hinders this calculation, i.e. for the first time without relying on the operator-product expansion or on perturbative QCD.
Except for isospin-breaking effects, all sources of systematic errors are under control. We obtain a value for the Cabibbo angle of $|V_{us}|_{\tau-\rm latt-incl} = 0.2189(7)\rm th(18)exp$, which shows a 3σ tension with purely hadronic determinations of $|V_{us}|$. We believe that this tension, which can no longer be

attributed to the OPE approximation, deserves further scrutiny of the experimental uncertainties and calls for a first-principles determination of the isospin-breaking corrections, which we are currently investigating.

Quark and lepton flavour physics / 126

Heavy-light Meson Decay Constants and Hyperfine Splittings with the Heavy-HISQ Method

Authors: Antonio Smecca[1]; Christine Davies[2]; Judd Harrison[2]; Kerr Miller[2]

[1] *Swansea University*

[2] *University of Glasgow*

Corresponding Authors: christine.davies@glasgow.ac.uk, antonio.smecca@swansea.ac.uk, judd.harrison@glasgow.ac.uk, k.miller.1@research.gla.ac.uk

We present preliminary new lattice QCD results for high-precision vector-to-pseudoscalar and tensor-to-vector ratios of decay constants of the $B^{(*)}$, $D^{(*)}$, $B_s^{(*)}$ and $D_s^{(*)}$ mesons, in which many uncertainties cancel, using the heavy-HISQ method. We use the Highly Improved Staggered Quark (HISQ) action for all valence quarks and second generation MILC $n_f = 2 + 1 + 1$ HISQ gluon field configurations, with lattice spacings ranging from $0.15\,\mathrm{fm}$ down to $0.045\,\mathrm{fm}$. Our pion masses range from $\approx 300\,\mathrm{MeV}$ down to the physical value, and our heavy quark masses range from the physical charm up to the physical bottom on the three finest ensembles. These quantities enable powerful tests of Standard Model flavour phenomenology and aid the search for new physics through their sensitivity to beyond-Standard-Model effects.

Quantum computing and quantum information / 253

Scattering wave packets of hadrons in gauge theories: Preparation on a quantum computer

Authors: Zohreh Davoudi[1]; Chung-Chun Hsieh[1]; Saurabh Kadam[2]

[1] *University of Maryland, College Park*

[2] *InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA*

Corresponding Authors: ksaurabh@uw.edu, cchsieh@umd.edu, davoudi@umd.edu

Quantum simulation holds promise of enabling a complete description of high-energy scattering processes rooted in gauge theories of the Standard Model. A first step in such simulations is preparation of interacting hadronic wave packets. To create the wave packets, one typically resorts to adiabatic evolution to bridge between wave packets in the free theory and those in the interacting theory, rendering the simulation resource intensive. In this work, we construct a wave-packet creation operator directly in the interacting theory to circumvent adiabatic evolution, taking advantage of resource-efficient schemes for ground-state preparation, such as variational quantum eigensolvers. By means of an ansatz for bound mesonic excitations in confining gauge theories, which is subsequently optimized using classical or quantum methods, we show that interacting mesonic wave packets can be created efficiently and accurately using digital quantum algorithms that we develop. Specifically, we obtain high-fidelity mesonic wave packets in the Z_2 and $U(1)$ lattice gauge theories coupled to fermionic matter in 1+1 dimensions. Our method is applicable to both perturbative and non-perturbative regimes of couplings. The wave-packet creation circuit for the case of the Z_2 lattice gauge theory is built and implemented on the Quantinuum H1-1 trapped-ion quantum computer using 13 qubits and up to 308 entangling gates. The fidelities agree well with classical benchmark

calculations after employing a simple symmetry-based noise-mitigation technique. This work serves as a step toward quantum computing scattering processes in quantum chromodynamics.

Software development and machines - parallel / 472

Deflation and polynomial preconditioning in the application of the overlap operator at nonzero chemical potential

Authors: Gustavo Ramirez-Hidalgo[1]; Jacob Finkenrath[2]

[1] *University of Wuppertal*

[2] *CERN*

Corresponding Author: ramirezhidalgo@uni-wuppertal.de

Solving linear systems is oftentimes the most demanding computation in lattice QCD simulations. The overlap discretization, which allows the implementation of chiral symmetry on the lattice, requires the solution of particularly demanding linear systems. When solving $D_{ov}x = b$ with an iterative method, with D_{ov} the overlap operator, every iteration requires applying the sign function of another operator over some vector, which at nonzero chemical potential takes the form $\mathrm{sign}(Q_\mu)b$, where $Q_\mu = \Gamma_5 D_\mu$, with D_μ the Dirac operator at nonzero chemical potential μ and $Q_\mu^H \neq Q_\mu$.

The evaluation of the application of the sign function over a vector, with a non-Hermitian operator Q_μ, is in general very demanding in both time and memory. We describe here how to substantially reduce both the time and memory required by this sign function evaluation via polynomial preconditioning when using an Arnoldi approximation. For this, a polynomial $q(Q_\mu^2)$ approximating $(Q_\mu^2)^{-1/2}$ is pre-built, followed by the evaluation of the sign function by means of an Arnoldi process on $q^2(Q_\mu^2)Q_\mu^2$. We show the effectiveness of this method via numerical experiments on a realistic configuration.

Furthermore, we describe how deflation can be combined with this form of preconditioning for the same problem of evaluating the sign function in the overlap discretization. In particular, we use LR deflation, and via numerical experiments illustrate the benefits of combining deflation and polynomial preconditioning for the problem at hand.

Theoretical developments / 182

Phase structure analysis of 2d CP(1) model with θ term by tensor network renormalization

Authors: Hayato Aizawa[None]; Shinji Takeda[1]; Yoshimura Yusuke[1]

[1] *Kanazawa University*

Corresponding Authors: takeda@hep.s.kanazawa-u.ac.jp, h_aizawa@hep.s.kanazawa-u.ac.jp

We analyze the phase structure of 2d CP(1) model with θ term by using the tensor renormalization group method. We propose a new tensor network representation for the model using the quadrature scheme and confirm that its accuracy is improved compared to the previous one. For the coarse-graining algorithm, we employ not only the conventional one but also the bond-weighted one in order to further improve the accuracy. As a probe to study the phase structure we adopt the central charge and find that $c = 1$ for $\beta > 0.55$ at $\theta = \pi$. This result indicates the BKT transition, which is consistent with the Halden conjecture.

Algorithms and artificial intelligence / 129

A new method for calculating false vacuum decay rates on the lattice

Authors: Joshua Swaim[1]; Luchang Jin[1]

[1] *University of Connecticut*

Corresponding Authors: luchang.jin@uconn.edu, joshua.swaim@uconn.edu

Many quantum field theories, including (potentially) the Standard Model, have metastable false vacuum states. Usually, false vacuum decay rates are calculated using the semi-classical approximation. We present a method for calculating false vacuum decay rates using lattice Monte Carlo simulations. As a proof-of-concept, we test the method using one-dimensional quantum mechanics. This method does not rely on the semi-classical approximation, and it works even when the decay rate is very small.

Applications outside particle physics - parallel / 401

Search for Stable States in Two-Body Excitations of the Hubbard Model on the Honeycomb Lattice

Author: Petar Sinilkov[None]

Co-authors: Evan Berkowitz [1]; Thomas Luu [2]

[1] *Forschungszentrum Jülich*

[2] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: p.sinilkov@fz-juelich.de, t.luu@fz-juelich.de, e.berkowitz@fz-juelich.de

We present one- and two-body measurements for the Hubbard model on the honeycomb (graphene) lattice from ab-initio HMC. Excitons, or particle/hole excitations in low-dimensional systems are analogous to the pion in QCD, but without confinement whether they are bound is a dynamical question. By measuring one- and two-body correlators across various spin- isospin channels we can compute energy shifts, and check for stable states.

Poster session and reception / 385

Lambda 1405 from lattice QCD

Authors: Carsten Urbach[1]; Haobo Yan[2]; Javier Suarez Sucunza[3]; Thomas Luu[4]

[1] *University of Bonn*

[2] *Peking University*

[3] *University of Bonn- HISKP*

[4] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: urbach@hiskp.uni-bonn.de, suarez@hiskp.uni-bonn.de, t.luu@fz-juelich.de

In this work we present ongoing work for the study of the two pole structure of the Λ (1405) baryon at the $SU(3)$ point. We construct the interpolation operators from the direct product of the pseudoscalar meson and baryon octets. In these combinations the singlet and octet representations of the

$SU(3)$ symmetry are attractive, so we choose the states belonging to this representation with the quantum numbers of the Λ (1405): S=-1 and I=0. Then, we aim to implement a distillation procedure to extract the discrete energy spectrum and, eventually, use it to extract the scattering amplitudes and obtain the location of the poles in the complex energy plane.

Poster session and reception / 459

QUDA-Accelerated Batched Solvers for LQCD Workflows

Author: Evan Weinberg[1]

Co-authors: Balint Joo [2]; Jiqun Tu [3]; Kate Clark [3]; Mathias Wagner [3]

[1] *NVIDIA Corporation*

[2] *Oak Ridge*

[3] *NVIDIA*

Corresponding Authors: mathiasw@nvidia.com, bjoo@nvidia.com, eweinberg@nvidia.com

Modern measurement workflows require the iterative solution of hundreds or thousands of linear systems with unique sources but a constant discrete Dirac fermion stencil. Algorithmically batching multiple independent linear solves with a fixed stencil improves compute throughput by exposing additional data parallelism and increasing data reuse. The multiplicative benefit of utilizing batched solves in LQCD workflows improves time-to-science with minimal additional work by users. The publicly available QUDA library for all GPUs now includes a feature-complete implementation of batched solves, including support for batched deflation and multi-grid algorithms. In this poster we present results from real science workflows driven by the MILC and Chroma applications and accelerated by the new batched algorithms in QUDA.

Poster session and reception / 403

Towards direct access to the charmonium decay parameters

Authors: Benoît Blossier[1]; Jan Neuendorf[2]; Jochen Heitger[3]; Miguel Teseo San José Pérez[1]

[1] *IJCLab*

[2] *Institut für Theoretische Physik, Westfälische Wilhelms-Universität*

[3] *University of Muenster, ITP*

Corresponding Authors: heitger@uni-muenster.de, san-jose-perez@ijclab.in2p3.fr, blossier@ijclab.in2p3.fr, jan.neuendorf@wwu.de

The width of a hadronic decay to two particles can be studied from ratios of three and two point functions if the initial and final states in the matrix elements are degenerate. In our work, we rederive this method to study the vector-charmonium decay $\psi(3770) \to \bar{D}D$, we discuss the specific systematics that we found, and present preliminary results. Furthermore, we study the width as a function of the charm-quark mass, adjusting the $\bar{D}D$ energy with twisted boundary conditions, and we compare to the predictions from quark models.

Poster session and reception / 384

Finite-temperature critical point of heavy-quark QCD on large lattices

Author: Kazuyuki Kanaya[1]

Co-authors: Ryo Ashikawa [2]; Shinji Ejiri [3]; Masakiyo Kitazawa [4]; Hiroto Sugawara [3]

[1] *Tomonaga Center for the History of the Universe, Univ. Tsukuba*

[2] *Osaka University*

[3] *Niigata University*

[4] *Yukawa Institute for Theoretical Physics*

Corresponding Authors: ejiri@muse.sc.niigata-u.ac.jp, kanaya@ccs.tsukuba.ac.jp, kitazawa@yukawa.kyoto-u.ac.jp

We study the finite-temperature critical point of QCD in the heavy-quark region by a scaling study of the Binder cumulant on large lattices to determine the critical point in the thermodynamic limit with a high precision. We perform simulations on $N_t = 6$ and 8 lattices with spatial volumes up to the aspect ratio $LT = N_s/N_t = 18$ and 15, respectively. To enable simulations with large spatial volumes, we adopt the hopping parameter expansion combined with a method to effectively incorporate high order terms of the expansion. The reliability of the method is confirmed by examining the effect of high order terms up to quite high orders. Together with our previous result at $N_t = 4$, we also attempt a preliminary continuum extrapolation of the critical point in physical units.

Poster session and reception / **362**

Semiconductor quantum simulator for lattice gauge theories

Authors: Zohreh Davoudi[1]; Michael Gullans[1]; Vinay Vikramaditya[2]

[1] *University of Maryland, College Park*

[2] *University of Maryland, College park*

Corresponding Authors: davoudi@umd.edu, vvinay@umd.edu, mgullans@umd.edu

Semiconductor spin qubits are ideal for scalable quantum computing due to their long coherence times and compatibility with existing semiconductor fabrication technology. For quantum simulation of lattice gauge theories, the encoding of fermionic d.o.f. into qubits becomes complicated in higher dimensions. Furthermore, encoding with bosonic d.o.f. in a digital scheme introduces additional qubit and gate costs. In a semiconductor platform, the presence of both electrons and (large) nuclear spins provides readily available fermionic and bosonic degrees of freedom, respectively. Moreover, parameters such as tunneling coefficients, chemical potentials, hyperfine couplings, and global magnetic fields are highly tunable. This tunability allows periodic driving of the parameters, which can potentially be used to engineer interactions that simulate gauge dynamics on a lattice.

In this poster, I'll present our ongoing work on implementing an analog simulation scheme for Z2 lattice gauge theory in (1+1)D. The Floquet-Magnus expansion is used to analyze the behavior of the system under high-frequency periodic drives of the parameters involved. Future research will explore the feasibility of implementing an analog or hybrid simulation of gauge theories in (2+1)D on this platform.

Poster session and reception / **458**

Gravitational form factors of glueballs in Yang-Mills theory

Author: Dimitra Pefkou[1]

Co-authors: Daniel Hackett [2]; Fernando Romero-Lopez [3]; Phiala Shanahan [4]; Ryan Abbott [4]

[1] *UC Berkeley*

[2] *Fermilab*

[3] *MIT / Uni Bern*

[4] *Massachusetts Institute of Technology*

Corresponding Authors: dhackett@fnal.gov, dpefkou@berkeley.edu, rabbott@mit.edu, pshana@mit.edu, fernando.romero-lopez@unibe.ch

While over the past few decades lattice QCD has provided information on the spectrum of glueballs, little is known about the structure of these exotic candidates. In this poster, we present preliminary results on the gravitational form factors of glueball states in pure Yang-Mills theory. We use $\mathcal{O}(10)$ million configurations with $\beta = 5.95$, and a large set of interpolators, to constrain the matrix elements of the energy momentum tensor (EMT). We study the use of GEVP on the extraction of the ground state matrix elements, as well as the effect of various choices of smearing of the EMT.

Poster session and reception / 434

Towards determining the (2+1)-dimensional Quantum Electrodynamics running coupling with Monte Carlo and quantum computing methods

Authors: Arianna Crippa[1]; Carsten Urbach[2]; Christiane Groß[3]; Karl Jansen[1]; Lena Funcke[2]; Paolo Stornati[4]; Simone Romiti[5]; Stefan Kühn[1]

[1] *DESY*

[2] *University of Bonn*

[3] *HISKP, Bonn University*

[4] *ICFO, Barcelona*

[5] *University of Bern*

Corresponding Authors: arianna.crippa@desy.de, simone.romiti.1994@gmail.com, lfuncke@uni-bonn.de, karl.jansen@desy.de, gross@hiskp.uni-bonn.de, paolo.stornati@icfo.eu, stefan.kuehn@desy.de, urbach@hiskp.uni-bonn.de

We investigate the step scaling approach in compact pure U(1) lattice gauge theory in 2+1 dimensions combining Monte Carlo and quantum computing methods. We present results for the step scaling deep into the small gauge coupling region and discuss the non-perturbative matching between Monte Carlo and quantum computing simulations.

Poster session and reception / 180

Web-Based UI Tools for the ILDG

Author: Giovanni Pederiva[1]

[1] *Forschungszentrum Jülich - Jülich Supercomputing Centre*

Corresponding Author: g.pederiva@fz-juelich.de

We present the current development status and plans for the tooling for a user-friendly and modern interface for the International Lattice Data Grid (ILDG), that is being developed as part of the PUNCH4NFDI project.
In particular, we'd like to present the current web-based UI for searching ensembles in the Metadata Catalog and for generating the XML (templated) metadata files, which are required to upload configurations to the data grid.

This is also an opportunity to gather useful feedback and more ideas from the broader community on how to improve the tools further.

Poster session and reception / 453

The QED contributions to the short and intermediate windows of the hadronic vacuum polarization contribution to the muon g−2

Authors: Aida El-Khadra[1]; Alejandro Vaquero[2]; Alexei Bazavov[3]; Andreas Kronfeld[4]; Andrew Lytle[5]; Anthony Grebe[6]; Carleton DeTar[2]; Christine Davies[7]; Craig McNeile[8]; Curtis Peterson[9]; David Anthony Clarke[2]; Elvira Gamiz[10]; Ethan Neil[None]; G. Peter Lepage[None]; Gaurav Ray[8]; Hwancheol Jeong[11]; Jake Sitison[9]; James Simone[4]; Michael Lynch[12]; Ruth Van de Water[None]; Shaun Lahert[None]; Steven Gottlieb[13]; William Jay[14]

[1] *University of Illinois Urbana-CHampaign*

[2] *University of Utah*

[3] *Michigan State University*

[4] *Fermilab*

[5] *University of Illinois at Urbana-Champaign*

[6] *Fermi National Accelerator Laboratory*

[7] *University of Glasgow*

[8] *Plymouth University*

[9] *University of Colorado Boulder*

[10] *University of Granada*

[11] *Seoul National University*

[12] *University of Illinois, Urbana-Champaign*

[13] *Indiana University*

[14] *MIT*

Corresponding Authors: ml11@illinois.edu, christine.davies@glasgow.ac.uk, sonchac@gmail.com, jasi7117@colorado.edu, megamiz@ugr.es, willjay@mit.edu, axk@illinois.edu, agrebe@mit.edu, shaun.lahert@gmail.com, alexvaq@physics.utah.edu, atlytle@illinois.edu, ask@fnal.gov, clarke.davida@gmail.com, bazavov@msu.edu, cupe6205@colorado.edu, craig.mcneile@plymouth.ac.uk, sg@indiana.edu, thegman19951@gmail.com, detar@physics.utah.edu

To compare the results from different calculations of the leading-order HVP contribution to the muon's anomalous magnetic moment, either using lattice QCD or phenomenological input, it has been found useful to use window observables. We report blinded results on the connected QED contributions to the short distance and intermediate windows. The calculations use the highly-improved staggered quark (HISQ) formulation. The gauge configurations are generated with four flavors of HISQ sea quarks with physical sea-quark masses. The analysis includes ensembles with three lattice spacings: 0.15, 0.12 and 0.09 fm. We also report results on the QED corrections to meson masses and discuss the scheme dependence of comparing the results from QCD+QED and QCD simulations.

Poster session and reception / 324

Porting Lattice QCD benchmark to upcoming STX stencil/tensor accelerator

Author: Simon Schlepphorst[1]

Co-author: Stefan Krieg [2]

[1] *Forschungszentrum Jülich*

[2] *JSC, Forschungszentrum Juelich/HISKP, University of Bonn*

Corresponding Authors: s.schlepphorst@fz-juelich.de, s.krieg@fz-juelich.de

Developed under the European Processor Initiaive (EPI) the STX stencil/tensor accelerator aims to achieve a 5-10x higher energy efficiency over general purpose compute units.
The architectue consists of specialiced MIMD compute units which are supported and controlled by RISC-V cores.

We describe a co-design effort between hardware, software, and application development focused around porting a LQCD benchmark to this new architecture.

Poster session and reception / 389

Smeared R-ratio in isoQCD with Low Mode Averaging

Author: Francesca Margari[1]

Co-author: ETM Collaboration

[1] *Univ. of Roma Tor Vergata and INFN - Roma Tor Vergata*

Corresponding Author: margari@roma2.infn.it

Low Mode Average (LMA) is a technique to improve the quality of the signal-to-noise ratio in the long time separation of Euclidean correlation functions. We report on its beneficial impact in computing the vector-vector light connected two-point correlation functions $V_{kk}(t)$ and derived physical quantities in the mixed action lattice setup adopted by ETMC. We focus on preliminary results of the computation within isospin symmetric QCD of the R-ratio smeared with Gaussian kernels of widths down to $\sigma \sim 200$ MeV, which is enough to appreciate the ρ resonance around 770 MeV, using the Hansen-Lupo-Tantalo spectral-density reconstruction method.

Poster session and reception / 237

B-meson semileptonic decay form factors from highly improved staggered quarks

Authors: Aida El-Khadra[1]; William Jay[2]

Co-authors: Alejandro Vaquero [3]; Andreas Kronfeld [4]; Andrew Lytle [5]; Carleton DeTar [3]; Elvira Gamiz [6]; Jack Laiho [7]; James Simone [4]; Steven Gottlieb [8]

[1] *University of Illinois Urbana-CHampaign*

[2] *MIT*

[3] *University of Utah*

[4] *Fermilab*

[5] *University of Illinois at Urbana-Champaign*

[6] *University of Granada*

[7] *Syracuse University*

[8] *Indiana University*

Corresponding Authors: megamiz@ugr.es, ask@fnal.gov, atlytle@illinois.edu, willjay@mit.edu, axk@illinois.edu, detar@physics.utah.edu, alexvaq@physics.utah.edu, sg@indiana.edu

We present an update for our ongoing calculation of B-meson semileptonic form factors, using the highly improved staggered quark (HISQ) action on FNAL-MILC $N_f = 2 + 1 + 1$ HISQ gauge ensembles. We compute the scalar, vector, and tensor form factors for the $B \to \pi$, $B \to K$, $B_s \to K$, and $B_{(s)} \to D_{(s)}$ transitions . We have recently added data with $a \approx 0.03$ fm into our analysis, allowing simulation directly at the physical b-quark mass.

Poster session and reception / 438

Towards a discretization of supersymmetric QCD

Author: Enno Carstensen[1]

Co-author: Georg Bergner [2]

[1] *Karl-Franzens Universität Graz*

[2] *University of Jena*

Corresponding Authors: enno.carstensen@uni-graz.at, georg.bergner@uni-jena.de

We study possible discretizations of the action of supersymmetric QCD. Supersymmetry is broken on the lattice and improved lattice formulations should reduce the amount of fine-tuning required to recover it in the continuum limit. The discrepancy between the conventional scalar field discretization and the Wilson fermion discretization contributes to the breaking of supersymmetry. We investigate an alternative formulation of the scalar sector, that avoids part of this mismatch. In addition, we examine the properties of the scalar sector of $\mathcal{N} = 1$ super QCD using this alternative discretization and its connections to other theories.

Poster session and reception / 185

Variational Quantum Algorithms for Non-Hermitian Systems

Author: Craig McNeile[1]

Co-authors: Davide Vadacchino [2]; James Hancock [2]

[1] *Plymouth University*

[2] *University of Plymouth*

Corresponding Authors: davide.vadacchino@plymouth.ac.uk, james.hancock@plymouth.ac.uk, craig.mcneile@plymouth.ac.uk

In this poster, we report on our investigation of two specific systems that are hard to simulate with ordinary Monte Carlo methods: the transverse Ising model with an imaginary magnetic field (CTIM) and the quantum harmonic oscillator in a complex cubic potential (CQHO). We focus on understanding the quantum phase transition in CTIM with varying field strengths, and the PT-symmetry breaking in CQHO through a change in potential strength. Due to hardware limitations, our analysis is restricted to small systems, but see good promise for future scalability.

Poster session and reception / 380

Extracting the distribution amplitude of light pseudoscalar mesons using the HOPE method

Authors: Alex Chang[1]; Anthony Grebe[2]; C.-J David Lin[1]; Issaku Kanamori[3]; Robert Perry[4]; William Detmold[5]; Yong Zhao[6]

[1] *National Yang Ming Chiao Tung University*

[2] *Fermi National Accelerator Laboratory*

[3] *RIKEN*

[4] *University of Barcelona*

[5] *MIT*

[6] *Argonne National Lab*

Corresponding Authors: dlin@nycu.edu.tw, kanamori-i@riken.jp, agrebe@mit.edu, perryrobertjames@ub.edu, yong.zhao@anl.gov, s44930e0@gmail.com, wdetmold@mit.edu

The pseudoscalar meson light cone distribution amplitudes (LCDAs) are essential non-perturbative inputs for a range of high-energy exclusive processes in quantum chromodynamics. In this poster, progress towards a determination of the second and fourth Mellin moments of pseudoscalar meson LCDAs by the HOPE Collaboration is reported.

Poster session and reception / 418

Status of the ETMC ensemble generation effort

Authors: Constantia Alexandrou[1]; Simone Bacchio[2]; Jacob Finkenrath[3]; Roberto Frezzotti[4]; Marco Garofalo[5]; Bartosz Kostrzewa[6]; Giannis Koutsou[2]; Simone Romiti[7]; Carsten Urbach[5]; Urs Wenger[7]

[1] *University of Cyprus and The Cyprus Institute*

[2] *The Cyprus Institute*

[3] *CERN*

[4] *University of Rome Tor Vergata, Physics Department and INFN - Sezione di Roma Tor Vergata*

[5] *University of Bonn*

[6] *High Performance Computing & Analytics Lab, University of Bonn*

[7] *University of Bern*

Corresponding Authors: marcogarofalo31@gmail.com, wenger@itp.unibe.ch, roberto.frezzotti@roma2.infn.it, bkostrze@uni-bonn.de, s.bacchio@gmail.com, alexand@ucy.ac.cy, simone.romiti.1994@gmail.com, urbach@hiskp.uni-bonn.de, g.koutsou@cyi.ac.cy

We report the status of the ensemble generation effort of the Extended Twisted Mass Collaboration towards controlled continuum and infinite volume extrapolations for a variety of physical observables through simulations employing $N_f = 2+1+1$ Wilson clover twisted mass fermions at physical quark masses using five lattice spacings. We further give an update on the status of the tmLQCD software suite. Through extensions of the QUDA lattice QCD library and a corresponding interface in tmLQCD, we are able to offload a significant portion of our HMC to GPUs, enabling efficient simulations on the current generation of heterogeneous machines.

Poster session and reception / 451

Progress on the GPU porting of HiRep

Authors: Antonio Rago[1]; Claudio Pica[2]; Emiliano Molinaro[2]; Erik Kjellgren[2]; Sofie Martins[2]

[1] *QTC & IMADA, University of Southern Denmark*

[2] *University of Southern Denmark*

Corresponding Authors: pica@cp3.sdu.dk, kjellgren@sdu.dk, rago@qtc.sdu.dk, molinaro@imada.sdu.dk, martinss@imada.sdu.dk

HiRep allows flexible simulations of higher representations of Wilson Fermions with various actions and gauge groups and a range of inverters and integrators. This is particularly important for enabling evaluations of observables relevant to phenomenological inputs for Beyond-the-Standard-Model physics from lattice field theory. We present progress on the GPU porting of available features.

Poster session and reception / 124

The spectrum of open confining strings in the large-N limit

Author: Alireza sharifian[1]

Co-authors: Andreas Athenodorou [2]; Pedro Bicudo [1]

[1] *CeFEMA, Departamento de F\'isica, Instituto Superior T\'ecnico (Universidade de Lisboa)*

[2] *Computation-based Science and Technology Research Center, The Cyprus Institute*

Corresponding Authors: a.athenodorou@cyi.ac.cy, bicudo@tecnico.ulisboa.pt, sharifian.isf@gmail.com

We compute the spectra of open flux tubes formed between a static quark-antiquark pair for various $SU(N)$ gauge groups in the large-N limit, focusing on different symmetries. Specifically, we present spectra up to N=6 and for eight different symmetries of the flux tube. In this study, we employed an anisotropic Wilson action, a large number of suitable operators, and solved the generalized eigenvalue problem to identify a significant number of excitations for different flux tube symmetries. The spectra are compared with the Nambu-Goto string model, revealing novel phenomena such as the presence of massive axions in the flux tube. We find that the mass of the axion in the open flux tube spectra sector is consistent with the mass obtained in the closed flux tube sector.

Poster session and reception / 164

Model Averaging Tool for Parameter Estimation in LFT

Authors: Giovanni Pederiva[1]; Marcel Rodekamp[2]

[1] *Forschungszentrum Jülich - Jülich Supercomputing Centre*

[2] *Forschungszentrum Jülich*

Corresponding Authors: m.rodekamp@fz-juelich.de, g.pederiva@fz-juelich.de

We demonstrate the use of Bayesian fitting combined with a model averaging technique based on the Bayesian Akaike information criterion, with the intention to release a general purpose python package for typical correlator analysis coming from LFT. As examples we concentrate on two-point functions, one from a recent study on the Hubbard model and one on hadron correlators, extracting energies and amplitudes. A simple bootstrap analysis is performed including statistical and systematic uncertainties.

Poster session and reception / 175

Spectrum of preconditioned Moebius domain-wall operators

Authors: Issaku Kanamori[1]; WEI-LUN CHEN[2]; Hideo Matsufuru[3]

[1] *RIKEN*

[2] *Sokendai*

[3] *High Energy Accelerator Research Organization (KEK)*

Corresponding Authors: wlchen@post.kek.jp, hideo.matsufuru@kek.jp, kanamori-i@riken.jp

The convergence property of iterative solvers strongly depends on the spectrum of Dirac operator. For most of the standard algorithms to work, the real part of the spectrum should be positive. The domain-wall operator does not satisfy this condition, and this is one the reasons for difficulty in applying the multi-grid algorithms. In this presentation, we examine several preconditioning operators for the Moebius domain-wall operator and investigate their spectra. We implement the code using Bridge++ code set, and report its performance. We will also discuss application to multi-grid algorithm with the preconditioned operators.

Poster session and reception / 193

Towards the Analysis of Exotic Hadrons with 6-Stout Smeared Ensembles and Distillation

Author: Grant Bradley[1]

Co-authors: Christoph Hanhart [2]; Evan Berkowitz [3]; Giovanni Pederiva [4]; Stefan Krieg [5]; Thomas Luu [6]

[1] *Forschungszentrum Juelich*

[2] *German*

[3] *Forschungszentrum Jülich*

[4] *Forschungszentrum Jülich - Jülich Supercomputing Centre*

[5] *JSC, Forschungszentrum Juelich/HISKP, University of Bonn*

[6] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: g.pederiva@fz-juelich.de, e.berkowitz@fz-juelich.de, g.bradley@fz-juelich.de, t.luu@fz-juelich.de, s.krieg@fz-juelich.de, c.hanhart@fz-juelich.de

We present the preliminary results for a study of exotic states using 6-stout smeared ensembles approaching the physical point. Benchmarks for the optimal distillation parameters and number of sources are presented in order to maximize the signal while keeping the total computational resources low.

The runs are all preformed with resources at JSC. We use the latest architectures to show the expected total cost of a di-meson calculation using our machines.

Poster session and reception / 244

2024 Update on ϵ_K with lattice QCD inputs

Authors: Seungyeob Jwa[1]; Weonjong Lee[1]

Co-authors: Jaehoon Lim [2]; Jeehun Kim [1]; Sunghee Kim [1]; Sungwoo Park [3]; Sunkyu Lee [1]

[1] *Seoul National University*

[2] *Samsung Electronics*

[3] *Lawrence Livermore National Laboratory*

Corresponding Authors: thoth@snu.ac.kr, wlee@snu.ac.kr, park49@llnl.gov

We present recent updates for ϵ_K determined directly from the standard model (SM) with lattice QCD inputs such as $\hat{B}_K$, $|V_{cb}|$, $|V_{us}|$, $|V_{ud}|$, ξ_0, ξ_2, ξ_{LD}, f_K , and m_c. We find that the standard model with exclusive $|V_{cb}|$ and other lattice QCD inputs describes only 2/3 of the experimental value of $|\epsilon_K|$ and does not explain its remaining 1/3, which leads to a strong tension in $|\epsilon_K|$ at the 5σ level between the SM theory and experiment. We also find that this tension disappears when we use the inclusive value of $|V_{cb}|$ obtained using the heavy quark expansion based on the QCD sum rule approach.

Poster session and reception / 289

Using Machine Learning for Noise Resilient Optimization of Variational Quantum Eigensolvers

Authors: Luca Johannes Wagner[1]; Kim A. Nicoli[2]; Lena Funcke[3]

[1] *HISKP Uni Bonn*

[2] *knicoli@uni-bonn.de*

[3] *University of Bonn*

Corresponding Authors: knicoli@uni-bonn.de, lfuncke@uni-bonn.de, s6lawagn@uni-bonn.de

Variational Quantum Eigensolvers (VQEs) are a powerful class of hybrid quantum-classical algorithms designed to approximate the ground state of a quantum system described by its Hamiltonian. VQEs hold promise for various applications, including lattice field theory and quantum chemistry. However, the inherent noise present in Noisy Intermediate-Scale Quantum (NISQ) devices poses a significant challenge for running VQEs. These algorithms are particularly susceptible to noise, such as measurement shot noise and hardware noise.

In the talk by Kim Nicoli, it was proposed to enhance the classical optimization of VQEs with Gaussian Processes and Bayesian Optimization, as these machine learning techniques are well-suited for handling noisy data.
In this poster, we provide additional insights into this new algorithm and present further numerical experiments. First, we show results for more complex Hamiltonians using classical simulations of quantum hardware without hardware noise. Second, we examine the impact of hardware noise and error mitigation on the performance of the algorithm.
All numerical experiments demonstrate a significant outperformance of state-of-the-art baselines, laying the foundation for future studies of applying our machine learning techniques for VQEs to real quantum hardware and lattice field theory setups.

Poster session and reception / 374

Equivariant Normalizing Flows for the Hubbard Model

Authors: Janik Kreit[None]; Dominic Schuh[None]

Co-authors: Evan Berkowitz [1]; Lena Funcke [2]; Thomas Luu [3]; Kim A. Nicoli [2]; Marcel Rodekamp [1]

[1] *Forschungszentrum Jülich*

[2] *University of Bonn*

[3] *Forschungszentrum Jülich / University of Bonn*

Corresponding Authors: schuh@hiskp.uni-bonn.de, lfuncke@uni-bonn.de, kreit@hiskp.uni-bonn.de, e.berkowitz@fz-juelich.de, knicoli@uni-bonn.de, t.luu@fz-juelich.de, m.rodekamp@fz-juelich.de

Generative models, in particular normalizing flows, have demonstrated exceptional performance in learning probability distributions across various domains of physics, including statistical mechanics, collider physics, and lattice field theory. In lattice field theory, using normalizing flows for accurately learning the Boltzmann distribution has been applied to a wide range of tasks, such as the direct estimation of thermodynamic observables and the sampling of independent and identically distributed (i.i.d.) configurations.

In the talk by Dominic Schuh, it was shown how normalizing flows can be used to learn the Boltzmann distribution for the Hubbard model. These machine learning techniques may overcome potential ergodicity problems of state-of-the-art Hamiltonian Monte Carlo (HMC) methods.
In this poster, we explain the properties and symmetries of the probability distributions that we aim to learn using generative models. Specifically, we discuss the implementation of a symmetry-equivariant normalizing flow for the Hubbard model. Incorporating physics prior knowledge as an inductive bias substantially enhances the learning process.

Poster session and reception / 351

Strangeness-neutral line in dense and magnetized QCD at imaginary chemical potential

Author: Marc-André Petri[1]

Co-authors: Szabolcs Borsanyi [1]; Bastian Brandt [2]; Gergely Endrodi [3]; Jana N. Guenther [1]; Adeilton Dean Marques Valois [3]

[1] *University of Wuppertal*

[2] *University of Bielefeld*

[3] *Bielefeld University*

Corresponding Authors: brandt@physik.uni-bielefeld.de, borsanyi@uni-wuppertal.de, dvalois@physik.uni-bielefeld.de, petri@uni-wuppertal.de, endrodi@physik.uni-bielefeld.de, jguenther@uni-wuppertal.de

We simulate QCD with 3 Quark flavours for the case of an external magnetic field and imaginary chemical potential in the temperature range of the crossover. This poster clarifies how to match experimental conditions, i.e bringing the system into strangeness neutrality as well as predicting the new simulation parameters for runs with increasing imaginary chemical potential by comparing different approaches.

Poster session and reception / 421

Portable Lattice QCD implementation based on OpenCL

Authors: Chik Him Wong[1]; Jana N. Guenther[1]; Piyush Kumar[1]; Szabolcs Borsanyi[1]

[1] *University of Wuppertal*

Corresponding Authors: jguenther@uni-wuppertal.de, kumar@uni-wuppertal.de, borsanyi@uni-wuppertal.de, cwong@uni-wuppertal.de

The presence of GPU from different vendors demands the Lattice QCD codes to support multiple architectures. To this end, Open Computing Language (OpenCL) is a viable framework for writing portable code. It is of interest to find out how the OpenCL implementation performs as compared to the code based on a dedicated programming interface such as CUDA for Nvidia GPUs. We have developed an OpenCL backend for our already existing code of the Wuppertal-Budapest collaboration. In this contribution, we show benchmarks of the computationally intensive kernel, namely, the inversion of the Dirac operator on the JUWELS Supercomputer based on Nvidia graphics cards, and compare with the CUDA backend implementation.

Poster session and reception / 363

Proton decay matrix elements on PACS configurations

Author: Ryutaro Tsuji[1]

Co-authors: Eigo Shintani [2]; Yasumichi Aoki [3]; Yoshinobu Kuramashi [2]

[1] *KEK*

[2] *University of Tsukuba*

[3] *RIKEN*

Corresponding Authors: kuramasi@het.ph.tsukuba.ac.jp, eigo.shintani@gmail.com, yasumichi.aoki@riken.jp, rtsuji@post.kek.jp

We report our current status of lattice calculation of proton decay matrix elements on the PACS configurations of 64^4 volume with lattice spacing $a = 0.085$ fm at physical point for 2+1 flavor QCD. We carefully study the various systematic effects, especially for the renormalization scheme, and show the comparison with the previous results.

Poster session and reception / 10

Higgs Portal to Dark Vector Physics

Author: Natasha Mahmood[1]

Co-authors: Tajdar Mufti [2]; Muhammad Saad [2]

[1] *Lahore University of Management Sciences(LUMS)*

[2] *Lahore University of Management Sciences (LUMS)*

Corresponding Authors: muhammad.saad@lums.edu.pk, tajdar.mufti@lums.edu.pk, natasha.mahmood@lums.edu.pk

The quantum field theories of the Higgs boson interacting with light vector particles offer a number of non-trivial features to study. Bound states, phase structure, dynamical mass generation, and the Higgs mechanism are among them. As light vector particles are dark matter candidates, a thorough understanding of the involved physics is crucial as experimental searches continue. It requires methods beyond perturbation theory to capture all aspects of the new physics. We have used the lattice simulation method to study a model containing a real U(1) (gauge symmetry) breaking vector field and a SU(2) preserving complex doublet field in terms of different correlation functions and the bound state masses.

Poster session and reception / 92

Taste-splittings of KW and BC fermions with gradient flow

Author: Stephan Durr[1]

Co-author: Stefano Capitani [2]

[1] *University of Wuppertal*

[2] *BUW*

Corresponding Author: duerr@uni-wuppertal.de

Karsten-Wilczek (KW) and Borici-Creutz (BC) fermions show a near-degeneracy similar to staggered fermions. In the eigenvalue spectrum this near-degeneracy is simpler to quantify than in spectroscopic quantities. Therefore we determine the low-lying eigenvalues of these fermion operators at a fixed flow time (either in lattice or physical units) in the quenched Schwinger model and study the ascent to the continuum.

Poster session and reception / 205

BBGKY hierarchy for quantum error mitigation

Author: Theo Saporiti[1]

Co-authors: Mohamed Tamaazousti [2]; Oleg Kaikov [3]; Vasily Sazonov [2]

[1] *Université Paris-Saclay / CEA*

[2] *University Paris-Saclay, CEA, List*

[3] *University Paris-Saclay, CEA-List*

Corresponding Authors: theosaporiti@gmail.com, mohamed.tamaazousti@cea.fr, oikaikov@gmail.com, vasily.sazonov@cea.fr

The confinement/deconfinement phase transition of QCD at finite densities is still numerically inaccessible by classical computations. The exponential speedup of quantum computers could avoid this issue, but their current physical implementations are subjected to quantum noise. In my poster, I will present a novel quantum error mitigation scheme based on the BBGKY hierarchy, applicable to any arbitrary digital quantum simulation. The idea is to improve zero-noise extrapolations through additional constraints coming from the BBGKY dynamical equations of the digital spin system. Our preliminary results show that on average the mitigation scheme improves the quality of the (1+1)-Schwinger model measurements, therefore encouraging us to study more realistic models.

Poster session and reception / 462

Scaling of Normalizing Flows for Lattice Gauge Theories: Automated Hyperparameter Optimization and Transfer Learning

Author: Christopher Kirwan[1]

Co-authors: Michael Johnston [2]; Sinead Ryan [1]; Srikumar Venugopal [2]; Vassilis Vassiliadis [2]

[1] *Trinity College Dublin*

[2] *IBM Research Europe. Dublin*

Corresponding Authors: srikumarv@ie.ibm.com, vassilis.vassiliadis@ibm.com, michaelj@ie.ibm.com, kirwanch@tcd.ie, ryan@maths.tcd.ie

In this study, we present an analysis of the weak and strong scaling behaviours of normalizing flow methods applied to SU(2) and SU(3) gauge theories. We investigate the performance of these normalizing flows across varying lattice volumes and spacings, providing insights into their scalability and computational demands. Additionally, we perform an automated hyper-parameter optimization process, which facilitates efficient transfer learning of models with different lattice parameters. Our results demonstrate the potential of automated hyper-parameter optimization to enhance the robustness and adaptability of Flow-based methods

Poster session and reception / 482

Towards the application of random matrix theory to neural networks

Authors: Biagio Lucini[1]; Chanju Park[1]; Gert Aarts[1]; Matteo Favoni[1]

[1] *Swansea University*

Corresponding Authors: c.j.park@swansea.ac.uk, matteo.favoni@gmail.com, g.aarts@swansea.ac.uk, b.lucini@swansea.ac.uk

Random matrix theory was first examined in the context of nuclear physics to investigate properties of heavy atom nucleus spectra. This theory is suited for an application to machine learning algorithms, specifically to study the properties of their weight matrices.
In this presentation, we report the effect of varying the learning rate and the batch size used in the stochastic gradient descent algorithm and explore the role of hidden layers in teacher-student models, show that the matrix eigenvalues characterizing well-trained models are distributed according to the Wigner's surmise and Wigner's semicircle, and discuss preliminary results for neural networks.

Poster session and reception / 427

Exploring gauge-fixing conditions with gradient-based optimization

Authors: William Detmold[1]; Gurtej Kanwar[2]; Yin Lin[1]; Phiala Shanahan[3]; Michael Wagman[4]

[1] *MIT*

[2] *University of Bern*

[3] *Massachusetts Institute of Technology*

[4] *Fermilab*

Corresponding Authors: mwagman@fnal.gov, gurtejkanwar@gmail.com, wdetmold@mit.edu, yin01@mit.edu, pshana@mit.edu

Lattice gauge fixing is necessary to compute gauge-variant quantities, for example those used in RI-MOM renormalization. Recently, gauge-variant observables have also been found to be more amenable to signal-to-noise optimization using contour deformations. These applications motivate systematic parameterization and exploration of gauge-fixing schemes. This work introduces a differentiable parameterization which is broad enough to cover Landau gauge, Coulomb gauge, and maximal tree gauges. The adjoint state method allows gradient-based optimization to select gauge-fixing schemes that minimize an arbitrary target loss function.

Poster session and reception / 226

Fourier-accelerated HMC for the 2D SU(N) X SU(N) principal chiral model

Author: Brian Pendleton[1]

Co-authors: Pablo Morande [1]; Roger Horsley [2]

[1] *The University of Edinburgh*

[2] *University of Edinburgh*

Corresponding Authors: rhorsley@ph.ed.ac.uk, p.morande@sms.ed.ac.uk, bjp@ph.ed.ac.uk

We report the results of Fourier-accelerated HMC simulations of 2D SU(N) X SU(N) principal chiral models for N = 2, 3, 4, 6, 9. These models share several key properties with 4D QCD, for example asymptotic freedom and dynamical mass generation. Even for modest correlation lengths, we find integrated autocorrelation times are decreased by an order of magnitude relative to standard HMC, with relatively little computational overhead. Our results suggest that the relative advantage of Fourier Acceleration over traditional HMC decreases as N increases, possibly due to the enlarged group space associated with larger N. Our Monte Carlo results agree with the exact mass spectra and continuum scaling behaviour predicted by the exact solution obtained using the Bethe ansatz.

Poster session and reception / 220

Topological susceptibility of SU(3) pure-gauge theory from out-of-equilibrium simulations

Authors: Alessandro Nada[1]; Claudio Bonanno[2]; Davide Vadacchino[3]

[1] *Università di Torino*

[2] *IFT UAM/CSIC Madrid*

[3] *University of Plymouth*

Corresponding Authors: alessandro.nada@unito.it, davide.vadacchino@plymouth.ac.uk, claudio.bonanno@csic.es

In JHEP 04 (2024) 126 [arXiv:2402.06561] we recently proposed an out-of-equilibrium setup to reduce the large auto-correlations of the topological charge in two-dimensional CP^{N-1} models. Our proposal consists of performing open-boundaries simulations at equilibrium, and gradually switching on periodic boundary conditions out-of-equilibirum. Our setup allows to exploit the reduced auto-correlations achieved with open-boundaries, avoiding at the same time unphysical boundary effects thanks to an Jarzynski-inspired reweighting-like procedure. We present preliminary results obtained applying this setup to the 4d SU(3) pure-gauge theory and we outline a computational strategy to mitigate topological freezing in this theory.

Poster session and reception / 490

Variational Autoencoders and Metropolis-Hastings

Author: Joseph Hadley[1]

[1] *University of Liverpool*

Corresponding Author: jjhadley@liverpool.ac.uk

The use of generative models to learn and sample complex distributions is increasingly common in computational physics. Many generative approaches are being used with a view to improving algorithms for complex lattice systems like QCD. One such generative model is the Variational Autoencoder, which can simplify a complex distribution by identifying the distribution with a Gaussian in a latent space. In this work we use a Variational Autoencoder to learn efficient Monte-Carlo updates to the Ising model. We use this model as an example to discuss ergodicity and detailed balance conditions within the Metropolis-Hastings algorithm.

Poster session and reception / 436

Using AI for Efficient Statistical Inference of Lattice Correlators Across Mass Parameters

Authors: Aida El-Khadra[1]; Andrew Lytle[2]; Jiayu Shen[3]; Octavio Vega[3]

[1] *University of Illinois Urbana-CHampaign*

[2] *University of Illinois at Urbana-Champaign*

[3] *University of Illinois Urbana-Champaign*

Corresponding Authors: atlytle@illinois.edu, octavio5@illinois.edu, jiayus3@illinois.edu, axk@illinois.edu

We study an application of supervised learning to infer two-point lattice correlation functions at one input mass from correlator data computed at a different target mass. Learning across the mass parameters could potentially reduce the cost of expensive calculations involved in light Dirac inversions, which can be a computational bottleneck for performing simulations of quantum chromodynamics on the lattice. Leveraging meson two-point functions computed on an ensemble of gauge configurations generated by the MILC collaboration, we use a simple method for separating the data into training and correction samples that avoids the need for intensive retraining or bootstrapping to quantify uncertainties on our observables of interest. We employ a variety of machine learning models, including decision tree-based models and neural networks, to predict uncomputed correlators at the target mass. Additionally, we apply a simple ratio method which we compare and combine with the machine learning models to benchmark our inference methods. Special attention is given to validating the models we use.

Poster session and reception / 287

Resolving the critical bubble in SU(8) confinement transition

Authors: David Weir[1]; Kari Rummukainen[1]; Riikka Seppä[1]

[1] *University of Helsinki*

Corresponding Authors: kari.rummukainen@helsinki.fi, david.weir@helsinki.fi, riikka.seppa@helsinki.fi

Recently, confining strongly coupled models have been considered as dark matter candidates, and to predict the gravitational wave spectrum from a possible early universe phase transition, the nucleation rate is needed as an input. The nucleation rate of a confinement transition for strongly coupled theories has not so far been determined from lattice, but is instead often estimated using various methods like thin wall approximation.

Motivated by this, we investigate the confinement-deconfinement transition in pure gauge SU(8) model using multicanonical lattice simulations in four dimensions. We attempt to resolve the critical bubble configuration and measure the probability of the configuration, from which the nucleation rate can be estimated. Large volumes are required for the bubble to fit on the lattice, and modifications to the usual Polyakov loop order parameter are needed to accurately resolve the bubble configurations.

Poster session and reception / 192

Energy-momentum tensor in the 2d O(3) non-linear sigma model on the lattice

Authors: Mika Lauk[1]; Agostino Patella[2]

[1] *Humboldt university Berlin*

[2] *Humboldt-Universität zu Berlin*

Corresponding Authors: mika.akim.lauk@hu-berlin.de, agostino.patella@physik.hu-berlin.de

The long-term goal of this project is the non-perturbative renormalization of the energy-momentum tensor in the 2d O(3) nonlinear sigma model using different methods which have been developed for QCD applications.
As a first step, we have identified all operators that mix with the energy-momentum tensor once a lattice discretization is employed, that is all which are compatible with power counting and with the symmetries of the theory. Since these operators are constrained by non-linear Ward identities arising from the non-linear realization of the O(3) symmetry, this is not entirely straightforward on the technical level. We will also present some preliminary results of numerical simulations with shifted boundary conditions and an optimized constraint action to minimize lattice artifacts. These simulations will be used to calculate the mixing coefficients with a strategy initially proposed by Giusti and Meyer.

Poster session and reception / 109

Topology in 2D $U(N_c)$ lattice gauge theories

Author: Philip Rouenhoff[None]

Co-author: Stephan Durr [1]

[1] *University of Wuppertal*

Corresponding Authors: duerr@uni-wuppertal.de, p.rouenhoff@gmail.com

In two dimensions $U(N_c)$ gauge theories on a torus exhibit a non-trivial topological structure (both on the lattice and in the continuum). Like in 4D $SU(3)$ gauge theories the phase spaces are divided into topological sectors, characterized by a topological index (a.k.a. "topological charge"). These sectors are separated by action barriers, which diverge if the lattice spacing is taken small, resulting in an algorithmic problem known as "topological freezing". We study these theories in various box sizes and at various couplings, with a specific focus on the evolution of representative gauge configurations under extensive gradient flow. We compare the action and charge of these smoothed configurations to the respective properties of analytical instanton-like solutions which we derive.

Poster session and reception / 299

Observing black hole features in the collapsed phase of EDT

Author: Jan Smit[1]

[1] *University of Amsterdam*

Corresponding Author: jansmit0000@chello.nl

Propagators of massless scalar fields have been computed on configurations of Euclidean dynamical triangulations (EDT) in the collapsed phase. They are used to calculate – up to an integration constant – the scale factor of a rotational invariant metric. This scale factor is non-zero at the origin, which we assume to be caused by the presence of the well-known singular structure in the collapsed phase. A transformation to a metric in (1+3)-dimensions reveals Euclidean black hole features at an instant in time, with a horizon separating interior and exterior parts. Assuming effective Einstein equations, the energy and pressure of a 'geometric condensate' are computed with the software OGRe. arXiv [gr-qc] 2301.07081 and 2305.16011

Poster session and reception / 214

Matching Curved Lattices to Anisotropic Tangent Planes

Authors: George Fleming[1]; Jinyun Lin[2]; Nobuyuki Matsumoto[3]; Richard Richard Brower[3]

[1] *Fermi National Accelerator Laboratory*

[2] *Carnegie Mellon University*

[3] *Boston University*

Corresponding Authors: gfleming@fnal.gov, jinyunl@cmu.edu, brower@bu.edu, nmatsum@bu.edu

Radial quantization would be the ideal formalism for studying strongly-coupled conformal and near-conformal quantum field theories but it requires the ability to perform lattice calculations on static, curved manifolds, specifically a very long cylinder whose cross section is a sphere. Smoothly discretizing the surface of a sphere requires a graph with unequal edge lengths. The geometry of such graphs is well understood since 1961 using Regge Calculus. But, lattice quantum field theories are defined in terms of couplings which appear in the action rather than edge lengths and so the relationship between couplings and lengths must be determined dynamically. A simple example is computing the ratio of spatial to temporal lattice spacings in anisotropic lattice QCD. I will discuss our progress in solving the critical 3D Ising model on a fully anisotropic FCC lattice, which is a necessary input to solving the critical 3D Ising model on a 3-sphere.

Poster session and reception / 373

Numerical study of the dimensionally reduced 3D Ising model

Author: Tolga Kiel[1]

Co-author: Stephan Durr [1]

[1] *University of Wuppertal*

Corresponding Authors: tolga.kiel@uni-wuppertal.de, duerr@uni-wuppertal.de

We study the 3D Ising model in the infinite volume limit $N_{x,y,z} \to \infty$ by means of numerical simulations. We determine T_c as well as the critical exponents α, β, γ and ν, based on finite-size scaling and histogram reweighting techniques. In addition, we study a "dimensionally reduced" scenario where N_z is kept fixed (e.g. at 2, 4, 8), while the limit $N_{x,y} \to \infty$ is taken. For each fixed N_z we determine T_c as well as $\alpha, \beta, \gamma, \nu$. For T_c we find a smooth transition curve which connects the well known critical temperatures of the 2D and the 3D Ising model. Regarding $\alpha, \beta, \gamma, \nu$ our data suggest that the "dimensionally reduced" Ising model is in the same universality class as the 2D Ising model, regardless of N_z.

Poster session and reception / 378

HMC and gradient flow with machine-learned classically perfect fixed point actions

Authors: Andreas Ipp[1]; David Müller[1]; Kieran Holland[2]; Urs Wenger[3]

[1] *TU Wien*

[2] *University of the Pacific*

[3] *University of Bern*

Corresponding Authors: andreas.ipp@tuwien.ac.at, dmueller@hep.itp.tuwien.ac.at, kholland@pacific.edu, wenger@itp.unibe.ch

Fixed point (FP) lattice actions are classically perfect, i.e., they have continuum classical properties unaffected by discretization effects. They have suppressed lattice artefacts and therefore provide a possible way to extract continuum physics with coarser lattices, allowing to circumvent problems with critical slowing down and topological freezing towards the continuum limit. We use machine-learning methods to parameterize a FP action for four-dimensional SU(3) gauge theory using lattice gauge-covariant convolutional neural networks (L-CNNs). The large operator space allows us to find superior parametrizations compared to previous studies and we show how such actions can be efficiently simulated with HMC algorithms. Furthermore, we argue that FP lattice actions can be used to define a classically perfect gradient flow without any lattice artefacts at tree level.

Poster session and reception / 122

Update on the octet baryon charges with $N_f = 2{+}1$ non-perturbatively improved Wilson fermions

Author: Simon Weishäupl[None]

Co-authors: Gunnar Bali [1]; Sara Collins [1]; Wolfgang Soeldner [2]

[1] *University of Regensburg*

[2] *Regensburg University*

Corresponding Authors: simon.weishaeupl@physik.uni-regensburg.de, wolfgang.soeldner@ur.de, gunnar.bali@ur.de, sara.collins@ur.de

The axial charge of the nucleon, g_A, has been computed extensively on the lattice. However, the axial charges for other octet baryons (hyperons) such as the Σ and Ξ baryons are less well known experimentally and theoretically. Here we present results from our updated analysis of the isovector axial, scalar and tensor charges, as well as first results for the second Mellin moments of isovector PDFs. Our calculations are performed on a large set of $N_f = 2 + 1$ CLS ensembles of non-perturbatively $O(a)$ improved Wilson fermions with tree-level Symanzik improved gauge action.

Poster session and reception / 282

High statistical computation of the Landau gauge ghost-gluon vertex

Authors: Nuno Brito[1]; Orlando Oliveira[2]; Paulo Silva[3]

[1] *PhD Student University of Plymouth*

[2] *University of Coimbra, Portugal*

[3] *Center for Physics, University of Coimbra*

Corresponding Authors: psilva@uc.pt, nmrbrito2000@gmail.com, orlando@uc.pt

The lattice computation of the one-particle irreducible ghost-gluon Green function in the Landau gauge is revisited with a set of large gauge ensembles. The large statistical ensembles enable a precision determination of this Green function over a wide range of momenta, accessing its IR and UV properties with a control on the lattice effects.

Poster session and reception / 431

Online or in-person?

Authors: Antonin Portelli[1]; Bipasha Chakraborty[2]; Fernando Romero-López[3]; Finn Stokes[4]; Indrakshi Raychowdhury[5]; Martha Constantinou[6]; Nilmani Mathur[7]; Sofie Martins[8]; Tereza Mendes[9]

[1] *The University of Edinburgh*

[2] *University of Southampton*

[3] *University of Bern*

[4] *The University of Adelaide*

[5] *Department of Physics, BITS Pilani, KK Birla Goa Campus*

[6] *Temple University*

[7] *Tata Institute of Fundamental Research*

[8] *University of Southern Denmark*

[9] *University of São Paulo*

Corresponding Authors: finn.stokes@adelaide.edu.au, mendes@ifsc.usp.br, martinss@imada.sdu.dk, b.chakraborty@soton.ac.uk, fernando.romero-lopez@unibe.ch, indrakshir@goa.bits-pilani.ac.in, nilmani@theory.tifr.res.in, antonin.portelli@ed.ac.uk, marthac@temple.edu

Following from LDIC survey performed last year in May and June 2023, we show more information about the preferences regarding online or in person workshops and connect them to diversity concerns. People with disabilities, women and non-binary respondents, and ethnic and religious minorities express the opinion that online workshops are more inclusive. However, we find a slight effect that the opposite is true for respondents with care responsibilities for children or vulnerable relatives, suggesting that feelings of welcomeness play a significant role in the perception of inclusivity of a workshop and practical concerns do not outweigh the inclusivity of being able to participate in person.

Poster session and reception / 395

Partially connected contributions to baryon masses in QCD+QED

Author: Sara Rosso[1]

[1] *IFCA & CSIC*

Corresponding Author: rosso@ifca.unican.es

Full QCD+QED simulations allow to evaluate isospin breaking corrections to hadron masses. With the openQxD code, we are able to perform these simulations employing C-periodic boundary conditions, implemented through a doubling of the physical lattice along one spatial direction.
The use of these boundary conditions introduces non-zero Wick contractions between two quark or two antiquark fields, that, in the case of the computation of baryon masses, lead to partially connected additional contributions that we expect to vanish in the infinite volume limit. These contributions are challenging because they involve an all-to-all propagator connecting one point in the physical lattice and one in the mirror lattice. We present a way to compute these corrections to the Ω^- baryon mass using a combination of point and stochastic source inversions.
This work is part of the program of the RC* collaboration.

Poster session and reception / 489

Update on semileptonic B-decays with HISQ light quarks and clover b-quarks in Fermilab interpretation

Author: Hwancheol Jeong[1]

Co-authors: Aida El-Khadra [2]; Alejandro Vaquero [3]; Andreas Kronfeld [4]; Andrew Lytle [5]; Carleton DeTar [3]; Elvira Gamiz [6]; Steven Gottlieb [1]; William Jay [7]; Zechariah Gelzer [8]

[1] *Indiana University*

[2] *University of Illinois Urbana-CHampaign*

[3] *University of Utah*

[4] *Fermilab*

[5] *University of Illinois at Urbana-Champaign*

[6] *University of Granada*

[7] *MIT*

[8] *U. Illinois, Urbana-Champaign*

Corresponding Authors: sonchac@gmail.com, ask@fnal.gov, alexvaq@physics.utah.edu, detar@physics.utah.edu, megamiz@ugr.es, axk@illinois.edu, zgelzer@illinois.edu, sg@indiana.edu, atlytle@illinois.edu, willjay@mit.edu

We compute the vector, scalar, and tensor form factors for the $B \to \pi$, $B \to K$, and $B_s \to K$ amplitudes, which are needed to describe semileptonic B-meson decay rates for both the charged and neutral current cases. We use the highly improved staggered quark (HISQ) action for the sea and light valence quarks. The bottom quark is described by the clover action in the Fermilab interpretation. Simulations are carried out on seven $N_f = 2 + 1 + 1$ MILC HISQ ensembles at approximate lattice spacings from 0.15 fm down to 0.057 fm with both physical and unphysical sea-quark masses. We present blinded preliminary results for the form factors in the continuum limit.

Poster session and reception / 369

Support of domain decomposition-based solvers in Chroma

Authors: Eloy Romero Alcalde[1]; Kostas Orginos[2]

[1] *Jefferson Lab*

[2] *College of William and Mary/JLAB*

Corresponding Authors: eromero@jlab.org, kostas@wm.edu

In multilevel integration, the correlation functions are decomposed into factors that depend only on fields localized into lattice subdomains so that they can be independently integrated. Although the standard formulation of the LQCD action is not local in the presence of fermions, past studies have shown approximations of the quark propagator and the fermionic determinant dependent on the gauge fields within specific subdomains can still be effective.

We will present our current progress in supporting domain decomposition within Chroma, which is necessary for multilevel integration approaches. The efforts are focused on extending the code base to efficiently manipulate subdomains for lattice fields and operators and performing inversions and eigendecompositions within domains.

Poster session and reception / 139

Domain Decomposition of the Dirac operator in QUDA

Authors: Balint Joo[1]; Evan Weinberg[2]; Ferenc Pittler[3]; Jacob Finkenrath[4]; Jiqun Tu[2]; Kate Clark[2]; Matthias Wagner[5]

[1] *Oak Ridge*

[2] *NVIDIA*

[3] *Eötvös University*

[4] *CERN*

[5] *Nvid*

Corresponding Authors: bjoo@nvidia.com, pittlerferenc@gmail.com

In this poster, we will present our implementation strategy of domain decomposition techniques for the Dirac operator within QUDA. We are developing a generic 4-dimensional domain decomposition aiming to support algorithms such as Red-Black Schwartz Alternating Procedure (SAP), time-slice domains and multilevel algorithms. We will also discuss how we plan to support preconditioned operators, BLAS routines and reductions acting on the domains, as well as, to use the techniques within multigrid solvers.

Poster session and reception / 470

Preliminary results for the intermediate-distance window contribution from the BMW collaboration

Author: Balint Toth[1]

[1] *Bergische Universität Wuppertal*

Corresponding Author: btoth@uni-wuppertal.de

In this talk I will present new blinded lattice results for the intermediate-distance window observable of the anomalous muon magnetic moment. Results are obtained on several staggered ensembles covering lattice spacings down to a ~ 0.048 fm. I will discuss the details of the continuum extrapolation and of other sources of systematic uncertainties.

Poster session and reception / 467

Computing scattering phase shift of wavepackets in Gross-Neveu model

Author: Muhammad Asaduzzaman[1]

Co-authors: Goksu Can Toga [2]; Simon Catterall [3]; Yannick Meurice [1]; Zheyue Hang [1]

[1] *University of Iowa*

[2] *North Carolina State U*

[3] *Syracuse University*

Corresponding Authors: masaduzzaman@uiowa.edu, zheyue-hang@uiowa.edu, yannick-meurice@uiowa.edu, smcatterall@gmail.com, gctoga@syr.edu

We consider the two-flavor Gross-Neveu model and compute the real time evolution of probabilities relevant to the calculation of the scattering phase shift with a digital quantum computer. We demonstrate the different intermediate steps of preparing the ground state, preparing a Gaussian wave packet and performing a Quantum Fourier transform on the quantum device. The phase shift

is computed from the time-delays measured from normalized probabilities with and without inter-flavor interaction. Calculating the time evolution during the collision process is desirable since it is difficult to get access to asymptotic states after the interaction.

Poster session and reception / 172

Towards the gradient flow beta function of SU(2) with $N_f = 1$ and 2 adjoint Dirac fermions

Authors: Ed Bennett[1]; Andreas Athenodorou[2]; Georg Bergner[3]; Pietro Butti[4]; Biagio Lucini[1]

[1] *Swansea University*

[2] *The Cyprus Institute*

[3] *University of Jena*

[4] *University of Zaragoza*

Corresponding Authors: pietro.butti.fl@gmail.com, b.lucini@swansea.ac.uk, a.athenodorou@cyi.ac.cy, e.j.bennett@swansea.ac.uk, georg.bergner@uni-jena.de

The family of SU(2) theories with matter transforming in the adjoint representation has attracted interest from many angles. The 2-flavour theory, known as Minimal Walking Technicolor, has a body of evidence pointing to it being in the conformal window with anomalous dimension $\gamma_* \approx 0.3$. Perturbative calculations would suggest that the 1-flavour theory should be confining and chirally broken; however, lattice studies of the theory have been inconclusive. In this poster we present a first look at efforts towards the computation of the beta function of these theories using the gradient flow methodology. Following an exploration of the phase diagram of the two theories with Wilson fermions and additional Pauli–Villars fields, we tune the bare fermion mass to near the chiral limit, and subsequently generate ensembles at five lattice volumes and a range of lattice spacings.

Poster session and reception / 209

Opening up a Coulomb Phase in Z_3 Gauge Theory

Author: David Lanners[1]

Co-authors: Jeffrey Giansiracusa [1]; Tin Sulejmanpasic [1]

[1] *Durham University*

Corresponding Author: jhtb65@durham.ac.uk

The investigation of $\mathbb{Z}_N$ lattice gauge theories was initially undertaken to gain insights into the phase structure of lattice gauge theories. It is established that for $N < 5$, these theories exhibit two phases: an ordered, deconfining phase at low temperatures and a disordered, confining phase at high temperatures. For $N \geq 5$, an additional Coulomb phase emerges at intermediate temperatures. In their recent work, Nguyen, Sulejmanpasic, and Ünsal gave a theoretical argument that even for $N < 5$, the $\mathbb{Z}_N$ theory can be deformed to reveal an intermediate phase. In our research, we propose a deformation of the $\mathbb{Z}_3$ theory by suppressing monopoles and provide numerical evidence suggesting the appearance of a phase with an emergent $U(1)$ symmetry, not present in the undeformed theory.

Poster session and reception / 236

Progress in generating gauge ensembles in OpenLat

Authors: Andera Shindler[1]; Andre Walker-Loud[2]; Anthony Francis[3]; Antonio Rago[4]; Giovanni Pederiva[5]; Jangho KIM[6]; Patrick Fritzsch[7]; Savvas Zafeiropoulos[8]

[1] *Michigan State University*

[2] *LBNL*

[3] *National Yang Ming Chiao Tung University*

[4] *QTC & IMADA, University of Southern Denmark*

[5] *Forschungszentrum Jülich - Jülich Supercomputing Centre*

[6] *Universität Bielefeld*

[7] *Trinity College Dublin*

[8] *Aix Marseille University*

Corresponding Authors: g.pederiva@fz-juelich.de, kim.jangho1120@gmail.com, afrancis@nycu.edu.tw, walkloud@lbl.gov, rago@qtc.sdu.dk, fritzscp@tcd.ie

We presents the status of our program to generate $n_f = 2 + 1$ quark flavor gauge configurations using stabilized Wilson fermions within OpenLat. Updates on our ongoing production at the four lattice spacings $a = 0.12, 0.094, 0.077$ and 0.064 fm are shown and, aside from the flavor symmetric point, advancements in going towards physical pion masses are discussed. High-statistics ensembles are now available at $m_\pi \simeq 300$ MeV for all lattice spacings, and additionally we show preliminary results at $m_\pi \simeq 200$ MeV and lower.

Poster session and reception / 399

One-loop Analysis for QCD Schrodinger functional

Author: ChunFei Leung[1]

[1] *Trinity College Dublin*

Corresponding Author: chleung@tcd.ie

The one-loop matching between the overlinee coupling and the MS coupling is done in two steps. First, we
calculate the relation of the overlinee coupling to a renormalised lattice coupling. Combination with the known one-loop relation between the lattice and the MS couplings then yields the desired result.

\subsection{The basic calculation}
Expand $\overline{g}(L)$ the running coupling in terms of g_0 the overlinee coupling:
\begin{equation}
\overline{g}^2 = g_0^2 + p_1 g_0^4 + O(g_0^6),
\end{equation}
where the coefficient p_1 depends on the number of flavors n_f the overlinee quark mass in lattice units m_0 and the lattice size l≡ $\frac{L}{a}.For later convenience this dependence is split into the pure gauge part and the quark contribution$
$p_1(n_f, z, l) = p_{1,0}(l) + n_f p_{1,1}(z, l),$ (1) with:

$$z = \overline{m}L, \qquad \overline{m} = \frac{1}{a}\ln(1 + m_0 a). \tag{2}$$

Note that expansion of $\overline{m}$ w.r.t. small lattice spacing a gives the first order result $\overline{m} = m_0$.

Now expand g_0 in terms of renormalised coupling $g_{lat}(\mu)$ at the μ scale gives:

$$g_0^2 = g_{lat}^2 + z_1 g_{lat}^4 + O(g_{lat}^6), \tag{3}$$

$$z_1 \equiv z_{1,0}(a\mu) + n_f z_{1,1}(a\mu) = 2b_0(n_f, 0)\ln(a\mu), \tag{4}$$

where $b_0(n_f, 0)$ is known:

$$b_0(n_f, 0) = \frac{1}{4\pi^2}(11 - \frac{2}{3}n_f) \tag{5}$$

Then we have the relation between renormalised coupling constants $\overline{g}$ and g_{lat}:

$$\overline{g}^2 = g_{lat}^2 + (p_1 + z_1)g_{lat}^4 + O(g_{lat}^6). \tag{6}$$

The goal is to calculate the quark field contribution $p_{1,1}$. Using the standard Wilson plaquette action, we have:
\begin{equation}
p_{1,1}(z,l)= (k n_f)^{-1} \frac{\partial}{\partial{\eta}} \ln \det(D_5)|{\eta=\nu=0},
\end{equation}
where:
\begin{align}
k =& 12 l^2 (\sin{\frac{\pi}{3l^2}}+\sin{\frac{2\pi}{3l^2}}) = 12 (L/a)^2 \left[\sin(\frac{1}{3}\pi(a/L)^2) + \sin(\frac{2}{3}\pi(a/L)^2)
\right]
\\
D_5 =& \gamma_5 (D + m_0)
\\
D =& \sum{\mu}(\frac{\gamma_\mu}{2}(\nabla_\mu^+ \nabla_\mu) - \frac{a}{2}\nabla_\mu^\nabla_\mu) + \sum_{\mu\nu}
c_{sw} \frac{ia}{4}\sigma_{\mu\nu}P_{\mu\nu}
\\
\sigma_{\mu\nu} =& \frac{i}{2} [\gamma_\mu,\gamma_\nu]
\end{align}

Poster session and reception / 1

Maximally supersymmetric Yang–Mills in three dimensions

Author: David Schaich[1]

[1] *University of Liverpool*

Corresponding Author: david.schaich@liverpool.ac.uk

Recent years have seen significant progress in numerical lattice studies of supersymmetric gauge theories, exploiting formulations that exactly preserve a supersymmetry sub-algebra at non-zero lattice spacing. These investigations remain computationally demanding, especially in the large-N limit of the SU(N) gauge group. Three-dimensional theories offer a promising balance between computational costs and rich non-perturbative dynamics, including connections to quantum gravity via holographic dualities. I will present new lattice investigations of maximally supersymmetric Yang–Mills theory in three dimensions, focusing on its non-perturbative phase diagram.

Plenary / 83

Qubit Regularization: Asymptotic Freedom via New Renormalization Group flows

Author: Shailesh Chandrasekharan[1]

[1] *Duke University*

Corresponding Author: sch@phy.duke.edu

In order to study quantum field theories on a quantum computer we need to begin with lattice theories with a finite dimensional local Hilbert space. We view this as a new type of regularization of quantum field theories, and refer to it as qubit regularization, which can be explored both in Minkowski and Euclidean spaces. Such a finite dimensional regularization of a quantum field theory was proposed long ago as a general idea for many quantum field theories and was called

the D-theory approach. Here the local Hilbert spaces were allowed to grow via an additional dimension if needed. The D-theory approach often provides a very good effective field theory of the original theory with a small additional dimension. However, we have recently discovered examples in $1+1$ dimensions where asymptotic freedom seems to emerge exactly even with a strictly finite dimensional local Hilbert space. But the renormalization group flow to the UV fixed point in these examples is quite novel. One starts with a critical quantum field theory which is quite different from the desired continuum asymptotically free quantum field theory. A relevant perturbation then takes us arbitrarily close to the desired theory. These examples implore us to understand if other asymptotically free quantum field theories including Yang Mills theories and QCD can also emerge via similar RG flows within a strict finite dimensional local Hilbert space. Qubit regularized Hilbert spaces of gauge theories do contain both confined and deconfined phases. The challenge is to discover Hamiltonians in the qubit regularized Hilbert space, which may be different from traditional Hamiltonians, but have interesting critical phase transitions between the phases and are governed by novel RG flows.

Plenary / 405

Lattice fermions, topological materials and Floquet insulators

Author: Srimoyee Sen[1]

[1] *Iowa State University*

Corresponding Author: srimoyee@iastate.edu

Different subfields of physics sometimes share a common thread which is often recognized only in hindsight. I will briefly highlight such an example from the past pointing to ties between lattice QCD and condensed matter physics. I will then share recent developments which suggest that similar ties may exist between a class of non-equilibrium quantum systems known as Floquet insulators and discrete time lattice fermion theories. Floquet insulators are periodically driven quantum systems that can host novel topological phases as a function of the drive parameters. I will show that the spectrum of a certain 1+1 dimensional Floquet system can be replicated exactly using a discrete time static relativistic fermion.

Plenary / 406

Symmetric Mass Generation

Corresponding Author: d.tong@damtp.cam.ac.uk

Algorithms and artificial intelligence / 104

Random Matrix Theory for Stochastic Gradient Descent

Authors: Biagio Lucini[1]; Chanju Park[1]; Gert Aarts[1]

[1] *Swansea University*

Corresponding Authors: g.aarts@swansea.ac.uk, c.j.park@swansea.ac.uk, b.lucini@swansea.ac.uk

Investigating the dynamics of learning in machine learning algorithms is of paramount importance for understanding how and why an approach may be successful. The tools of physics and statistics provide a robust setting for such investigations. Here we apply concepts from random matrix theory to describe stochastic weight matrix dynamics, using the framework of Dyson Brownian motion. We derive the linear scaling rule between the step size of the optimisation and the batch size, and identify universal and non-universal aspects of the weight matrix dynamics. We test our hypothesis in the (near-)solvable case of the Gaussian Restricted Boltzmann Machine, and explicitly identify the Wigner surmise and semi-circle, and the linear scaling rule.

Theoretical developments / 315

SymEFT for local tastes of staggered lattice QCD

Author: Nikolai Husung[1]

[1] *IFT UAM/CSIC*

Corresponding Author: nikolai.husung@uam.es

The applicability of Symanzik Effective theory (SymEFT) for the description of lattice artifacts assumes a local formulation of the lattice theory. We discuss the symmetries realised by tastes local in spacetime of unrooted staggered quarks, approaching mass-degenerate 4-flavour QCD in the continuum limit. An outlook on some implications for the asymptotic lattice-spacing dependence is given for spectral quantities as well as local composite fields.

Hadronic and nuclear spectrum and interactions / 469

Quark-mass dependence of the $\Delta(1232)$ resonance parameters.

Author: Srijit Paul[1]

Co-authors: Andrew Pochinsky [2]; Ferenc Pittler [3]; John W Negele [2]; Luka Leskovec [4]; Marcus Petschlies [5]; Sergey Syritsyn [6]; Stefan Krieg [7]; Stefan Meinel [8]

[1] *University of Maryland*

[2] *MIT*

[3] *The Cyprus Institute*

[4] *University of Ljubljana*

[5] *U. Bonn*

[6] *Stony Brook University*

[7] *JSC, Forschungszentrum Juelich/HISKP, University of Bonn*

[8] *University of Arizona / RIKEN BNL Research Center*

Corresponding Authors: avp@mit.edu, f.pittler@cyi.ac.cy, spaul137@umd.edu, smeinel@email.arizona.edu, s.krieg@fz-juelich.de, syritsyn@gmail.com, luka.leskovec@ijs.si, negele@mit.edu

We present results for the $N\pi$ finite-volume spectra on three different lattice volumes with fixed lattice spacing $a = 0.116$ fm and m_π ranging from 249 MeV to 137 MeV. The calculations employ $N_f = 2+1$ doubly-HEX-smeared clover fermions. We perform the calculations with total momenta up to $\vec{P} = (1,1,1)\frac{2\pi}{L}$ and all relevant irreps. Using the L\"uscher method we fit Breit-Wigner parametrizations of the $N\pi$ scattering amplitude to the spectra to obtain the mass and decay width of the lightest baryon resonance, the $\Delta(1232)$.

Quark and lepton flavour physics / 116

Divide and conquer the sea of quarks: an application to the HVP short-distance window

Author: Sebastian Spiegel[1]

Co-author: Christoph Lehner [2]

[1] *Universität Regensburg*

[2] *University of Regensburg*

Corresponding Authors: sebastian.spiegel@physik.uni-regensburg.de, christoph.lehner@ur.de

The standing tension between experimental and theoretical results regarding the hadronic vacuum polarization (HVP) contribution to the anomalous magnetic moment of the muon motivates the development of novel methods to enhance theoretical estimates. We present a Lattice QCD study aimed at estimating the short-distance window to the HVP using an improved continuum extrapolation without the need of perturbative input. We combine a quenched continuum extrapolation using 18 lattice spacings ($a^2 \approx 0.001-0.016\,\mathrm{fm}^2$) with a separate continuum extrapolation of the sea quark effects. This method allows the computationally expensive correction to be estimated using only a few ensembles at coarser lattice spacings, while largely isolating the logarithmic dependency of the continuum extrapolation in the quenched component.

QCD at non-zero temperature / 261

NRQCD Bottomonium spectrum at non-zero temperatures using Backus-Gilbert regularisations

Author: Antonio Smecca[1]

Co-authors: Ben Page [1]; Benjamin Jäger [2]; Chris Allton [1]; Gert Aarts [1]; Jon-Ivar Skullerud [3]; Maria Paola Lombardo [4]; Rachel Horohan D'arcy [3]; Ryan Bignell [5]; Seyong Kim [6]; Sinéad Ryan [5]; Timothy Burns [1]; Tom Spriggs [1]

[1] *Swansea University*

[2] *University of Southern Denmark*

[3] *Maynooth University*

[4] *INFN Firenze*

[5] *Trinity College Dublin*

[6] *Sejong University*

Corresponding Authors: antonio.smecca@swansea.ac.uk, ryan@maths.tcd.ie, benjaminpage.acer@gmail.com, mariapaola.lombardo@lnf.infn.it, skim@sejong.ac.kr, c.r.allton@swansea.ac.uk, bignellr@tcd.ie, g.aarts@swansea.ac.uk, rachel.horohandarcy.2018@mumail.ie, t.burns@swansea.ac.uk, jonivar@thphys.nuim.ie, jaeger@imada.sdu.dk

Understanding how the properties of heavy mesons change as temperature increases is crucial for gaining valuable insights into the properties of the quark-gluon plasma. The information about meson mass and decay width is encoded in the meson spectral function, which, in principle, can be extracted from Euclidean correlation functions via Laplace transformation. Unfortunately, this inverse problem is ill-posed when working with lattice correlators, hence it must be regularised. In this talk, we will present our latest results for bottomonium spectral functions obtained within the lattice NRQCD framework using the Backus-Gilbert regularization, along with two other variants (one of which is commonly referred to as the HLT method). This study employs the latest anisotropic lattice configurations produced by the FASTSUM collaboration.

Vacuum structure and confinement / 38

Investigating the Flux Tube Structure within Full QCD

Authors: Marshall Baker[1]; Paolo Cea[2]; Volodymyr Chelnokov[3]; Leonardo Cosmai[2]; Alessandro Papa[4]

[1] *Department of Physics, University of Washington*

[2] *INFN*

[3] *Goethe University, Frankfurt*

[4] *INFN and Univ. della Calabria*

Corresponding Authors: chelnokov@itp.uni-frankfurt.de, mbaker4@uw.edu, alessandro.papa@fisica.unical.it, paolo.cea@ba.infn.it, leonardo.cosmai@ba.infn.it

A characteristic signature of quark confinement is the concentration of the chromoelectric field between a static quark–antiquark pair in a flux tube.
Here we report on lattice measurements of field distributions on smeared Monte Carlo ensembles in QCD with (2+1) HISQ flavors. We measure the field distributions for several distances between static quark-antiquark sources, ranging from 0.6 fm up to the distance where the color string is expected to break.

QCD at non-zero density / 37

Resummation methods for effective theories of LQCD

Authors: Christoph Konrad[1]; Owe Philipsen[1]

[1] *Goethe-University Frankfurt am Main*

Corresponding Authors: philipsen@itp.uni-frankfurt.de, konrad@itp.uni-frankfurt.de

The study of LQCD at finite baryon density is hindered by the infamous sign problem. This motivated the derivation of effective Polyakov loop theories from LQCD via strong-coupling and hopping parameter expansion techniques. These effective theories were shown to have a significantly reduced sign problem. By applying different mean field approximations to those theories we investigate how to minimize truncation effects on the phase diagram.

Particle physics beyond the Standard Model / 488

On the spectrum of observable particles in BSM-like theories

Author: Elizabeth Dobson[1]

[1] *University of Graz*

Corresponding Author: elizabeth.dobson@uni-graz.at

Analytical investigations and lattice simulations have previously suggested that the spectrum of observable particles in "BSM-like" theories may differ from that expected naively from perturbation theory. We consider a GUT-like toy theory, which already showed such qualitative discrepancies in exploratory lattice simulations, and perform a detailed quantitative investigation of its physical spectrum, covering different channels and lines of constant physics. We find indeed a substantial different spectrum than the elementary one. In particular, stable states with quantum numbers different from the elementary ones are observed.

Quark and lepton flavour physics / 464

Machine-learning techniques as noise reduction strategies in lattice calculations of the muon $g-2$

Author: Hartmut Wittig[1]

Co-authors: Alessandro Conigli [2]; Alexander Segner [2]; Lukas Geyer [2]; Simon Kuberski [3]; Tom Blum [4]

[1] *University of Mainz*

[2] *Johannes Gutenberg-Universität Mainz*

[3] *CERN*

[4] *University of Connecticut, Storrs*

Corresponding Authors: aconigli@uni-mainz.de, asegner@students.uni-mainz.de, hartmut.wittig@uni-mainz.de, thomas.blum@uconn.edu, skubersk@uni-mainz.de, lgeyer@students.uni-mainz.de

Lattice calculations of the hadronic contributions to the muon anomalous magnetic moment are numerically highly demanding due to the necessity of reaching total errors at the sub-percent level. Noise-reduction techniques such as low-mode averaging have been applied successfully to determine the vector-vector correlator with high statistical precision in the long-distance regime, but display an unfavourable scaling in terms of numerical cost. This is particularly true for the mixed ("high-low") contribution in which one of the two quark propagators is described in terms of low modes. Here we report on an ongoing project that employs machine learning as a cost-effective tool to produce approximate estimates of the mixed contribution, which are then bias-corrected to produce an exact result. A second example concerns the determination of electromagnetic isospin-breaking corrections by combining the predictions from a trained model with a bias correction.

Algorithms and artificial intelligence / 452

Progress in normalizing flows for 4d gauge theories

Authors: Daniel Hackett[1]; Fernando Romero-Lopez[2]; Gurtej Kanwar[3]; Phiala Shanahan[4]; Ryan Abbott[4]

[1] *Fermilab*

[2] *MIT / Uni Bern*

[3] *University of Bern*

[4] *Massachusetts Institute of Technology*

Corresponding Authors: gurtejkanwar@gmail.com, rabbott@mit.edu, pshana@mit.edu, dhackett@fnal.gov, fernando.romero-lopez@unibe.ch

Normalizing flows have recently arisen as a potential tool for aiding in sampling lattice field theories. In this talk I will give an overview of our groups' recent progress in applying normalizing flows to 4-dimensional nonabelian gauge theories, as well as current efforts to scale normalizing flows towards modern lattice field theory calculations.

Theoretical developments / 170

Locality and symmetry properties of staggered fermions with taste splitting mass term

Author: Nuha Chreim[1]

Co-author: Christian Hoelbling [1]

[1] *University of Wuppertal*

Corresponding Authors: nuha.chreim@uni-wuppertal.de, hch@uni-wuppertal.de

We present analytical and numerical results on locality and symmetry properties of staggered fermions with taste splitting mass terms. As staggered species split differently for different types of taste splitting masses, various lattice symmetry subgroups and symmetry properties emerge. Preliminary numerical results are given for lattice sizes up to 8^4.

Hadronic and nuclear spectrum and interactions / 379

Studying lattice artifacts in baryon-baryon variational bounds

Authors: Anthony Grebe[1]; Assumpta Parreño[2]; Marc Illa[3]; Michael Wagman[4]; Phiala Shanahan[5]; Robert Perry[2]; William Detmold[6]; William Jay[6]; Zohreh Davoudi[7]

[1] *Fermi National Accelerator Laboratory*

[2] *University of Barcelona*

[3] *University of Washington*

[4] *Fermilab*

[5] *Massachusetts Institute of Technology*

[6] *MIT*

[7] *University of Maryland, College Park*

Corresponding Authors: pshana@mit.edu, mwagman@fnal.gov, davoudi@umd.edu, perryrobertjames@ub.edu, assum@fqa.ub.edu, wdetmold@mit.edu, marcilla@uw.edu, willjay@mit.edu, agrebe@mit.edu

The quantification of lattice artifacts in two-baryon variational bounds is an essential prerequisite for a controlled determination of multi-baryon scattering parameters. Recent work suggests the existence of large lattice artifacts in the SU(3) flavor singlet channel. This channel is phenomenologically interesting because the ground state is the hypothesized H-dibaryon. In this talk I summarize progress by the NPLQCD Collaboration towards a continuum-limit extrapolation of baryon-baryon variational bounds in several flavor channels at a pion mass of $m_\pi \approx 800$ MeV, utilizing a larger variational set of operators than previously employed.

QCD at non-zero temperature / 443

NRQCD Bottomonium at non-zero temperature using time-derivative moments

Author: Rachel Horohan D'arcy[1]

Co-authors: Antonio Smecca [2]; Benjamin Jaeger [3]; Chris Allton [2]; Gert Aarts [2]; Jon-Ivar Skullerud [1]; Maria Paola Lombardo [4]; Ryan Bignell [5]; Seyong Kim [6]; Sinead Ryan [5]; Timothy Burns [2]

[1] *Maynooth University*

[2] *Swansea University*

[3] *University of Southern Denmark*

[4] *INFN Firenze*

[5] *Trinity College Dublin*

[6] *Sejong University*

Corresponding Authors: t.burns@swansea.ac.uk, mariapaola.lombardo@lnf.infn.it, jaeger@imada.sdu.dk, skim@sejong.ac.kr, g.aarts@swansea.ac.uk, bignellr@tcd.ie, ryan@maths.tcd.ie, antonio.smecca@swansea.ac.uk, c.r.allton@swansea.ac.uk, jonivar@thphys.nuim.ie, rachel.horohandarcy.2018@mumail.ie

We will discuss our recent results for the thermal mass and width of bottomonium. A well-known challenge for the lattice community is calculating the spectral function from the Euclidean correlator. We have approximated the spectral function and derived the mass and width of particles through the time derivatives of the lattice correlator.
We have focused on extracting the properties of bottomonium states, specifically Upsilon and Chi_b1, from lattice correlators. We will give an overview of the time-derivative moments approach and look at results for the temperature dependance of the mass and width of both bottomonium states. The zero temperature results are consistent with experimental values, while results at higher temperatures are similar to those obtained using other methods.

Vacuum structure and confinement / 121

Towards an Effective String Theory for the flux-tube

Author: Andreas Athenodorou[1]

Co-authors: Michael Teper [2]; Conghuan Luo [3]; Sergei Dubovsky [3]

[1] *The Cyprus Institute*

[2] *University of Oxford*

[3] *New York University*

Corresponding Author: a.athenodorou@cyi.ac.cy

The quest to develop an effective string theory capable of describing the confining flux-tube has been a longstanding objective within the theoretical physics community. Recent lattice results indicate that the low-lying spectrum of the flux-tube in both three and four dimensions can be partially described by the Nambu-Goto string with minor deviations. However, several excitation states exhibit significant corrections that have remained unexplained until recently.

Recent advancements suggest that a Thermodynamic Bethe Ansatz analysis, expanded in both $1/R\sqrt{\sigma}$ and the softness of phonons, can lead to a robust effective string theory for the flux-tube with length R. Furthermore, lattice data points to the existence of an axion field on the world-sheet of the flux-tube, implying that an Axionic String Ansatz should accompany the Nambu-Goto framework.

In our presentation, we will provide compelling evidence that this approach can closely approximate the flux-tube data. We will demonstrate this by comparing results obtained for the spectrum of the $SU(N)$ closed flux-tube using lattice techniques in four dimensions.

QCD at non-zero density / 58

Grassmann tensor-network approach for two-dimensional QCD in the strong-coupling expansion

Author: Thomas Samberger[1]

Co-authors: Jacques Bloch [2]; Robert Lohmayer [1]

[1] *Universität Regensburg*

[2] *University of Regensburg*

Corresponding Authors: jacques.bloch@ur.de, thomas.samberger@ur.de, robert.lohmayer@physik.uni-regensburg.de

For non-zero chemical potential, the sign problem prohibits the simulation of lattice QCD using traditional Monte-Carlo methods. I will present a tensor-network approach based on singular value decomposition to compute the partition function and thermodynamic observables of two-dimensional lattice QCD in the strong-coupling expansion for general orders of the coupling parameter β. Additionally, I will show results for the particle density and chiral condensate up to O(β^3).

Particle physics beyond the Standard Model / 12

Spectroscopy of lattice gauge theories from spectral densities

Author: Niccolo Forzano[1]

Co-authors: Alessandro Lupo [2]; Biagio Lucini [1]; C.-J David Lin [3]; Davide Vadacchino [4]; Deog Ki Hong [5]; Ed Bennett [1]; Fabian Zierler [1]; Ho Hsiao [3]; Jong-Wan Lee [6]; Luigi Del Debbio [7]; Maurizio Piai [1]; Ryan Hill [7]

[1] *Swansea University*

[2] *Aix-Marseille Universite*

[3] *National Yang Ming Chiao Tung University*

[4] *University of Plymouth*

[5] *Pusan National University*

[6] *Institute for Basic Science (IBS)*

[7] *University of Edinburgh*

Corresponding Authors: m.piai@swansea.ac.uk, j.w.lee@ibs.re.kr, dkhong@pusan.ac.kr, dlin@nycu.edu.tw, nic.forz@gmail.com

We critically discuss the algorithmic process of estimating spectral densities using the Hansen-Lupo-Tantalo method. A novel approach at finite volume is deployed to extract the spectrum of lattice gauge theories. As a case study, our discussion focuses on symplectic gauge theories with matter field consisting of a mixed fermion representation—fundamental and two-index antisymmetric one. We extensively discuss potential sources of systematic effects. The results obtained with the spectral densities are critically compared with conventional data analysis techniques, such as the generalised eigenvalue problem. Our algorithm and code can be applied to theories with other group and matter field content.

Particle physics beyond the Standard Model / 199

Spectral densities from Euclidean-time lattice correlation functions

Authors: Leonardo Giusti[1]; Matteo Saccardi[1]; Mattia Bruno[2]

[1] *University of Milano-Bicocca*

[2] *Universita' di Milano-Bicocca*

Corresponding Authors: leonardo.giusti@unimib.it, m.saccardi@campus.unimib.it, mattia.bruno@unimib.it

In quantum field theories, spectral densities are directly related to relevant physical observables. In Lattice QCD, their non-perturbative extraction from first principles requires the Inverse Laplace transform of Euclidean-time correlation functions, a notorious ill-posed problem. In this talk we present a new strategy to perform this inversion both in the continuum and on the lattice, also suitable for smeared spectral densities.

Theoretical developments / 51

Chiral Lagrangian for Karsten-Wilczek Minimally Doubled Fermion

Authors: Dipankar Chakrabarti[1]; Kunal Shukre[2]; Subhasish Basak[3]

[1] *Indian Institute of Technology, Kanpur*

[2] *National Institute of Science Education and Research, Bhubaneswar*

[3] *National Institute of Science Education and Research Bhubaneswar*

Corresponding Authors: kunalsatyajit.shukre@niser.ac.in, dipankar@iitk.ac.in, sbasak@niser.ac.in

Lattice chiral perturbation theory is constructed for the Karsten-Wilczek (KW) minimally doubled fermion action. Symanzik expansion based on the symmetries of the lattice KW action and subsequent spurion analysis have been carried out. This led to the chiral Lagrangian which can be arranged in powers of quark masses and lattice spacing.

Hadronic and nuclear spectrum and interactions / 267

Lattice QCD study on Λ_c−N central and tensor potentials with physical masses

Author: Liang Zhang[1]

Co-authors: Takumi Doi [2]; Tetsuo Hatsuda [2]

[1] *RIKEN iTHEMS; SINAP, CAS*

[2] *RIKEN*

Corresponding Authors: tetsuohatsuda@gmail.com, zhangliang@sinap.ac.cn, doi@ribf.riken.jp

$\Lambda_c - N$ central and tensor potentials in the spin singlet channel ($^1S_0$) and the spin triplet coupled channel ($^3S_1 - {}^3D_1$) from lattice QCD by using HAL QCD method. We perform the first physical point simulation by employing gauge configurations generated by the HAL Collaboration at $m_\pi \simeq 137$ MeV, $m_K \simeq 502$ MeV, and $a \simeq 0.0844$ fm on 96^4 lattices (HAL-Conf-2023) in which a high statistical precision was achieved by 8000 Monte Carlo trajectories.

Our calculations of the $\Lambda_c - N$ show a weak mid-range attractive and short-range repulsive central potential, along with a weak tensor force. This is qualitatively similar to the previous results obtained by HAL QCD Collaboration at heavier pion masses, $m_\pi \simeq 410,\ 570,\ 700$ MeV, while the current results at the physical point indicate a shallower mid-range attraction compared to the previous results. With the ALICE upgraded for LHC Run-3, the increased statistics of charm baryons may enhance the feasibility to analyzing the $\Lambda_c - N$ interaction using both lattice QCD and experimental data. The present results at the physical point with the coupled-channel effect would also make a significant impact on the studies of $\Lambda_c - N$ interactions based on chiral effective field theory.

Quark and lepton flavour physics / 460

Preliminary results for the short-distance window contribution to the muon g-2

Author: Andrey Kotov[1]

[1] *Juelich Forschungszentrum*

Corresponding Author: a.kotov@fz-juelich.de

In this talk I will present new blinded lattice results for the short-distance window observable of the anomalous muon magnetic moment. Results are obtained on several staggered ensembles covering lattice spacings down to a ~ 0.048 fm. I will discuss the details of the continuum extrapolation and of other sources of systematic uncertainties.

QCD at non-zero temperature / 414

Anisotropic excited bottomonia from a basis of smeared operators

Author: Ryan Bignell[1]

Co-authors: Gert Aarts [2]; Chris Allton [2]; Rachel Horohan D'arcy [3]; Benjamin Jaeger [4]; Seyong Kim [5]; Maria Paola Lombardo [6]; Sinead Ryan [1]; Jon-Ivar Skullerud [3]; Antonio Smecca [2]

[1] *Trinity College Dublin*

[2] *Swansea University*

[3] *Maynooth University*

[4] *University of Southern Denmark*

[5] *Sejong University*

[6] *INFN Firenze*

Corresponding Authors: c.r.allton@swansea.ac.uk, antonio.smecca@swansea.ac.uk, rachel.horohandarcy.2018@mumail.ie, bignellr@tcd.ie, skim@sejong.ac.kr, ryan@maths.tcd.ie, jonivar@thphys.nuim.ie, jaeger@imada.sdu.dk, mariapaola.lombardo@lnf.infn g.aarts@swansea.ac.uk

Bottomonia plays a crucial role in our understanding of the quark gluon plasma phase. It is thus essential to have a thorough basis which which to examine bottomoniun states. We thus present lattice non-relativistic QCD calculations of bottomonia at temperatures in the range $T \in [47, 380]$ MeV using the FASTSUM Generation 2L anisotropic $N_f = 2 + 1$ ensembles. The use of a basis of smeared operators allows the extraction of excited state masses at zero temperature, and an investigation of their thermal properties at non-zero temperature. We find that the ground state signal is substantially improved by this variational approach at finite temperature and also apply spectral function investigation methods to the projected or optimal correlation functions.

Vacuum structure and confinement / 259

Intrinsic width of the flux tube in 2+1 dimensional Yang-Mills theories

Authors: Alessandro Nada[1]; Dario Panfalone[2]; Elia Cellini[3]; Lorenzo Verzichelli[4]; Michele Caselle[1]

[1] *Università di Torino*

[2] *Univesita' di Torino*

[3] *University of Turin / INFN Turin*

[4] *Università di Torino, INFN sezione di Torino*

Corresponding Authors: alessandro.nada@unito.it, elia.cellini@unito.it, dario.panfalone@unito.it, caselle@to.infn.it, lorenzo.verzichelli@unito.it

In this talk we present a study of the flux tube in Yang-Mills theories with a particular focus on its intrinsic width.
In the Effective String Theory description of flux tubes, this quantity is typically neglected, since it

has no measurable effects on the inter-quark static potential. However, it can be directly observed in the profile of the flux tube as a deviation from the expected gaussian shape.
In the recent past numerical lattice results on these deviations have been interpreted in terms of a dual superconductor model. We discuss the pros and cons of this proposal and compare it with the results of an effective description of the flux tube based on the Svetitsky-Yaffe mapping of Yang-Mills theories into spin models in the vicinity of the deconfinement transition.
We study in particular the $\mathrm{SU}(2)$ and $\mathrm{SU}(3)$ models in 2+1 dimensions, which are mapped into the Ising and Z_3 spin models in two dimensions respectively. The main feature of this description is that the intrinsic width is not a new independent quantity but can be related to the same physical scale appearing in the confining inter-quark static potential.
We test this prediction with precise numerical simulations of the $\mathrm{SU}(2)$ and $\mathrm{SU}(3)$ models, finding a good agreement with the numerical results.

QCD at non-zero density / 455

Complex Langevin simulations of QCD: the effects of dynamical stabilization

Author: Michael Westh Hansen[None]

Co-author: Denes Sexty [1]

[1] *University of Graz*

Corresponding Authors: denes.sexty@uni-graz.at, westh1313@gmail.com

Simulating full QCD for non-zero chemical potential introduces a sign-problem, which we here circumvent using the Complex Langevin method. At lower temperatures, the simulations are unstable, therefore the dynamical stabilization was proposed, which is a soft cutoff in imaginary directions of the complexified field manifold. Before simulating full QCD, we look at a simpler toy-model to study the bias which the dynamical stabilization introduces. We find that extrapolation to zero stabilization force is possible and gives good results. Similar behavior is observed in QCD for a slightly modified stabilization force.

Algorithms and artificial intelligence / 55

Stochastic Normalizing Flows for Effective String Theory.

Authors: Michele Caselle[1]; Elia Cellini[1]; Alessandro Nada[2]

[1] *University of Turin / INFN Turin*

[2] *Università di Torino*

Corresponding Authors: elia.cellini@unito.it, alessandro.nada@unito.it

Normalizing Flows (NFs) are a class of deep generative models recently proposed as a promising alternative to traditional Markov Chain Monte Carlo methods in lattice field theory calculations. By combining NF layers with out-of-equilibrium stochastic updates, we obtain Stochastic Normalizing Flows (SNFs), an intriguing class of machine learning algorithms that can be explained in terms of stochastic thermodynamics. In this talk, we show that SNFs can be successfully applied as samplers for Effective String Theory (EST) on the lattice, a powerful non-perturbative approach to describe confinement in Yang-Mills theory which represents a significant challenge for standard sampling methods.

Hadronic and nuclear spectrum and interactions / 188

NJ/ψ and $N\eta_c$ interactions from lattice QCD

Author: YAN LYU[1]

Co-authors: Takumi Doi [2]; Takuya Sugiura [3]; Tetsuo Hatsuda [4]

[1] *RIKEN iTHMES*

[2] *RIKEN*

[3] *RCNP, Osaka University*

[4] *RIKEN iTHEMS*

Corresponding Authors: helvetia@pku.edu.cn, thatsuda@riken.jp, sugiura@rcnp.osaka-u.ac.jp, doi@ribf.riken.jp

The interaction between the nucleon and charmonia (J/ψ and η_c) is expected to deepen our understanding of various aspects in nonperturbative QCD ranging from the origin of nucleon mass to J/ψ suppression in heavy ion collisions and properties of hidden-charm pentaquark states. Here, we present the first lattice QCD studies on low-energy NJ/ψ and $N\eta_c$ interactions based on (2+1) flavor configurations with nearly physical pion mass $m_\pi = 146$ MeV. The interactions, extracted from the spacetime correlations of nucleon and charmonium system by using HAL QCD method, are found to be attractive in all distances and manifest a characteristic long-range tail, which is consistent with the two-pion exchange interaction between a nucleon and a color-dipole. The resulting scattering lengths are around 0.4 fm, 0.3 fm and 0.2 fm for NJ/ψ with spin $1/2$, with spin $3/2$, and $N\eta_c$, respectively. Our results are orders of magnitude larger than those from the photo-production experiments assuming the vector meson dominance.

Quark and lepton flavour physics / 223

Short- and intermediate-distance HVP contributions to muon g-2

Authors: Fermilab Lattice HPQCD and MILC Collaboration[None]; Shaun Lahert[None]

Corresponding Author: shaun.lahert@gmail.com

We report on the Fermilab Lattice, HPQCD and MILC collaboration effort to compute the hadronic vacuum polarization correction to the muon g-2. In particular, we present new results for the connected light-quark, strange, and charm contributions to the short- and intermediate-window quantities. For the short-distance observables, we compare with results from perturbative QCD. We outline our calculational strategy for obtaining our completely updated determination of the HVP, including isospin-breaking corrections, which are described in separate talks. All the calculations are performed on 2+1+1 highly-improved staggered-quark (HISQ) ensembles with a physical pion mass.

QCD at non-zero temperature / 477

Nonrelativistic QCD Study of Bottomonia at Finite Temperatures on a Finer Lattice

Authors: Heng-Tong Ding[1]; Wei-Ping Huang[1]; Rasmus Larsen[2]; Swagato Mukherjee[3]; Peter Petreczky[4]

[1] *Central China Normal University*

[2] *Bielefeld University*

[3] *Brookhaven National Laboratory*

[4] *BNL*

Corresponding Authors: huangweiping@mails.ccnu.edu.cn, hengtong.ding@mail.ccnu.edu.cn, rlarsen@physik.uni-bielefeld.de, petreczk@bnl.gov, swagato@bnl.gov

Lattice nonrelativistic QCD study of ground and excited bottomonia at finite temperatures is presented. The correlation functions are computed using extended bottomonium operators with wave-function optimizing for excited states and also Gaussian shape for ground S- and P-wave states. Lattice calculations are performed on (2+1)-flavor gauge configurations using HISQ action near physical point within a wide temperature range 133-250 MeV, with fixed spatial extent equal to 64 and a finer lattice spacing 0.0493 fm compared with previous studies [1, 2]. We analyze the bottomonium correlation functions based on the parametrization adopted from previous studies [1, 2] to get insights into the in-medium modifications of excited bottomonia. We compare the temperature dependence of the correlators with different types of extended sources and find that this temperature dependence is very similar for different types of correlators [3].

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Vacuum structure and confinement / 419

Entanglement entropy of a color flux tube in 2 + 1-D Yang-Mills theory

Authors: Rocco Amorosso[1]; Sergey Syritsyn[1]; Raju Venugopalan[2]

[1] *Stony Brook University*

[2] *Stony Brook University, BrookHaven National Lab*

Corresponding Authors: rocco.amorosso@stonybrook.edu, syritsyn@gmail.com, raju.venugopalan@gmail.com

We study entanglement entropy in SU(2) pure gauge theory due to the presence of static quarks in $d = 2+1$. Using a replica approach we investigate the $q = 2$ Renyi entropy across various partitions of space A and $\bar{A}$. We use Polyakov lines to define the entanglement entropy associated with a quark pair in confinement, finding this entropy scales to a finite, uniquely defined, and non-zero value in the continuum limit. We study the entanglement entropy of various sizes and locations of region A relative to the quark pair and compare our results to the predictions of a string model.

QCD at non-zero density / 240

The chiral critical point from the strong coupling expansion

Authors: Jangho Kim[1]; Pratitee Pattanaik[2]; Wolfgang Unger[2]

[1] *Institute for Advanced Simulation (IAS-4), Forschungszentrum Juelich*

[2] *Bielefeld University*

Corresponding Authors: wunger@physik.uni-bielefeld.de, j.kim@fz-fuelich.de, pratiteep@physik.uni-bielefeld.de

The strong coupling expansion for staggered fermions allows for Monte Carlo simulations using a dual representation. It has a mild sign problem for low values of the inverse gauge coupling β , hence the phase diagram in the full μ_B - T plane can be evaluated. We have extended this framework to include $O(\beta^2)$ corrections, by mapping the degrees of freedom to a vertex model. We present results on the β-dependence of the chiral critical point from those simulations.

Algorithms and artificial intelligence / 177

Sampling SU(3) pure gauge theory with Stochastic Normalizing Flows

Author: Alessandro Nada[1]

Co-authors: Andrea Bulgarelli [2]; Elia Cellini [3]

[1] *Università di Torino*

[2] *University of Turin and INFN Turin*

[3] *University of Turin / INFN Turin*

Corresponding Authors: andrea.bulgarelli@unito.it, alessandro.nada@unito.it, elia.cellini@unito.it

Non-equilibrium Monte Carlo simulations based on Jarzynski's equality are a well-understood method to compute differences in free energy and also to sample from a target probability distribution without the need to thermalize the system under study. In each evolution, the system starts from a given base distribution at equilibrium and it is gradually driven out-of-equilibrium while evolving towards the target parameters. If the target distribution suffers from long autocorrelation times, this approach represents a promising candidate to mitigate critical slowing down. Out-of-equilibrium evolutions are conceptually similar to Normalizing Flows and they can be combined into a recently-developed architecture called Stochastic Normalizing Flows (SNF). In this contribution we first focus on the promising scaling with the volume guaranteed by the purely stochastic approach in the $\mathrm{SU}(3)$ lattice gauge theory in 4 dimensions; then, we define an SNF by introducing gauge-equivariant layers between the out-of-equilibrium Monte Carlo updates, and we analyse the improvement obtained as well as the inherited scaling with the volume. Finally, we discuss how this approach can be systematically improved and how simulations of lattice gauge theories in four dimensions for large volumes and close to criticality can be realistically achieved.

Theoretical developments / 42

Eigenspectra of Minimally Doubled Fermions

Authors: Abhijeet Kishore[1]; Dipankar Chakrabarti[1]; Subhasish Basak[2]

[1] *Indian Institute of Technology Kanpur (IIT Kanpur)*

[2] *National Institute of Science Education and Research (NISER)*

Corresponding Authors: dipankar@iitk.ac.in, sbasak@niser.ac.in, akishore@alumni.iitd.ac.in

We determined the eigenspectra of minimally doubled fermions (MDF), in both Karsten-Wilczek and Borici-Creutz realizations, and studied the chiralities of the eigenmodes and topological charges for background SU(3) gauge fields in four spacetime dimensions. We employed the spectral flow of the eigenvalues for this work.

Particle physics beyond the Standard Model / 283

Updates on the density of states method in finite temperature Symplectic gauge theories

Authors: Biagio Lucini[1]; David Mason[2]; Davide Vadacchino[3]; Ed Bennett[1]; Enrico Rinaldi[4]; Fabian Zierler[1]; Maurizio Piai[1]

[1] *Swansea University*

[2] *University of Swansea*

[3] *University of Plymouth*

[4] *RIKEN (iTHEMS)*

Corresponding Authors: 2036508@swansea.ac.uk, erinaldi.work@gmail.com, m.piai@swansea.ac.uk

First order phase transitions in the early universe have rich phenomenological implications, such as the production of potentially detectable background gravitational waves. Density of states methods, and in particular the linear logarithmic relaxation method, can be used to resolve issues related to the meta-stable dynamics around the critical point and allow for the accurate determination of the thermodynamic observables that are otherwise inaccessible, such as the free energy. In this contribution, we present an update on results for the analysis of the finite temperature deconfinement phase transition in a pure $Sp(4)$ gauge theory, a model for physics beyond the standard model, using the LLR method. We present an analysis of the properties of the transition in the thermodynamic limit.

Hadronic and nuclear spectrum and interactions / 270

Lattice Calculation of Proton-Proton Fusion Matrix Element

Author: Zi-Yu Wang[1]

[1] *Peking University*

Corresponding Author: wangziyu15@pku.edu.cn

We determined the proton-proton fusion matrix element and constrained the corresponding low energy constant L_{1,A} in the pionless EFT at a pion mass of 432 MeV. To control the systematics, we employed both bilocal and hexaquark interpolation operators. Given that the two-nucleon system at unphysical pion mass is likely to be a shallow bound state or scattering state, the finite volume effects are not negligible. We estimated its finite volume correction by using the two-nucleon spectrum obtained from our lattice data.

Quark and lepton flavour physics / 160

Light-quark connected HVP contributions to muon g-2

Author: Michael Lynch[1]

[1] *University of Illinois, Urbana-Champaign*

Corresponding Author: ml11@illinois.edu

We present recent results on the Fermilab Lattice, HPQCD, and MILC collaborations project to compute the hadronic vacuum polarization (HVP) contribution to the muon's anomalous magnetic moment. In this talk, we show preliminary results for the light-quark–connected HVP contribution, including low-mode–improved data sets on our finest ensembles. All ensembles use the 2+1+1 Highly-Improved Staggered Quark (HISQ) action with physical pion mass.

QCD at non-zero temperature / 341

Quarkonia Spectral Functions from (2+1)-flavor QCD using Non-perturbative Thermal Potential

Author: Sajid Ali[1]

Co-authors: Dibyendu Bala [2]; Olaf Kaczmarek [1]

[1] *Bielefeld University, Germany*

[2] *Bielefeld University*

Corresponding Authors: dibyendu.bala@physik.uni-bielefeld.de, sajid.ali@physik.uni-bielefeld.de, okacz@physik.uni-bielefeld.de

Quarkonia, the bound states of heavy quark-antiquark pairs, are crucial probes for studying quark-gluon plasma (QGP). The color screening properties of the QGP weaken the interactions between quark-antiquark pairs, leading to the suppression of quarkonia yields within the QGP. Here, we present some preliminary results on the fate of quarkonia bound states in the QGP by performing spectral reconstruction from lattice correlators. The spectral function is reconstructed by combining the vacuum part, which is valid at large energy, with the part obtained from the thermal potential near the threshold. We observe that this spectral function effectively describes the lattice data. Our findings indicate that the thermal interaction shifts the bound state mass and results in a significantly larger thermal width. In the charmonium system, the width is much larger than in the bottomonium system.

Vacuum structure and confinement / 133

Effective string description of the reconfined phase in the trace deformed SU(2) Yang-Mills theory in (2+1) dimensions.

Authors: Michele Caselle[1]; Claudio Bonati[2]; Alessio Negro[3]; Dario Panfalone[4]; Lorenzo Verzichelli[5]

[1] *Università di Torino*

[2] *Università di Pisa*

[3] *Physics Dep. Torino University*

[4] *Univesita' di Torino*

[5] *Università di Torino, INFN sezione di Torino*

Corresponding Authors: michele.caselle@unito.it, dario.panfalone@unito.it, claudio.bonati@df.unipi.it, lorenzo.verzichelli@unito.it

We study the behaviour of the flux tube in the reconfined phase of the trace deformed $SU(2)$ Yang-Mills theory in (2+1) dimensions. In this phase the Polyakov loop has a vanishing expectation value (and center symmetry is recovered) even at high temperatures. We study, by means of numerical simulations, the confining potential between two Polyakov loops and show that its behaviour is very different from that of usual confining gauge models and shows a remarkable agreement with the predictions of the so called "rigid string" in the limit in which the rigidity term (which is driven in the action by a term proportional to the square of the extrinsic curvature of the string) is very large and is the dominant contribution in the action.

Algorithms and artificial intelligence / 307

Normalizing flows for SU(n) gauge theories employing singular value decomposition

Authors: Komijani Javad[1]; Marina Krstic Marinkovic[2]

[1] *Technische Universit\"at M\"unchen*

[2] *ETH Zurich*

Corresponding Authors: marinama@phys.ethz.ch, jkomijani@gmail.com

In this talk, we give a progress report on exploring the method of normalizing flows for generating gauge configurations. We discuss how to use the singular value decomposition (SVD) to construct gauge-invariant quantities, which can be employed to build gauge equivariant transformations of SU(n) gauge links.
We discuss this algorithm's efficiency compared to Wilson loops' spectral flow.

Theoretical developments / 158

Formulation of SU(N) Lattice Gauge Theories with Schwinger Fermions

Author: Hanqing Liu[1]

Co-authors: Tanmoy Bhattacharya [1]; Shailesh Chandrasekharan [2]; Rajan Gupta [3]

[1] *Los Alamos National Laboratory*

[2] *Duke University*

[3] *Los ALamos National Lab*

Corresponding Authors: tanmoy@lanl.gov, sch@phy.duke.edu, hanqing.l@outlook.com, rajan@lanl.gov

The recent advancements towards scalable fault-tolerant quantum computing have brought excitement about simulating lattice gauge theories on quantum computers. However, digital quantum computers require truncating the infinite-dimensional link Hilbert space to finite dimensions. In this talk, we focus on the $\mathrm{SU}(N)$ gauge theory coupled to N_f flavor of quarks and propose a formulation of the gauge field using Schwinger fermions. Remarkably, the resulting theory can be expressed purely in terms of gauge-invariant operators. This formulation applies to any $\mathrm{SU}(N)$ gauge group in any spacetime dimension. To explore the potential for reproducing the continuum physics, we study this model at $N = 2$ in two spacetime dimensions, where the low-energy continuum physics is expected to be described by a coset Wess-Zumino-Witten (WZW) model. Using tensor network methods, we find that the critical theory can indeed be understood as an $\mathrm{SU}(2)_1$ WZW model.

Standard Model parameters / 45

Quark mass determination using various fermion actions

Authors: Mengchu Cai[1]; Yi-Boo Yang[None]

[1] *Institute of Theoretical Physics, Chinese Academy of Sciences*

Corresponding Authors: ybyang@itp.ac.cn, caimengchu@pku.edu.cn

RI/MOM renormalization scheme is known to have poor perturbative convergence for the scalar current and then would not be very suitable for precise quark mass renormalization. I shall present our recent investigation on suppressing this uncertainty and also renormalized quark masses with this strategy using the overlap and clover fermions.

Algorithms and artificial intelligence / 36

Hessian-free force-gradient integrators and their application to lattice QCD simulations

Author: Kevin Schäfers[1]

Co-authors: Francesco Knechtli [1]; Jacob Finkenrath ; Michael Günther [1]

[1] *University of Wuppertal*

Corresponding Authors: finkenrath@uni-wuppertal.de, knechtli@physik.uni-wuppertal.de, kschaefers@uni-wuppertal.de, guenther@uni-wuppertal.de

We present a novel class of Hessian-free force-gradient integrators \[arXiv:2403.10370\]. Unlike traditional force-gradient integrators, the Hessian-free variants do not require the analytical expression of the force-gradient term, which includes the Hessian of the potential. Instead, this term is approximated through an additional force evaluation.

We examine the order conditions and geometric properties of this new framework. Additionally, we perform a linear stability analysis of (Hessian-free) force-gradient integrators and discuss the relevance of this analysis to interacting field theories.

Among all self-adjoint Hessian-free force-gradient integrators with up to eleven stages, we identify the most promising ones in terms of computational efficiency and stability.

Finally, we demonstrate the application of these integrators in the molecular dynamics step of the Hybrid Monte Carlo algorithm for four-dimensional gauge field simulations in lattice QCD with Wilson fermions, showcasing the efficiency of the new decomposition algorithms.

Hadronic and nuclear spectrum and interactions / 33

Scalar and tensor charmonium resonances in coupled-channel scattering

Author: David Wilson[1]

[1] *University of Cambridge*

Corresponding Author: d.j.wilson@damtp.cam.ac.uk

I will discuss scalar and tensor charmonium resonances determined using lattice QCD. Working at $m_\pi \approx 391$ MeV, more than 200 finite-volume energy levels are computed and these are used in extensions of the Lüscher formalism to determine infinite volume scattering amplitudes. Working in the approximation where charm-annihilation is forbidden, the ground state $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ states are stable. Below 4000 MeV we find a single χ_{c0} and a single χ_{c2} resonance, both strongly-coupled to several decay channels consisting of pairs of open-charm mesons. Both resonances are found on the closest unphysical sheet just below 4000 MeV with widths of ≈ 60 MeV. The largest couplings are to the closed $D^*\bar{D}^*$ channels in S-wave, but several open-charm channels are also found to be large and significant in both cases. All closed-charm channels are found to be approximately decoupled. No additional states are found beyond what would be expected from quark-model-like $c\bar{c}$ excitations.

Hadronic and nuclear spectrum and interactions / 319

Relativistic corrections to the quark-anti-quark static potential with gradient flow

Author: Michael Eichberg[1]

Co-author: Marc Wagner [1]

[1] *Goethe University Frankfurt*

Corresponding Authors: eichberg@itp.uni-frankfurt.de, mwagner@itp.uni-frankfurt.de

We present lattice gauge theory results for $O(1/m)$ and $O(1/m^2)$ relativistic corrections to the static potential. These results are based on Wilson loops with two field strength insertions, which we renormalize using gradient flow. Moreover, we use tree-level improvement to reduce discretization errors in the Wilson loop at small temporal and spatial separation. We use computations for several values of the lattice spacing and the gradient flow time and present selected preliminary results of an extrapolation to the continuum and to zero flow time.

Quark and lepton flavour physics / 231

Disconnected contribution to the muon $g-2$ hadronic vacuum polarization

Author: David Anthony Clarke[1]

Co-author: Fermilab Lattice HPQCD and MILC Collaboration

[1] *University of Utah*

Corresponding Author: clarke.davida@gmail.com

We report on the Fermilab-HPQCD-MILC collaboration's effort updating our calculation of the HVP for the muon anomalous magnetic moment. Using physical $N_f = 2+1+1$ HISQ ensembles at multiple lattice spacings, we focus on the isospin-symmetric, quark-line-disconnected contribution to the HVP for various windows quantities.

Structure of hadrons and nuclei / 392

Unlocking Higher Moments of Parton Distribution Functions in Lattice QCD

Author: Shindler Andrea[1]

Co-authors: Jangho Kim [2]; Dimitra Pefkou [3]; Andre Walker-Loud [4]

[1] *RWTH - Aachen*

[2] *Institute for Advanced Simulation (IAS-4), Forschungszentrum Juelich*

[3] *UC Berkeley*

[4] *LBNL*

Corresponding Authors: walkloud@lbl.gov, shindler@physik.rwth-aachen.de, dpefkou@berkeley.edu, j.kim@fz-fuelich.de

We describe a novel procedure, based on the gradient flow for fermion and gauge fields, to determine moments of parton distribution functions of any order in lattice QCD. This method resolves the problems that have hampered the determination of moments of any order of parton distribution functions on the lattice. The flowed matrix elements of twist-2 operators renormalize multiplicatively, and the matching with the physical matrix elements can be obtained using continuum symmetries and the irreducible representations of Euclidean 4-dimensional rotations. In this new framework, it is possible to choose operators with identical Lorentz indices and still retain multiplicative renormalization and matching. One can then use twist-2 operators exclusively with temporal indices, substantially improving the signal-to-noise ratio in the computation of the hadronic matrix elements. We test the method numerically by estimating moments of parton distribution functions of pseudoscalar mesons as a function of flow-time and performing a perturbative matching to determine the renormalized moments in the $\overline{\text{MS}}$ scheme.

Tests of fundamental symmetries / 17

Update on the lattice calculation of K->pipi decays with G-parity boundary conditions on a second lattice spacing

Author: Christopher Kelly[1]

[1] *Brookhaven National Laboratory*

Corresponding Author: ckelly@bnl.gov

We present preliminary results of a second, finer-lattice-spacing calculation of the I=0 K->pi pi decay amplitude in the 3 flavor theory with physical kinematics and G-parity boundary conditions, performed by the RBC & UKQCD collaborations. This new calculation will enable a continuum limit extrapolation, reducing/eliminating the significant finite-lattice spacing systematic error on our previous result. These measurements provide a Standard Model prediction for direct CP violation in kaon decays that is directly comparable to experiment.

QCD at non-zero density / 364

Equation of state of isospin asymmetric QCD with small baryon chemical potentials

Authors: Bastian Brandt[1]; Gergely Endrodi[2]; Gergely Marko[2]

[1] *University of Bielefeld*

[2] *Bielefeld University*

Corresponding Authors: gmarko@physik.uni-bielefeld.de, endrodi@physik.uni-bielefeld.de, brandt@physik.uni-bielefeld.de

We extend our measurement of the equation of state of isospin asymmetric QCD to small baryon and strangeness chemical potentials, using the leading order Taylor expansion coefficients computed directly at non-zero isospin chemical potentials. The challenging extrapolations of the fully connected contributions to vanishing pion source are facilitated by using information from isospin chemical potential derivatives. Using the Taylor coefficients, we present, amongst others, first results for the equation of state along the charge chemical potential axis, which is potentially of relevance for the evolution of the early Universe at large lepton flavour asymmetries.

Standard Model parameters / 130

Gradient Flow for Quark Mass Determination

Author: Hiromasa Takaura[1]

[1] *YITP, Kyoto University*

Corresponding Author: hiromasa.takaura@yukawa.kyoto-u.ac.jp

I propose a new method to determine quark mass using the vacuum expectation values (VEVs) of bilinear operators of the flowed quark field. This method allows for the determination of quark mass through a comparison of its perturbative calculation with its lattice data, where a precise measurement is expected, without gauge dependence or UV divergences. In this context, I present preliminary results of a two-loop perturbative calculation of these VEVs, analyzed in both large-mass and small-mass expansions.

Algorithms and artificial intelligence / 376

Parallel Tempered Metadynamics

Authors: Christian Hoelbling[1]; Gianluca Fuwa[2]; Lukas Varnhorst[3]; Timo Eichhorn[3]

[1] *Wuppertal University*

[2] *Universität Wuppertal*

[3] *University of Wuppertal*

Corresponding Authors: hch@uni-wuppertal.de, timo.eichhorn@protonmail.com, varnhorst@uni-wuppertal.de, gianlucafuwa@gmail.com

When approaching the continuum, conventional update algorithms in lattice QCD and other topologically non-trivial theories experience a particularly severe form of critical slowing down that is caused by high action barriers separating the different topological sectors. Previous tests in different theories have shown that Metadynamics can be used to overcome these barriers and reduce the effects of topological freezing by including an additional bias potential that enhances the weight of the barrier regions. However, the required reweighting involved in the method may significantly reduce the effective sample size.

Here, we show that modifications to the bias potential and the combination of Metadynamics with parallel tempering with respect to the bias potential are successful in dealing with this problem. Results from both 2-dimensional U(1) and 4-dimensional SU(3) gauge theories indicate that the new Parallel Tempered Metadynamics algorithm is similarly efficient in reducing autocorrelation times compared to Metadynamics, while at the same time requiring no reweighting and showing no reduction in the effective sample size.

Hadronic and nuclear spectrum and interactions / 69

Extraction of the S and P wave DD* scattering phase shifts using twisted boundary conditions

Authors: Masato Nagatsuka[1]; Shoichi Sasaki[1]

[1] *Tohoku University*

Corresponding Authors: masato.nagatsuka.r4@dc.tohoku.ac.jp, ssasaki@nucl.phys.tohoku.ac.jp

In this talk, we present a study on the behavior of DD^* scattering phase shifts at low energy using twisted boundary conditions. Although it is natural to use Lüscher's method for calculating the scattering phase shift between two hadrons from the energy spectra to address the properties of multiquark states, it is not realistic to calculate a high-resolution scattering phase shift using only periodic boundary conditions due to the finiteness of the volume. On the other hand, twisted boundary conditions enable us to calculate the scattering phase shifts in detail. In our research, we apply this method to the DD^* system.

Hadronic and nuclear spectrum and interactions / 148

1^{-+} Light Hybrid Decay

Authors: Chunjiang Shi[1]; Juzheng Liang[2]; Siyang Chen[1]; Wei Sun[1]; Ying Chen[1]

[1] *Institude of High-Energy Physics*

[2] *University of Science and Technology of China*

Corresponding Authors: shichujiang@ihep.ac.cn, cheny@ihep.ac.cn, juzheng.liang@ihep.ac.cn, chensiyang@ihep.ac.cn, sunwei@ihep.ac.cn

We explore the decay properties of the isovector and isoscalar 1^{-+} light hybrids π_1 and η_1 π_1 in $N_f = 2$ lattice QCD at a pion mass $m_\pi \approx 417$ MeV. The McNeile and Michael method is adopted to extract the effective couplings in $N_f = 2$ QCD for the decays.
The $N_f = 3$ degenerate QCD result with physical mixing angle is also a partial quench result.

Quark and lepton flavour physics / 235

Strong isospin breaking correction to hadronic vacuum polarization for the muon $g - 2$

Authors: Fermilab Lattice HPQCD and MILC Collaboration[None]; Jake Sitison[1]

[1] *University of Colorado Boulder*

Corresponding Author: jasi7117@colorado.edu

An ongoing project of the Fermilab Lattice, HPQCD, and MILC collaborations is the precision calculation of the hadronic vacuum polarization (HVP) contribution to the anomalous magnetic moment of the muon. In this talk, we present the strong isospin breaking corrections to the light-quark connected and disconnected contributions to HVP. This calculation employs seven HISQ ensembles with $N_f = 2 + 1 + 1$ flavors with lattice spacings in [0.06, 0.15] fm. The contribution is computed on various windows.

Structure of hadrons and nuclei / 423

Higher moments of the pion parton distribution functions using gradient flow

Author: Dimitra Pefkou[1]

Co-authors: Jangho Kim [2]; Shindler Andrea [3]; Andre Walker-Loud [4]

[1] *UC Berkeley*

[2] *Institute for Advanced Simulation (IAS-4), Forschungszentrum Juelich*

[3] *RWTH - Aachen*

[4] *LBNL*

Corresponding Authors: walkloud@lbl.gov, dpefkou@berkeley.edu, shindler@physik.rwth-aachen.de, j.kim@fz-juelich.de

We implement a recent proposal using gradient flow to compute higher moments of hadron parton distribution functions, circumventing the power divergent mixing problem. We discuss how to efficiently implement this computationally, as well as data analysis approaches. We present preliminary

results on the first few moments of the unpolarized flavor non-singlet PDF of the pion in the MS-bar scheme, using ensembles at the SU(3) flavor symmetric point, generated with stabilized Wilson fermions by the OpenLat Initiative.

Tests of fundamental symmetries / 66

Gradient Flow of the Weinberg Operator

Author: Tanmoy Bhattacharya[1]

Co-authors: Shohini Bhattacharya [1]; Vincenzo Cirigliano [2]; Rajan Gupta [3]; Emanuele Mereghetti [1]; Sungwoo Park [4]; Jun-Sik Yoo [1]; Boram Yoon [5]

[1] *Los Alamos National Laboratory*

[2] *University of Washington*

[3] *Los ALamos National Lab*

[4] *Lawrence Livermore National Laboratory*

[5] *NVIDIA*

Corresponding Authors: tanmoy@lanl.gov, emereghetti@lanl.gov, rajan@lanl.gov, tug23108@temple.edu, park49@llnl.gov, junsik@lanl.gov

We will present latest results on the gradient flow of our Weinberg three-gluon operator and its mixing with the topological term. This will allow us to combine our calculation of neutron electric dipole moments (nEDM) due to the lattice Weinberg operator with our previous results on the nEDM due to the topological term to constrain beyond-the-standard model contributions to the Weinberg operator.

QCD at non-zero density / 106

Phase and equation of state of finite density QC_2D at lower temperature

Authors: Daiki Suenaga[None]; Etsuko Itou[1]; Kei Iida[None]; Kotaro Murakami[2]

[1] *YITP, Kyoto U.*

[2] *Tokyo Institute of Technology*

Corresponding Authors: itou@yukawa.kyoto-u.ac.jp, suenaga.daiki.j1@f.mail.nagoya-u.ac.jp, kotaro.murakami@yukawa.kyoto-u.ac.jp

We investigate the phase structure and the equation of state (EoS) for dense two-color QCD (QC2D) at low temperature (T=40 MeV, 32^4 lattice) for the purpose of extending our previous works at T=80 MeV (16^4 lattice). Indeed, a rich phase structure below the pseudo-critical temperature Tc as a function of quark chemical potential μ has been revealed, but finite volume effects in a high-density regime sometimes cause a wrong understanding. Therefore, it is important to investigate the temperature dependence down to zero temperature with large-volume simulations. By performing 32^4 simulations, we obtain essentially similar results to the previous ones, but we are now allowed to get a fine understanding of the phase structure via the temperature dependence. Most importantly, we find that the hadronic-matter phase, which is composed of thermally excited hadrons, shrinks with decreasing temperature and that the diquark condensate scales as $\langle qq \rangle \propto^2$ in the BCS phase, a property missing at T=80 MeV. From careful analyses, furthermore, we confirm a tentative conclusion that the topological susceptibility is independent of μ. We also show the temperature dependence of the pressure, internal energy, and sound velocity as a function of μ. The pressure increases around the hadronic-superfluid phase transition more rapidly at the lower temperature, while the temperature dependence of the sound velocity is invisible. Breaking of the conformal bound is also confirmed

thanks to the smaller statistical error.
This talk is based on arXiv:2405.20566.

Standard Model parameters / 120

The hadronic contribution to the running of α and the electroweak mixing angle

Author: Alessandro Conigli[1]

Co-authors: Georg von Hippel [1]; Hartmut Wittig [1]; Harvey B. Meyer [1]; Konstantin Ottnad [1]; Simon Kuberski [2]

[1] *University of Mainz*

[2] *CERN*

Corresponding Authors: kottnad@uni-mainz.de, simon.kuberski@cern.ch, aconigli@uni-mainz.de, meyerh@uni-mainz.de, hartmut.wittig@uni-mainz.de, hippel@uni-mainz.de

We report on our update to [JHEP 08 (2022) 220] on the hadronic running of electroweak couplings from $O(a)$-improved Wilson fermions with $N_f = 2+1$ flavours. The inclusion of additional ensembles at very fine lattice spacings together with a number of techniques to split the different contributions for a better control of cutoff effects allow us to achieve improved precision. We employ two different discretizations of the vector current to compute the subtracted Hadronic Vacuum Polarization (HVP) functions $\bar{\Pi}^{\gamma\gamma}$ and $\bar{\Pi}^{Z\gamma}$ for Euclidean time momenta up to $Q^2 \leq 9\ \mathrm{GeV}^2$. To reduce cutoff effects in the short distance region we apply a suitable subtraction to the TMR kernel function, which cancels the leading x_0^4 behaviour. The subtracted term is then computed in perturbative QCD using the Adler function and added back to compensate for the subtraction. Chiral-continuum extrapolations are performed with five values of the lattice spacings and several pion masses, including its physical value, and several fit ansätze are explored to estimate the systematics arising from model selection. Our results show excellent prospects for high-precision estimates of $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ at the Z-pole.

Algorithms and artificial intelligence / 342

Accelerating Metadynamics to overcome action barriers in 4D-SU(3) gauge theory with an eye on full QCD

Authors: Christian Hoelbling[None]; Gianluca Fuwa[1]; Lukas Varnhorst[2]; Timo Eichhorn[2]

[1] *Universität Wuppertal*

[2] *University of Wuppertal*

Corresponding Authors: varnhorst@uni-wuppertal.de, hch@uni-wuppertal.de, timo.eichhorn@protonmail.com, gianlucafuwa@gmail.com

MCMC simulations of topologically non-trivial gauge theories such as QCD are plagued by long autocorrelation times, due to systems spending exponentially longer time stuck in a single topological sector at finer lattice spacings, which are necessary for high precision studies. This phenomenon is known as topological freezing, and several algorithms have been suggested to amend it throughout the years.

A relatively novel algorithm, Metadynamics (MetaD), introduces a so-called bias potential dependent on a collective variable (CV) to the theory and has been shown to improve this behavior. One drawback is a required reweighting procedure, which can significantly reduce the effective sample

size. We combine MetaD with parallel tempering (PT-MetaD) to eliminate this cost altogether, with only a single additional parallel simulation stream. In this way, the algorithm shows significantly better scaling than conventional algorithms in 2-dimensional U(1) gauge theory and is shown to work in 4-dimensional SU(3) gauge theory as well, with no apparent hurdles for full QCD.

Apart from the smearing necessary to define a suitable CV for non-Abelian theories in 4 dimensions, the only other, albeit more up-front, cost is the computational time required to build or thermalize the bias potential. In this talk, we discuss some strategies that are employed to reduce the overhead, potentially making the application of the algorithm reasonable within the scope of full QCD.

Hadronic and nuclear spectrum and interactions / 232

$DK/D\pi$ scattering and an exotic virtual bound state at the SU(3) flavour symmetric point

Authors: Christopher Thomas[1]; Daniel Yeo[1]; David Wilson[1]

[1] *University of Cambridge*

Corresponding Authors: c.e.thomas@damtp.cam.ac.uk, jdey2@cam.ac.uk, d.j.wilson@damtp.cam.ac.uk

The nature of the lightest open-charm mesons in the scalar ($J^P = 0^+$) sector remains elusive despite many years of studies. These mesons do not appear to have properties in line with expectations and many possible explanations have been proposed. In this talk, we report on a study where finite-volume spectra obtained from lattice QCD were used with the Lüscher method to provide constraints on infinite-volume scattering amplitudes, from which the pole singularities were determined. Working with SU(3) flavour symmetry, different scattering channels separate into SU(3) flavour irreps which allowed us to disentangle the different contributions to the $J^P = 0^+$ open-charm sector. We found a deeply bound state strongly coupled to elastic scattering threshold, corresponding to the $D^*_{s0}(2317)$, and a virtual bound state in an exotic flavour channel. These findings will be compared with other approaches and the light-quark mass dependence will be discussed. This talk is based on arXiv:2403.10498.

Hadronic and nuclear spectrum and interactions / 437

Towards glueball scattering in lattice Yang-Mills theory

Authors: Antonio Rago[1]; Mattia Bruno[2]; Maxwell Hansen[3]

[1] *QTC & IMADA, University of Southern Denmark*

[2] *Universita' di Milano-Bicocca*

[3] *University of Mainz*

Corresponding Authors: rago@qtc.sdu.dk, mattia.bruno@unimib.it, maxwell.hansen@ed.ac.uk

We present progress in the determination of glueball masses and scattering parameters computed using lattice $SU(3)$ Yang-Mills theory. Focusing on the vacuum-quantum-number ($J^{PC} = 0^{++}$) sector, the computation makes use of a number of techniques to improve the extraction of energies from Euclidean correlators, including anisotropic lattices, the multi-level algorithm, and a large set of operators applied in a variational method. In addition to various algorithmic considerations, our main result is a volume-dependent extraction of the ground state energy. This enables a prediction of the mass in the infinite volume limit and the trilinear coupling governing the coefficient of the leading volume-dependent exponential. This result is a first step towards using excited finite-volume states to extract the glueball scattering amplitude, with potential applications in QCD and strongly interacting dark matter models.

Quark and lepton flavour physics / 138

UV-finite QED correction to the hadronic vacuum polarization contribution to $(g-2)_\mu$

Authors: Harvey B. Meyer[1]; Julian Parrino[2]; En-Hung Chao[None]

Co-authors: Volodymyr Biloshytskyi [3]; Franziska Hagelstein [4]; Vladimir Pascalutsa [3]; Dominik Erb [3]

[1] *University of Mainz*

[2] *Johannes Gutenberg-Universität Mainz*

[3] *JGU Mainz*

[4] *JGU, PSI*

Corresponding Authors: domerb@uni-mainz.de, hagelste@uni-mainz.de, meyerh@uni-mainz.de, juparrin@uni-mainz.de, pascalut@uni-mainz.de, vbiloshy@uni-mainz.de, en-hung.chao@m4x.org

In the anomalous magnetic moment of the muon, the determination of the hadronic vacuum polarization (HVP) contribution must reach sub-percent precision in order for the Standard Model prediction to match the precision of the experimental measurement. To achieve this, one needs to include QED corrections that break the isospin symmetry, which is usually imposed in lattice calculations. One typically treats these corrections perturbatively in the electromagnetic fine-structure constant α, expressing them through Feynman diagrams with hadronic n-point functions calculated in isospin symmetric QCD, where individual vertices are connected by the photon propagator.
We present a study of one of the disconnected diagrams, which is UV-finite and not suppressed by SU(3) flavour symmetry. We employ a lattice calculation, performed in coordinate space with QED treated in the continuum, on seven CLS ensembles with four different lattice spacings and pion masses ranging from 170-420 MeV. We extrapolate the result to the physical point by making use of a phenomenological description in terms of the pseudoscalar meson exchange and the charged pion loop, where we also take into account the effect of $\eta\eta'$-mixing.

Structure of hadrons and nuclei / 285

LCDA moments of meson

Authors: Ji-Hao Wang[1]; Mengchu Cai[1]; Yi-Boo Yang[None]

[1] *Institute of Theoretical Physics, Chinese Academy of Sciences*

Corresponding Authors: wangjihao@itp.ac.cn, caimengchu@pku.edu.cn, ybyang@itp.ac.cn

We calculate the leading-twist light-cone distribution amplitude (LCDA) moments of mesons on MILC ensembles using the hyp-smeared clover action. For pseudoscalar mesons, we compute the first moments of the K meson and the second moments of the π and K mesons. For vector mesons, we compute the first moments of the K^* meson and the second moments of the ρ, K^*, and ϕ mesons.

Tests of fundamental symmetries / 163

Unitarity triangles and the lattice

Author: Amarjit Soni[1]

[1] *BNL*

Corresponding Author: adlersoni@gmail.com

First, in brief historically important role of the lattice in the confirmation
of the KM theory of CP violation via the (Standard or B) unitarity triangle(UT) is recapitulated.
We then briefly remark on the current tensions between inclusive
and exclusive (i.e. lattice) determinations of Vxb that are important for the BUT. Wrt the KUT, special role of eps'is discussed. Furthermore, noting that for the gold plated $K_L \to \pi^0 \nu\bar{\nu}$ mode, the currently measured upper bound is still about two orders of magnitude above the prediction of the SM, it'd suggest that the experimental measurement of this very important but also very challenging mode is likely over a decade away. That motivates us to make progress in the meantime with very closely related modes $K^0 \to \pi^0 l^+ l^-$ experimentally, phenomenologically and also via the use of the lattice in order to help improve the constraint on the gold plated mode.

QCD at non-zero density / 225

Dense QC2D: What's up with that?!?

Authors: Dale Lawlor[1]; Jon-Ivar Skullerud[2]; Seyong Kim[3]; Simon Hands[4]

[1] *National University of Ireland, Maynooth*

[2] *Maynooth University*

[3] *Sejong University*

[4] *University of Liverpool*

Corresponding Authors: jonivar@thphys.nuim.ie, skim@sejong.ac.kr, dalel487@thphys.nuim.ie, simon.hands@liverpool.ac.uk

We present recent updates and results from two-colour lattice QCD simulations at non-zero baryon density, including progress toward determining the speed of sound.

Standard Model parameters / 204

$\mathrm{O}(a)$ improvement of the flavour singlet scalar density in a setup with Wilson fermions

Author: Pia Leonie Jones Petrak[1]

Co-authors: Anastassios Vladikas [2]; Fabian Joswig [3]; Jochen Heitger [4]

[1] *University of Münster*

[2] *INFN, Roma "Tor Vergata"*

[3] *University of Edinburgh*

[4] *University of Muenster, ITP*

Corresponding Authors: heitger@uni-muenster.de, p_petr04@uni-muenster.de, tassos.vladikas@roma2.infn.it

We report on our Ward identity determination of the $\mathrm{O}(a)$ improvement coefficient for the flavour singlet scalar density, namely g_S, from three-flavour lattice QCD with Wilson-clover fermions and the tree-level Symanzik improved gauge action. We employ five couplings, $g_0^2 \in [1.5, 1.77]$, that cover the range used in large-volume CLS simulations.
While g_S itself is for instance relevant for the $\mathrm{O}(a)$ improvement of meson and baryon sigma terms, a relation to b_g, the $\mathrm{O}(a)$ improvement parameter of the gauge coupling, can also be established, allowing for its non-perturbative extraction as well. With Wilson fermions, b_g is in principle required for full $\mathrm{O}(a)$ improvement at non-vanishing sea quark masses. We outline our procedure for extracting b_g.

Algorithms and artificial intelligence / 320

Automated tuning for HMC mass ratios

Authors: Joseph Torsiello[1]; George Fleming[2]; Sam Foreman[3]; Xiao-Yong Jin[3]; James Osborn[4]

[1] *Temple University*

[2] *Fermilab*

[3] *Argonne National Laboratory*

[4] *ANL*

Corresponding Authors: foremans@anl.gov, osborn@alcf.anl.gov, xjin@anl.gov, joseph.torsiello@temple.edu, gfleming@fnal.gov

We will extend previous work on tuning HMC parameters using gradient information to include Hasenbusch mass ratios. The inclusion of mass ratios adds many more parameters that need to be tuned, and also allows for lots of variations in the choice of integrator pattern. We will investigate the effectiveness of automatically tuning a large number of HMC parameters and compare the optimally tuned versions over a range of integrator variants.

Hadronic and nuclear spectrum and interactions / 296

Near-threshold states in coupled $DD^* - D^*D^*$ scattering from lattice QCD

Author: Travis Whyte[1]

Co-authors: Christopher Thomas [2]; David Wilson [2]

[1] *Trinity College Dublin*

[2] *University of Cambridge*

Corresponding Authors: whytetr@tcd.ie, c.e.thomas@damtp.cam.ac.uk, d.j.wilson@damtp.cam.ac.uk

The first determination of doubly-charmed isospin-0 coupled-channel $DD^* - D^*D^*$ scattering amplitudes from lattice QCD is presented. The finite-volume spectrum is computed for three lattice volumes with a light-quark mass corresponding to $m_\pi \approx 391$ MeV and is used to extract the scattering amplitudes in $J^P = 1^+$ via the L\"{u}scher quantization condition. By analytically continuing the scattering amplitudes to complex energies, a T_{cc} pole corresponding to a virtual bound state is found below DD^* threshold. We also find a second pole, T'_{cc}, corresponding to a resonance pole below the kinematically closed D^*D^* channel, to which it has a strong coupling. A non-zero coupling is robustly found between the S-wave DD^* and D^*D^* channels producing a clear cusp in the DD^* amplitude at the D^*D^* threshold energy. This suggests that the experimental T'_{cc} should be observable in DD^* and D^*D^* final states at ongoing experiments.

Hadronic and nuclear spectrum and interactions / 56

Scattering of Dark Pions in Sp(4) gauge theory

Authors: Axel Maas[1]; Fabian Zierler[2]; Yannick Dengler[1]

[1] *University of Graz*

[2] *Swansea University*

Corresponding Authors: yannick.dengler@uni-graz.at, fabian.zierler@swansea.ac.uk, axel.maas@uni-graz.at

Analyzes of astrophysical data provide hints on the self-interactions of dark matter at low energies. Lattice calculations of strongly interacting dark matter (SIMP) theories are needed for motivating these models also from first principles. Sp(4) gauge theory with two fundamental fermions is a candidate SIMP theory. We compute the scattering phase shift for the scattering of two dark pions and determine the parameters of the effective range expansion. Our exploratory results in the supposedly most common interaction channel provide a lower limit for the dark matter mass when compared to astrophysical data. We also provide first benchmarks of velocity-weighted cross-sections in the relevant non-relativistic domain.

Quark and lepton flavour physics / 137

The isospin-violating part of the hadronic vacuum polarisation

Authors: Antoine Gerardin[1]; Dominik Erb[2]; Franziska Hagelstein[3]; Harvey B. Meyer[4]; Julian Parrino[5]; Vladimir Pascalutsa[2]; Volodymyr Biloshytskyi[2]

[1] *Centre de Physique Théorique de Marseille*

[2] *JGU Mainz*

[3] *JGU, PSI*

[4] *University of Mainz*

[5] *Johannes Gutenberg-Universität Mainz*

Corresponding Authors: vbiloshy@uni-mainz.de, domerb@uni-mainz.de, pascalut@uni-mainz.de, juparrin@uni-mainz.de, meyerh@uni-mainz.de, hagelste@uni-mainz.de, antoine.gerardin@univ-amu.fr

The experimental precision for the muon (g-2) currently exceeds that of the Standard-Model based prediction. In the latter, the biggest contribution to the uncertainty results from the calculation of the Hadronic Vacuum Polarisation (HVP). To achieve a higher precision, one needs in particular to determine the small, QED induced corrections to the HVP. These corrections can be calculated at leading order in the fine-structure constant using lattice QCD.

Here we present a calculation of the isospin-violating part of the HVP. We use a covariant coordinate-space approach, where the photon propagator is treated in the continuum. In order to handle the divergence originating from large photon virtualities, we use a (doubly) Pauli-Villars regulated photon propagator and calculate the required isovector mass-counterterm, which is determined from the Kaon mass splitting. These calculations are performed on four SU(3) flavour-symmetric CLS ensembles with different lattice spacings and with varying Pauli-Villars masses.

Structure of hadrons and nuclei / 84

Quark and gluon momentum fractions in the pion and in the kaon

Authors: Bartosz Kostrzewa[1]; Carsten Urbach[2]; Constantia Alexandrou[3]; Fernanda Steffens[4]; Gregoris Spanoudes[5]; Jacob Finkenrath[None]; Joseph Delmar[6]; Luis Alberto Rodriguez Chacon[7]; Marcus Petschlies[4]; Martha Constantinou[6]; Simone Bacchio[8]; Urs Wenger[9]

[1] *High Performance Computing & Analytics Lab, University of Bonn*

[2] *University of Bonn*

[3] *University of Cyprus and The Cyprus Institute*

[4] *U. Bonn*

[5] *University of Cyprus*

[6] *Temple University*

[7] *The Cyprus Institute*

[8] *University of Cyprus, University of Wuppertal*

[9] *University of Bern*

Corresponding Authors: spanoudes.gregoris@ucy.ac.cy, urbach@hiskp.uni-bonn.de, finkenrath@uni-wuppertal.de, bkostrze@uni-bonn.de, wenger@itp.unibe.ch, alexand@ucy.ac.cy, l.a.chacon@cyi.ac.cy, marthac@temple.edu, s.bacchio@gmail.com

We present the full decomposition of the momentum fraction carried by quarks and gluons in the pion and the kaon. We employ three gauge ensembles generated with Nf = 2 + 1 + 1 Wilson twisted-mass clover-improved fermions at the physical quark masses. For both mesons we perform a continuum extrapolation directly at the physical pion mass, which allows us to determine for the first time the momentum decomposition at the physical point. We find that the total momentum fraction carried by quarks is 0.532(56) and 0.618(32) and by gluons 0.388(49) and 0.408(61) in the pion and in the kaon, respectively, in the MS scheme and at the renormalization scale of 2 GeV. Having computed both the quark and gluon contributions in the continuum limit, we find that the momentum sum is 0.926(68) for the pion and 1.046(90) for the kaon, verifying the momentum sum rule.

Tests of fundamental symmetries / 171

Study of symmetry of $N_f = 2$ QCD near the critical temperature using Mobius Domain Wall Fermions

Author: David Ward[1]

Co-authors: Hidenori Fukaya [1]; Issaku Kanamori [2]; Jishnu Goswami [2]; Shoji Hashimoto [3]; Sinya Aoki [4]; Takashi Kaneko [5]; Yasumichi Aoki [2]; Yoshifumi Nakamura [2]; Yu Zhang [6]

[1] *Osaka University*

[2] *Riken - R-CCS*

[3] *KEK - Sokendai*

[4] *Kyoto University - YITP*

[5] *KEK*

[6] *Bielefeld University*

Corresponding Author: ward@het.phys.sci.osaka-u.ac.jp

We report on the ongoing study of symmetry of $N_f = 2$ QCD around the critical temperature. Our simulations of $N_f = 2$ QCD employ the Mobius domain-wall fermion action with residual mass $\sim$ 1MeV or less, maintaining a good chiral symmetry. Using the screening masses from the two point spatial correlators we compare the mass difference between channels connected through symmetry transformation. Our analysis focuses on restoration of the $SU(2)_L \times SU(2)_R$ as well as anomalously broken axial $U(1)_A$. We also present additional study of a potential $SU(2)_{CS}$ symmetry which may emerge at very high temperatures.

QCD at non-zero density / 151

QCD constraints on isospin-dense matter and the nuclear equation of state

Author: William Detmold[1]

[1] *MIT*

Corresponding Author: wdetmold@mit.edu

Lattice QCD calculations of many-meson systems at multiple volumes and lattice spacings and at quark masses above and below the physical values are used to compute the QCD equation of state for isospin-dense matter over a wide range of isospin chemical potentials at zero temperature. Agreement is seen with chiral perturbation theory predictions for small chemical potentials and comparison to perturbative QCD calculations for large chemical potentials allows for an estimate of the gap in the superconducting phase. Combining LQCD with chiral perturbation theory and perturbative QCD leads to a complete determination of the low temperature equation of state of isospin-dense matter. The partition function for an isospin chemical potential, μ_I, bounds the partition function for a baryon chemical potential $\mu_B = 3\mu_I/2$, through QCD ineqaulities. Consequently, the LQCD calculations provide rigorous bounds on the nuclear equation of state over a wide range of baryon densities for the first time.

Standard Model parameters / 301

Non-singlet axial current improvement for massless and massive sea quarks

Authors: Patrick Fritzsch[1]; Jochen Heitger[2]; Justus T. Kuhlmann[3]

[1] *Trinity College Dublin*

[2] *University of Muenster, ITP*

[3] *University of Münster*

Corresponding Authors: heitger@uni-muenster.de, j_kuhl19@uni-muenster.de, fritzscp@tcd.ie

We present results on the improvement coefficient of the non-singlet axial-vector current, with particular emphasis on imposing improvement conditions in the chiral limit and at the flavour-symmetric point.
For its determination, the established Ward-identity method is employed in $N_\mathrm{f} = 3$ QCD with stabilised Wilson-Clover fermions.
We simulate with Schrödinger functional boundary conditions and box-sizes of about $3\,\mathrm{fm}$ for $a \in [0.120, 0.055]\,\mathrm{fm}$.
Furthermore, we report on our plans to extend such calculations to access other improvement coefficients and renormalisation factors.

Algorithms and artificial intelligence / 386

Multilevel algorithm for glueball calculations

Authors: Lorenzo Barca[1]; Jacob Finkenrath[2]; Francesco Knechtli[3]; Sofie Martins[4]; Michael Peardon[5]; Stefan Schaefer[6]; Juan Andres Urrea Nino[7]

[1] *DESY*

[2] *CERN*

[3] *University of Wuppertal*

[4] *University of Southern Denmark*

[5] *Trinity College Dublin*

[6] *NIC, DESY*

[7] *Bergische Universität Wuppertal*

Corresponding Authors: urreanino@uni-wuppertal.de, martinss@imada.sdu.dk, mjp@maths.tcd.ie, stefan.schaefer@desy.de, knechtli@physik.uni-wuppertal.de, lorenzo.barca@desy.de

In this talk I will present the main results of our recent use of multilevel sampling to more efficiently reduce the error of glueball two-point functions in pure gauge theory. I will then discuss how multilevel can be combined with distillation techniques for quenched QCD simulations. In particular, I will present some preliminary results for disconnected contributions of two-pion correlation functions that enter into the analysis of glueball-meson mixing.

Hadronic and nuclear spectrum and interactions / 305

Open-charm axial-vector and tensor meson resonances from Lattice QCD

Authors: David Wilson[1]; Nicolas Lang[2]

[1] *University of Cambridge*

[2] *Universitat de València, IFIC*

Corresponding Authors: nicolas.lang@ific.uv.es, d.j.wilson@damtp.cam.ac.uk

The spectroscopy of open-charm mesons offers new insights into the dynamics of low-energy QCD and a point to connect with both experiment and EFT calculations.
In this talk I present the first extraction of the lowest axial-vector and tensor D-meson resonances from a coupled $D^*\pi$, $D^*\eta$ and $D_s^*\bar{K}$ scattering calculation in $N_f = 2+1$ lattice QCD at a pion mass of 391 MeV. The spectrum is computed from a large basis of interpolating operators using distillation and the generalised-eigenvalue method. A finite-volume quantisation condition constrains the S- and D-wave amplitudes which are analytically continued to the complex plane and examined for singularities. I discuss our findings in the context of experiment and unitarised-chiral-perturbation theory results.

Hadronic and nuclear spectrum and interactions / 211

Results on meson-meson scattering at large N_c

Author: Jorge Baeza-Ballesteros[1]

Co-authors: Fernando Romero-Lopez [2]; Pilar Hernández [3]

[1] *University of Valencia/IFIC*

[2] *MIT / Uni Bern*

[3] *University of Valencia and IFIC*

Corresponding Authors: m.pilar.hernandez@uv.es, fernando.romero-lopez@unibe.ch, jorge.baeza@ific.uv.es

In this talk, we present results on the dependence of meson-meson scattering observables on number of colors, N_c. We work in a theory with $N_\mathrm{f} = 4$ degenerate light quark flavors, and run lattice simulations with varying $N_\mathrm{c} = 3-6$ and pion mass $M_\pi \approx 590$ MeV. We focus on three different scattering channels, two of which possess the quantum numbers of some recently-found tetraquarks states at LHC. These include the the scalar $T_{c\bar{s}0}^{++}(2900)$ state or the vector $T_{c\bar{s}1}^{0}(2900)$ particle. Finite-volume energies are extracted using two-particle operators corresponding to either two pions or two vector mesons, complemented by local tetraquark operators. Using Lüscher's formalism, we constrain the N_c dependence of the infinite-volume scattering phase shift of the studied channels and investigate the possible presence of tetraquark resonances.

Quark and lepton flavour physics / 388

Valence leading isospin breaking contributions to $a_\mu^{\mathrm{HVP-LO}}$

Author: Antonio Evangelista[1]

Co-author: ETM Collaboration

[1] *University and INFN of Rome Tor Vergata*

Corresponding Author: antonio.evangelista@roma2.infn.it

In the framework of the ongoing computation by ETMC of the leading-order hadronic vacuum polarization (HVP) contribution to the muon anomalous magnetic moment a_μ^{HVP} in QCD+QED, we present preliminary results about the valence quark-connected isospin−breaking corrections to $a_\mu^{\mathrm{HVP-LO}}$, at leading order in $\alpha_{\mathrm{em}} = e^2/4\pi$ and $(m_d - m_u)/\Lambda_{\mathrm{QCD}}$. In our computation, we employ the RM123 approach to QCD+QED and here we focus on two different volumes ($L \sim 3.8$ fm and $L \sim 5.1$ fm) and a fixed lattice spacing (corresponding to $a_{isoQCD} \sim 0.07951(4)$ fm).

Structure of hadrons and nuclei / 25

Transverse Force Distributions in the Proton from Lattice QCD

Author: Joshua Crawford[1]

Co-authors: Gerrit Schierholz [2]; Hinnerk Stüben [3]; James Zanotti [4]; K. Utku Can [1]; Paul Rakow [5]; Roger Horsley [6]; Ross Young [4]

[1] *The University of Adelaide*

[2] *DESY*

[3] *Universität Hamburg*

[4] *University of Adelaide*

[5] *University of Liverpool*

[6] *University of Edinburgh*

Corresponding Authors: kadirutku.can@adelaide.edu.au, james.zanotti@adelaide.edu.au, rakow@liverpool.ac.uk, hinnerk.stueben@uni-hamburg.de, rhorsley@ph.ed.ac.uk, joshua.crawford@adelaide.edu.au, ross.young@adelaide.edu.au, gerrit.schierholz@desy.de

Single-spin asymmetries observed in polarised deep-inelastic scattering are important probes of hadron structure. The Sivers asymmetry provides information about the transverse momentum of the struck quark and can be related to final-state interactions. Understanding these asymmetries at the quark level has been the subject of much interest in QCD phenomenology. In this talk, we present a lattice QCD calculation of the transverse spatial distribution of a colour-Lorentz force acting on the struck quark in a proton. Our lattice calculations employ $N_f = 2 + 1$ flavours of dynamical fermions at the SU(3) symmetric point across three lattice spacings. We determine a central, spin-independent confining force, as well as spin-dependent force distributions with local forces larger than the QCD string tension. These distributions offer a new, complimentary picture of the Sivers asymmetry in transversely polarised deep-inelastic scattering.

Tests of fundamental symmetries / 187

Lattice techniques to investigate the strong CP problem: lessons from a toy model

Authors: David Albandea[1]; Guilherme Catumba[2]; Alberto Ramos[3]

[1] *IFIC - University of Valencia*

[2] *IFIC*

[3] *CERN*

Corresponding Authors: alberto.ramos@cern.ch, david.albandea@uv.es, gtelo@ific.uv.es

Recent studies have claimed that the strong CP problem does not occur in QCD, proposing a new order of limits in volume and topological sectors when studying observables on the lattice. In this talk I will study the effect of the topological -term on a simple quantum mechanical rotor that allows a lattice description. I will particularly focus on recent proposals to face the challenging problems that this study poses in lattice QCD and that are also present in the quantum rotor, such as topology freezing and the sign problem.

QCD at non-zero density / 215

Pion condensation at non-zero isospin chemical potential with Wilson fermions

Authors: Rocco Francesco Basta[1]; Bastian Brandt[2]; Francesca Cuteri[3]; Gergely Endrodi[4]; Owe Philipsen[5]

[1] *Goethe University Frankfurt*

[2] *University of Bielefeld*

[3] *Goethe University - Frankfurt*

[4] *Bielefeld University*

[5] *Goethe-University Frankfurt am Main*

Corresponding Authors: philipsen@itp.uni-frankfurt.de, brandt@physik.uni-bielefeld.de, cuteri@th.physik.uni-frankfurt.de, endrodi@physik.uni-bielefeld.de, basta@itp.uni-frankfurt.de

In contrast to the case of non-zero baryon chemical potential, the isospin chemical potential does not introduce a sign problem and can be simulated on the lattice. When the isospin chemical potential is large enough, a phase transition to a Bose-Einstein condensate of pions takes place. Currently available results in the literature on the phase diagram and the equation of state in this setup employ staggered fermions. We present preliminary results on the onset of the pion condensation phase in simulations with Wilson fermions.

Algorithms and artificial intelligence / 239

Improving HISQ quark solves using deflation

Authors: Leon Hostetler[1]; Kate Clark[2]; Carleton DeTar[3]; Steven Gottlieb[1]; Evan Weinberg[2]

[1] *Indiana University*

[2] *NVIDIA*

[3] *University of Utah*

Corresponding Authors: detar@physics.utah.edu, sg@indiana.edu, leonhost@iu.edu

Typically, the conjugate gradient (CG) algorithm employs mixed precision and even-odd preconditioning to compute propagators for highly improved staggered quarks (HISQ). This approach suffers from critical slowing down as the light quark mass is decreased to its physical value. Multigrid is one alternative to combat critical slowing down, however, it involves setup costs which are not always easy to amortize. We consider deflation, which can also remove critical slowing down, but incurs its own setup cost to compute eigenvectors. Results using the MILC and QUDA software libraries

to generate eigenvectors and to perform deflated solves on lattices up to $144^3 \times 288$ (with lattice spacing 0.042 fm) and with a range of quark masses from the physical strange down to the physical light quark values will be presented. We compare with CG and comment on deflation versus multigrid.

Hadronic and nuclear spectrum and interactions / 201

Precise decay rate for $\eta_b \to \gamma\gamma$ with Highly Improved Staggered Quarks

Authors: Brian Colquhoun[1]; Christine Davies[1]; G. Peter Lepage[None]

[1] *University of Glasgow*

Corresponding Authors: christine.davies@glasgow.ac.uk, brian.colquhoun@glasgow.ac.uk

We calculate the decay rate for the η_b meson to two photons for the first time in lattice QCD, building on our previous accurate calculation of the rate for $\eta_c \to \gamma\gamma$. Using the Highly Improved Staggered Quark formalism for valence and sea quarks, we work at lattice spacings from 0.12 fm down to 0.03 fm. Gluon configurations with the effect of u, d, s and c quarks in the sea were provided by the MILC Collaboration. Extracting a form factor, $F(0, 0)$, for two on-shell photons over a range of heavy quark masses m_h between that of the b and c quarks, we can accurately determine the value of the ratio $f_{\eta_h}/(F_{\eta_h}(0, 0)M^2_{\eta_h})$, with f_{η_h} and M_{η_h} the pseudoscalar meson decay constant and mass. This can be compared to the approximate value of 0.5 from leading order nonrelativistic QCD. We determine the decay rate $\Gamma(\eta_b \to \gamma\gamma)$ at the b quark mass, providing a precise prediction for searches by the Belle II Collaboration.

Hadronic and nuclear spectrum and interactions / 143

$X(3872)$ relevant $D\bar{D}^*$ scattering in $N_f = 2$ lattice QCD

Authors: Chunjiang Shi[1]; Ying Chen[2]; Haozheng Li[3]

[1] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China*

[2] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China}*

[3] *School of Physics and Technology, Wuhan University, Wuhan 430072, People's Republic of China*

Corresponding Authors: cheny@ihep.ac.cn, shichunjiang@ihep.ac.cn

We study the S-wave $D\bar{D}^*(I = 0)$ scattering at four different pion masses m_π ranging from 250 MeV to 417 MeV from $N_f = 2$ lattice QCD. There exists a state below $D\bar{D}^*$ threshold, which can be related to $X(3872)$ and can be either a bound state or a virtual state up to the analysis strategies applied. This observation is likely unaffected by the possible left-hand cut effect of the one pion exchange interaction. On the other hand, different analysis procedures of the finite volume energies give the same hint at the existence of a 1^{++} resonance below 4.0 GeV.

Quark and lepton flavour physics / 471

Checks on QED and strong-isospin breaking corrections to the HVP contribution in the standard model prediction of the muon g-2

Author: Andreas Risch[1]

[1] *Bergische Universität Wuppertal*

Corresponding Author: andreas.risch@uni-wuppertal.de

At the current levels of precision reached in the measurement of the muon g-2 by Fermilab, it is essential to control QED and strong-isospin breaking corrections to the HVP contribution to the muon g-2. Here we present a number of cross-checks performed on the results for those corrections presented in the BMW's collaboration 2020 computation.

Tests of fundamental symmetries / 478

Subtleties and systematics in obtaining a sub-percent determination of gA

Author: Andre Walker-Loud[1]

[1] *LBNL*

Corresponding Author: walkloud@lbl.gov

The nucleon axial charge has evolved from being a critical benchmark quantity to one that can be used to provide a competitive constraint on BSM right handed currents. In order to achieve this goal, we must be able to determine g_A with sub-percent precision which presents us with several systematic uncertainties that must be addressed. The most glaring issue is the need to provide a non-perturbative determination of the radiative QED corrections to g_A, which may be as large as a few percent. Assuming these QED corrections can be isolated, we must confront non-monotonic finite volume corrections which are evident in current results. I will discuss these two challenges.

QCD at non-zero density / 75

Condensation of lighter-than-physical pions in QCD

Authors: Bastian Brandt[1]; Francesca Cuteri[2]; Gergely Endrodi[1]; Volodymyr Chelnokov[3]

[1] *Bielefeld University*

[2] *Goethe University - Frankfurt*

[3] *Goethe University Frankfurt*

Corresponding Authors: endrodi@physik.uni-bielefeld.de, brandt@physik.uni-bielefeld.de, cuteri@th.physik.uni-frankfurt.de, chelnokov@itp.uni-frankfurt.de

We report on the results of the 2+1 flavour QCD simulations at nonzero isospin chemical potential performed at half the physical light quark mass. At low temperatures and large isospin chemical potential Bose-Einstein Condensation (BEC) occurs, creating a pion condensed phase, separated from the hadronic and quark-gluon plasma phases by the BEC transition line. We show that for lighter than physical pions the hadronic/pion condensed section of the BEC line remains vertical, and goes to zero chemical potential linearly with the pion mass, giving a prediction of the phase diagram in the chiral limit.

Standard Model parameters / 79

RG running from step-scaling matrices in χSF schemes for ΔF = 2 Four-Fermion Operators

Authors: Isabel Campos Plasencia[1]; Mattia Dalla Brida[2]; Giulia Maria de Divitiis[3]; Andrew Lytle[4]; Riccardo Marinelli[5]; Mauro Lucio Papinutto[6]; Anastassios Vladikas[7]

[1] *InstitutodeFísica de Cantabria, Santander*

[2] *DESY - Zeuthen*

[3] *Università di Roma "Tor Vergata"*

[4] *University of Glasgow*

[5] *"Sapienza" University of Rome*

[6] *Sapienza Università di Roma*

[7] *INFN, Roma "Tor Vergata"*

Corresponding Authors: isabel.campos@csic.es, mattia.dalla.brida@cern.ch, tassos.vladikas@roma2.infn.it, riccardo.marinelli@uniroma1.it, giulia.dedivitiis@roma2.infn.it, andrew.lytle@glasgow.ac.uk, mauro.papinutto@uniroma1.it

We present preliminary results for the Renormalization Group (RG) running of the complete basis of $\Delta F = 2$ four-fermion operators in QCD with $N_{\rm f} = 3$ dynamical massless flavors. We use $O(a)$-improved Wilson fermions in a mixed action setup, with chirally rotated Schrödinger functional (χSF) boundary conditions for the valence quarks and Schrödinger functional (SF) boundary conditions for the sea quarks. New results are shown for several renormalised couplings, spanning a range of low energy scales Λ_{QCD}
$lesssim \mu$
$lesssim 2$GeV. They complement the results presented in ref.1 for high energy scales 2GeV
$lesssim \mu$
$lesssim 100$ GeV; for this range results at a new value of the gauge coupling have also been added.

Theoretical developments / 196

Scattering Amplitudes from Euclidean Correlators

Authors: Agostino Patella[1]; Nazario Tantalo[2]

[1] *Humboldt-Universität zu Berlin*

[2] *Rome University Tor Vergata and INFN sez. of Rome Tor Vergata*

Corresponding Authors: nazario.tantalo@gmail.com, agostino.patella@physik.hu-berlin.de

Hadronic scattering amplitudes can be approximated as linear combinations of spatially-smeared Euclidean correlators, sampled at discrete non-coinciding times. The resulting approximation formula holds in infinite-volume continuum QCD, however the approximant has an obvious representation in the discrete finite-volume theory. This observation can be used to design a numerical strategy to obtain scattering amplitudes from Lattice QCD calculations, which is complementary to Lüscher's method in finite volume. Unlike Lüscher's method, the proposed strategy works exactly the same independently of the energy of the process and the number of open channels. In this talk, I will present the approximation formula and discuss how it can be used in practical calculations. I will not dwell on its mathematical proof, which is based on the Haag-Ruelle scattering theory.

Hadronic and nuclear spectrum and interactions / 339

Lattice calculaiton of hadron spectrum including isospin breaking effect

Author: Chenfei Lu[1]

[1] *Peking University*

Corresponding Author: 2201110107@stu.pku.edu.cn

We develope a new method to calculate hadron spectrum including isospin breaking effect on lattice, where we treat ud quark mass spltting and QED effect perturbatively. In this method we define a new value related to a certain hadron mass. This value is irrelevant to quark mass to the first order so that the renormalization of quark mass is no longer needed. We apply this method on a real lattice calculation and give mass splittings of several hadrons.

Hadronic and nuclear spectrum and interactions / 60

Left-hand cut and the HAL QCD method

Authors: Sinya Aoki[1]; Takumi Doi[2]; Yan Lyu[2]

[1] *Yukawa Institute for Theoretical Physics, Kyoto University*

[2] *RIKEN*

Corresponding Authors: doi@ribf.riken.jp, saoki@yukawa.kyoto-u.ac.jp, yan.lyu@riken.jp

In this talk, we discuss an issue related to the left-hand cut in the scattering amplitude, which has been recently pointed out to be relevant for an analysis on the nature of the tetra quark state T_{cc}.
We first discuss a relation between the left-hand cut from the Yukawa potential in non-relativistic quantum field theory and t-channel cut in the S-matrix for a relativistic quantum filed theory.
We then demonstrate how the issue appears in the infinite volume limit from finite volume simulations.
We finally discuss how we treat the left-hand cut in the HAL QCD potential method.

Quark and lepton flavour physics / 184

Study on the P-wave form factors of the B_s to D_s semi-leptonic decays from inclusive lattice simulations

Author: Zhi HU[1]

Co-authors: Ahmed Elgaziari [2]; Alessandro Barone [3]; Andreas Juettner [2]; Ryan Kellermann [1]; Shoji Hashimoto [4]; Takashi Kaneko [4]

[1] *High Energy Accelerator Research Organization (KEK)*

[2] *University of Southampton*

[3] *Johannes Gutenberg University Mainz*

[4] *KEK*

Corresponding Authors: takashi.kaneko@kek.jp, kelry@post.kek.jp, juettner@soton.ac.uk, shoji.hashimoto@kek.jp, abarone@uni-mainz.de, huzhi0826@gmail.com, ae3e22@soton.ac.uk

We present a pilot study on extracting the P-wave form factors of the B_s to D_s semi-leptonic decays from the Bs four-point correlators. With their inclusive nature, four-point correlators include all the exclusive states from Bs with valence content of c and s quarks. We access the P-wave form factors by excluding the contributions from the S-wave final states. In this pilot study, 2+1-flavour domain-wall fermion actions with approximately physical masses are utilized for light quarks. Heavy quarks, c and b, are simulated using relativistic-heavy quark actions. A single lattice ensemble with a lattice spacing of 0.11 fm is used for the analysis.

Structure of hadrons and nuclei / 330

Neutral pion polarizabilities from four-point functions

Author: Frank Lee[1]

Co-authors: Walter Wilcox [2]; Andrei Alexandru [1]; Chris Culver [3]; Shayan Nadeem [2]

[1] *George Washington University*

[2] *Baylor University*

[3] *University of Liverpool*

Corresponding Authors: fxlee@gwu.edu, c.culver@liverpool.ac.uk, aalexan@gwu.edu, shayan_nadeem1@baylor.edu, walter_wilcox@baylor.edu

We report a lattice QCD simulation of electric and magnetic polarizabilities of π^0 using the four-point function method. The connected diagrams are evaluated on the $24^3 \times 48$ lattice using Wilson action with a=0.1 fm and pion mass from 1100 to 370 MeV. Results are compared with existing calculations from the background field method.

Algorithms and artificial intelligence / 393

Studies of Gauge-fixed Fourier acceleration for SU(3) gauge theory

Authors: Yikai Huo[1]; Norman Christ[1]; Rana Urek[1]

[1] *Columbia University*

Corresponding Authors: yh3285@columbia.edu, ru2149@columbia.edu, nhc@phys.columbia.edu

We report results from the application of Fourier acceleration to $SU(3)$ lattice gauge theory using softly-fixed Landau gauge. Acceleration of the HMC algorithm is studied on a 16^4 lattice volume with the Wilson gauge action and different values of β. Two types of boundary conditions with fixed boundary links are explored. The boundary links are fixed either to unit matrices or to the matrices present on the boundaries of an initial gauge configuration equilibrated with periodic boundary conditions, anticipating a possible application in which a large lattice is continually divided into subvolumes that are evolved independently.

Standard Model parameters / 295

RIMOM renormalization using domain wall and staggered fermions

Authors: Mengchu Cai[1]; Yi-Boo Yang[None]

[1] *Institute of Theoretical Physics, Chinese Academy of Sciences*

Corresponding Authors: ybyang@itp.ac.cn, caimengchu@pku.edu.cn

We present the scalar, pseudoscalar, vector and axial-vector renormalization constants with the regularization independent momentum subtraction (RI/MOM) scheme as the intermediate scheme using domain wall fermion on 2+1 flavors ensembles from RBC/UKQCD collaboration and highly improved staggered quark on 2+1+1 flavors ensembles from MILC. A two-step matching method is used to reduce the systematic uncertainties. After converting the renormalization constants in the RI/MOM scheme to the $\overline{\mathrm{MS}}$ scheme perturbatively and applying the relation that the mass renormalization

constant is the reciprocal of the scalar composite operator renormalization constant for the chiral fermion, one can determine the physical light and strange quark masses of those actions as a verification of the previous results obtained through the symmetric momentum subtraction (SMOM) scheme.

Theoretical developments / 273

Numerical simulation of fractional topological charge in SU(N) gauge theory coupled with $\mathbb{Z}_N$ 2-form gauge fields

Author: Motokazu Abe[1]

Co-author: Okuto Morikawa [2]

[1] *Kyushu University*

[2] *RIKEN*

Corresponding Authors: abe.motokazu@phys.kyushu-u.ac.jp, okuto.morikawa@riken.jp

In recent years, the low-energy physics of gauge theories has been explored through the concept of generalized symmetries, which extends the notion of the traditional symmetry. In this talk, by using a lattice QCD code set, LatticeQCD.jl, we carry out numerical simulations of lattice $SU(N)$ gauge theory coupled with $\mathbb{Z}_N$ 2-form gauge fields. Such couplings provide a completely local description of the 't Hooft twisted boundary condition. We explicitly demonstrate the fractional topological charge, a key element in observing anomaly of generalized symmetry.

Hadronic and nuclear spectrum and interactions / 318

Error Scaling of Sea Quark Isospin-Breaking Effects

Author: Alessandro Cotellucci[1]

[1] *Humboldt-Universität zu Berlin*

Corresponding Author: alessandro.cotellucci@physik.hu-berlin.de

Sea-quark isospin-breaking effects (IBE) are difficult to compute since they require the evaluation of all-to-all propagators. However, the quest for high-precision calculations motivates a detailed study of these contributions. There are theoretical arguments that the stochastic error associated with these quantities should diverge in the continuum and infinite-volume limit, resulting in a possible bottleneck for the method. In this talk, we present the study of the error scaling for these quantities using $N_f = 3$ O(a) improved Wilson fermions QCD with C-periodic boundary conditions in space, a pion mass $M_\pi \approx 415$ MeV, a range of lattice spacings $a \approx 0.05,\ 0.075,\ 0.1$ fm, and spacial extensions $L \approx 1.6,\ 2.4,\ 3.2$ fm. This work is part of the program of the RC* collaboration. The analysis of the error as a function of the number of stochastic sources shows that we reach the gauge error for the dominant contributions. The errors do not show the leading order divergence $1/a$ for strong-IBE and $1/a^2$ for electromagnetic IBE, in the considered range of lattice spacings. On the other hand, our error data are consistent with the predicted leading divergence $\sqrt{V}$.

Hadronic and nuclear spectrum and interactions / 484

The Lüscher scattering formalism on the left-hand cut: an update

Authors: Andre Raposo[1]; Maxwell Hansen[1]; Raul Briceno[2]

[1] *University of Edinburgh*

[2] *Thomas Jefferson National Accelerator Facillity*

Corresponding Authors: a.baiao-raposo@sms.ed.ac.uk, maxwell.hansen@ed.ac.uk, rbriceno@jlab.org

The Lüscher scattering formalism is a popular method which allows the extraction of two-to-two scattering amplitudes from the finite-volume spectrum. Recent lattice calculations have highlighted the limitations of the formalism in systems in which a lighter particle can be exchanged between the two scatterers (e.g. NN or DD^* scattering). This leads to the presence of a left-hand cut just below the two-particle threshold in the partial-wave-projected amplitudes, on which the sub-threshold analytic continuation of the standard method breaks down. In this talk, we review our proposed extension of the formalism to the left-hand cut and give an update on formal developments, including the extension to non-identical scatterers (applicable to DD^* and similar processes) and some limiting cases. We present also some developments in solving the integral equations used to retrieve scattering amplitudes from intermediary K-matrices, making contact with the three-particle RFT formalism.

Quark and lepton flavour physics / 475

Spectator effects in inclusive lifetimes of heavy hadrons

Authors: Joshua Lin[1]; Stefan Meinel[2]; William Detmold[1]

[1] *MIT*

[2] *University of Arizona / RIKEN BNL Research Center*

Corresponding Authors: smeinel@email.arizona.edu, wdetmold@mit.edu, joshlin@mit.edu

A dominant source of uncertainty in theoretical determinations of ratios of inclusive lifetimes of heavy hadrons are 'Spectator effects', wherein the light degrees of freedom participate in the decay process. The heavy-quark expansion describes these effects as matrix elements of four-quark HQET operators in the heavy-hadron states of interest. Using a recently developed position-space scheme to nonperturbatively renormalize these operators in lattice HQET, we present updates on the spectator-effect matrix elements.

Structure of hadrons and nuclei / 50

Charged kaon electric polarizability from lattice four-point functions

Authors: Frank Lee[1]; Shayan Nadeem[2]; Walter Wilcox[2]

[1] *George Washington University*

[2] *Baylor University*

Corresponding Authors: fxlee@gwu.edu, shayan_nadeem1@baylor.edu, walter_wilcox@baylor.edu

We study the electric polarizability of a charged kaon from four-point functions in lattice QCD as an alternative to the background field method. Lattice four-point correlation functions are constructed from quark and gluon fields to be used in Monte Carlo simulations. The elastic form factor (charge radius) is needed in the method which can be obtained from the same four-point functions at large current separations. Preliminary results from the connected quark-line diagrams will be presented.

Algorithms and artificial intelligence / 375

Chiral rank-k truncations for the multigrid preconditioner of Wilson fermions

Author: Travis Whyte[1]

Co-authors: Andreas Stathopoulos [2]; Eloy Romero Alcalde [3]

[1] *Trinity College Dublin*

[2] *William & Mary*

[3] *Jefferson Lab*

Corresponding Authors: andreas@cs.wm.edu, whytetr@tcd.ie, eromero@jlab.org

A modification to the setup algorithm for the multigrid preconditioner of Wilson fermions is presented. A larger basis of test vectors than used in conventional multigrid is calculated by the smoother and is truncated by a singular value decomposition on the chiral components of the test vectors. The truncated basis is used to form the prolongation and restriction matrices of the multigrid hierarchy. The efficacy of the approach is demonstrated on an anisotropic lattice with $m_\pi \approx$ 280 MeV and an isotropic lattice with $m_\pi \approx 220$ MeV. The scaling of the method with lattice volume is also examined.

Standard Model parameters / 432

Strong coupling constant in (2+1+1)-flavor QCD

Author: Viljami Leino[1]

Co-authors: Alexei Bazavov [2]; Nora Brambilla [3]; Andreas Kronfeld [4]; Julian Mayer-Steudte [5]; Peter Petreczky [6]; Sebastian Steinbeißer [3]; Antonio Vairo [3]; Johannes Heinrich Weber [7]

[1] *Johannes Gutenberg University Mainz*

[2] *Michigan State University*

[3] *Technical University München*

[4] *Fermilab*

[5] *Technical University of Munich (TUM)*

[6] *BNL*

[7] *Technische Universität München*

Corresponding Authors: julian.mayer-steudte@tum.de, petreczk@bnl.gov, viljami.leino@uni-mainz.de, ask@fnal.gov, nora.brambilla@ph.tum.de, bazavov@msu.edu, johannes.weber@tum.de

The strong coupling constant α_s can be obtained from the static energy as shown in previous lattices studies. For short distances, the static energy can be calculated both on the lattice with the use of Wilson line correlators, and with the perturbation theory up to three loop accuracy with leading ultrasoft log resummation. Comparing the perturbative expression and lattice data allows for precise measurement of α_s. We will present preliminary results for the determination of α_s in (2+1+1)-flavor QCD using the configurations made available by the MILC-collaboration with smallest lattice spacing reaching 0.0321fm.

Theoretical developments / 428

U(1)-gauged 2-flavor spin system in 3-D

Authors: Christof Gattringer[1]; Tin Sulejmanpasic[None]

[1] *Austrian Science Fund FWF*

Corresponding Author: christof.gattringer@fwf.ac.at

We study a U(1)-gauged 2-flavor spin system in 3 dimensions. For the gauge fields we use the Villain formulation with a constraint that removes lattice monopoles and in this form couple the gauge fields to 2-component spins. We discuss the simulation strategies for this highly constraint system and present first results for the phase structure.

Hadronic and nuclear spectrum and interactions / 332

Update on the isospin breaking corrections to the HVP with C-periodic boundary conditions

Author: Letizia Parato[1]

[1] *ETH Zürich*

Corresponding Author: lparato@phys.ethz.ch

In the RC* collaboration, we simulate lattice QCD+QED using C-periodic spatial boundary conditions to ensure locality, gauge invariance, and translational invariance are preserved throughout the calculation. In this talk, we present progress in computing isospin-breaking (IB) corrections to the leading hadronic contribution to $(g-2)$. We compare two ways of computing the IB corrections: the RM123 method on a QCD ensemble and dynamical QCD+QED simulations, both with C-periodic boundary conditions. Both calculations are performed at $\beta = 3.24$ with four flavours of O(a)-improved Wilson fermions; the QCD ensemble features SU(3)-symmetric sea quarks plus charm, while down and strange quarks are degenerate in QCD+QED gauge ensembles. We discuss the limitations and merits of the two approaches.

Hadronic and nuclear spectrum and interactions / 81

The finite-volume spectrum in the presence of a long-range force

Author: Akaki Rusetsky[1]

Co-authors: Fabian Müller [2]; Hans-Werner Hammer [3]; Jia-Jun Wu [4]; Jin-Yi Pang [5]; Rishabh Bubna [2]

[1] *HISKP, University of Bonn and Tbilisi State University*

[2] *HISKP, University of Bonn*

[3] *TU Darmstadt and EMMI and HFHF*

[4] *University of Chinese Academy of Sciences, Beijing*

[5] *University of Shanghai for Science and Technology*

Corresponding Authors: rusetsky@hiskp.uni-bonn.de, f.mueller@hiskp.uni-bonn.de, bubna@hiskp.uni-bonn.de, jypang@usst.edu.cn, hans-werner.hammer@physik.tu-darmstadt.de, wujiajun@ucas.ac.cn

Long-range forces are present in different systems which are studied on the lattice. For example, the role of the long-range force is very prominent in extracting the properties of the $T_{cc}^+(3875)$-meson from lattice data. Furthermore, the one-pion exchange provides a very significant contribution to the nucleon-nucleon scattering. In the presence of such a long-range interaction, the interpretation of the finite-volume spectrum becomes more difficult, due to a strong partial-wave mixing. In addition,

the so-called left-hand cut moves very close to the physical threshold, and the finite-volume energy levels that lie below the upper rim of the left-hand cut cannot be analyzed with the use of the standard Lüscher formula which contains real scattering phases.

We suggest a solution of the problem, based on the finite-volume generalization of the well-known Modified Effective Range Expansion (MERE) approach. Within this approach, the long- and short-range parts of the interaction potential are split. An exact solution is found for the long-range part, whose explicit form is known. It is then only the short-range part of the infinite-volume amplitude that is extracted on the lattice, and it is analytic in a much larger domain of the complex plane in the vicinity of the physical threshold than the full amplitude. The problems related to the left-hand cut and the partial-wave mixing do not emerge in this approach anymore. Last but not least, the implementation of the present method is not very different from the original Lüscher framework and can be carried out with a comparable effort.

In conclusion, I briefly review alternative approaches to the problem at hand which are available in the literature, and carry out a detailed comparison to the framework suggested in the present work.

Quark and lepton flavour physics / 222

Systematic effects in the lattice calculation of inclusive semileptonic decays

Author: Ryan Kellermann[1]

Co-authors: Ahmed Elgaziari [2]; Alessandro Barone [3]; Andreas Juettner [2]; Shoji Hashimoto [4]; Takashi Kaneko [4]; Zhi HU [1]

[1] *High Energy Accelerator Research Organization (KEK)*

[2] *University of Southampton*

[3] *Johannes Gutenberg University Mainz*

[4] *KEK*

Corresponding Authors: takashi.kaneko@kek.jp, juettner@soton.ac.uk, shoji.hashimoto@kek.jp, kelry@post.kek.jp, abarone@uni-mainz.de, ae3e22@soton.ac.uk, huzhi0826@gmail.com

We report on the nonperturbative calculation of the inclusive decay rate for semileptonic decays of the D_s meson from lattice QCD. In this talk we address systematic effects associated with the analysis. Namely, we focus on the systematic errors introduced by the finite polynomial order in the Chebyshev approximation used in the analysis and the error due to finite-volume effects. The former is estimated by a combination of the required limits and employing properties of the Chebyshev polynomials, while the latter is estimated by formulating a model under the assumption of two-body final states which is combined with the lattice data to extrapolate the infinite volume limit.

Structure of hadrons and nuclei / 40

Applications of nucleon four-point correlation functions

Authors: Xu Feng[1]; Yang Fu[2]; Lu-Chang Jin[None]; Cheng-Fei Lu[1]; Peng-Xiang Ma[1]; Xuan-He Wang[1]; Zhaolong Zhang[1]

[1] *Peking University*

[2] *MIT*

Corresponding Authors: 2301110116@pku.edu.cn, yangfu@mit.edu, 2001110084@pku.edu.cn, xu.feng@pku.edu.cn

I will discuss the recent progress in lattice QCD calculations of nucleon four-point correlation functions, with a focus on nucleon electromagnetic polarizability.

Algorithms and artificial intelligence / 328

Digitised Hamiltonian SU(2) Gauge Theories at Weak Couplings

Authors: Carsten Urbach[1]; Johann Ostmeyer[2]; Karl Jansen[3]; Marco Garofalo[1]; Simone Romiti[4]; Timo Jakobs[5]; Tobias Hartung[6]

[1] *University of Bonn*

[2] *Bonn University*

[3] *DESY*

[4] *University of Bern*

[5] *University Bonn*

[6] *King's College London*

Corresponding Authors: timojakobs99@gmail.com, simone.romiti.1994@gmail.com, urbach@hiskp.uni-bonn.de, karl.jansen@desy.de, tobias.hartung@kcl.ac.uk, ostmeyer@hiskp.uni-bonn.de, marcogarofalo31@gmail.com

Hamiltonian Simulations of non-abelian lattice gauge theories promise new insights into multiple areas of QCD. To run numerical simulations, the operators contained in the Kogut Susskind Hamiltonian need to be discretised. While this is a mostly solved problem at strong couplings, simulations in the weak coupling limit remain tricky. In this talk, we report on our ongoing efforts to find a discretization scheme suitable for simulations at weak couplings.

Plenary / 412

Ken Wilson Award

Plenary / 496

Real time simulations on the lattice: quantum, classical, and in between

Author: Anders Tranberg[1]

[1] *University of Stavanger, Norway*

Corresponding Author: anders.tranberg@uis.no

The real time dynamics of quantum (field) systems is well suited for lattice implementation, although standard Monte-Carlo methods must be adapted, supplemented or even replaced by other approaches. I will attempt to give an overview of some of these, focussing on how they relate to each other and when each of them may be expected to give reliable results. Relevant keywords include

Classical Statistical, 2PI/Schwinger-Dyson, Complex Langevin and Lefschetz Thimbles. The talk is meant to be a pedagogical introduction rather than a complete review.

Plenary / 413

50 years of lattice QCD

Corresponding Authors: jbkogut@umd.edu, jansmit0000@chello.nl

John Kogut: How was Lattice Gauge Theory born? What was it like in the "early days" of ~1975? How did High Energy Physics and Condensed Matter Theory get together? What were the BIG physics problems and technical challenges of the day? This short talk looks at these topics from one person's recollections and perspective.

Jan Smit: Recalling early years of Lattice Gauge Theory

Plenary / 269

Selected topics on the QCD phase diagram at finite temperature and density

Author: Christian Schmidt[1]

[1] *Universitaet Bielefeld*

Corresponding Author: schmidt@physik.uni-bielefeld.de

I will give an overview on recent results on the QCD phase diagram at finite temperature and density.

Plenary / 416

Panel discussion on open data and reproducibility

Corresponding Authors: urbach@hiskp.uni-bonn.de, anna@eotvos.colorado.edu, a.athenodorou@cyi.ac.cy, e.j.bennett@swansea.ac.uk

Algorithms and artificial intelligence / 323

Unfreezing topology with nested sampling

Authors: Gurtej Kanwar[1]; Simone Romiti[1]; Urs Wenger[1]

[1] *University of Bern*

Corresponding Authors: simone.romiti.1994@gmail.com, wenger@itp.unibe.ch, gurtejkanwar@gmail.com

We consider nested sampling as a generic integration technique over the space of lattice configurations and discuss its application to compute the density of states and the free energy. We show the benefits of this alternative sampling method for systems which suffer from ergodicity problems due to non-efficient tunneling, e.g. topological freezing. As a proof of principle, we apply nested sampling in the 2D U(1) gauge theory.

Theoretical developments / 102

Novel Lattice Formulation of 2D Chiral Gauge Theory via Bosonization

Author: Soma Onoda[1]

Co-authors: Hiroshi Suzuki [1]; Okuto Morikawa [2]

[1] *Kyushu University*

[2] *RIKEN*

Corresponding Authors: okuto.morikawa@riken.jp, hsuzuki@phys.kyushu-u.ac.jp, onoda.soma@phys.kyushu-u.ac.jp

Recently, lattice formulations of Abelian chiral gauge theory in two dimensions have been devised on the basis of the Abelian bosonization. A salient feature of these 2D lattice formulations is that the gauge invariance is exactly preserved for anomaly free theories and thus is completely free from the question of the gauge mode decoupling. In the present paper, we propose a yet another lattice formulation sharing this desired property. A particularly unique point in our formulation is that the vertex operator of the dual scalar field, which carries the vector charge of the fermion and the "magnetic charge"in the bosonization, is represented by a "hole"excised from the lattice; this is the excision method formulated recently by Abe et al. in a somewhat different context.

Quark and lepton flavour physics / 85

Update of kaon semileptonic form factor using $N_f = 2{+}1$ PACS10 configurations

Author: Takeshi Yamazaki[1]

Co-authors: Ken-Ichi Ishikawa [2]; Naruhito Ishizuka [3]; Yoshinobu Kuramashi [4]; Yusuke Namekawa [2]; Yusuke Taniguchi [3]; Naoya Ukita [3]

[1] *Univ. of Tsukuba*

[2] *Hiroshima University*

[3] *University of Tsukuba*

[4] *University of Tsukuba/RIKEN AICS*

Corresponding Authors: tanigchi@het.ph.tsukuba.ac.jp, kuramasi@het.ph.tsukuba.ac.jp, yamazaki@het.ph.tsukuba.ac.jp, ishikawa@theo.phys.sci.hiroshima-u.ac.jp, namekawa@hiroshima-u.ac.jp

We calculate the form factors for the kaon semileptonic decay process using the PACS10 configurations, whose physical volume is more than $(10\text{ fm})^4$ at very close to the physical point. The configurations were generated with the Iwasaki gauge action and $N_f = 2 + 1$ stout-smeared nonperturbatively $O(a)$ improved Wilson quark action at the three lattice spacings, 0.085, 0.063, and 0.042 fm. We present updated results for the form factors, and discuss their continuum extrapolations, momentum transfer interpolation, and short chiral extrapolation to tune the simulated pion and kaon masses to the physical ones. The value of $|V_{us}|$ is determined using our result. It is compared with those using the previous

calculations and also those determined through the kaon leptonic decay process.

Hadronic and nuclear spectrum and interactions / 22

Exploring Single-Flavor Dibaryons: A lattice perspective

Authors: Navdeep Singh Dhindsa[1]; M. Padmanath[1]; Nilmani Mathur[2]

[1] *The Institute of Mathematical Sciences, Chennai*

[2] *Tata Institute of Fundamental Research, Mumbai*

Corresponding Authors: nilmani@theory.tifr.res.in, padmanath@imsc.res.in, navdeep.s.dhindsa@gmail.com

We present a lattice calculation of dibaryons composed of single-flavor quarks, specifically focusing on baryons made up of either charm or strange quarks. We utilize various set of lattice QCD ensembles with $N_f = 2 + 1 + 1$ dynamical HISQ fields, two spatial volumes, and three different lattice spacings generated by MILC collaboration. By using an overlap action for the valence charm and strange quark propagators, we calculate the ground state energies of dibaryons consisting of either two Ω_{ccc} or two Ω_{sss} baryons, in both the $S = 0$ and $S = 2$ channels. By analyzing the energy difference between the ground state of the dibaryon and the respective non-interacting baryons, we provide insights into the interactions involved in different spin channels.

Structure of hadrons and nuclei / 26

Axialvector diquark Mass and quark-diquark potential in Sigma_c

Author: Soya Nishioka[1]

Co-author: Noriyoshi Ishii [2]

[1] *RCNP, Osaka Univ*

[2] *Research Center for Nuclear Physics (RCNP), Osaka University*

Corresponding Authors: ishiin@rcnp.osaka-u.ac.jp, nishioka@rcnp.osaka-u.ac.jp

We will present a lattice QCD study of the axialvector diquark. We note that obtaining the diquark mass from the bound-state pole of the two-point correlator is not straightforward due to color confinement. To circumvent this issue, we regard the diquark mass as a parameter in the quark-diquark model, constructed using the potential method developed by the HAL QCD Collaboration. For the axialvector diquark study, we focus on the Sigma_c system, which is treated as a bound state of a charm quark and an axialvector diquark.

Using 2+1 flavor QCD gauge configurations on a 32^3 x 64 lattice, generated by the PACS-CS Collaboration (with m_pi approximately 700 MeV), we calculate a four-point correlator of the axialvector diquark and charm quark. From this, we extract the equal-time Nambu-Bethe-Salpeter (NBS) wave function in the large t region. The HAL QCD potential method is then used to determine the quark-diquark potential between the charm quark and the axialvector diquark. We find a spin-independent central potential of the Cornell type and a spin-dependent potential resembling a smeared delta function.

To determine the diquark mass, we apply an additional condition similar to the one proposed by Kawanai and Sasaki for studying the ccbar system, which requires the spin-dependent potential to vanish at long distances. As a result, we obtain a diquark mass that tends to be small. This appears to be due to (1) poor statistics of the spin-dependent potential at long distances and (2) uncertainty in determining the charm quark mass.

Vacuum structure and confinement / 284

Observations on spontaneous chiral symmetry breaking and mass gap of QCD in finite volume

Author: Xiaolan Meng[1]

[1] *Institute of Theoretical Physics, Chinese Academy of Sciences*

Corresponding Author: mengxiaolan@itp.ac.cn

We present the lattice QCD simulation with the 2+1+1 flavor full QCD ensembles using near-physical quark masses and different spatial sizes L, at $a \sim 0.055$ fm. The results show that the scalar and pesudoscalar 2-point correlator with the valence pion mass of approximately 230 MeV become degenerated at $L \leq 1.0$ fm, and such an observation suggests that the spontaneous chiral symmetry breaking disappears effectively there. At the same time, the mass gap between the nucleon and pion masses remains larger then $\Lambda_{\rm QCD}$ at the entire $L \in [0.2, 0.7]$ fm range.

QCD at non-zero density / 260

Quark number susceptibility and conserved charge fluctuation for (2+1)-flavor QCD with Möbius domain wall fermions

Author: Jishnu Goswami[1]

Co-authors: Hidenori Fukaya [2]; Issaku Kanamori [3]; Shoji Hashimoto [4]; Takashi Kaneko [5]; Yasumichi Aoki [3]; Yoshifumi Nakamura [3]; Yu Zhang [6]

[1] *RIKEN Center for Computational Science*

[2] *Osaka University*

[3] *Riken - R-CCS*

[4] *KEK - Sokendai*

[5] *KEK*

[6] *Bielefeld University*

Corresponding Authors: jishnu.goswami@riken.jp, yzhang@physik.uni-bielefeld.de

We explore the phase diagram of (2+1)-flavour QCD through the fluctuations of conserved charges calculated with Möbius domain-wall Fermions (MDWF). We present quark number susceptibilities and conserved charge fluctuations at pion masses around 220 MeV and 135 MeV for aspect ratios of lattices LT=2 and LT=3, respectively. Results are compared with the previous works by the previous works by HotQCD and Wuppertal-Budapest collaborations obtained with the staggered quarks.

Particle physics beyond the Standard Model / 47

Progress on the spectroscopy study of the composite Higgs model with Sp(4) gauge theory and multiple fermion representations

Authors: Biagio Lucini[1]; C.-J David Lin[2]; Davide Vadacchino[3]; Deog Ki Hong[4]; Ed Bennett[1]; Fabian Zierler[1]; Ho Hsiao[2]; Jong-Wan Lee[5]; Maurizio Piai[1]; Niccolo Forzano[1]

[1] *Swansea University*

[2] *National Yang Ming Chiao Tung University*

[3] *University of Plymouth*

[4] *Pusan National University*

[5] *Institute for Basic Science (IBS)*

Corresponding Authors: e.j.bennett@swansea.ac.uk, davide.vadacchino@plymouth.ac.uk, dlin@nycu.edu.tw, 2227764@swansea.ac. fabian.zierler@swansea.ac.uk, thepaulxiao.sc09@nycu.edu.tw, j.w.lee@ibs.re.kr, dkhong@pusan.ac.kr, m.piai@swansea.ac.uk, b.lucini@swansea.ac.uk

We report our preliminary results for the mass spectrum of the Sp(4) gauge theory coupled to two Dirac fermions transforming in the fundamental representation and three transforming in the antisymmetric representation, which serves as an ultra-violet completion of the strongly interacting gauge sector in a composite Higgs model. We mainly focus on the mass of the top partners in the context of top partial compositeness—chimera baryons. We employ Wilson fermions in fully dynamical simulations and utilize smearing techniques and the GEVP to extract the masses.

Quark and lepton flavour physics / 371

Split-even approach to the rare kaon decay $K \to \pi\ell^+\ell^-$

Author: Raoul Hodgson[1]

[1] *DESY*

Corresponding Author: raoul.hodgson@desy.de

In recent years the rare kaon decay has been computed directly at the physical point. However, this calculation is currently limited by stochastic noise stemming from a light and charm quark loop GIM subtraction. The split-even approach is an alternative estimator for such loop differences, and has shown a large variance reduction in certain quantities. We present an investigation into the use of the split-even estimator in the calculation of the rare kaon decay.

Algorithms and artificial intelligence / 279

Nested Sampling for U(1) in 2+1 dimensions

Authors: Simone Romiti[1]; Gurtej Kanwar[1]; Urs Wenger[1]

[1] *University of Bern*

Corresponding Authors: gurtejkanwar@gmail.com, wenger@itp.unibe.ch, simone.romiti.1994@gmail.com

We present the application of the Nested Sampling (NS) algorithm to lattice gauge theories. It allows to scan the β dependence of any observable in a custom range of values, avoiding the need to run multiple simulations at different values of the coupling. As a concrete example, we consider the case of a pure gauge U(1) theory in 2+1 dimensions, a toy model for QCD showing confinement at all values of the coupling.

Theoretical developments / 306

Lattice Weyl Fermion on a single spherical domain-wall 1

Author: Shoto Aoki[1]

Co-authors: Hidenori Fukaya [2]; Naoto Kan [3]

[1] *The University of Tokyo*

[2] *Osaka Univ.*

[3] *Osaka University*

Corresponding Authors: naotokan000@gmail.com, shotoaoki@g.ecc.u-tokyo.ac.jp, hfukaya@het.phys.sci.osaka-u.ac.jp

In the standard lattice domain-wall fermion formulation, two flat domain-walls are put where both of the left- and right-handed massless modes appear on the walls. In this work we investigate a single spherical domain-wall fermion mass term embedded into a flat square three-dimensional lattice. In the free fermion case, we find that a single Weyl fermion appears at the wall and it feels gravity through the induced spin connection. With nontrivial link variables we discuss the perturbative anomaly inflow between the bulk and edge fermions.

Hadronic and nuclear spectrum and interactions / 198

Universality of the continuum limit for the H dibaryon

Author: Jeremy Green[1]

Co-authors: Amy Nicholson [2]; Andre Walker-Loud [3]; Andrea Shindler [4]; Andrew Hanlon [5]; Anthony Francis [6]; Colin Morningstar [5]; Fernando Romero-Lopez [7]; Hartmut Wittig [8]; Henry Monge-Camacho [9]; Kate Clark [10]; Parikshit Junnarkar [11]; Pavlos Vranas [12]; Renwick Hudspith [13]; Savvas Zafeiropoulos [14]; Srijit Paul [15]

[1] *DESY*

[2] *University of North Carolina*

[3] *LBNL*

[4] *Michigan State University*

[5] *Carnegie Mellon University*

[6] *National Yang Ming Chiao Tung University*

[7] *MIT / Uni Bern*

[8] *University of Mainz*

[9] *Oak Ridge National Laboratory*

[10] *NVIDIA*

[11] *Technische Universität Darmstadt*

[12] *Lawrence Livermore National Laboratory*

[13] *GSI Darmstadt*

[14] *Aix Marseille University*

[15] *University of Maryland*

Corresponding Authors: fernando.romero-lopez@unibe.ch, walkloud@lbl.gov, afrancis@nycu.edu.tw, hartmut.wittig@uni-mainz.de, cmorning@andrew.cmu.edu, ddhanlon@gmail.com, renwick.james.hudspith@gmail.com, jeremy.green@desy.de, annichol@unc.edu, spaul137@umd.edu

A previous calculation of the binding energy of the H dibaryon in SU(3)-flavour-symmetric lattice QCD showed unexpectedly large discretization effects. To better understand this, we have repeated the calculation using different lattice actions based on $N_f = 3$ ensembles from CLS and OpenLat and newly generated $N_f = 3 + 1$ ensembles with highly improved staggered quarks. Results will be shown for two different unitary setups and at least three different mixed actions. Although we obtain compatible continuum limits, we find that the size of discretization effects varies considerably.

Structure of hadrons and nuclei / 27

Gauge dependence of ccbar potential from Nambu-Bethe-Salpeter wave function in Lattice QCD

Author: Tianchen Zhang[None]

Co-author: Noriyoshi Ishii [1]

[1] *Research Center for Nuclear Physics (RCNP), Osaka University*

Corresponding Authors: ishiin@rcnp.osaka-u.ac.jp, zhangtc@rcnp.osaka-u.ac.jp

We calculate $c\bar{c}$ potential from the equal-time Nambu-Bethe-Salpeter wave function in Lattice QCD to consider its gauge dependence, i.e., we compare the results with Coulomb gauge and Landau gauge. In previous works by Kawanai, Sasaki and Watanabe, Coulomb gauge is employed. However, the renormalizability of Coulomb gauge is controversial so that we desire to change it to some renormalizable gauge such as Landau gauge. To construct the $c\bar{c}$ potential, we need to determine the charm quark mass for which we employ both the original formalism proposed by Kawanai and Sasaki and a modified one proposed by Watanabe. In this talk, we compare the charm quark masses and $c\bar{c}$ potentials obtained in different gauges and different formalisms employing $2+1$ flavor QCD gauge configurations with almost physical pion mass (156 MeV) generated by PACS-CS Collaboration.

Vacuum structure and confinement / 71

The four gluon vertex from lattice QCD

Authors: Manuel Colaço[1]; Orlando Oliveira[2]; Paulo Silva[3]

[1] *Center for Physics, University of Coimbra, Portugal*

[2] *University of Coimbra, Portugal*

[3] *Center for Physics, University of Coimbra*

Corresponding Authors: manuel.sc.colaco@gmail.com, orlando@uc.pt, psilva@uc.pt

The four gluon one-particle irreducible Green function contributes to various quantities with phenomenological relevance. An example where the four gluon plays a role is the determination of the gluon propagator, a basic building block for QCD, using continuum methods. This four leg Green function is poorly known and we are only starting to grasp its non-perturbative structure. Here, we report on the computation of the one-particle irreducible four gluon Green function, in the Landau gauge, with lattice simulations. Besides stating the problems associated with the computation, several form factors that characterise this Green functions are measured.

QCD at non-zero density / 297

Continuum extrapolated high order baryon fluctuations

Authors: Jana N. Guenther[1]; Szabolcs Borsanyi[1]; Zoltan Fodor[2]; Sandor Katz[3]; Paolo Parotto[4]; Attila Pasztor[1]; Dávid Pesznyák[5]; Kalman Szabo[6]; Chik Him Wong[1]

[1] *University of Wuppertal*

[2] *University of Wuppertal, Penn State University, Eotvos University, IAS Jülich, UC San Diego*

[3] *Eotvos University, Budapest*

[4] *Università di Torino*

[5] *Eötvös Loránd University, HUN-REN Wigner Research Centre for Physics*

[6] *Forschungszentrum Juelich*

Corresponding Authors: apasztor@bodri.elte.hu, david.pesznyak@gmail.com, borsanyi@uni-wuppertal.de, cwong@uni-wuppertal.de, katz@bodri.elte.hu, szaboka@general.elte.hu, jguenther@uni-wuppertal.de

Fluctuations play a key role in the study of QCD phases. Lattice QCD is a valuable tool to calculate them, but going to high orders is challenging. Up to the fourth order, continuum results are available since 2015. We present the first continuum results for sixth order baryon fluctuations for temperatures between $T = 130{-}200$ MeV, and eighth order at $T = 145$ MeV in a fixed volume. We show that for $T\ 145T\ 145$ MeV, relevant for criticality search, finite volume effects are under control. Our results are in sharp contrast with well known results in the literature obtained at finite lattice spacing.

Particle physics beyond the Standard Model / 181

Progress in lattice simulations for two Higgs doublet models

Authors: Alberto Ramos[1]; C.-J David Lin[2]; Guilherme Catumba[3]

[1] *CERN*

[2] *National Yang Ming Chiao Tung University*

[3] *IFIC*

Corresponding Authors: dlin@nycu.edu.tw, alberto.ramos@cern.ch, gtelo@ific.uv.es

The custodial Two-Higgs-Doublet-Model with SU(2) gauge fields is studied on the lattice. This model has the same global symmetry structure as the Standard Model but the additional Higgs field enlarges the scalar spectrum and opens the possibility for the occurrence of non-SM spontaneous symmetry breaking. Both the spectrum and the running of the gauge coupling of the custodial 2HDM are studied on a line of constant Standard Model physics with cutoff energy ranging from 300 to 600 GeV. The bounds of the realizable masses for the additional BSM scalar states are found to be well bellow the W boson mass. In fact, for the choice of quartic couplings the estimated lower mass is found to be about $\sim 0.2 m_W$ and independent of the cutoff.

Quark and lepton flavour physics / 186

Two photon contribution to the K->mumu decay amplitude on a $1/a \approx$ 1 GeV lattice

Authors: En-Hung Chao[None]; Ceran Hu[1]

[1] *Columbia University*

Corresponding Authors: en-hung.chao@m4x.org, ceranhu@gmail.com

The decay of a long-lived kaon to a pair of charged muons is a clean rare kaon decay channel which has been measured to the percent-level from experiment. Although the short-distance part of this decay mode is well known from the Standard Model, a direct comparison between theory and experiment is not straightforward due to the sizeable long-distance contribution from the exchange of two virtual photons. We have developed a formalism allowing the latter amplitude to be computed from lattice QCD, within which a final theory estimate at the ten-percent level should be plausible. In this contribution, we present our first preliminary result on a single ensemble at physical pion mass with $1/a \approx 1$ GeV including the connected and the leading disconnected diagrams.

Algorithms and artificial intelligence / 304

Studying the SU(3) confinement transition with nested sampling

Authors: Gurtej Kanwar[1]; Simone Romiti[1]; Urs Wenger[1]

[1] *University of Bern*

Corresponding Authors: wenger@itp.unibe.ch, gurtejkanwar@gmail.com, simone.romiti.1994@gmail.com

Nested Sampling (NS) gives access to observables across a range of couplings and temperatures from one Monte Carlo simulation. This talk demonstrates an application of NS to the first-order confinement transition in 3+1D SU(3) gauge theory, highlighting practicalities of the implementation, such as how NS handles the suppressed tunneling between coexisting phases at the phase transition.

Theoretical developments / 255

Lattice Weyl Fermion on a single spherical domain-wall 2

Author: Naoto Kan[1]

Co-authors: Hidenori Fukaya [2]; Shoto Aoki [3]

[1] *Osaka University*

[2] *Osaka Univ.*

[3] *The University of Tokyo*

Corresponding Authors: shotoaoki@g.ecc.u-tokyo.ac.jp, hfukaya@het.phys.sci.osaka-u.ac.jp, naotokan000@gmail.com

We discuss a single domain-wall system with a nontrivial curved background by considering a massive fermion on a 3D square lattice, where the domain-wall is a 2D sphere. In the presence of a topologically nontrivial U(1) link gauge field, we observe the emergence of a zero mode with opposite chirality localized at the center where the gauge field is singular. This results in the low-energy effective theory becoming vectorlike rather than chiral. We also discuss how to circumvent this obstacle in formulating lattice chiral gauge theory in the single domain-wall fermion system.

Hadronic and nuclear spectrum and interactions / 345

Connecting Lattice QCD Nucleon-Pion Scattering to Nuclear Ab Initio Calculations

Author: Aaron Meyer[1]

[1] *Lawrence Livermore National Laboratory*

Corresponding Author: asmeyer.physics@gmail.com

Quantum chromodynamics (QCD) is the driving mechanism behind the binding of quarks and gluons into nucleons and nuclei. Though rich in physics, the nonperturbative nature of QCD stymies the direct formulation of nuclear physics using quark and gluon degrees of freedom. Instead, perturbative approaches such as chiral effective theory that use pions and nucleons as degrees of freedom have become a mainstay of nuclear physics. State of the art ab initio calculations provide a systematic approach for obtaining properties of nuclei with uncertainty quantification. These calculations

are based on chiral effective theories with low energy constants (LECs) that are calibrated against experimental data. We present work towards further grounding ab initio calculations in QCD by providing additional constraints on nucleon-pion LECs entering chiral EFT nucleon-nucleon and three-nucleon forces using Lattice QCD simulations of nucleon-pion scattering. We will show that a combined fit employing a recent LQCD computation of nucleon-pion scattering at unphysical pion mass is consistent with the baseline fit to LECs using experimental data only. Even a modest set of LQCD spectra is sufficiently uncorrelated with experimental data to significantly improve nucleon-pion LEC constraints.

Structure of hadrons and nuclei / 468

Long-range interactions in double heavy tetraquarks $\bar{Q}\bar{Q}qq$

Author: Muhammad Naeem Anwar[1]

[1] *Swansea University*

Corresponding Author: m.n.anwar@swansea.ac.uk

At the large distances compared to the chiral symmetry breaking scale, a four-quark state $\bar{Q}\bar{Q}qq$ (with Q as heavy and q as light quarks) can be treated as two asymptotic mesons interacting via strong residual forces. To analyse the long-range strong force in such a system, we study the interaction between two bottom mesons in the heavy quark limit using chiral effective field theory and dispersion theory. In this contribution, methods to deal with the two-pion-exchange interaction between two static heavy mesons at non-physical pion mass will be discussed. A possible solution, where we use the Khuri-Treiman formalism to properly include the left- and right-hand cuts, will be presented. Finally, a comparison of the obtained results with the corresponding lattice QCD potentials (obtained using the Born-Oppenheimer approximation) will be made.

Vacuum structure and confinement / 144

An introduction to topological data analysis for lattice field theory

Author: Jeffrey Giansiracusa[1]

Co-authors: Biagio Lucini [2]; Xavier Crean [2]

[1] *Durham University*

[2] *Swansea University*

Corresponding Authors: jeffrey.giansiracusa@durham.ac.uk, 2237451@swansea.ac.uk

Topological data analysis (TDA) is a powerful and flexible data analysis toolset that provides computational methods for extracting and quantifying non-local topological features in data. I will give an introduction to one of the main tools in TDA - persistent homology - with a view towards applications to lattice field theory configuration data. The input is a geometric data structure called a *filtered complex* which functions as a lens in determining what kinds of structures the method can detect. The output is a data structure called a *persistence diagram* that I will explain how to interpret and work with.

QCD at non-zero density / 271

Taylor series coefficients at $\mu = 0$ from imaginary μ computations

Authors: Francesco Di Renzo[1]; Marco Aliberti[2]

[1] *University of Parma & INFN*

[2] *University of Parma and INFN - Istituto Nazionale di Fisica Nucleare*

Corresponding Authors: francesco.direnzo@unipr.it, marco.aliberti@unipr.it

Taylor expansion at $\mu = 0$ and computations at imaginary values of the chemical potential are the two most popular approaches to tackle the sign problem in finite-density lattice QCD. The two methods are obviously related. In particular, the Taylor coefficients are often reconstructed from the data obtained at imaginary μ.
In the context of the Bielefeld-Parma collaboration, we have been generating data which fed our multi-point Padé analysis of the QCD phase diagram. We report on our studies on the different techniques to compute the Taylor coefficients at $\mu = 0$.

Particle physics beyond the Standard Model / 361

Lattice vs perturbation theory : Testing the Abelian-Higgs model at three loops

Author: Andreas Ekstedt[1]

[1] *Uppsala University*

Corresponding Author: andreas.ekstedt@physics.uu.se

In this talk I compare perturbative and lattice results for the Abelian-Higgs model in three dimensions. In particular, I show that new lattice results agree remarkably well with three-loop perturbative predictions. I also present the second-order end point for the theory and discuss lattice vs perturbation theory for related models.

Theoretical developments / 348

Loop-string-hadron approach to the SU(3) gauge invariant Hilbert space

Authors: Aahiri Naskar[1]; Indrakshi Raychowdhury[2]; Jesse Stryker[3]; Saurabh Kadam[4]

[1] *BITS Pilani, KK Birla Goa Campus*

[2] *Department of Physics, BITS Pilani, KK Birla Goa Campus*

[3] *Lawrence Berkeley National Laboratory (LBNL)*

[4] *InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA*

Corresponding Authors: ksaurabh@uw.edu, indrakshir@goa.bits-pilani.ac.in, jstryker@lbl.gov

The construction of gauge invariant states of SU(3) lattice gauge theories has garnered new interest in recent years, but the explicit realization of them is complicated by the difficulties of SU(3) Clebsch-Gordon coefficients. In the loop-string-hadron (LSH) approach to lattice gauge theories, the elementary excitations are strictly gauge invariant, and constructing the basis requires no knowledge of Clebsch-Gordon coefficients. Originally developed for SU(2), the LSH formulation was recently generalized to SU(3), but limited to one spatial dimension. In this talk, I introduce the LSH approach to

constructing the basis of SU(3) gauge invariant states at a trivalent vertex – the essential building block for multidimensional space. A direct generalization from the SU(2) vertex yields a legitimate basis; however, in certain sectors of the Hilbert space, the naive LSH basis vectors so defined suffer from being nonorthogonal. The issues with orthogonality are directly related to the "missing label"or "outer multiplicity"problem associated with SU(3) tensor products, and may also be phrased in terms of Littlewood-Richardson coefficients or the need for a seventh Casimir operator. For the states that are unaffected by the problem, we present closed-form solutions to the orthonormal basis. For the sectors that are afflicted, we present the nonorthogonal bases and discuss their orthogonalization. A few choices for seventh Casimir operators are readily constructed from the suite of LSH gauge-singlet operators. The diagonalization of a seventh Casimir represents one algorithmic solution to obtaining a complete orthonormal basis, but a closed-form general solution remains elusive.

Quark and lepton flavour physics / 127

Contribution of the eta to a lattice calculation of K->mumu decay

Authors: Ceran Hu[1]; En-Hung Chao[None]

[1] *Columbia University*

Corresponding Authors: ceranhu@gmail.com, en-hung.chao@m4x.org

In the lattice calculation of the two-photon contribution to the $K_{\mathrm{L}} \longrightarrow \mu^+\mu^-$ decay amplitude, the unphysical contribution from the η intermediate state appears as a slowly decaying tail which is hard to remove due to the tiny mass difference between the K_{L} and η. We have developed methods to remove such an unphysical η contribution from our lattice results. In this contribution, we present a preliminary GEVP study of the η and η' masses, with which we determine the relevant matrix elements of η. Different methods to remove the unphysical η contribution from the decay amplitude are examined, giving comparable results.

Algorithms and artificial intelligence / 189

Density of observables from local derivatives

Author: Rasmus Larsen[1]

[1] *Bielefeld University*

Corresponding Author: rlarsen@physik.uni-bielefeld.de

The extraction of interesting physics from lattice data is dependent on how precisely the expectation values of observables can be obtained.
I will in this talk present a method to utilize the smoothness of observables to improve the level of precision by calculating how the volume contracts or expands as the observable changes.
To do this, we will derive a formula to calculate the local change to the log of any density of states for smooth real observables. Using this in Monte-Carlo simulations, we can from the obtained density of states calculate the expectation value of observables with a precision often better than standard sampling. The method can be applied to previously generated configurations, as long as the analysis uses the same action used to generate the configurations. We show that for observables such as Wilson line correlators, errors are reduced by up to 4 times at large complex time, which is the part which is most crucial to improve, due to the exponential decay of the correlator.

Hadronic and nuclear spectrum and interactions / 117

Spectral analysis for nucleon-pion and nucleon-pion-pion states in both parity sectors using distillation with domain wall fermions

Author: Andreas Hackl[1]

Co-author: Christoph Lehner [1]

[1] *University of Regensburg*

Corresponding Authors: andreas.hackl@ur.de, christoph.lehner@ur.de

We present a study using the distillation method to analyze the spectra of nucleon, nucleon-pion, and nucleon-pion-pion states in the positive parity sector as well as nucleon and nucleon-pion states in the negative sector. The study involves using five domain wall fermion ensembles with varying pion masses ($m_\pi = 139 - 279$ MeV), lattice spacings ($a^{-1} = 1.730$ GeV and $a^{-1} = 2.359$ GeV) and volumes ($m_\pi L = 3.84 - 7.59$). To tackle the large number of contractions in this project, we implemented an algorithm to automate the contraction of general nucleon pion correlation functions containing an arbitrary number of pions.

Structure of hadrons and nuclei / 200

Gluon nonlocal operator mixing in lattice QCD

Authors: Demetrianos Gavriel[1]; Haralambos Panagopoulos[1]; Gregoris Spanoudes[1]

[1] *University of Cyprus*

Corresponding Authors: dgavri02@ucy.ac.cy, spanoudes.gregoris@ucy.ac.cy, panagopoulos.haris@ucy.ac.cy

In this study, we explore the renormalization of a comprehensive set of gauge-invariant gluon nonlocal operators on the lattice. We calculate the renormalization factors for these operators in the modified Minimal Subtraction ($\overline{\rm MS}$) scheme up to one-loop, utilizing both dimensional and lattice regularizations in the Wilson gluon action. To facilitate a non-perturbative renormalization approach, we examine an appropriate version of the modified regularization-invariant (${\rm RI}'$) scheme and determine the conversion factors from this scheme to $\overline{\rm MS}$. Additionally, by employing symmetry arguments on the lattice, we identify the mixing pattern of these operators under renormalization.

Vacuum structure and confinement / 145

Topological Data Analysis of Monopole Currents in U(1) Lattice Gauge Theory

Author: Xavier Crean[1]

Co-authors: Biagio Lucini [1]; Jeffrey Giansiracusa [2]

[1] *Swansea University*

[2] *Durham University*

Corresponding Authors: jeffrey.giansiracusa@durham.ac.uk, b.lucini@swansea.ac.uk, 2237451@swansea.ac.uk

Compact $U(1)$ Lattice Gauge Theory is known to have a confinement phase that can be explained in terms of condensation of magnetic monopoles. In this talk, we shall explain how Topological Data Analysis (TDA) may be used to quantitatively analyse monopoles across the deconfinement phase transition of the model. We construct a cubical complex from monopole current networks and show that homological invariants associated to current networks allow for a precise estimation of the critical inverse coupling. Further, by designing a suitable filtration, we show that persistent homology may be used to quantitatively characterise the nature of current networks in the deconfined phase.

QCD at non-zero density / 251

Finite-size scaling of Lee-Yang zeros and its application to 3-state Potts model and heavy-quark QCD

Authors: Tatsuya Wada[1]; Kazuyuki Kanaya[2]; Masakiyo Kitazawa[3]

[1] *Kyoto University/YITP*

[2] *Tomonaga Center for the History of the Universe, Univ. Tsukuba*

[3] *Yukawa Institute for Theoretical Physics*

Corresponding Authors: kitazawa@yukawa.kyoto-u.ac.jp, kanaya@ccs.tsukuba.ac.jp, wada.tatsuya.24x@st.kyoto-u.ac.jp

We propose a general procedure to use the finite-size scaling of Lee-Yang zeros (LYZ) for investigating critical points (CP). This method makes use of the multiple LYZ obtained on finite-volume simulations for determining the properties of the CP, such as the location, universality class, and axes to embed the scaling function.
We apply this method to the analysis of the CP in the 3-state Potts model and QCD in the heavy-quark regime, which are believed to belong to the same universality class as the 3D Ising model. In these models, a direct calculation of the partition function at complex parameters is possible using the reweighting method. By using the numerical results of the LYZ, we demonstrate that our method determines the location of the CP and t,h-axes of the Ising model in the parameter space of these models, for embedding the scaling function.

Particle physics beyond the Standard Model / 89

Progress on holographic vacuum misalignment

Authors: Ali Fatemiabhari[1]; Daniel Elander[None]; Maurizio Piai[1]

[1] *Swansea University*

Corresponding Authors: m.piai@swansea.ac.uk, 2127756@swansea.ac.uk

We present a bottom-up holographic model that contains the dual description of a strongly coupled field theory. The spontaneous breaking of an approximate global symmetry in the theory produces the SO(5)/SO(4) coset relevant to minimal composite-Higgs models.

Some boundary-localised terms are introduced in the dual gravity for consistency and production of the desired properties of the model. Via vacuum misalignment, the interplay of bulk and boundary-localised couplings leads to the breaking of the SO(5) symmetry to its SO(4) or SO(3) subgroup. In the dual field theory, the model contains a SO(4) gauge symmetry, which is spontaneously broken into its SO(3) subgroup. We investigate the consequences of the higgsing phenomenon by analysing the spectrum of fluctuations within the model, interpreted in terms of four-dimensional field theory, across selected parameter configurations.
The talk is based on arXiv:2405.08714.

Theoretical developments / 241

Quantum thermodynamics, lattice gauge theories, and quantum simulation

Authors: Zohreh Davoudi[1]; Christopher Jarzynski[1]; Niklas Mueller[2]; Greeshma Oruganti[1]; Connor Powers[1]; Nicole Yunger Halpern[1]

[1] *University of Maryland, College Park*

[2] *University of Washington, Seattle*

Corresponding Authors: gshivali@umd.edu, davoudi@umd.edu, niklasmu@uw.edu, cdpowers@umd.edu, cjarzyns@umd.edu, nicoleyh@umd.edu

Thermodynamic studies of gauge theories in the presence of a finite fermionic density and in real-time, out-of-equilibrium processes, can be facilitated by Hamiltonian-simulation methods, such as tensor networks and quantum computing. A suitable framework for such studies is quantum thermodynamics, a subfield of thermodynamics that extends traditional thermodynamics to quantum systems. Due to the intricate structure of lattice-gauge-theory Hilbert spaces rooted in Gauss's laws, the partitioning of states defined over a system and reservoir is nontrivial, mimicking the situation occurred in strong-coupling thermodynamics. Consequently, the system's internal energy, and its division to work and heat exchanged during a thermodynamic process, must be defined carefully. We propose definitions consistent with first and second laws of thermodynamics, and use them to study a spontaneous quench process in a simple 1+1 D lattice gauge theory. Thermodynamic quantities are seen to exhibit enhanced sensitivity to a phase transition in this model compared with when traditional weak-coupling thermodynamics are applied. Quench processes are the simplest non-equilibrium processes studied in quantum-simulation experiments nowadays. We demonstrate how certain thermodynamic quantities can be efficiently measured in these experiments using entanglement-tomography tools in quantum-information theory.

Algorithms and artificial intelligence / 336

Real-time dynamics from convex geometry

Author: Scott Lawrence[1]

[1] *Los Alamos National Laboratory*

Corresponding Author: srlawrence@lanl.gov

A quantum mechanical system comes naturally equipped with a convex space: each (Hermitian) operator has a (real) expectation value, and the expectation value of the square any Hermitian operator must be non-negative. This space is of exponential (e.g. in volume) dimension, but low-dimensional projections can be efficiently explored by standard algorithms. Such approaches have been used to precisely constrain critical exponents of conformal field theories ("conformal bootstrap") and, more recently, to constrain the ground state physics of various quantum mechanical systems, including lattice field theories. In this talk we discuss related approaches to systematically constraining the real-time dynamics of quantum systems, which are otherwise obstructed from study by sign problems and the ill-posed nature of analytic continuation.

Quark and lepton flavour physics / 125

$\Delta I = 1/2$ process of $K \to \pi\pi$ decay on multiple ensembles with periodic boundary conditions

Author: Masaaki Tomii[1]

[1] *University of Connecticut*

Corresponding Author: masaaki.tomii1987@gmail.com

Calculation of ε', a measure of direct CP violation, using periodic boundary conditions (PBC) is desired to complement our previous lattice calculations performed with G-parity boundary conditions (GPBC). This approach will also be an important step towards incorporating electromagnetic and isospin-violating effects. Last year, we published our first PBC result for ε', demonstrating its feasibility despite the challenges in extracting the signal of the two-pion excited state to realize the physical kinematics in a periodic box. Now we extend our production including a smaller lattice spacing, which is the same as the earlier GPBC calculation, to control the finite lattice spacing error, one of the largest systematic errors. In this talk, some preliminary results from these new calculations will be presented.

Hadronic and nuclear spectrum and interactions / 110

Pole trajectories of the Λ(1380) and Λ(1405) resonances from the combination of lattice and experimental data

Author: Ferenc Pittler[1]

Co-author: Maxim Mai [2]

[1] *Eötvös University*

[2] *Helmholtz-Institut für Strahlen- und Kernphysik of the University Bonn, George Washington University*

Corresponding Authors: mai@hiskp.uni-bonn.de, pittlerferenc@gmail.com

Chiral unitary models predict an interchange of the two trajectories of the $\Lambda(1380)$ and the $\Lambda(1405)$ away from the SU(3) limit at next-to-leading order. Recently the BaryonScattering collaboration has performed a coupled channel ($\pi\Sigma - \bar{K}N$) lattice spectral analysis in the region of $\Lambda(1405)$ for $m_\pi \sim$ 200MeV pion mass. In the present contribution we reanalyze the energy levels using a coupled-channel chiral approach constrained by experimental data. In addition we investigate the contributions of heavy channels and higher partial waves.

Structure of hadrons and nuclei / 422

Lanczos for matrix elements

Authors: Daniel Hackett[1]; Michael Wagman[1]

[1] *Fermilab*

Corresponding Authors: mwagman@fnal.gov, dhackett@fnal.gov

We present a new method for extracting hadronic matrix elements from simultaneous analysis of two- and three-point correlation functions. We demonstrate its advantages over previous approaches in applications to both synthetic and lattice data.

Vacuum structure and confinement / 141

Topological Data Analysis, Monopoles and Colour Confinement in SU(3) Yang-Mills

Author: Biagio Lucini[1]

Co-authors: Jeffrey Giansiracusa [2]; Xavier Crean [1]

[1] *Swansea University*

[2] *Durham University*

Corresponding Authors: jeffrey.giansiracusa@durham.ac.uk, b.lucini@swansea.ac.uk, 2237451@swansea.ac.uk

Techniques derived from topological data analysis have been recently explored to study non-perturbative phenomena in lattice field theories in which configurations with non-trivial topology are expected or conjectured to play a central role. In this talk, we apply methods of topological data analysis to the investigation of the behaviour of Abelian monopole currents (defined in the Maximal Abelian Gauge) across the deconfinement phase transition of SU(3) Yang-Mills theory. In particular, we study the average number of connected components and the average number of cycles of these currents as a function of the temperature. Performing a finite size scaling analysis, we study the effectiveness of these observables and of the corresponding susceptibilities at identifying the critical temperature and reproducing the scaling properties of the expected first-order deconfinement phase transition. We conclude discussing the extension of the developed approach to QCD with dynamical quarks.

QCD at non-zero density / 430

Search for a Lee-Yang edge singularity in high-statistics Wuppertal-Budapest data

Authors: Alexander Adam[1]; Szabolcs Borsanyi[1]; Zoltan Fodor[2]; Jana N. Guenther[1]; Paolo Parotto[3]; Attila Pasztor[1]; Dávid Pesznyák[4]; Ludovica Pirelli[5]; Chik Him Wong[1]

[1] *University of Wuppertal*

[2] *University of Wuppertal, Penn State University, Eotvos University, IAS Jülich, UC San Diego*

[3] *Università di Torino*

[4] *Eötvös Loránd University, HUN-REN Wigner Research Centre for Physics*

[5] *Bergische Universität Wuppertal*

Corresponding Authors: pirelli@uni-wuppertal.de, apasztor@bodri.elte.hu, jguenther@uni-wuppertal.de, dpesznyak@student.elte.l borsanyi@uni-wuppertal.de, cwong@uni-wuppertal.de, alexander.adam@uni-wuppertal.de

Near a critical endpoint the Lee-Yang edge singularity approaches the real axis in the complex chemical potential plane. In the vicinity of the critical point the functional form of this approach depends on the universality class. Assuming a three dimensional Ising critical point in the QCD phase diagram the location of the critical endpoint can be extrapolated provided that the position of the Lee-Yang edge singularity is known at multiple temperatures. A popular method to estimate the position of a singularity is to model the free energy as a rational function of the baryon chemical potential μ_B. The parameters of this model can be constrained by the cumulants of the net baryon density taken at $\mu_B^2 \leq 0$. Using high-statistics simulations on a $16^3 \times 8$ lattice by the Wuppertal-Budapest Collaboration we estimate the location of the closest singularity in the QCD phase diagram. We also compare various models for the functional form of the free energy and discuss the predictive power of this approach.

Particle physics beyond the Standard Model / 49

Dilaton Forbidden Dark Matter

Authors: James Ingoldby[1]; Maurizio Piai[2]; Thomas Appelquist[3]

[1] *IPPP, Durham University*

[2] *Swansea University*

[3] *Yale University*

Corresponding Authors: james.ingoldby@gmail.com, thomas.appelquist@yale.edu, m.piai@swansea.ac.uk

We take a dilaton EFT that has been successfully used to analyze lattice data for confining gauge theories near the conformal window boundary, and show that it can form a viable description of composite dark matter. The EFT contains a dilaton that is slightly heavier than a multiplet of stable pNGBs, and naturally implements the forbidden dark matter mechanism for relic density generation. Our framework therefore provides a novel and concrete way to connect recent developments in dark matter studies with lattice measurements in specific underlying gauge theories. Our presentation is based on arXiv:2404.07601.

QCD at non-zero density / 313

On analytic continuation from imaginary to real chemical potential in Lattice QCD

Authors: Francesco Di Renzo[1]; Marco Aliberti[2]

[1] *University of Parma & INFN*

[2] *University of Parma and INFN - Istituto Nazionale di Fisica Nucleare*

Corresponding Authors: francesco.direnzo@unipr.it, marco.aliberti@unipr.it

Imaginary baryon number chemical potential simulations are a popular workaround for the (in)famous sign problem plaguing finite density QCD studies on the lattice. One is necessarily left with the problem of analytically continuing results to real values of μ_B. In the framework of the Bielefeld Parma Collaboration, we have in recent years studied a multi-point Padé description of the net baryon number density computed as a function of imaginary baryon number chemical potential. While our main emphasis has till now been on the determination of Lee-Yang singularities, the method is per se a natural tool to analytically continue results. We report on the status of our projects with this respect, comparing the Padé approach to analytic continuation to other possible strategies.

Hadronic and nuclear spectrum and interactions / 166

Lambda(1405) in the flavor SU(3) limit using a separable potential in the HAL QCD method

Authors: Kotaro Murakami[1]; Sinya Aoki[2]

[1] *Tokyo Institute of Technology*

[2] *Yukawa Institute for Theoretical Physics, Kyoto University*

Corresponding Authors: kotaro.murakami@yukawa.kyoto-u.ac.jp, saoki@yukawa.kyoto-u.ac.jp

We perform a numerical study in lattice QCD on $\Lambda(1405)$ in the flavor SU(3) limit. One of the most promising interpretations of $\Lambda(1405)$ is the so-called two-pole structure: the spectrum corresponding to $\Lambda(1405)$ observed in experiments may be explained by two poles. In order to elucidate such a property from lattice QCD, we calculate the HAL QCD potentials for the meson-baryon systems in the octet and singlet channels of the flavor SU(3). In our numerical calculation, we employ gauge configurations in the flavor SU(3) limit on 32^4 lattices at the meson mass $m_M \approx 460$ MeV. In our previous analysis, we found that local potentials both in octet and singlet channels have singular behaviors at the vanishing point of NBS wave functions, which prevent us from reliably extracting binding energies. To avoid such singular behaviors, we introduce separable potentials for the first time in the HAL QCD method, rather than the standard local approximation usually employed. In this talk, we present first results for our analysis with separable potentials, and discuss their physical interpretations.

Structure of hadrons and nuclei / 174

Exploring Nuclear Beta Decay Through Nuclear Lattice Effective Field Theory

Author: Teng Wang[1]

Co-authors: Bing-Nan Lu [2]; Xu Feng [1]

[1] *Peking University*

[2] *Graduate School of China Academy of Engineering Physics*

Corresponding Authors: 2101110109@stu.pku.edu.cn, xu.feng@pku.edu.cn, bnlv@gscaep.ac.cn

We report the first exploratory study on nuclear β-decay through nuclear lattice effective field theory, including ^{3}H and ^{6}He β-decays. We employ nuclear forces and nuclear one-body and two-body axial currents consistently derived from chiral effective field theory to calculate the Gamow-Teller matrix element(GTME). We first combine the GTME of ^{3}H β-decay together with ^{3}H's binding energy to fix the low-energy constants c_D and c_E in the three-body nuclear force. We then carry out Monte Carlo calculation to predict the GTME of ^{6}He β-decay. New techniques are developed to make the calculation reliable and efficient. The result shows good agreement with the experiment.

Quark and lepton flavour physics / 157

Enhanced Lattice QCD Studies on ϵ_K and ΔM_K

Author: Yikai Huo[1]

Co-authors: Bigeng Wang [2]; Norman Christ [1]

[1] *Columbia University*

[2] *University of Kentucky*

Corresponding Authors: bwa271@g.uky.edu, nhc@phys.columbia.edu, yh3285@columbia.edu

Two second-order quantities related to K meson mixing, ϵ_K and ΔM_K, are Standard Model observables that are highly sensitive to possible new physics. The RBC and UKQCD collaborations have presented results for ΔM_K with physical quark masses and the first lattice calculation of the long-distance part of ϵ_K. Utilizing new-generation computers and new lattice configurations with an inverse lattice spacing of 2.7GeV and physical quark masses, we can extend this previous work to obtain more precise results. We will present preliminary results and the methods being applied to control systematic errors.

Particle physics beyond the Standard Model / 344

Finite temperature transition in Hyper Stealth Dark Matter using Mobius Domain Wall fermions

Author: Sungwoo Park[1]

Co-authors: Nobuyuki Matsumoto [2]; Venkitesh Ayyar

[1] *Lawrence Livermore National Laboratory*

[2] *Boston University*

Corresponding Authors: nmatsum@bu.edu, park49@llnl.gov, venkiteshayyar@gmail.com

The first-order confinement transition of a strongly coupled composite dark matter theory can provide a possible source of gravitational waves in the early universe. In this talk, on behalf of the Lattice Strong Dynamics (LSD) Collaboration, we present our recent investigation on the finite temperature confinement transition of the 1-flavor SU(4) dark gauge theory named Hyper Stealth Dark Matter (HSDM). The dark matter candidate in this theory is a composite bosonic baryon and can have a remarkably low mass bound of a few GeV. We expect the finite temperature transition to be first-order over at least some finite range of fermionic mass and to be a potential source of observable gravitational radiation. The finite temperature simulation of 1-flavor SU(4) is done using Mobius Domain wall fermions. Using various lattice volumes, the order of the transition and its fermionic mass dependence are explored by monitoring the Wilson-flowed Polyakov loop and chiral condensate.

Standard Model parameters / 276

Cutoff effects and scale determinations in pure gauge theory

Authors: Alberto Ramos[1]; Guilherme Catumba[2]; Nicolas Lang[3]

[1] *CERN*

[2] *IFIC*

[3] *Universitat de València, IFIC*

Corresponding Authors: nicolas.lang@ific.uv.es, alberto.ramos@cern.ch, gtelo@ific.uv.es

In this talk we will investigate the approach to the continuum limit using different gauge actions. We will argue that solid and precise QCD calculations need to reach lattice spacings finer than the current standard, or that several actions need to be consider for a proper estimate of the systematic. Flow scales for different actions will be determined. Together with lattice perturbation theory these can be used to extract the pure gauge Lambda parameter from lattice quantities defined at the scale of the cutoff.

Algorithms and artificial intelligence / 228

Generalized HMC using Nambu mechanics

Author: Erik Lundstrum[1]

[1] *Columbia University*

Corresponding Author: ell2156@columbia.edu

I describe a generalization of the Hybrid Monte Carlo (HMC) algorithm with molecular dynamics (MD) steps which use Nambu's generalized Hamiltonian dynamics. Characterized by multiple Hamiltonian functions, this formalism allows me to include forces from non-local objects in the MD

evolution while still preserving the target probability distribution. In this way, the local changes proposed by the MD have instantaneous knowledge of the long-distance behavior of the gauge field. This represents a promising method for fighting critical slowing down in lattice QCD simulations. Results will be presented for a few choices of the second non-local auxiliary Hamiltonian.

Theoretical developments / 111

Grassmann bond-weighted tensor renormalization group approach to 1+1D two-color QCD with staggered fermions at finite density

Authors: Ho Pai Kwok[1]; Shinichiro Akiyama[2]; Synge Todo[3]

[1] *Department of Physics, The University of Tokyo*

[2] *University of Tsukuba*

[3] *Department of Physics, University of Tokyo*

Corresponding Authors: hpkwok@g.ecc.u-tokyo.ac.jp, akiyama@ccs.tsukuba.ac.jp

Tensor renormalization group is expected to be a promising method to simulate lattice field theories at finite density since it does not suffer from the sign problem. We construct a Grassmann tensor network representing the partition function of 1+1D SU(2) lattice gauge theory coupled with staggered fermions. At finite couplings, a random sampling is applied to discretize the group integration. The initial bond dimension turns out to be $16K$ where K is the number of SU(2) matrices sampled for each link variable. We introduce an efficient initial tensor compression scheme to reduce the size of initial tensors. Then, Grassmann bond-weighted tensor renormalization group approach is adopted to investigate a phase diagram in the (m, μ) plane with the quark mass m and chemical potential μ. The free energy density, number density, and diquark condensate at different gauge couplings are computed as a function of the chemical potential. We discuss the efficiency of random sampling method, our initial tensor compression scheme, and the future application toward the corresponding higher-dimensional models.

QCD at non-zero temperature / 114

Computation of the latent heat of the deconfinement phase transition of SU(3) Yang-Mills theory

Authors: Leonardo Giusti[1]; Mitsuaki Hirasawa[1]; Michele Pepe[2]; Luca Virzì[3]

[1] *University of Milano-Bicocca*

[2] *INFN - Sez. Milano Bicocca*

[3] *Università degli Studi di Milano - Bicocca, Istituto Nazionale di Fisica Nucleare (INFN, MiB)*

Corresponding Authors: mitsuaki.hirasawa@mib.infn.it, michele.pepe@mib.infn.it, l.virzi1@campus.unimib.it, leonardo.giusti@unimib.it

The latent heat of the first-order deconfinement phase transition in SU(3) Yang-Mills theory can be determined from the discontinuity in the entropy density $s(T_c)$ at the critical temperature T_c. Using shifted boundary conditions, the entropy density becomes a primary thermal observable that can be computed from the expectation value of the space-time components T_{0k} of the renormalized energy-momentum tensor. This approach provides a convenient framework for such calculation. We present an accurate determination of the latent heat using Monte Carlo simulations on systems with large spatial size $LT_c \simeq 30$ and at four different lattice spacings.

Structure of hadrons and nuclei / 94

The leading-twist distribution amplitude of the η_c meson

Author: Miguel Teseo San José Pérez[1]

Co-authors: Benoît Blossier [1]; Jose Manuel Morgado Chávez [2]; Mariane Mangin-Brinet [3]

[1] *IJCLab*

[2] *LSN/DPhN/Irfu CEA-Saclay*

[3] *Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3*

Corresponding Authors: blossier@ijclab.in2p3.fr, jose-manuel.morgadochavez@cea.fr, mariane@lpsc.in2p3.fr, san-jose-perez@ijclab.in2p3.fr

We apply the method of pseudo parton distributions to compute the distribution amplitude of the η_c meson, which is a necessary ingredient in cross sections of exclusive meson production. We present results in the continuum for physical quark masses and we compare to alternative methods to compute this object, mainly non-relativistic QCD and Dyson-Schwinger equations. We find a large disagreement with the former.

Particle physics beyond the Standard Model / 476

The mass of the σ in a chiral ensemble in $SU(2)$ with two fundamental flavours

Authors: Antonio Rago[1]; Fernando Romero-Lopez[2]; Laurence Sebastian Bowes[3]; Patrick Fritzsch[4]; Sofie Martins[5]; Vincent Drach[3]

[1] *QTC & IMADA, University of Southern Denmark*

[2] *MIT / Uni Bern*

[3] *University of Plymouth*

[4] *Trinity College Dublin*

[5] *University of Southern Denmark*

Corresponding Authors: fritzscp@tcd.ie, laurence.bowes@plymouth.ac.uk, martinss@imada.sdu.dk, vincent.drach@plymouth.ac.uk, fernando.romero-lopez@unibe.ch, rago@qtc.sdu.dk

$SU(2)$ with two fundamental flavours is a minimal model for the Composite Higgs sector proposed to tackle the hierarchy and naturalness problems associated with the Standard Model Higgs boson. We present an update on lattice results for the spectrum of $SU(2)$ with two fundamental flavours with the exponential clover Wilson fermion action. This includes the final non-perturbative tuning of c_{SW} for all $\beta \geq 2.15$, and for the first time in this setup the mass of the σ towards the chiral limit, just below the threshold of decay into two pions.

Quark and lepton flavour physics / 5

Lattice QCD Calculation of Electroweak Box Contributions to Superallowed Nuclear and Neutron Beta Decays

Authors: Bi-Geng Wang[None]; Chien-Yeah Seng[None]; Keh-Fei Liu[None]; Lu-Chang Jin[None]; Mikhail Gorchtein[None]; Peng-Xiang Ma[1]; Xu Feng[1]; Zhaolong Zhang[1]

[1] *Peking University*

Corresponding Authors: xu.feng@pku.edu.cn, 2001110084@pku.edu.cn, 2301110116@pku.edu.cn

We present the first lattice QCD calculation of the universal axial γW-box contribution $square_{\gamma W}^{VA}$ to both superallowed nuclear and neutron beta decays.
This contribution emerges as a significant component within the theoretical uncertainties surrounding the extraction of $|V_{ud}|$ from superallowed decays.
Our calculation is conducted using two domain wall fermion ensembles at the physical pion mass.
To construct the nucleon 4-point correlation functions, we employ the random sparsening field technique. Furthermore, we incorporate long-distance contributions to the hadronic function using the infinite-volume reconstruction method.
Upon performing the continuum extrapolation, we arrive at
$square_{\gamma W}^{VA} = 3.65(8)_{\mathrm{lat}}(1)_{\mathrm{PT}} \times 10^{-3}$. Consequently, this yields a slightly higher value of $|V_{ud}| = 0.97386(11)_{\mathrm{exp.}}(9)_{\mathrm{RC}}(27)_{\mathrm{NS}}$,
reducing the previous 2.1σ tension with the CKM unitarity to 1.8σ.
Additionally, we calculate the vector γW-box contribution to the axial charge g_A, denoted as $square_{\gamma W}^{VV}$, and explore its potential implications.

Hadronic and nuclear spectrum and interactions / 13

Learning Hadron Interactions from Lattice QCD

Author: Lingxiao Wang[1]

Co-authors: Takumi Doi [1]; Tetsuo Hatsuda [1]; Yan Lyu [1]

[1] *RIKEN*

Corresponding Authors: yan.lyu@riken.jp, lingxiao.wang@riken.jp, doi@ribf.riken.jp, tetsuohatsuda@gmail.com

In this study, we develop a deep learning method to learn hadron interactions from Lattice QCD calculated correlations unsupervisedly. We present our approach of using neural networks to model potential functions that are learned from Nambu-Bethe-Salpeter (NBS) wave functions. This allows most general forms of interaction potentials to be incorporated into a Schrödinger-like equation for detailed hadron interaction analysis. Our results include validations with separable potentials, Yukawa potentials, and the $\Omega_{ccc} - \Omega_{ccc}$ potentials. The neural networks accurately capture the essential features of these interactions, providing a reliable tool for predicting and analyzing hadron scattering properties. Finally, we present the potential for joint learning from lattice QCD and experimental observations to further improve our understanding of hadron interactions.

Standard Model parameters / 372

The scales r_0 & r_1 in $N_f = 2 + 1$ QCD.

Author: Tom Asmussen[None]

Co-authors: Francesco Knechtli [1]; Roman Höllwieser [1]; Tomasz Korzec [2]

[1] *University of Wuppertal*

[2] *Bergische Universität Wuppertal*

Corresponding Authors: korzec@uni-wuppertal.de, knechtli@physik.uni-wuppertal.de, hoellwieser@uni-wuppertal.de, asmussen@uni-wuppertal.de

We give an update and final result for the determination of the scales r_0, r_1, and $\frac{r_0}{r_1}$ for 2 + 1 flavour QCD ensembles generated by CLS and calculated from an improved definition of the static force measured using Wilson loops. This update includes full control over systematic and full statistics with various continuum and chiral extrapolations of data covering pion masses between 130 MeV and

420 MeV over five lattice spacings down to 0.038 fm. Furthermore, the shape of the static potential is studied and, as an application of the scale r_0, we compute the Lambda parameter of the ALPHA collaboration in units of r_0.

Algorithms and artificial intelligence / 233

Tuning the Riemannian Manifold Hybrid Monte Carlo with Fermions

Authors: Sarah Fields[1]; Norman Christ[1]; Chulwoo Jung[2]

[1] *Columbia University*

[2] *Brookhaven National Laboratory*

Corresponding Authors: chulwoo@bnl.gov, nhc@phys.columbia.edu, scf2157@columbia.edu

The Riemannian Manifold HMC (RMHMC) is designed to tackle critical slowing down by utilizing a rational function of the SU(3) gauge covariant laplace operator in place of the canonical mass term in the HMC algorithm. The RMHMC has been demonstrated to be effective at increasing the rate of change of long distance modes. We present the results of the recent studies done to tune the algorithm and improve its efficiency.

Theoretical developments / 68

Entanglement entropy by tensor renormalization group approach

Authors: Daisuke Kadoh[1]; Gota Tanaka[2]; Shinji Takeda[3]; Takahiro Hayazaki[3]

[1] *Keio Univ.*

[2] *Meiji Gakuin University*

[3] *Kanazawa University*

Corresponding Authors: tanaka.gota.14@cii.shizuoka.ac.jp, takeda@hep.s.kanazawa-u.ac.jp, kadoh@keio.jp, t_hayazaki@hep.s.kanazawa-u.ac.jp

We present a general method to analyze the size dependence of entanglement entropy (EE) within the tensor renormalization group (TRG). Much attention has been paid to the TRG method since it does not suffer from the sign problem and enables us to take the large-volume limit easily. We represent the density matrix of a 1D quantum system as a 2D tensor network and develop a method to calculate the EE of any subsystem size. Applying this method to 1D quantum Ising model, we compute EE and show that the size dependence of EE agrees with the known result.

QCD at non-zero temperature / 62

Non-perturbative thermal QCD at very high temperatures

Authors: Leonardo Giusti[1]; Matteo Bresciani[2]; Mattia Dalla Brida[3]; Tim Harris[4]; Davide Laudicina[None]; Michele Pepe[5]

[1] *University of Milano-Bicocca*

[2] *Università di Milano Bicocca*

[3] *DESY - Zeuthen*

[4] *Helmholtz-Institut Mainz*

[5] *INFN - Sez. Milano Bicocca*

Corresponding Authors: m.bresciani9@campus.unimib.it, michele.pepe@mib.infn.it, leonardo.giusti@unimib.it, d.laudicina1@campus.unimib.it, harrist@phys.ethz.ch, mattia.dalla.brida@cern.ch

We discuss a recently introduced strategy to study non-perturbatively thermal QCD up to temperatures of the order of the electro-weak scale, combining step scaling techniques and shifted boundary conditions. The former allow to renormalize the theory for a range of scales which spans several orders of magnitude with a moderate computational cost. Shifted boundary conditions remove the need for the zero temperature subtraction in the Equation of State. As a consequence, the simulated lattices do not have to accommodate two very different scales, the pion mass and the temperature, at the very same spacing. Effective field theory arguments guarantee that finite volume effects can be kept under control safely.
The entire strategy has been implemented by discretizing fermions with the O(a)-improved Wilson–Dirac operator. This is a theoretically-sound regularization which enjoys de-facto automatic O(a)-improvement at high temperature. Several computations, carried out with the proposed strategy, are underway and will be presented in other (related) talks to this conference.

Structure of hadrons and nuclei / 108

Proton radii for muonic hydrogen spectroscopy from lattice QCD

Author: Miguel Salg[1]

Co-authors: Dalibor Djukanovic [2]; Georg von Hippel [1]; Harvey B. Meyer [1]; Konstantin Ottnad [1]; Hartmut Wittig [1]

[1] *University of Mainz*

[2] *Helmholtz Institute Mainz*

Corresponding Authors: kottnad@uni-mainz.de, hippel@uni-mainz.de, hartmut.wittig@uni-mainz.de, meyerh@uni-mainz.de, d.djukanovic@him.uni-mainz.de, msalg@uni-mainz.de

The size of the proton is of lasting and high interest in the subatomic physics community. The most well-known example is the electric radius which has been beclouded by the proton radius puzzle for more than a decade. While tremendous progress in ep-scattering, atomic spectroscopy and lattice QCD has brought this puzzle closer to its resolution, one also finds discrepant results for the magnetic radius. In light of the upcoming high-precision measurements of the hyperfine splitting (HFS) in muonic hydrogen, other definitions of radii gain relevance as well. On the one hand, to infer the electric radius from the observed Lamb shift in muonic hydrogen, higher-order nuclear structure corrections need to be subtracted, which depend on the Friar radius of the proton. The magnetic properties of the proton, on the other hand, only enter the HFS via the proton's Zemach radius. Based on our previous calculation of the electromagnetic form factors of the proton and neutron, which includes both quark-connected and -disconnected contributions and assesses all sources of systematic uncertainties, we now present results for the Zemach and Friar radii. The overall precision of our results for the proton, which point to small values both for the Zemach and for the Friar radius, is sufficient to make a meaningful comparison to data-driven evaluations.

Quark and lepton flavour physics / 61

Four-quark operators with ΔF = 2 in the GIRS scheme

Authors: Gregoris Spanoudes[1]; Haralambos Panagopoulos[1]; Herodotos Herodotou[1]; Marios Kosta[2]; Martha Constantinou[3]

[1] *University of Cyprus*

[2] *University of Cyprus, Rinnoco Ltd*

[3] *Temple University*

Corresponding Authors: spanoudes.gregoris@ucy.ac.cy, panagopoulos.haris@ucy.ac.cy, hherod01@ucy.ac.cy, marthac@temple.edu, ph06km1@ucy.ac.cy

We calculate the mixing matrices of four-quark operators that change flavor numbers by two units. Our approach employs two schemes: the coordinate-space Gauge Invariant Renormalization Scheme (GIRS) and the Modified Minimal Subtraction scheme. From our perturbative computations, we extract the conversion factors between these two renormalization schemes at the next-to-leading order. A significant challenge in the study of four-quark operators is that they mix among themselves upon renormalization. Additionally, computations in GIRS at a given order in perturbation theory require Feynman diagrams with at least one additional loop. The extraction of the conversion factors involves calculating two-point Green's functions, which include products of two four-quark operators, and three-point Green's functions, which involve one four-quark operator and two bilinear operators, with all operators located at distinct spacetime points. Furthermore, we focus on both parity-conserving and parity-violating four-quark operators. This calculation is crucial for determining Cabibbo–Kobayashi–Maskawa (CKM) matrix elements from numerical simulations using the GIRS scheme.

Hadronic and nuclear spectrum and interactions / 18

Generalized boost transformations in finite volumes and application to Hamiltonian methods

Authors: Yan Li[1]; Jia-jun Wu[2]; T-S Harry Lee[3]; Ross Young[4]

[1] *University of Cyprus*

[2] *University of Chinese Academy of Science*

[3] *Argonne National Laboratory*

[4] *University of Adelaide*

Corresponding Authors: ross.young@adelaide.edu.au, li.yan@ucy.ac.cy, wujiajun@ucas.ac.cn, tshlee@anl.gov

The investigation of hadron interactions within lattice QCD has been facilitated by the well-known quantisation condition, linking scattering phase shifts to finite-volume energies. Additionally, the ability to utilise systems at finite total boosts has been pivotal in smoothly charting the energy-dependent behaviour of these phase shifts. The existing implementations of the quantization condition at finite boosts rely on momentum transformations between rest and moving frames, defined directly in terms of the energy eigenvalues. This energy dependence is unsuitable in the formulation of a Hamiltonian. In this work, we introduce a novel approach to generalise the three-momentum boost prescription, enabling the incorporation of energy-independent finite-volume Hamiltonians within moving frames. We demonstrate the application of our method through numerical comparisons, employing a phenomenological $\pi\pi$ scattering example.

Particle physics beyond the Standard Model / 356

Determination of the pseudoscalar decay constant from SU(2) with two fundamental flavors

Authors: Antonio Rago[1]; Fernando Romero-Lopez[2]; Laurence Bowes[3]; Patrick Fritzsch[4]; Sofie Martins[5]; Vincent Drach[3]

[1] *QTC & IMADA, University of Southern Denmark*

[2] *MIT / Uni Bern*

[3] *University of Plymouth*

[4] *Trinity College Dublin*

[5] *University of Southern Denmark*

Corresponding Authors: laurence.bowes@plymouth.ac.uk, fritzscp@tcd.ie, vincent.drach@plymouth.ac.uk, fernando.romero-lopez@unibe.ch, rago@qtc.sdu.dk, martinss@imada.sdu.dk

The SU(2) gauge group with two fundamental flavors is a candidate for a composite Higgs extension of the Standard Model. Central to Higgs phenomenology is a non-perturbative determination of observables of the theory, such as the decay constant of the pseudo-Nambu-Goldstone Bosons. We present preliminary results for the continuum limit of the pseudoscalar decay constant using a mixed-action setup, with non-perturbatively improved stabilized Wilson Fermions on the sea, and maximally twisted valence quarks. Pivotal to this study is the recent porting of our simulation suite HiRep to GPU architecture.

Standard Model parameters / 397

Scale setting from a combination of lattice QCD formulations with Wilson and Wilson twisted mass valence quarks

Author: Alejandro Saez-Gonzalvo[1]

Co-authors: Alessandro Conigli [2]; Carlos Pena [1]; Gregorio Herdoiza [1]

[1] *IFT UAM-CSIC*

[2] *HIM - JGU*

Corresponding Authors: alejandro.saezg@uam.es, gregorio.herdoiza@uam.es, carlos.pena@uam.es, aconigli@uni-mainz.de

We report about an update of a scale setting procedure of a mixed action setup consisting of $N_f = 2+1$ flavours of $O(a)$ improved Wilson sea quarks, based on CLS ensembles, and Wilson twisted mass valence quarks at maximal twist. We employ as external input the isoQCD masses and decay constants of pions and kaons, and the gradient flow scale t_0 as an intermediate scale. The analysis includes ensembles in the vicinity of the physical point and five values of the lattice spacing down to $a \approx 0.038$ fm. The determination of t_0 is carried out using three approaches: the unitary setup where Wilson quarks are used in the sea and valence sectors, the mixed action setup with Wilson twisted mass valence quarks, and by combining the data from the two previous cases. We observe that this combination leads to an improved control over the systematics uncertainties. We will furthermore explore the impact of setting the scale using solely f_π, instead of a flavour averaged linear combination of f_π and f_K.

Algorithms and artificial intelligence / 420

On the geometric convergence of HMC on Riemannian manifolds

Authors: Xinhao Yu[1]; Anthony Kennedy[1]

[1] *University of Edinburgh*

Corresponding Authors: adk@ph.ed.ac.uk, s1871834@ed.ac.uk

On the geometric convergence of HMC on Riemannian manifolds.

In this presentation we apply Harris' ergodic theorem on Markov chains to prove the geometric convergence of Hamiltonian Monte Carlo: first on compact Riemannian manifolds, and secondly on a large class of non-compact Riemannian manifolds by introducing an extra Metropolis step in the radial direction. We shall use ϕ^4 theory as an explicit example of the latter case.

Theoretical developments / 72

Tensor renormalization group study of (1+1)-dimensional U(1) gauge-Higgs model at θ=π with Lüscher's admissibility condition

Author: Shinichiro Akiyama[1]

Co-author: Yoshinobu Kuramashi [2]

[1] *University of Tsukuba*

[2] *University of Tsukuba/RIKEN AICS*

Corresponding Authors: akiyama@ccs.tsukuba.ac.jp, kuramasi@het.ph.tsukuba.ac.jp

We use the tensor renormalization group to investigate the phase structure of the (1+1)-dimensional U(1) gauge-Higgs model with a θ term. The U(1) gauge action is constructed with Lüscher's admissibility condition. Using the tensor renormalization group, both the complex action problem and topological freezing problem in the standard Monte Carlo simulation are avoided. We find a first-order phase transition for a large positive Higgs mass-squared regime at $\theta = \pi$, where the $\mathbb{Z}_2$ charge conjugation symmetry is spontaneously broken. On the other hand, the symmetry is restored for sufficiently small Higgs mass-squared. We determine the critical endpoint as a function of the Higgs mass parameter and show the critical behavior is in the two-dimensional Ising universality class.

Hadronic and nuclear spectrum and interactions / 96

Distillation and position-space sampling for local multiquark interpolators

Author: Andres Stump[1]

Co-author: Jeremy Green [2]

[1] *Humboldt-Universität zu Berlin*

[2] *DESY*

Corresponding Authors: andres.stump@hu-berlin.de, jeremy.green@desy.de

The distillation method in lattice QCD is a smearing method that uses the eigenvectors of the spatial Laplacian to construct an N-dimensional subspace in which the Dirac operator can be fully inverted. This approach works well for nonlocal operators such as meson-meson or baryon-baryon interpolators. But when studying exotic hadrons we also want to include local multiquark interpolators with four or more quarks to arrive at the correct spectrum. This is computationally expensive within distillation because of the large rank of the involved tensors: the cost scales as N^5 or N^7 for tetraquark or hexaquark interpolators respectively. I will present a position-space sampling method which addresses this issue by computing the momentum projection only over a sparse grid instead of over the full spatial lattice. I will show the efficiency of this method for simple two-point functions. Our first real application is the doubly charmed tetraquark $T_{cc}^+(3875)$ observed at LHCb for which I may show spectroscopy results for local tetraquark interpolators in combination with nonlocal meson-meson interpolators using the variational method.

QCD at non-zero temperature / 87

The Equation of State of QCD up to the Electro-Weak scale - part 1

Authors: Leonardo Giusti[1]; Matteo Bresciani[2]; Mattia Dalla Brida[1]; Michele Pepe[3]

[1] *University of Milano-Bicocca*

[2] *Università di Milano Bicocca*

[3] *INFN - Sez. Milano Bicocca*

Corresponding Authors: m.bresciani9@campus.unimib.it, mattia.dallabrida@unimib.it, michele.pepe@mib.infn.it, leonardo.giusti@unimib.it

We present two non-perturbative strategies for computing the QCD Equation of State up to high temperatures, designed to be computationally efficient and based on shifted boundary conditions. Using Monte Carlo lattice simulations of QCD with 3 flavours of O(a)-improved Wilson massless quarks and the Wilson gauge action, we obtain results for the entropy density $s(T)/T^3$ in the continuum limit. Our findings cover a temperature range from a few GeV up to the Electro-Weak scale. Additionally, we compare our results with predictions from high-temperature perturbation theory. The details of the numerical computation are discussed in the companion talk (part 2) of this contribution.

Structure of hadrons and nuclei / 159

Studies of nucleon isovector structures with the PACS10 superfine lattice

Author: Ryutaro Tsuji[1]

Co-authors: Eigo Shintani [2]; Hiromasa Watanabe [3]; Ken-Ichi Ishikawa [4]; Kohei Sato [2]; Shoichi Sasaki [5]; Takeshi Yamazaki [6]; Yasumichi Aoki [7]; Yoshinobu Kuramashi [2]

[1] *KEK*

[2] *University of Tsukuba*

[3] *YITP, Kyoto University*

[4] *Hiroshima University*

[5] *Department of Physics, Tohoku University*

[6] *Univ. of Tsukuba*

[7] *RIKEN*

Corresponding Authors: yamazaki@het.ph.tsukuba.ac.jp, eigo.shintani@gmail.com, ishikawa@theo.phys.sci.hiroshima-u.ac.jp, rtsuji@post.kek.jp, yasumichi.aoki@riken.jp, ssasaki@nucl.phys.tohoku.ac.jp, ksatoh@het.ph.tsukuba.ac.jp, kuramasi@het.ph.tsukuba.ac.jp

We present results of nucleon structures measured in 2+1 flavor QCD with the physical light quarks in a large spatial extent of about 10 fm. Our calculations are carried out with the PACS10 gauge configurations generated by the PACS Collaboration with the stout-smeared $O(a)$ improved Wilson fermions and Iwasaki gauge action at β=1.82, 2.00 and 2.20 corresponding to the lattice spacings of 0.09 fm (coarse), 0.06 fm (fine) and 0.04 fm (superfine) respectively. In this talk, we will mainly report our preliminary results of nucleon isovector form factors obtained with the superfine lattice.

Quark and lepton flavour physics / 263

Bringing near-physical QCD+QED calculations beyond the electro-quenched approximation

Author: Ryan Hill[1]

[1] *University of Edinburgh*

Corresponding Author: ryan.hill@ed.ac.uk

In this talk I will present ongoing work to calculate quark-disconnected isospin-breaking corrections to leptonic meson decays at leading order on RBC-UKQCD physical-point domain-wall ensembles. We follow on from previous work at non-physical masses by making use of efficient estimators to address the computational challenges in estimating the relevant quark-disconnected subdiagrams. Efficiently estimating these diagrams at near-physical masses lowers the computational barrier for ab-initio electro-unquenched calculations of precision observables, such as hadronic mass-splittings and meson decay constants. I will present preliminary findings at a coarse lattice spacing and provide an outlook for the future.

Particle physics beyond the Standard Model / 153

Symmetric mass generation for staggered fermions

Author: Simon Catterall[1]

[1] *Syracuse University*

Corresponding Author: smcatterall@gmail.com

I will describe new strongly coupled phases of staggered fermions in which all states can be given mass without breaking any exact lattice symmetries.
Numerical results for Higgs-Yukawa and gauge theories will be shown.
A necessary condition for the existence of such phases is the cancellation
of a certain exact lattice 't Hooft anomaly. I will show that the minimal
anomaly free theory has a continuum limit with the global
symmetries and matter representations of the well known Pati-Salam GUT containing the Standard Model.

Standard Model parameters / 446

Scale setting on the 2+1+1 HISQ ensembles: progress report

Author: Alexei Bazavov[1]

Co-authors: Aida El-Khadra [2]; Andreas Kronfeld [3]; Anthony Grebe [4]; Carleton DeTar [5]; Claude Bernard [6]; Elvira Gamiz [7]; Leon Hostetler [8]; Steven Gottlieb [8]; Urs Heller [9]; William Jay [10]; Yin Lin [10]

[1] *Michigan State University*

[2] *University of Illinois Urbana-CHampaign*

[3] *Fermilab*

[4] *Fermi National Accelerator Laboratory*

[5] *University of Utah*

[6] *Washington University*

[7] *University of Granada*

[8] *Indiana University*

[9] *Physical Review D, American Physical Society*

[10] *MIT*

Corresponding Authors: ask@fnal.gov, sg@indiana.edu, bazavov@msu.edu, cb@lump.wustl.edu, leonhost@iu.edu, megamiz@ugr.es, agrebe@mit.edu, detar@physics.utah.edu, heller@aps.org, yin01@mit.edu, axk@illinois.edu, willjay@mit.edu

We discuss recent progress on determining the gradient flow scales t0 and w0 on the 2+1+1 HISQ ensembles generated by the MILC collaboration. For the relative scale setting we explore several discretization schemes of the action density for the flow and observable. For the absolute scale setting, we report some preliminary results on the Omega baryon mass computation with HISQ.

Algorithms and artificial intelligence / 441

Worldvolume Hybrid Monte Carlo algorithm for group manifolds

Author: Masafumi Fukuma[1]

Co-author: Yusuke Namekawa [2]

[1] *Kyoto University*

[2] *Hiroshima University*

Corresponding Authors: fukuma@gauge.scphys.kyoto-u.ac.jp, namekawa@hiroshima-u.ac.jp

The Worldvolume Hybrid Monte Carlo (WV-HMC) method [arXiv:2012.08468] is a reliable and versatile algorithm for solving the sign problem. This method eliminates the ergodicity problem inherent in methods based on Lefschetz thimbles at low cost. In this talk, in preparation for its application to lattice QCD, we extend the WV-HMC method to the case where the configuration space is a group manifold. The discussion will focus on models with topological terms.

Theoretical developments / 46

Spectroscopy by Tensor Renormalization Group Method

Authors: Fathiyya Izzatun Az Zahra[1]; Shinji Takeda[1]

Co-author: Takeshi Yamazaki [2]

[1] *Kanazawa University*

[2] *Univ. of Tsukuba*

Corresponding Authors: fathiyyaazzahra@gmail.com, takeda@hep.s.kanazawa-u.ac.jp, yamazaki@het.ph.tsukuba.ac.jp

We present a spectroscopy scheme for lattice field theory by using tensor renormalization group method combining with transfer matrix formalism. By using this scheme, we can not only compute the energy spectrum for the lattice theory but also determine the quantum number of the energy eigenstate. Unlike spectroscopy by Monte Carlo algorithm, this scheme can extract the energy spectrum with relatively small error without considering large time extent in the lattice. Furthermore, the wave function of one-particle state energy can also be obtained, and its momentum can be classified. Additionally, this scheme can also identify the momentum of two-particle state energy. Lastly, we use Lüscher formula to obtain the scattering phase shift from the two-particle state energy whose total momentum is zero. As a demonstration, we apply this scheme to (1+1)d Ising Model.

Hadronic and nuclear spectrum and interactions / 382

Progress in Reconstructing the Hadronic Tensor from Euclidean Correlators

Authors: Andreas Kronfeld[1]; Douglas Stewart[2]; Luchang Jin[2]; William Jay[3]; thomas blum[4]

[1] *Fermilab*

[2] *University of Connecticut*

[3] *MIT*

[4] *UConn*

Corresponding Authors: ask@fnal.gov, douglas.stewart@uconn.edu, thomas.blum@uconn.edu, willjay@mit.edu, luchang.jin@uconn.edu

Calculations in lattice QCD are typically carried out in Euclidean time. Many quantities of physical interest require analytic continuation from Euclidean to Minkowski spacetime. This Wick rotation enacting a spectral reconstruction presents a difficult challenge in numerical inversion. We report on work to replicate the calculation by Alexandrou, *et al.* of the smeared R-ratio from lattice datasets computed via the Hansen-Lupo-Tantalo method using Domain Wall and Staggered fermion actions. Although computationally advantageous, staggered fermions present certain additional challenges for spectral reconstructions. In addition to the R-ratio, we also report on a Euclidean window quantity for the HVP contribution to the muon anomaly using the spectral reconstruction technique.

QCD at non-zero temperature / 100

The Equation of State of QCD up to the Electro-Weak scale - part 2

Authors: Matteo Bresciani[1]; Mattia Dalla Brida[2]; Leonardo Giusti[2]; Michele Pepe[3]

[1] *Università di Milano Bicocca*

[2] *University of Milano-Bicocca*

[3] *INFN - Sez. Milano Bicocca*

Corresponding Authors: m.bresciani9@campus.unimib.it, mattia.dallabrida@unimib.it, michele.pepe@mib.infn.it, leonardo.giusti@unimib.it

In this talk we detail the non-perturbative computation of the entropy density in QCD with $N_f = 3$ massless O(a)-improved Wilson fermions, in a temperature range from a few GeV up to the Electro-Weak scale. This contribution complements the companion talk (part 1) where the theoretical strategy and main results for determining the QCD Equation of State are reported. We formulate QCD in a moving reference frame, where the fields satisfy shifted boundary conditions along the temporal direction and periodic boundary conditions otherwise. In this setup the entropy density can be computed as the derivative of the free-energy density with respect to the shift. At each physical value of the temperature we simulate four lattice spacings and extrapolate the entropy density to the continuum limit, attaining a final accuracy of about 1 percent.

Structure of hadrons and nuclei / 218

Renormalisation Group Equations for 2+1 clover Fermions

Author: Roger Horsley[1]

[1] *University of Edinburgh*

Corresponding Author: rhorsley@ph.ed.ac.uk

Many simulations now have many lattice spacings available, and it is of interest to investigate how they scale.In this talk we first derive renormalisation group equations appropriate for 2+1 clover fermions. This is then used together with pion mass and wilson flow data at five lattice spacings to study scaling.

Quark and lepton flavour physics / 400

Finite-volume formalism for physical processes with an electroweak loop integral

Authors: Xinyu Tuo[1]; Xu Feng[2]

[1] *Brookhaven national laboratory*

[2] *Peking University*

Corresponding Authors: xu.feng@pku.edu.cn, ttxxyy.tuo@outlook.com

This study investigates finite-volume effects in physical processes involving the combination of long-range hadronic matrix elements with electroweak loop integrals. We adopt the idea of implementing the electroweak part in the infinite-volume version. A general approach is established for correcting finite-volume effects in cases where the hadronic intermediate states are dominated by either a single particle or two particles. The finite-volume formalism developed in this study has broad applications, including the QED corrections in various processes and the two-photon exchange contribution in $K_L \to \mu^+\mu^-$ decay.

Particle physics beyond the Standard Model / 155

Renormalization group studies of the 8-flavor SU(3) system

Authors: Anna Hasenfratz[1]; Curtis Peterson[2]; Oliver Witzel[3]

[1] *University of Colorado*

[2] *University of Colorado Boulder*

[3] *University of Siegen*

Corresponding Authors: anna@eotvos.colorado.edu, oliver.witzel@uni-siegen.de, cupe6205@colorado.edu

Lattice models with 2 sets of staggered fermions, corresponding to 8 Dirac flavors at the perturbative fixed point, are free of all 't Hooft anomalies. They can support symmetric mass generation phase (SMG) where mass generation occurs without symmetry breaking.
The SU(3) gauge model has an SMG phase in the strong coupling that appears to be separated from the weak coupling phase by a continuous phase transition.
We investigate the renormalization group β function in our quest to describe the infrared nature of the weak coupling phase.

Standard Model parameters / 365

Progress on the infinite volume based gradient flow for high precision determination of the $\Lambda_{\bar{MS}}$ scale of QCD.

Authors: Chik Him Wong[1]; Julius Kuti[2]; Szabolcs Borsanyi[1]; Zoltan Fodor[3]

[1] *University of Wuppertal*

[2] *U.C. San Diego*

[3] *University of Wuppertal, Penn State University, Eotvos University, IAS Jülich, UC San Diego*

Corresponding Authors: borsanyi@uni-wuppertal.de, jkuti@ucsd.edu, cwong@uni-wuppertal.de

We recently introduced and tested the application of the infinite volume based gradient flow for the scale dependent renormalization of the strong coupling. Recent developments of this alternative approach are reported for the high precision determination of the beta-function and the physical scale of the $\Lambda_{\bar{MS}}$ parameter in QCD with three massless flavors and its Yang-Mills limit.

QCD at non-zero temperature / 86

Baryonic screening masses at very high temperatures

Authors: Davide Laudicina[None]; Leonardo Giusti[1]; Michele Pepe[2]; Pietro Rescigno[3]; Tim Harris[4]

[1] *University of Milano-Bicocca*

[2] *INFN - Sez. Milano Bicocca*

[3] *University of Milano Bicocca*

[4] *Helmholtz-Institut Mainz*

Corresponding Authors: harrist@phys.ethz.ch, d.laudicina1@campus.unimib.it, michele.pepe@mib.infn.it, p.rescigno1@campus.unimib.it, leonardo.giusti@unimib.it

We present the first detailed investigation of the baryonic screening masses with nucleon quantum numbers in the extremely high temperature regime of QCD. Baryonic screening masses have been computed non-perturbatively on the lattice in the range of temperature from 1 GeV up to 160 GeV as well as at next-to-leading order in the dimensionally reduced effective theory, where quarks are treated as heavy fields. In the entire range of temperature, the non-perturbative results exhibit at most a 8% positive deviation due to interactions with respect to the free theory value $3\pi T$. The contribution due to the interactions is clearly visible up to the highest temperature considered, and cannot be explained by the expected leading behavior in the QCD coupling constant g over the entire range of temperatures explored.

Algorithms and artificial intelligence / 321

Applying the Worldvolume Hybrid Monte Carlo method to the (1+2)-dim Hubbard model

Author: Yusuke Namekawa[1]

Co-author: Masafumi Fukuma [2]

[1] *Hiroshima University*

[2] *Kyoto University*

Corresponding Authors: fukuma@gauge.scphys.kyoto-u.ac.jp, namekawa@hiroshima-u.ac.jp

The Worldvolume Hybrid Monte Carlo (WV-HMC) method [arXiv:2012.08468] is
a low-cost algorithm for solving the sign and the ergodicity problems simultaneously. We apply the WV-HMC method to the (1+2)-dim Hubbard model, which can be regarded as a prototype of QCD

at finite density. We investigate the computational scaling and compare the results of observables with those obtained by a non-thimble method using the ALF code.

Theoretical developments / 21

Tensor-network Toolbox for probing dynamics of non-Abelian Gauge Theories

Authors: Emil Mathew[1]; Indrakshi Raychowdhury[1]; Jesse Stryker[2]; Navya Gupta[3]; Nicholas Pomata[4]; Saurabh Kadam[5]; Zohreh Davoudi[6]

[1] *BITS Pilani KK Birla Goa Campus*

[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[3] *University of Maryland, College Park*

[4] *Joint Quantum Institute, University of Maryland at College Park, College Park, MD 20742, USA*

[5] *InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA*

[6] *Department of Physics, University of Maryland, College Park, MD 20742 USA*

Corresponding Authors: ksaurabh@uw.edu, navyag@umd.edu, davoudi@umd.edu, p20210036@goa.bits-pilani.ac.in, jstryker@lbl.gov, pomata@umd.edu, indrakshir@goa.bits-pilani.ac.in

Tensor-network methods are valuable Hamiltonian-simulation methods which enable probing dynamics of strongly-interacting quantum-many-body systems, including gauge theories, without encountering sign problems. They also have the potential to inform efficient quantum-simulation algorithms of the same theories. We develop and benchmark a matrix-product-state (MPS) ansatz for the SU(2) lattice gauge theory using the loop-string-hadron (LSH) framework. The LSH framework has been demonstrated to be advantageous in Hamiltonian simulation of non-Abelian gauge theories. It is applicable to varying gauge groups [SU(2) and SU(3)], boundary conditions, and in higher dimensions. In this talk, I report on progress in achieving the continuum limit of the static observables in a SU(2) gauge theory in (1+1) D and pushing the boundary of dynamical studies. The current toolbox can be applied to studying scattering processes in this model. It can also be straightforwardly generalized to (2+1)D given the simplified constraints in an LSH framework.

Hadronic and nuclear spectrum and interactions / 479

Reconstruction of the vector meson propagator using a generalized eigenvalue problem

Author: Fabian Justus Frech[1]

[1] *Bergische Universität Wuppertal*

Corresponding Author: frech@uni-wuppertal.de

For long distances in the euclidean time the vector meson () propagator has an exponentially decreasing signal-to-noise ratio.
However, the vector correlator not only consists of the vector meson but also of the propagator of a two-pion system with the same quantum numbers. We measure all two-pion propagators with an energy lower than the mass of the resting vector meson and employ a generalized eigenvalue problem (GEVP) to resolve the different contributing energy states. Using those we can reconstruct the propagator with a much smaller noise at large euclidean time
distances.
In this talk I present an efficient way to measure two-pion propagators and our results on reconstruction of the vector meson propagator with staggered fermions in a box.

Structure of hadrons and nuclei / 248

Updates on the parity-odd structure function of the nucleon from the Compton amplitude

Author: K. Utku Can[1]

Co-authors: Gerrit Schierholz [2]; James Zanotti [3]; Paul Rakow [4]; Roger Horsley [5]; Ross Young [3]

[1] *The University of Adelaide*

[2] *DESY*

[3] *University of Adelaide*

[4] *University of Liverpool*

[5] *University of Edinburgh*

Corresponding Authors: gerrit.schierholz@desy.de, james.zanotti@adelaide.edu.au, rakow@liverpool.ac.uk, ross.young@adelaide.edu.au, kadirutku.can@adelaide.edu.au, rhorsley@ph.ed.ac.uk

The parity-odd structure function, F_3, accessible via neutrino-nucleon deep-inelastic scattering, plays an important role in estimating the hadronic uncertainties in the extracted weak parameters of the Standard Model (SM). Controlled and reduced uncertainties in SM processes are crucial for beyond the standard model searches progressing via CKM matrix elements or the weak mixing angle. Incidentally, the electroweak box diagrams contribute the dominant theoretical uncertainty and can be related to the lowest Nachtmann moment of F_3 through a dispersive approach, enabling a model-independent estimation of their contributions. Unfortunately, the experimental data for F_3 either do not exist or belong to a separate isospin channel which requires modelling, thus, makes it challenging to control the systematic uncertainties. Therefore a first-principles calculation of F_3 is highly desirable to reliably calculate the electroweak boxes. Additionally, the Gross-Llewellyn Smith (GLS) sum rule is also associated with the lowest moment of F_3 structure function and in the parton model, it counts the number of valence quarks in a nucleon, with known perturbative corrections up to $\mathcal{O}(\alpha_s^4)$. A precise first-principles determination of the Q^2 dependence of the GLS sum rule would therefore provide a pathway to a high-accuracy extraction of α_s from an hadronic observable.

In this contribution, we provide an update on the CSSM/QCDSF/UKQCD Collaboration's progress in calculating the lowest moment of the F_3 structure function from the forward Compton amplitude at the SU(3) symmetric point. We study the Q^2 dependence of the lowest moment and give a comparison to the GLS sum rule. We discuss the effects of higher-twist/power corrections, extraction of α_s, and a possible determination of electroweak box contributions.

Quark and lepton flavour physics / 480

On-shell derivation of QED finite-volume effects

Author: Matteo Di Carlo[1]

[1] *CERN*

Corresponding Author: matteo.dicarlo@cern.ch

In this talk we present a derivation of power-like electromagnetic finite-volume effects to charged hadron masses and leptonic decay rates, which only relies on hadronic matrix elements evaluated on shell. We make comparisons with existing calculations in the literature and discuss, more in general, the status and prospects of lattice calculations of electromagnetic corrections to hadronic observables that make use of finite-volume massless photon actions.

Particle physics beyond the Standard Model / 229

Investigating SU(3) with Nf=8 fundamental fermions at strong renormalized coupling

Author: Oliver Witzel[1]

Co-author: Anna Hasenfratz [2]

[1] *University of Siegen*

[2] *University of Colorado*

Corresponding Authors: oliver.witzel@uni-siegen.de, anna@eotvos.colorado.edu

Tantalizing signs for a novel phase with symmetric mass generation have been reported for the SU(3) gauge system with $N_f = 8$ fundamental fermions (represented by two sets of staggered fields) at very large renormalized coupling (g^2_{GF}
$gtrsim 25$). To scrutinize these findings, we are generating a set of large volume zero temperature ensembles using nHYP improved staggered fermions with additional Pauli-Villars fields to tame gauge field fluctuations. We consider the low-lying meson spectrum, the eigenmodes of the Dirac operator, as well as gradient flow measurements and attempt to understand their implications on the nature of SU(3) with $N_f = 8$ fundamental fermions.

Standard Model parameters / 466

Precision determination of the Wilson-flow scale w_0

Author: Gen Wang for the BMW collaboration[1]

[1] *Centre de Physique Theorique*

Corresponding Author: gen.wang@univ-amu.fr

I will present a precise determination of the Ω baryon mass in lattice units at seven lattice spacings down to a ~ 0.048 fm with N_f=2+1+1 staggered quarks, including QED and strong-isospin corrections. We perform these measurements by solving the Generalized Eigenvalue Problem, adapted to staggered fermions to fully resolve the negative parity and excited states. The measurements are then used to determine the value of the Wilson-flow scale w_0, in the continuum limit at physical quark masses, with unprecedented precision.

Theoretical developments / 457

Entropy in the gravitational collapse or a scalar field

Authors: Christian Hölbing[1]; Jana N. Guenther[1]; Lukas Varnhorst[1]

[1] *University of Wuppertal*

Corresponding Authors: jguenther@uni-wuppertal.de, varnhorst@uni-wuppertal.de

As a first step towards semiclassically simulating a gravitationally collapsing spherical symmetric configuration of a scalar quantum field, we numerically study such a system in the quenched case. In this approximation, only the uniquely defined classical part of the stress energy tensor is considered as a source in the Einstein equation. While avoiding complications with renormalization, this approximation still contains interesting physics on its own. Here, we focus on the entanglement entropy of the quantum field and related observables and compare them to the result of Srednicki in

flat spacetime as well as to the Beckenstein-Hawking value for the entropy of a Schwarzschild black hole. We also discuss possible strategies towards unquenching.

Hadronic and nuclear spectrum and interactions / 445

Updates on anisotropic pure gauge ensembles with HISQ

Authors: Alexei Bazavov[1]; Ioannis Trimis[1]; Johannes Heinrich Weber[2]

[1] *Michigan State University*

[2] *Humboldt-Universität zu Berlin*

Corresponding Authors: trimisio@msu.edu, johannes.weber@physik.hu-berlin.de, bazavov@msu.edu

The primary goal of this project is the reconstruction of quarkonium spectral functions from thermal lattice correlators, relevant for the study of Quark-Gluon Plasma in heavy-ion collisions. To this end, we pursue the generation of fully dynamical anisotropic HISQ ensembles, aiming at a physical strange quark and a heavier-than-physical light quark mass, corresponding to a 300 MeV continuum pion mass. We report on tuning the gauge anisotropy and the lattice spacing of anisotropic pure gauge ensembles with tree-level Symanzik action using the gradient flow and compare various tuning schemes. We also discuss the simultaneous tuning of the strange quark mass and the quark anisotropy with HISQ, using spectrum measurements on quenched ensembles. We compare different ways to tune the quark anisotropy. Finally, we discuss pion taste splittings for HISQ at anisotropies up to 8.

Quark and lepton flavour physics / 435

A massive nonperturbative renormalisation scheme for heavy quark observables

Author: Rajnandini Mukherjee[1]

Co-authors: Felix Erben [2]; J. Tobias Tsang [2]; Jonathan Flynn [1]; Luigi Del Debbio [3]

[1] *University of Southampton*

[2] *CERN*

[3] *University of Edinburgh*

Corresponding Authors: r.mukherjee@soton.ac.uk, j.t.tsang@cern.ch, j.m.flynn@soton.ac.uk, felix.erben@cern.ch

Heavy quark observables on the lattice commonly suffer from (am_q)-sized discretisation errors, which affects their extrapolation to the continuum. We present results from a first numerical implementation of a massive NPR scheme, RI/mSMOM, with the aim of absorbing cutoff effects. In particular, we compute renormalisation constants for fermion bilinears at non-vanishing heavy quark masses and compare the approach to the continuum of the renormalised charm quark mass with that from a mass-independent scheme.

Plenary / 277

Hadron Structure via PDFs

Author: Tie-Jiun Hou[1]

[1] *University of South China*

Corresponding Author: tiejiun.hou@gmail.com

Parton Distribution Functions (PDFs) are essential ingredients in realistic cross-section calculations within the framework of perturbative QCD. They describe the x-dependent structure of hadrons based on global analyses of hard-scattering measurements. PDFs play a crucial role in the search for new physics and precision measurements at hadron colliders, making the control of PDF uncertainties paramount. A limitation of PDFs from global analyses is their larger uncertainty in regions where experimental data is scarce. Starting from first principle operator definitions of PDFs, PDF-related quantities are computed in the framework of Lattice QCD, and they provide comparisons and supplements for PDF from global analysis. This presentation will discuss the current status and future prospects of PDF global analyses incorporating Lattice QCD inputs, highlighting their potential to enhance our understanding of hadron structure.

Plenary / 366

Hadron structure via GPDs

Author: Shohini Bhattacharya[1]

[1] *Los Alamos National Laboratory*

Corresponding Author: tug23108@temple.edu

Recent advancements have facilitated the approximate computation of light-cone correlation functions in lattice QCD through the evaluation of their Euclidean counterparts. In this presentation, we will provide a brief overview of these significant developments and discuss their direct implications for Generalized Parton Distributions (GPDs). Additionally, we will highlight the importance of GPDs in understanding the internal structure of hadrons.

Plenary / 311

Lattice QCD in the Frontier of Electron Ion Colliders

Author: Swagato Mukherjee[1]

[1] *Brookhaven National Laboratory*

Corresponding Author: swagato@bnl.gov

In our quest to uncover the secrets of hadrons, a groundbreaking tool emerges—the Electron Ion Collider (EIC). Set to be constructed at the Brookhaven National Laboratory, the EIC will be one of the world's largest and most advanced accelerator facilities. With unmatched resolving power and intensity, it acts as a powerful microscope, allowing us to explore how hadrons emerge from the fundamental particles—quarks and gluons.

The synergy between real-world observations from the EIC and the virtual laboratory of Lattice Quantum Chromodynamics (Lattice QCD) is crucial, offering a comprehensive understanding of how these fundamental particles govern the emergence and properties of hadrons. Together, they promise to reveal the underlying components and dynamics, deepening our knowledge and marking a significant leap forward in the exploration of particle physics. This talk will highlight the pioneering and essential role of Lattice QCD in the upcoming EIC frontier.

Plenary / 491

Hadron Spectroscopy from lattice QCD: current status and future

Author: Nilmani Mathur[1]

[1] *Tata Institute of Fundamental Research*

Corresponding Author: nilmani@theory.tifr.res.in

From the early days of lattice QCD, hadron spectroscopy has been an integral part of it. With improved control over statistical and systematic errors, ground states of many hadrons are now very well determined by lattice QCD calculations. Significant progress has also been made in excited state calculations. These advancements, along with developments in amplitude analysis formalisms, have greatly enhanced the study of multi-hadron scatterings. Lattice QCD calculations are making excellent contributions to the study of exotic hadrons and can help decipher their structures, potentially aiding in the discovery of many new hadrons in the future. However, lattice QCD-based studies of nuclear physics have not yet reached the same level of precision, and much progress is still needed. In this talk, I will provide an overview of the current status of hadron spectroscopy, including exotic hadrons, and discuss future prospects and implications.

Plenary / 288

Prospects for lattice field theory beyond the Standard Model

Author: Georg Bergner[1]

[1] *University of Jena*

Corresponding Author: georg.bergner@uni-jena.de

This talk summarises the explorations of theories beyond the Standard Model using lattice simulation methods. After a brief comment on the current status of the Standard Model extensions, the essential contribution made by numerical simulations in various approaches will be discussed. However, this also poses new challenges for simulation methods. The interplay with new theories gives rise to more general theoretical considerations that establish a close relationship with investigations of fundamental concepts such as gauge/gravity duality, confinement, or renormalisation group flow. The investigation of theories beyond standard QCD applications therefore opens up a broader perspective for our fundamental understanding, which could ultimately also lead to alternative ways of thinking about the shortcomings of the Standard Model

Plenary / 195

Update on Glueballs

Author: Colin Morningstar[1]

[1] *Carnegie Mellon University*

Corresponding Author: cmorning@andrew.cmu.edu

An update on glueball studies in lattice QCD and from some other methods is presented. The recent BES III announcement of a pseudoscalar glueball candidate is discussed.

Plenary / 347

Nuclear Matrix Elements for Neutrinoless Double-Beta Decay

Author: Anthony Grebe[1]

[1] *Fermi National Accelerator Laboratory*

Corresponding Author: agrebe@mit.edu

Neutrinoless double-beta decay ($0\nu\beta\beta$) is a hypothesized decay mode of certain nuclear isotopes that, if observed, would demonstrate that neutrinos are their own antiparticles. Interpreting experimental measurements of $0\nu\beta\beta$ half-lives in terms of neutrino properties requires knowledge of the nuclear matrix elements encoding the hadronic physics involved in these decays. These matrix elements are currently estimated with nuclear models which produce large systematic uncertainties and are currently a major limiting factor in experimental searches. Nuclear effective field theory (EFT) can be used to express matrix elements of relevance to $0\nu\beta\beta$ in terms of a set of low-energy constants (LECs). Once these LECs are constrained using lattice QCD, they can inform the corresponding nuclear-structure calculations in larger nuclei. This talk will discuss recent developments in lattice QCD calculations of pion and two-nucleon matrix elements of relevance to $0\nu\beta\beta$ decay proceeding by both short- and long-distance mechanisms and the implications of these calculations for matching the relevant LECs of the EFTs.

Plenary / 359

$U(1)_A$ breaking in hot QCD in the chiral limit

Author: Tamas G. Kovacs[1]

[1] *Department of Physics and Astronomy, Eotvos University, Budapest*

Corresponding Author: tamas.gyorgy.kovacs@ttk.elte.hu

We propose a simple instanton-based random matrix model of hot QCD that in the quenched case precisely reproduces the distribution of the lowest lattice overlap Dirac eigenvalues. Even after including dynamical quarks the model can be easily simulated in volumes and for quark masses that will be out of reach for direct lattice simulations in the foreseeable future. Our simulations show that quantities connected to the $U(1)_A$ and $SU(N_f)_A$ chiral symmetry are dominated by eigenvalues in a peak of the spectral density that becomes singular at zero in the thermodynamic limit. This spectral peak turns out to be produced by an ideal instanton gas. By generalizing Banks-Casher type integrals for the singular spectral density, definite predictions can be given for physical quantities that are essential to test chiral symmetry breaking, but presently impossible to compute reliably with direct lattice simulations.