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Book of Abstracts

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$B \to K^*$ decays in a finite volume

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We propose a framework for the extraction of the $B \to K^*$ decay form factors from lattice data, based on the non-relativistic effective field theory in a finite volume. A possible admixture of the ηK channel is studied, and the multi-channel Lellouch-Luescher formula is reproduced. Further, a procedure is
formulated for the extraction of the form-factors at the resonance pole. The definition of the photon virtuality at the resonance pole is discussed. The limit of an infinitely narrow resonance is investigated in detail in the multi-channel case.

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$B \to \pi$ semileptonic decay form factors with NRQCD/HISQ quarks

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We report on our ongoing calculation of the $B \to \pi$ semileptonic decay form factors using NRQCD/HISQ valence quarks with MILC's $N_f = 2+1$ asqtad ensembles. The use of HISQ light quarks allows simulation at large pion momenta, corresponding to $q^2 \approx 0$, with controlled $(ap)^2$ errors. We perform a simultaneous chiral, continuum, and kinematic extrapolation using the Hard Pion ChPT modified z expansion developed in Phys. Rev. D 90, 054506 (2014). This approach permits lattice simulation in a kinematic region previously considered inaccessible to lattice QCD and promises significant reduction in form factor uncertainties at low q^2.

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$B_{(s)} \to D_{(s)}$ semileptonic decays with NRQCD-HISQ valence quarks

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We present a calculation of the form factors, f_0 and f_+, for the $B_{(s)}$ to $D_{(s)}$ semileptonic decays. Our work uses the MILC $n_f = 2 + 1$ asqtad configurations with NRQCD and HISQ valence quarks at four values of the momentum transfer q^2. We present preliminary results for our combined chiral-continuum extrapolation.

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D meson semileptonic decays in lattice QCD with Moebius domain-wall quarks

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We report on our study of D meson semileptonic decays in 2+1 flavor lattice QCD. Gauge ensembles are generated at the lattice cutoffs around 2.5 GeV and above and at pion masses as low as 300 MeV. We employ the Moebius domain-wall action for both light and charm quarks. We report our preliminary results for the vector and scalar form factors.

Chiral Symmetry / 244

θ-dependence of the massive Schwinger model

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Understanding the role of the θ parameter in QCD and its connection with the strong CP problem and axion physics is one of the major challenges for high energy theorists. Due to the sign problem, at present only the QCD topological susceptibility is well known. Using an algorithmic approach that could potentially be extended to QCD, we study as a first step the θ-dependence in the massive Schwinger model, and try to verify a conjecture of Coleman.

Weak Decays and Matrix Elements / 164

$|V_{cb}|$ from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ zero-recoil form factor using 2+1+1 flavour HISQ and NRQCD

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We present our recent calculation of the zero-recoil form factor for the semileptonic decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ using lattice QCD with 2+1+1 flavours of highly improved staggered quarks in the sea (the MILC HISQ configurations) and using non-relativistic QCD for the bottom quark. We obtain $\mathcal{F}(1)$ and combine this with the latest HFAG average of $\eta_{EW}\mathcal{F}(1)|V_{cb}|$ to get a value for $|V_{cb}|$.

Theoretical Developments / 303

’t Hooft model on the lattice

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We use a recently formulated expression for computing meson masses at large N to study the spectrum of two-dimensional QCD in the large N limit. The model serves as a testing ground to explore methodology of meson mass determination with different techniques and versions of lattice fermions.

Poster / 45

A G(2)-QCD Neutron Star

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G2-QCD, i.e. QCD with the gauge group SU(3) replaced by the exceptional group G(2), shares many features with SU(3). But it is accessible at finite density on the lattice, as it has no sign problem, and at the same time has a neutron.

Therefore, this theory can sustain in princple neutron star. Using the equation of state for this theory from lattice simulations, we solve the Oppenheimer-Volkoff equation and obtain the mass-radius-relation of such neutron stars.

This study shows how different phases, visible in the equation of state, influence the mass-radius relation, and therefore gives guidance for the case of full QCD and true neutron stars.

Plenary Session / 398

A New Perspective on Chiral Gauge Theories

David Kaplan[1]

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I review some of the different approaches that have been pursued in attempting to define chiral gauge theories on the lattice, all of which are procedures for eliminating unwanted mirror fermions from the theory. I then discuss a recently published proposal with D. Grabowska that combines domain wall fermions with gradient flow as a new idea for how to decouple the mirror fermions, and which seems to imply unexpected nonperturbative effects.

Nonzero Temperature and Density / 25

A gauge invariant Debye mass for the complex heavy-quark potential

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The concept of a screening mass is a powerful tool to simplify the intricate physics of in-medium test charges surrounded by light charge carriers. While it has been successfully used to describe electromagnetic properties, its definition and computation in QCD is plagued by questions of gauge invariance and the presence of non-perturbative contributions from the magnetic sector.

Here we present a recent alternative definition [1] of a gauge invariant Debye mass parameter following closely the original idea of Debye and Hueckel. Our test charges are a static heavy quark-antiquark pair whose complex potential and its in-medium modification can be extracted using lattice QCD [2]. By combining in a generalized Gauss-Law the non-perturbative aspects of quark binding with a perturbative ansatz for the medium effects, we succeed to describe the lattice values of Re[V] and Im[V] [3] with a single temperature dependent parameter, in turn identified with a Debye mass.

We find that its behavior evaluated both in quenched QCD [4], as well as dynamical Nf=2+1 QCD [3] deviates from that in other approaches, such as hard-thermal-loop perturbation theory or from electric field correlators on the lattice. Around the phase transition e.g. its values tend to zero significantly faster than at weak-coupling.

[1] Y. Burnier, A.R. Phys.Lett. B753 (2016) 232-236
[2] A.R., T. Hatsuda, S. Sasaki, Phys.Rev.Lett. 108 (2012) 162001
[3] Y.Burnier, O. Kaczmarek, A.R. Phys.Rev.Lett. 114 (2015) 082001
[4] Y.Burnier, A.R. in preparation

Hadron Structure / 386

A high-statistics lattice QCD study of nucleon sigma terms

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For the Budapest-Marseille-Wuppertal collaboration

We present a lattice study of the u, d and s quark contents of the nucleon, determined using the Feynman-Hellmann theorem. Results are obtained from twenty-nine high-statistics simulations with four flavors of O(a)-improved Wilson quarks, four lattice spacings and a variety of quark masses.

Poster / 356

A local update algorithm for supersymmetric Yang-Mills quantum mechanics

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We present a local update algorithm for gauge theories with dynamical fermions which allows simulations in fixed canonical sectors. As a first application we perform canonical simulations in N=4 supersymmetric Yang-Mills quantum mechanics without a sign problem. Compared to previous studies, we obtain results with significantly better accuracy. We also discuss some aspects of the physics of this theory, including the appearance of flat directions in the bosonic potential and of phase transitions related to those.

Standard Model Parameters and Renormalization / 176

A massive momentum-subtraction scheme

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A new renormalization scheme is defined for fermion bilinears in QCD at non vanishing quark masses. This new scheme, denoted RI/mSMOM, preserves the benefits of the nonexceptional momenta introduced in the RI/SMOM scheme, and allows a definition of renormalized composite fields away from the chiral limit.

Algorithms and Machines / **10**

A method to compute derivatives of functions of large complex matrices

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We present a method for the numerical calculation of derivatives of functions of general complex matrices which also works for implicit matrix function approximations such as Krylov-Ritz type algorithms. An important use case for the method is the overlap Dirac operator at finite quark chemical potential. The evaluation of the overlap Dirac operator at finite chemical potential calls for the computation of the product of the sign function of a non-Hermitian matrix with some source vector. For non-Hermitian matrices the sign function can no longer be efficiently approximated with polynomials or rational functions. Instead one invokes implicit approximation algorithms, like Krylov-Ritz methods, that depend on the source vector. Our method allows for an efficient calculation of the derivatives of such implicit approximations, which is necessary for the computation of conserved lattice currents or the fermionic force in Hybrid Monte-Carlo or Langevin simulations. We also give an explicit deflation prescription for the case when one knows several eigenvalues and eigenvectors of the matrix being the argument of the differentiated function. To show that the method is efficient and well suited for practical calculations we provide test results for the two-sided Lanczos approximation of the finite-density overlap Dirac operator on $SU(3)$ gauge field configurations on lattices with sizes up to 14×14^3

Algorithms and Machines / **44**

A performance evaluation of CCS QCD Benchmark on Intel Xeon Phi (KNC) systems

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The most computationally demanding part of Lattice QCD simulations is solving quark propagators.
Quark propagators are typically obtained with a linear equation solver utilizing HPC machines.
The success of Lattice QCD simulations owes much to the development of numerical algorithms and optimization for the quark solver, and evolution of HPC machines.
The CCS QCD Benchmark is a benchmark program solving the Wilson-Clover quark propagator, and is developed at Center of Computational Sciences (CCS), University of Tsukuba.
This is designed to be as simple as possible and is written in plain Fortran 90 so that new algorithms or new HPC architectures can be evaluated quickly with this benchmark program.
We optimized the benchmark program for a Intel Xeon Phi (Knights Corner, KNC) system named "COMA (PACS-IX)" at CCS Tsukuba under the Intel Parallel Computing Center program.
A single precision BiCGStab solver with the overlapped Restricted Additive Schwarz (RAS) preconditioner was implemented using SIMD intrinsics, OpenMP and MPI in the offload-mode.
In this talk, we will show the optimization methods and the performance of the CCS QCD benchmark on the COMA system.

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A simple method to optimize HMC performance

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We present a cheap strategy to optimize Hybrid Monte Carlo parameters in simulations of QCD and QCD-like theories. We specialize to the case of mass-preconditioning, with multiple-time-step Omelyan integrators. Starting from properties of the shadow Hamiltonian we show how the optimal setup for the integrator can be chosen once the forces and their variances are measured, assuming that those only depend on the mass-preconditioning parameter.

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A study of the radiative transition $\pi\pi \to \pi\gamma^*$ with lattice QCD

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Lattice QCD calculations of radiative transitions between hadrons have in the past been limited to processes of hadrons stable under the strong interaction. Recently developed methods for $1 \to 2$ transition matrix elements in a finite volume now enable the determination of radiative decay rates of strongly unstable particles. Our lattice QCD study focuses on the process $\pi\pi \to \pi\gamma^*$, where the ρ meson is present as an enhancement in the cross-section. We use 2+1 flavors of clover fermions, initially at a pion mass of approximately 320 MeV and a lattice size of approximately 3.6 fm. The required 2-point and 3-point correlation functions are constructed from a set of forward, sequential and stochastic light quark propagators. In addition to determining the ρ meson resonance parameters via the Lüscher method, the scattering phase shift is used in concert with the $1 \to 2$ transition matrix element formalism of Briceño et al. to compute the $\pi\pi \to \pi\gamma^*$ amplitude at several values of the momentum transfer and $\pi\pi$ invariant mass.

Theoretical Developments / 318

A variational method for spectral functions

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The Generalized Eigenvalue Problem (GEVP) has been intensively used in the past in order to reliably extract energy levels from time-dependent euclidean correlators calculated in Lattice QCD. We propose an alternative formulation of the GEVP in frequency space. Our approach consists in applying the model independent Backus-Gilbert method to a set of euclidean two-point functions with common quantum numbers. A GEVP analysis in frequency space is then applied to a matrix of estimators that allows us, among other things, to obtain particular linear combinations of the initial set of operators that optimally overlap to different local regions in frequency. This approach can be interesting both for vacuum physics as well as for finite temperature problems.

Nonzero Temperature and Density / 341

A worm algorithm for the lattice CP(N-1) model

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The CP(N-1) model in 2D is an interesting toy model for 4D QCD as it possesses confinement, asymptotic freedom and a non-trivial vacuum structure. Due to the lower dimensionality and the absence

of fermions, the computational cost for simulating 2D CP(N-1) on the lattice is much lower than the one for simulating 4D QCD. However to our knowledge, no efficient algorithm for simulating the lattice CP(N-1) model has been tested so far, which also works at finite density. To this end we propose a new type of worm algorithm which is appropriate to simulate the lattice CP(N-1) model in a dual, flux-variables based representation, in which the introduction of a chemical potential does not give rise to any complications.

Nonzero Temperature and Density / 63

Abelian color cycles: a new approach to strong coupling expansion and dual representation for non-abelian lattice gauge theory.

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We present a dual approach for SU(2) lattice gauge theory, i.e., an exact mapping of the partition sum to new, so-called dual variables. The dual representation is constructed by decomposing the Wilson gauge action into "abelian color cycles" (ACC), which are loops in color space around plaquettes. The ACCs are complex numbers and as such commute, such that a dual representation can be obtained as in the abelian case. The original SU(2) degrees of freedom are integrated out and the dual degrees of freedom are occupation numbers of the ACCs, subject to constraints reflecting the original SU(2) symmetry. The approach is then extended to the case of SU(2) gauge fields with fermions. Analyzing the strong coupling region we show that the system is free of sign problems up to $O(\beta^3)$. The ACC concept can be generalized to other non-abelian gauge groups such as SU(3).

Applications Beyond QCD / 147

Absence of bilinear condensate in three-dimensional QED

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There are plausibility arguments that QED in three dimensions has a critical number of flavors of massless two-component fermions, below which scale invariance is broken by the presence of bilinear condensate. We present numerical evidences from our dynamical lattice simulations using overlap as well as Wilson-Dirac fermions for the absence of bilinear condensate using the following methods: finite-size scaling analysis of the low-lying eigenvalues of the Dirac operator, comparison of the eigenvalue distributions to the non-chiral random matrix theory, and by checking if the inverse participation ratio and number variance show ergodic behavior.

Algorithms and Machines / 259

Accelerating Lattice QCD Multigrid on GPUs Using Fine-grained Parallelization

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The past decade has witnessed a dramatic acceleration of lattice quantum chromodynamics calculations in nuclear and particle physics. This has been due to both significant progress in accelerating the iterative linear solvers using multi-grid algorithms, and due to the throughput improvements brought by GPUs. Deploying hierarchical algorithms optimally on GPUs is non-trivial owing to the lack of parallelism on the coarse grids, and as such, these advances have not proved multiplicative. Using the QUDA library, we demonstrate that by exposing all sources of parallelism that the underlying stencil problem possesses, and through appropriate mapping of this parallelism to the GPU architecture, we can achieve high efficiency even for the coarsest of grids. Results are presented for the Wilson-clover discretization, where we demonstrate up to 10x speedup over present state-of-the-art GPU-accelerated methods on Titan. Finally, we consider how the combination of multigrid, NVIDIA's new Pascal architecture and block Krylov solvers result in a multiplicative speedup of 100x versus prior GPU state of the art.

Algorithms and Machines / 34

Adaptive Aggregation-based Domain Decomposition Multigrid for Twisted Mass Fermions

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We extend the Adaptive Aggregation Based Domain Decomposition Multigrid (DD-αAMG) algorithm to $N_f = 2$ twisted mass fermions. We show numerical results for an $N_f = 2$ ensemble of twisted fermions with a clover term simulated at the physical value of the pion mass. We fine-tuned the parameters to achieve a speedup comparable to the one obtained for clover fermions. We also present a complete analysis of the aggregation parameters that provides a novel insight on the multigrid methods for lattice QCD independently of the fermion discretization.

Physics Beyond the Standard Model / 279

Adjoint SU(2) with four fermion interactions

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Four fermion interactions appear in many models of Beyond Standard Model physics. In composite Higgs models Standard Model fermion masses can be generated by four fermion terms. They are also expected to modify the dynamics of the new strongly interacting sector. In particular in technicolour models it has been suggested that they can be used to break infrared conformality and produce a walking theory with a large mass anomalous dimension. We study the SU(2) gauge theory with 2 adjoint fermions and a chirally symmetric four fermion term. We demonstrate chiral symmetry breaking at large four fermion coupling and study the phase diagram of the model.

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Algorithms for disconnected diagrams.

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Computing disconnected diagrams on the lattice involves taking the trace of the inverse of the Dirac operator. This is a computationally challenging problem, however recent algorithmic improvements such as low mode averaging and hierarchical probing have increased the efficiency of this trace estimation. We detail an algorithm that builds upon hierarchical probing by deflating the near null space of the Dirac matrix. An additional order of magnitude of variance reduction is achieved by combining these two methods and we explore this synergy both theoretically and experimentally. Finally, we apply this algorithm to calculate contributions to the Pauli and Dirac form factors of the nucleon, and present initial results.

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An a_0 resonance in strongly coupled $\pi\eta$, $K\overline{K}$ scattering from lattice QCD

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We present the first calculation of coupled-channel meson-meson scattering in the isospin $=1$, G-parity negative sector, with channels $\pi\eta$, $K\overline{K}$ and $\pi\eta'$, in a first-principles approach to QCD. From the discrete spectrum of eigenstates in three volumes extracted from lattice QCD correlation functions we determine the energy dependence of the S-matrix, and find that the S-wave features a prominent cusp-like structure in $\pi\eta \to \pi\eta$ close to $K\overline{K}$ threshold coupled with a rapid turn on of amplitudes leading to the $K\overline{K}$ final-state. This behavior is traced to an $a_0(980)$-like resonance, strongly coupled to both $\pi\eta$ and $K\overline{K}$, which is identified with a pole in the complex energy plane, appearing on only a single unphysical Riemann sheet. Consideration of D-wave scattering suggests a narrow tensor resonance at higher energy.

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An application of stochastic LapH method to Hadron interaction in lattice QCD

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The first principle calculation of hadron-hadron interaction is an important step toward the understanding of nuclear physics from QCD. The HAL QCD method is largely contributing to this purpose by making it possible to calculate nuclear potentials in lattice QCD. We now try to extend the HAL QCD method to systems such as $\pi - \pi$ and $\pi - N$, where pair creation and annihilation of quarks become possible, employing the stochastic LapH smearing. In this talk, we explain our methodology and report the current status on the application to two meson interactions.

Nonzero Temperature and Density / 223

Anderson localisation of Dirac eigenmodes in high temperature QCD

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We investigate the properties of the background gauge field configurations that act as disorder for the Anderson localization mechanism in the Dirac spectrum of QCD at high temperatures. We compute the eigenmodes of the M\"obius domain-wall fermion operator on configurations generated for the $SU(3)$ gauge theory with two flavors of fermions, in the temperature range $[0.9, 1.9]T_c$. We identify the source of localization of the eigenmodes with gauge configurations that are self-dual and support negative fluctuations of the Polyakov loop P_L, in the high temperature sea of $P_L \sim 1$. The dependence of these observations on the boundary conditions of the valence operator is studied. We also investigate the spatial overlap of the left-handed and right-handed projected eigenmodes in correlation with the localization and the corresponding eigenvalue. We discuss an interpretation of the results in terms of monopole-instanton structures.

Hadron Spectroscopy and Interactions / 62

Angular and chiral content of the ρ and ρ' mesons

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We identify the chiral and angular momentum content of the leading quark-antiquark Fock component for the $\rho(770)$ and $\rho(1450)$ mesons using a two-flavor lattice simulation with dynamical Overlap Dirac fermions. We extract this information from the overlap factors of two interpolating fields with different chiral structure and from the unitary transformation between chiral and angular momentum basis. For the chiral content of the mesons we find that the $\rho(770)$ slightly favors the $(1,0) \oplus (0,1)$ chiral representation and the $\rho(1450)$ slightly favors the $(1/2,1/2)_b$ chiral representation. In the angular momentum basis the $\rho(770)$ is then a ${}^3S_1$ state, in accordance with the quark model. The $\rho(1450)$ is a ${}^3D_1$ state, showing that the quark model wrongly assumes the $\rho(1450)$ to be a radial excitation of the $\rho(770)$.

Poster / **345**

Applications of Gradient flow to Non-perturbative renormalization of quark bi-linears

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Results of a non-perturbative determination of RI-MOM renormalization constants for smeared quark bi-linear operators are presented. These operators are smeared using the gradient flow, enabling the smearing scale to be fixed in physical units. As a result, smeared matrix elements are free of power divergences in the lattice spacing, which allows easier control of the continuum limit of these matrix elements.
Potential applications to calculations of twist-2 matrix elements are discussed.

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Applications of Jarzynski's relation in lattice gauge theories

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Jarzynski's equality is a well-known result in statistical mechanics, relating free-energy differences between equilibrium ensembles with fluctuations in the work performed during non-equilibrium transformations from one ensemble to the other.

In this talk, an extension of this relation to lattice gauge theory will be presented, along with numerical results for the Z_2 gauge model in three dimensions and for the equation of state in SU(2) Yang-Mills theory in four dimensions. Then, further applications will be discussed, in particular for the Schroedinger functional and for the study of QCD
in strong magnetic fields.

Theoretical Developments / 285

Applying recursive numerical integration techniques for solving high dimensional integrals

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The error scaling for Markov Chain - Monte Carlo techniques (MC-MC)
with N samples behaves like $\frac{1}{\sqrt{N}}$. This scaling makes
it often very time intensive to reduce the error of calculated
observables, in particular for applications in lattice QCD.
It is therefore highly desirable to have alternative methods at hand
which show an improved error scaling. One candidate for such an
alternative integration technique is the method of recursive numerical
integration (RNI). The basic idea of this method is to use Gauss quadrature with Legendre polynomials and apply it iteratively to integrate over observable and
Boltzmann weight.
In this talk we will present the application of such an algorithm to
the topological rotor and the anharmonic oscillator and compare the
error scaling to MC-MC results. In particular, we demonstrate that the
RNI technique shows an error scaling in N that is at least
exponential.

Hadron Spectroscopy and Interactions / 221

Approaching the bottom using fine lattices with Domain-wall fermions.

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We explore the properties of heavy-light psuedoscalar mesons above the
charm mass sing Mobius domain-wall fermions on fine lattices at a~0.080,
0.055, and 0.044 fm. We examine masses and decay constants using a
series of heavy quark masses up to 3 times the charm quark. We attempt

to analyze the cutoff effects for heavy quarks above the charm and account for the low order effects using ideas from HQET. Using these results we extrapolate to B-physics and report preliminary results for M_B(s) and F_B(s).

Poster / 87

Approaching the conformal window in SU(2) field theory: a systematic study of the spectrum for Nf=2,4,6, and 8.

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It is expected that SU(2) gauge theory with Nf fundamental fermions has an infrared fixed point when Nf is between ~ 6 and 10. We study the hadron spectrum and scale setting in SU(2) gauge field theory with Nf = 2,4,6,8 using hypercubic stout smeared Wilson-clover (HEX) action. The case Nf = 2 is QCD-like, Nf = 6 is close to the lower edge of the conformal window, and Nf=8 is inside the conformal window. We study the hadron spectrum and decay constants of these theories, and use the gradient flow approach to determine the length scales.

Physics Beyond the Standard Model / 294

Asymptotically safe gauge-Yukawa theories and functional renormalisation group

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Recently, new four-dimensional (gauge-Yukawa) theories have been discovered which display exact interacting fixed points at highest energies. In a regime where asymptotic freedom is lost, these novel types of theories develop an asymptotically safe UV fixed point, strictly controlled by perturbation theory. In this talk, we extend these studies to include couplings with non-vanishing canonical mass dimension. Using the method of functional renormalisation, we determine the full fixed point potential including higher order invariants of e.g. the scalar and fermionic fields. We also compute the universal scaling exponents and establish consistency of the theory beyond the restriction to classically marginal operators.

Nonzero Temperature and Density / 365

Axion Phenomenology from Unquenched Lattice QCD

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We investigate the topological properties of $N_f = 2 + 1$ QCD with physical quark masses, both at zero and finite temperature. At zero temperature both finite size and finite cut-off effects have been studied by comparing the continuum extrapolated results for the topological susceptibility χ with the predictions from chiral perturbation theory. At finite temperature, we explore a region going from T_c up to around $4T_c$, where continuum extrapolated results for the topological susceptibility and for the fourth moment of the topological charge distribution are obtained. While the fourth moment converges to the dilute instanton gas prediction the topological susceptibility differs strongly both in the size and in the temperature dependence. This results in a shift of the axion dark matter window of almost one order of magnitude with respect to the instanton computation.

Poster / **393**

BSM Kaon mixing at the Physical Point

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I present preliminary results for Kaon Mixing Beyond the Standard Model at the physical point.

Weak Decays and Matrix Elements / **81**

B_c decays from highly improved staggered quarks and NRQCD

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We use both non-relativistic QCD (NRQCD) and fully relativistic formalisms to calculate semileptonic form factors for the decays B_c -> eta_c lv and B_c -> J/psi lv over the entire q^2 range.

To achieve this we employ a highly improved lattice quark action at several lattice spacings down to a=.044 fm, which allows a fully relativistic treatment of charm and simulation of the full q^2 range with controlled continuum extrapolation. We have two ways of treating the b quark: either with an O(alpha_s) improved NRQCD formalism or by extrapolating a heavy mass m_h to m_b in the relativistic formalism. Comparison of the two approaches provides an important cross-check of methodologies in lattice QCD. Nonperturbative renormalisation of the currents in the relativistic theory also allows us then to fix NRQCD-charm normalisation for b to c decays such as B -> D and B -> D^*.

Hadron Spectroscopy and Interactions / 135

Baryon interactions from lattice QCD with physical masses – Overview and S = 0, -4 sectors –

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The lattice QCD determination of baryon interactions corresponds to connecting a missing link between particle physics and nuclear and astrophysics. While previous studies are limited to the calculations with unphysically heavy quark masses, we are performing the first calculation employing the (almost) physical quark masses (m(pi) = 146 MeV) on a huge lattice volume of (8fm)^4, where the interactions are extracted from Nambu-Bethe-Salpeter (NBS) correlators by the time-dependent HAL QCD method. In this talk, we first give an overview on this project. We then present the latest numerical results for two-nucleon forces (strangeness S = 0) and two-Xi forces (S = -4).

Hadron Spectroscopy and Interactions / 208

Baryon interactions from lattice QCD with physical masses – S=-2 sector –

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Baryon interactions are crucial to study a bound and/or resonance state in multi-baryon systems.
In spite of their importance, phenomenological baryon potentials have large uncertainties because of the lack of experimental scattering data.
In recent studies, the HAL QCD method allow us to extract baryon interactions from the Nambu-Bethe-Salpeter wave functions without using experimental data.
We present our latest result on the S = -2 baryon interactions and discuss the H-dibaryon state using potentials which are calculated by using the (almost) physical point gauge configurations with large lattice volume of (8fm)^4 generated on the K-computer.

Hadron Spectroscopy and Interactions / 289

Baryon interactions from lattice QCD with physical masses – S=-3 sector: XiSigma & XiLambda-XiSigma –

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Nucleon-Nucleon interaction plays an essential role in nuclear physics. In the same way, hyperon-hyperon interactions should play an important role in hyper nuclear physics. However, unlike the nucleons which are quite stable, hyperons decay quickly so that the direct scattering experiments are difficult. As a result, phenomenological determination of hyperon potentials involves large uncertainly. In this talk, by using the gauge configurations at the (almost) physical point (m(pi)=146 MeV) on a huge spatial lattice (8fm)^4, we present our latest result on the hyperon-hyperon potentials for S=-3 sector (XiSigma & XiSigma-XiLambda) from the Nambu-Bethe-Salpeter wave functions based on the HAL QCD method.

Hadron Spectroscopy and Interactions / 110

Baryon interactions in lattice QCD: the direct method vs. the HAL QCD potential method

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In lattice QCD, both direct method for eigen-energy extraction and HAL QCD method for potential are employed so far to study hadron interactions. The scattering phase shifts, for example, are obtained through the Luscher's finite volume formula for the former,
but they are calculated via the Schroedinger equation with the potential in the infinite volume for the latter.
Although both methods should agree in principle, some systematically different conclusions are reported for existences of bound states in the previous studies: while the potential shows no sign of the bound state in two nucleon systems at heavier pion masses, for example, the eigen-energy indicates its existence.

In this work, we clarify that these discrepancies come from a failure of the eigen-energy extraction for the ground state due to the contamination of excited states in time correlation functions, while the HAL QCD potential method is free from this problem.
We finally establish consistencies between two lattice QCD approaches, and propose an improved extraction of eigen-energy for the time correlation functions using energy eigen-functions obtained from the HAL QCD potential.

Theoretical Developments / 42

Beyond complex Langevin equations:positive representation of Feynman path integrals directly in the Minkowski time

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A positive representation for an arbitrary complex, gaussian weight is derived and used to construct a statistical formulation of gaussian path integrals directly in the Minkowski time.

The positivity of Minkowski weights is achieved by doubling the number of real variables. The continuum limit of the new representation exists only if some of the additional couplings tend to infinity and are tuned in a specific way. The construction is then successfully applied to three quantum mechanical examples including a particle in a constant magnetic field – a simplest prototype of a Wilson line.

Further generalizations are shortly discussed and an intriguing interpretation of new variables is alluded to.

Plenary Session / 338

Beyond the Standard Model: Charting Fundamental Interactions via Lattice Simulations

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After the discovery of the Higgs boson, the primary objective of the Large Hadron Collider (LHC) experiments is to identify new physics beyond the Standard Model (SM). In fact, both ATLAS and CMS are providing precision tests of the Higgs sector and tantalizing hints of new, unexpected resonances.

One of the most intriguing possibilities would be the discovery of non-perturbative phenomena in electroweak physics. Most strikingly, there is no conclusive evidence yet on whether the Higgs boson is elementary or composite.

Lattice simulations can play a key role in advancing our theoretical understanding of strongly coupled gauge theories relevant for extensions of the SM and the LHC program. In this talk I will review the state of BSM lattice studies aimed to chart the phase diagram and to uncover the properties of such strongly coupled gauge theories.

Algorithms and Machines / 267

Block Solver for multiple right hand sides on NVIDIA GPUs

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Analysis tasks in Lattice QCD often requires solving linear equations for multiple right hand sides for a constant gauge field. Recently deflation methods have become more widely used and proven to be very efficient. They however do require the calculation and storing of eigenvectors which is either not always feasible or too expensive. Here we present results for an implementation of a block solver for multiple right hand sides using the QUDA library for QCD on NVIDIA GPUs. By making use of the gauge field reuse in the Dslash operator, mixed precision approaches and block Krylov space methods they do provide outstanding solver performance. We present results on NVIDIA's most recent Pascal architecture.

Theoretical Developments / 6

Borici-Creutz fermions on 2-dim lattice

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Minimally doubled fermions(MDF) having only two species could be promising formalism to study chiral fermion on a lattice. The action being ultra-local, one expects that the MDF formulations might provide computationally cheaper alternatives to the existing lattice chiral formulations. Borici-Creutz fermion is one such minimally doubled fermion formulation. In this work, we explore the Borici-Creutz fermion formulation in simple a 2d Gross-Neveu model and in QED2 with Hybrid Monte Carlo simulation. We study chiral symmetry breaking and mass spectrum in Gross-Neveu model .

Poster / 210

Calculation of Quark Condensates and Chirality using Improved Staggered Fermions

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We study quark condensates using improved staggered fermions, where zero modes of the Dirac operator give simple poles in the chiral limit. We present a new method to identify the zero modes and to subtract their contribution from the quark condensates. Meanwhile we also identify the quantum numbers of the zero modes in the staggered fermion formalism, using the spectral flow method. All the numerical results are calculated using HYP-smeared staggered fermions on MILC asqtad lattices and on MILC HISQ lattices.

Weak Decays and Matrix Elements / 328

Calculation of hadronic matrix elements contributing to the $B_s-\bar{B}_s$ width difference

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The width difference $\Delta\Gamma_s$ is one of three observables, along with the mass splitting ΔM_s and the semileptonic CP asymmetry $a^s_{\rm SL}$, whose measurements completely constrain the physics of $B_s - \bar{B}_s$ oscillations. One of the dominant uncertainties in theoretical calculations of the width difference is due to not knowing matrix elements of dimension-7 operators beyond the vacuum saturation approximation. In particular, progress requires a first-principles calculation of the matrix element of R_2, a $\Delta B = 2$ operator with a derivative acting on the strange quark field. We discuss our methodology and present preliminary results of a calculation of $\langle B_s|R_2|\bar{B}_s\rangle$ using nonrelativistic b quarks and highly-improved staggered s quarks on the MILC Collaboration's $n_f = 2+1+1$ configurations.

Vacuum Structure and Confinement / 396

Centre vortices are the seeds of dynamical chiral symmetry breaking

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We reveal a fundamental connection between centre vortices and several key features associated with dynamical chiral symmetry breaking and quark confinement. Calculations are performed in pure $\mathrm{SU}(3)$ gauge theory using the chiral overlap fermion action. Starting from the original gauge field, a vortex identification procedure yields vortex-removed and vortex-only backgrounds. By studying the quark mass function, we demonstrate the removal of dynamical mass generation via the removal of the centre-vortex degrees of freedom from the gauge fields. The low-lying hadron mass spectrum is also calculated, with results that are consistent with the restoration of chiral symmetry on vortex-removed backgrounds at light quark masses.

Remarkably, we observe that the vortex-only degrees of freedom are able to encapsulate the qualitative features of the original gauge fields. Through visualisations of the topological charge density, we find evidence of a link between centre vortices and the instanton structure of the vacuum, specifically vortex-only backgrounds provide gauge-field degrees of freedom sufficient to create instantons upon cooling. Furthermore, after some smoothing, we observe dynamical mass generation on the vortex-only backgrounds consistent with that of the original gauge-field ensemble.

Hadron Structure / 38

Charge radii and higher electromagnetic moments with lattice QCD in nonuniform background fields

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Nonuniform background electromagnetic fields, once implemented in lattice QCD calculations of hadronic systems, provide a means to constrain a large class of electromagnetic properties, from higher electromagnetic moments and charge radii to electromagnetic form factors. In this talk, I present the recent theoretical developments in realizing general background fields in periodic hypercubic lattices, along with a numerical illustration of the formalism. Additionally, I will briefly explain the formal procedure that allows the extraction of the charge radius and the quadruple moment of hadrons and light nuclei by matching an appropriate effective hadronic theory to lattice QCD correlation functions in a linearly varying electric field in space.

Weak Decays and Matrix Elements / 1

Charm Physics with Domain Wall fermions

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This talk will provide an overview of RBC/UKQCD's charm project on their 2+1 flavour physical point ensembles using Domain Wall Fermions for the light as well as for the charm quarks. I will discuss the analysis strategy and present the latest results for the D and D_s decay constants. I will also outline the wider charm-related physics program of RBC/UKQCD.

Hadron Spectroscopy and Interactions / 266

Charm physics by $N_f = 2 + 1$ Iwasaki gauge and the six stout smeared $O(a)$-improved Wilson quark actions on a 96^4 lattice

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We present our results of charm physics in
$N_f = 2 + 1$ lattice QCD. Our calculation is
performed on configurations generated
with Iwasaki gauge and the six stout smeared
$O(a)$-improved Wilson quark actions on a 96^4 lattice
at $\beta = 1.82$ ($a^{-1} = 2.3$ GeV) with the spatial
extent $L = 8.1$ fm. The pion mass is almost physical
$m_\pi = 145$~MeV. The relativistic heavy quark action
is utilized for the charm quark.
We exhibit the charmed spectrum and the charm
quark mass, focusing on stout smearing influence.

Nonzero Temperature and Density / 231

Charm quark diffusion coefficient from nonzero momentum Euclidean correlator in temporal channel

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We study the charm quark diffusion coefficient from nonzero momentum correlator in temporal channel on the quenched lattice. Euclidean correlator in temporal channel with zero momentum is constant as a function of the imaginary time because of the charge conservation. However this quantity with finite momentum is dependent on imaginary time and is more sensitive to the low energy structure of the spectral function than those in the spatial channel. We make estimates on the diffusion coefficient from this channel. We perform the numerical simulation on the lattice and apply the discussion for 1.5 < T/T_c<4.5.

Hadron Spectroscopy and Interactions / 2

Charm-strange mesons and D K scattering

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I will discuss a recent lattice QCD investigation of $D\ K$ scattering relevant for near-threshold charm-strange mesons such as the enigmatic $D_s(2317)$. By employing a range of techniques we extracted precise finite-volume spectra in a number of different channels. These were used to map out the energy dependence of the scattering phase shift and from the singularity structure of the scattering amplitude we determined the resonant and bound state content. I will conclude with some comments on future prospects.

Poster / 171

Charmed meson physics from three-flavour lattice QCD

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We report on analysis aspects within a joint ongoing effort of the
ALPHA and RQCD Collaborations to compute charmed meson masses and the
leptonic decay constants f_{D} and $f_{\mathrm{D_s}}$ in

$(2 + 1)$-flavour lattice QCD, employing non-perturbatively O(a) improved Wilson quarks and the tree-level Symanzik-improved gauge action.
Our studies make use of large-volume CLS configurations at two lattice spacings ($a \approx 0.086, 0.064$ fm) with open boundary conditions.
In particular, we present our implementation of distance preconditioning (as proposed by de Divitiis et al.) for the calculation of heavy quark propagators and discuss the resulting accuracy improvements of charmed meson correlators and its impact on the extraction of charmed meson masses and decay constants.

Hadron Spectroscopy and Interactions / 89

Charmed-bottom mesons from Lattice QCD

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We present ground state spectra of mesons containing a charm and a bottom quark. For the charm quark we use overlap valence quarks while a non-relativistic formulation is utilized for the bottom quark on a background of 2+1+1 flavor HISQ gauge configurations generated by the MILC collaboration. We also study the ratio of leptonic decay constants, $f_{B_c^*}/f_{B_c}$. Results are obtained at three lattice spacings.

Physics Beyond the Standard Model / 108

Check of a new non-perturbative mechanism for elementary fermion mass generation

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We consider a field theoretical model where a SU(2) doublet fermion, subjected to non-abelian gauge interactions, is also coupled to a complex scalar field doublet via a Yukawa and an irrelevant Wilson-like term. Despite the presence of these two chiral breaking operators in the Lagrangian, an exact symmetry acting on fermions and scalars prevents perturbative mass corrections. In the phase where

fermions are massless (Wigner phase) the Yukawa coupling can be tuned to a critical value at which chiral transformations acting on fermions only become a symmetry of the theory (up to cutoff effects). In the Nambu-Goldstone phase of the critical theory a fermion mass term of dynamical origin is expected to arise in the Ward identities of the purely fermionic chiral transformations. Such a non-perturbative mechanism of dynamical mass generation can provide a "natural" (a' la 't Hooft) alternative to the Higgs mechanism adopted in the Standard Model.

Weak Decays and Matrix Elements / 85

Chiral Perturbation Theory at finite volume or with twisted boundary conditions

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Recent progress in mesonic Chiral Perturbation Theory at finite volume and/or with twisted boundary conditions will be discussed. Topics include the finite volume at two-loop order calculations of masses and decay constants for the pseudoscalar of the normal case for two and three flavours [1], partially quenched three flavour [2] and the case for different patterns of spontaneous symmetry breaking [3].

Twisted boundary conditions lead to extra terms in Ward identities and form-factors which affects finite volume corrections and relations often used. This will be discussed for a number of cases, the older work [4] and the application to $K_{\ell 3}$ for staggered partially quenched [5]. Vector two-point functions relevant for the $g-2$ HVP calculation will be treated at two-loop order [6] allowing a better estimnate of twisting and finite volume corrections.

[1] Finite Volume at two-loops in Chiral Perturbation Theory,
J. Bijnens and T. Rössler,[arXiv:1411.6384] JHEP 1501 (2015) 034

[2] Finite Volume for Three-Flavour Partially Quenched Chiral Perturbation Theory through NNLO in the Meson Sector,
J. Bijnens and T. Rössler, [arXiv:1508.07238] JHEP 1511 (2015) 097

[3] Finite Volume and Partially Quenched QCD-like Effective Field Theories,
J. Bijnens and T. Rössler, [arXiv:1509.04082] JHEP 1511 (2015) 017

[4] Masses, Decay Constants and Electromagnetic Form-factors with Twisted Boundary Conditions, J. Bijnens and J. Relefors,
[arXiv:1402.1385] JHEP 05 (2014) 015

[5] C. Bernard, J. Bijnens, E. Gamiz and J. Relefors, work in progress

[6] J. Bijnens and J. Relefors, work in progress

Chiral Symmetry / 219

Chiral condensate from OPE of the overlap quark propagator

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Using 2+1-flavor domain wall fermion configurations, we calculate the overlap quark propagator in the Landau gauge. Then we try to extract the chiral condensate from the operator product expansion of the quark propagator in momentum space.

Poster / **154**

Chiral phase transition in (2 + 1)-flavor QCD on $N_\tau = 6$ lattices

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We present updated studies of chiral phase transition in $N_f = 2 + 1$ QCD. Simulations have been performed with Highly Improved Staggered Quarks (HISQ) on lattices with temporal extent $N_\tau = 6$ at vanishing baryon chemical potential. We updated our previous study (1511.00553) by extending the temperature window from (140MeV, 150MeV) to (140MeV, 170MeV). The strange quark mass was chosen to its physical value m_s^{phy}, and five values of two degenerate light quark masses (m_l) are varied from $m_s^{phy}/80$ to $m_s^{phy}/20$ which correspond to a Goldstone pion mass ranging from 80 MeV to 160 MeV in the continuum limit.

The universal scaling behaviour of the QCD chiral phase transition is investigated by studying the temperature and quark mass dependence of chiral condensates and chiral susceptibilities. The window of criticality compared to previous studies is also discussed.

Nonzero Temperature and Density / **146**

Chiral transition, eigenmode localisation and Anderson-like models

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I discuss chiral symmetry restoration and eigenmode localisation in finite-temperature QCD by looking at the lattice Dirac operator as a random Hamiltonian. I will argue that the features of QCD relevant to both phenomena are the presence of order in the Polyakov line configuration, and the correlations that this induces between spatial links across time slices. This ties the fate of chiral symmetry and of localisation of the lowest Dirac eigenmodes to the confining

properties of the theory. I then show numerical results obtained in a QCD-inspired Anderson-like toy model, derived by radically simplifying the QCD dynamics while keeping the important features mentioned above. The toy model reproduces all the important qualitative aspects of chiral symmetry breaking and localisation in QCD, thus supporting the central role played by the confinement/deconfinement transition in triggering both phenomena.

Plenary Session / 403

Closing Remarks

Chiral Symmetry / 332

Comparing different definitions of the topological charge

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We perform a numerical comparison of different lattice definitions of the topological charge by investigating the correlation coefficient between different definitions as well as the topological susceptibility. We use small-volume ensembles with 2 flavours of dynamical twisted mass fermions. We investigate the following definitions of the topological charge: index of the overlap Dirac operator, spectral flow of the Hermitian Wilson-Dirac operator, spectral projectors and field theoretic extracted with the smoothing schemes of APE, stout and HYP smearing schemes as well as cooling and the recently introduced gradient flow. Furthermore, we carry out a (tree-level) perturbative comparison between the smoothing procedures of the gradient flow, cooling as well as APE and stout smearing. We demonstrate both analytically and numerically that the above smoothing schemes are equivalent if the smoothing scales (flow time, number of cooling or smearing steps) are rescaled properly. Moreover, we demonstrate that HYP smearing is numerically equivalent with all the above smoothers. We show that the generally high correlation between different definitions increases towards the continuum limit.

Nonzero Temperature and Density / 395

Comparison of CLE and reweighting for QCD at nonzero density

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Lattice QCD at non-vanishing chemical potential is studied using the complex Langevin equation (CLE). We compare the results with multi-parameter reweighting both from μ=0 and phase quenched ensembles. A good agreement is found for lattice spacings below ≈0.15 fm. On coarser lattices the complex Langevin approach breaks down. Four flavors of staggered fermions are used on Nt=4,6 and 8 lattices. We also discuss the issue of poles for CLE simulations of HDQCD and full QCD.

Nonzero Temperature and Density / 144

Comparison of algorithms for solving the sign problem of the finite μ O(3) model in 1+1 dimensions

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We study the 1+1 dimensional nonlinear O(3) model at finite chemical potential using the complex Langevin algorithm and the worm algorithm. In the latter the sign problem is totally eliminated. We determine the range of parameters, where complex Langevin produces correct results and study whether taking the continuum limit allows the exploration of the full phase diagram of the model.

Applications Beyond QCD / 74

Competing order in the fermionic Hubbard model on the hexagonal graphene lattice

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We study the phase diagram of the fermionic Hubbard model on the hexagonal lattice in the space of on-site and nearest neighbor couplings with Hybrid-Monte-Carlo simulations. With pure on-site repulsion this allows to determine the critical coupling strength for spin-density wave formation. We compare the standard approach of introducing a small mass term, explicitly breaking the sublattice symmetry, with a purely geometric mass, i.e. using lattices and boundary conditions such that

the Dirac points fall in between the grid points inside the Brillouin zone without explicit sublattice-symmetry breaking. For the first method we extrapolate the corresponding susceptibility peaks towards zero mass and infinite volume in the usual way, while with the geometric mass only infinite volume extrapolation is needed. An added bonus is that it can be used with nearest neighbor repulsion and charge-density wave formation where the corresponding mass term would introduce a sign problem. The geometric mass thus provides a promising method to study the competition between these different types of order and the resulting phase diagram with ab-initio simulations.

Vacuum Structure and Confinement / 388

Complete Monopole Dominance of the Static Quark Potential

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In earlier work, we used a gauge independent Abelian Decomposition to show that Abelian degrees of freedom where wholly responsible for the static quark postential. The Abelian decomposition contains a Maxwell part and Topological part, whose contribution to the string tension can be analysed theoretically and numerically, and arises because of the existence of a certain type of monopole. If we also fix the gauge in a certain way, we show that the Topological part can wholly account for the string tension. We show using numerical simulations in SU(2) Yang-Mills theory that the monopoles which can at least partially explain confinement are present in the QCD vacuum.

Poster / 61

Complex Langevin Dynamics In 1+1d QCD At Non-Zero Densities

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We present our results obtained from gauge cooled complex Langevin simulations in 1+1D QCD at non-zero densities in the strong coupling regime with unrooted staggered fermions. For small quark masses there are regions of the chemical potential where this method fails to reproduce correct results. In theses parameter ranges we studied the effect of different gauge cooling schemes on the distributions of the fermion determinant as well as of observables.

Nonzero Temperature and Density / 33

Complex Langevin Dynamics for a Random Matrix Model of QCD at finite density

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We study a Random Matrix Model for QCD at finite density via Complex Langevin dynamics. This model has a phase transition to a phase with non-zero baryon density. We study the convergence of the algorithm as a function of the quark mass and the chemical potential and focus on two main observables: the baryon density and the chiral condensate. As expected, for simulations close to the chiral limit, the algorithm has wrong convergence properties when the quark mass is in the spectral domain of the quenched Dirac operator. Possible solutions of this problem are discussed.

Nonzero Temperature and Density / 20

Complex Langevin for Lattice QCD at $T = 0$ and $\mu \geq 0$.

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We simulate Lattice QCD with 2 light quark flavours at zero temperature and finite quark number chemical potential μ. Gauge cooling is applied, along with adaptive rescaling of the updating 'time' increment, to stabilize the algorithm. We see evidence for the expected transition at $\mu \approx m_N/3$ and for saturation at large μ. Limitations of the method are discussed.

Nonzero Temperature and Density / 114

Complex spectrum of spin models for finite-density QCD

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We consider the spectrum of transfer matrix eigenvalues associated with Polyakov loops in lattice QCD at strong coupling. The transfer matrix at finite density is non-Hermitian, and its eigenvalues become complex as a manifestation of the sign problem. We show that the symmetry under charge and complex conjugations ensures that the eigenvalues are either real or part of a complex conjugate pair, and the complex pairs lead to damped oscillatory behavior in Polyakov loop correlation functions, which also appeared in our previous phenomenological models using complex saddle points. We argue that the results reflect oscillatory behavior in color-charge densities and it should be observable in lattice simulations of QCD at finite density.

Algorithms and Machines / 387

Computing the density of states with the global Hybrid Monte Carlo

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The LLR algorithm is a recent proposal for computing the density of states in lattice gauge theory. This algorithm has been tested in several bosonic models at zero and finite chemical potential with impressive results. Its original formulation is based on the simulation of the theory on restricted action intervals using local Monte Carlo updates.I will discuss a new version of the method based on the global Hybrid Monte Carlo algorithm which is suitable for theories with dynamical fermions. I will present our preliminary result for the study of the SU(2) gauge theory.

Hadron Structure / 91

Computing the nucleon Dirac radius directly at $Q^2 = 0$

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We describe a lattice approach for directly computing momentum derivatives of nucleon matrix elements using the Rome method, which we apply to obtain the isovector magnetic moment and Dirac radius. We present preliminary results calculated at the physical pion mass using a 2HEX-smeared Wilson-clover action from the Budapest-Marseille-Wuppertal collaboration. For removing the effects of excited-states contamination, the calculations were done at three source-sink separations and the summation method was used.

Hadron Spectroscopy and Interactions / 170

Computing the static potential using non-string-like trial states

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We present a method for computing the static quark-antiquark potential, which is not based on Wilson loops, but where the trial states are formed by eigenvector components of the covariant Laplace operator. We have tested this method in SU(2) Yang-Mills theory and obtained results with statistical errors of similar magnitude compared to a standard Wilson loop computation. The runtime of the method is, however, significantly smaller, when computing the static potential not only for on-axis, but also for many off-axis quark-antiquark separations, i.e. when a fine spatial resolution is required.

Hadron Structure / 353

Constructing Nucleon Operators on a Lattice for Form Factors with High Momentum Transfer

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In typical nucleon structure calculations on a lattice, the interpolating fields are optimized to overlap with the nucleon ground state at rest, which in practice limits the momentum transfer in form factors to $Q^2 \leq 1\,GeV^2$. There is great interest in studying nucleon form factors up to few tens of GeV^2. New experiments at the JLab 12-GeV upgrade will measure nucleon form factors with momentum transfers up to $18\,GeV^2$ in an attempt to reach the regime of perturbative QCD scaling and investigate further the pattern in the GE/GM ratio in the proton. With current lattice QCD techniques, one can achieve momenta of several GeV^2 without risk of overwhelming discretization effects. In a boosted nucleon, however, excited state admixtures will become even more problematic to control than at rest, and will require computing nucleon correlators to high statistical precision. I will present some initial results from a lattice study of nucleon structure optimized for boosted nucleon initial and final states with the method recently adopted by the Regensburg collaboration. These methods will also be essential for the recently proposed novel method to compute parton distributions directly on a lattice.

Theoretical Developments / 364

Continuing the Saga of Fluffy Mirror Fermions

Dorota Grabowska[1]

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I discuss continuing work on a recent proposal for the nonperturbative regulator for chiral gauge theories which combines domain wall fermions and gradient flow, Phys.Rev.Lett. 116 (2016) 211602. Implementing chiral gauge theories on the lattice requires not only decoupling mirror fermions to allow for fermions in complex representations, but also a road to failure for theories with fermions in anomalous representations. Unlike attempts to gap the mirror fermion spectrum, this proposal gives the mirror fermions exponentially soft form factors, allowing them to decouple from ordinary matter except through nontrivial gauge field topology. I discuss progress on various open questions for this formulation that were left unresolved in the original work.

Nonzero Temperature and Density / 315

Continuum limit and universality of the Columbia plot

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In its lower left corner, the Columbia plot indicates a first-order finite-temperature phase transition, which turns into a crossover as the quark masses increase. The locus of quark masses giving a second-order transition is a feature of continuum QCD, and should be recovered with any fermion discretization. However, numerical evidence has been accumulating, disfavoring universality.
We explore this puzzle with 4 degenerate flavors of staggered fermions, thus avoiding any potential problem associated with rooting.

Hadron Spectroscopy and Interactions / 36

Coupled-channel analysis of $D\pi$, $D\eta$ and $D_s\bar{K}$ scattering using lattice QCD

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We present an extensive study of isospin $1/2$ coupled-channel $D\pi$, $D\eta$ and $D_s\bar{K}$ scattering, as well as isospin $3/2$ elastic $D\pi$ scattering, from $N_f = 2 + 1$ lattice QCD. Our use of distillation in combination with variationally optimised interpolating operators allows us to extract statistically precise two-meson spectra, which we use to constrain scattering amplitudes as a function of energy. We interpret our results in terms of poles in the scattering matrix, finding a near-threshold bound state in S-wave, a deeply bound vector state in P-wave and a narrow resonance in D-wave.

Nonzero Temperature and Density / 12

Critical endline of the finite temperature phase transition for 2+1 flavor QCD around the SU(3)-flavor symmetric point

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We investigate the critical endline of the finite temperature phase transition of QCD around the SU(3)-flavor symmetric point at zero chemical potential.
We employ the renormalization-group improved Iwasaki gauge action and non-perturbatively $O(a)$-improved Wilson-clover fermion action.
The critical endline is determined by using the intersection point of kurtosis, employing the multi-parameter, multi-ensemble reweighting method to calculate observables off the SU(3)-symmetric point, at the temporal size N_{T}=6 and lattice spacing as low as $a \approx 0.19$ fm.
We confirm that the slope of the critical endline takes the value of -2, and find that the second derivative is positive, at the SU(3)-flavor symmetric point on the Columbia plot parametrized with the strange quark mass m_s and degenerated up-down quark mass m_{l}.

Weak Decays and Matrix Elements / 241

Current correlators in the coordinate space at short distances

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We calculate the current correlators in the coordinate space and compare them with the experimental information obtained through the spectral functions of hadronic tau decays at ALEPH.
Lattice data are obtained with 2+1 Mobius domain-wall fermions at three lattice spacings 0.044, 0.055 and 0.080 fm and the continuum limit is taken.
On the experimental side, there is no information for the spectral functions above the tau lepton mass and one usually assumes that the perturbation theory is applicable there.
Through the comparison with the lattice data, we are able test the validity of this quark-hadron duality assumption to some extent.

Weak Decays and Matrix Elements / 372

D meson semileptonic form factors with HISQ valence and sea quarks

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We present a calculation of the form factors of the $D \to Kl\nu$ and $D \to \pi l\nu$ semileptonic decays at zero momentum transfer, ultimately for the purpose of determining the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$. This work uses MILC $N_f = 2+1+1$ configurations with the HISQ action for both sea quarks and valence quarks, including several physical mass ensembles and lattice spacings down to $0.042 fm$. The calculation is done directly at $q^2 = 0$ by employing twisted boundary conditions to tune the child particle momenta. Preliminary results at the physical point and in the continuum limit are achieved through the use of Heavy-Meson Staggered χPT.

Weak Decays and Matrix Elements / 378

D-Meson Mixing in 2+1 Lattice QCD and Related Topics

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We present results for neutral D-meson mixing in 2+1-flavor lattice QCD.
We compute the matrix elements for all five operators that contribute to D mixing at short distances, including those that only arise beyond the Standard Model.
We present a detailed error breakdown for all sources of statistical and systematic uncertainty and the corresponding set of correlations among the matrix elements.
Our results have an uncertainty similar to those of the ETM Collaboration (with 2 and with 2+1+1 flavors).
This work shares many features with a recent publication on B mixing and with ongoing work on heavy-light decay constants from the Fermilab Lattice and MILC Collaborations, both of which will be briefly summarized.

Physics Beyond the Standard Model / 173

D=5 Maximally Supersymmetric Yang-Mills on the Lattice

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Maximally supersymmetric Yang-Mills theory in five dimensions has generated a lot of interest in the recent years. It takes part in the gauge-gravity duality and its finite temperature properties have been investigated recently in the planar limit. This theory is also interesting through its conjectured relationship to the six-dimensional (2,0) theory, which is still controversial. In this talk we describe the lattice construction of D=5 maximally supersymmetric Yang-Mills theory. The lattice theory preserves one supercharge exact at finite lattice spacing. This supersymmetric lattice formulation can be used to explore the non-perturbative regime of the continuum target theory. It would be interesting to find a nontrivial UV fixed point from the lattice theory for D=5 theory since the fixed point can provide a UV completion and non-perturbative definition of the theory.

Weak Decays and Matrix Elements / 288

Decay constants f_B and f_{B_s} and quark masses m_b and m_c from HISQ simulations

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We present high-precision results for the decay constants f_B and f_{B_s} from simulations with HISQ heavy and
light valence and sea quarks. Calculations are carried out with several heavy valence-quark masses on ensembles with

2+1+1 flavors of HISQ sea quarks. We generate data at five lattice spacings with three light sea quark mass ratios,
including an approximately physical ensemble at every lattice spacing. This range of parameters provides excellent
control of the continuum limit and of heavy-quark discretization errors. In addition to the decay constants, we present
results for charm- and bottom-quark masses extracted from heavy-light meson masses using an approach based on HQET.

Plenary Session / 145

Density of States

Kurt Langfeld[1]

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Although Monte Carlo calculations using Importance Sampling have matured into the most widely employed method for determining first principle results in QCD, they spectacularly fail for theories with a sign problem or for which certain rare configurations play an important role. Non-Markovian Random walks, based upon iterative refinements of the density-of-states, overcome such overlap problems. In my talk, I will review the Linear Logarithmic Relaxation (LLR) method and, in particular, focus onto ergodicity and exponential error suppression. Applications include the high-state Potts model, U(1), SU(2) and SU(3) Yang-Mills theories as well as quantum field theories with a sign problem: the Z3 spin model and QCD at finite densities of heavy quarks.

Standard Model Parameters and Renormalization / 155

Determination of charm quark mass from temporal moments of charmonium correlator with Mobius domain-wall fermion

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We extract the charm quark mass and the strong coupling
constant
by using the charmonium current correlators with $n_f = 2 + 1$ Mobius
domain
wall fermions. The temporal moments of the correlators are sensitive to
short-distance physics, and could be also calculated in the
continuum theory by perturbative expansion, which is known up to four-
loop order.We match our lattice calculation with perturbative result, and extract the charm quark mass with the uncertainty less than 1%.
We also confirm the correlators in the vector channel to be consistent with experimental data for R-ratio.
We used the ensembles by the JLQCD collaboration at lattice spacings a = 0.083 fm, 0.055 fm and 0.044 fm, are extrapolated to the continuum limit.

Chiral Symmetry / 327

Determination of chiral condensate from low-lying eigenmodes of Mobius domain-wall Dirac operator

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We calculate the spectral function of the Mobius domain-wall Dirac operator utilizing a stochastic eigenvalue counting technique. From the low-end of the spectrum we extract the chiral condensate in 2+1-flavor QCD, and take the chiral and continuum limits. Lattice ensembles are those generated with Mobius domain-wall fermions at a~0.080, 0.055 and 0.044 fm.

Nonzero Temperature and Density / 167

Determination of latent heat at the finite temperature phase transition of SU(3) gauge theory

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We calculate the energy gap (latent heat) and pressure gap between the hot and cold phases of the SU(3) gauge theory at the first order deconfining phase transition point.
We perform simulations around the phase transition point with the lattice size in the temporal direction Nt=6, 8 and 12 and extrapolate the results to the continuum limit.
The energy density and pressure are evaluated by the derivative method with non-perturbative anisotropy coefficients and by a method using the Yang-Mills gradient flow.
We find that the pressure gap vanishes at all values of Nt when the derivative method is used.
The spatial volume dependence in the latent heat is found to be small on large lattices.
Performing extrapolation to the continuum limit, we obtain
$\Delta\epsilon/T^4 = 0.75 \pm 0.17$
and
$\Delta(\epsilon - 3p)/T^4 = 0.623 \pm 0.056$.

Theoretical Developments / 127

Determination of topological charge following several definitions

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On the lattice, many definitions of the topological charge Q coexist, and can give very different numbers on a given configuration.
Those definitions will only converge when one takes the continuum limit of the moments $\langle Q^n \rangle$ (provided that Q has been correctly renormalised).
Additionally, other complications arise when one wants to study the mass dependence of the topological susceptibility, because of the mixing of the two operators under renormalisation. It is therefore unclear to which extent each definition of Q is compatible with each definition of the masses.
Here we will present the results of some tests following various choices of definition. In a second part, we will discuss the potential consequences of that ambiguity on the discarding of $m_u = 0$ as a solution to the strong CP problem.

Standard Model Parameters and Renormalization / 234

Determining α_s by using the gradient flow in the quenched theory

Eliana Lambrou[1]

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We present preliminary results to determine the strong coupling constant by using the gradient flow. Pure SU(3) gauge theory is studied. We carry out a direct analysis on very fine zero temperature lattices. In addition we attempt to move towards the perturbative regime by using step-scaling.

Theoretical Developments / 46

Diagrammatic Monte-Carlo simulations of the large N SU(N)xSU(N) principal chiral model based on the weak-coupling trans-series expansion

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I present a Diagrammatic Monte-Carlo algorithm for the large N SU(N)xSU(N) principal chiral model, which stochastically samples planar Feynman diagrams of the lattice perturbation theory. The latter is constructed using the Cayley map from SU(N) group manifold to the space of Hermitian matrices. I demonstrate that the Jacobian of this map results in the massive bare lattice propagator with the mass proportional to the bare coupling. This bare mass term ensures that perturbative series are IR finite and do not have factorial divergences at high orders, which makes the series suitable for Monte-Carlo sampling and stochastic summation. On the other hand, since the bare mass is proportional to the coupling itself, the expansion is no longer an expansion in powers of coupling, but rather has the form of trans-series involving both powers and logs of coupling. I discuss possible resurgent structure of these trans-series, the strength of the sign problem in Monte-Carlo sampling, as well as the extension of the present approach to lattice gauge theory.

Hadron Structure / **18**

Disconnected and light connected HVP contributions to the muon anomalous magnetic moment

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I present our recent results for the disconnected HVP contribution and report the current status of our light connected HVP contribution to the muon anomalous magnetic moment.

Hadron Structure / **178**

Disconnected diagrams with twisted-mass fermions

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The latest results from the Twisted-Mass collaboration on disconnected diagrams at the physical value of the pion mass are presented. In particular, we focus on the sigma terms, the axial charges and the momentum fraction. A detailed error analysis for each observable follows, showing the strengths and weaknesses of the one-end trick. Alternatives are discussed.

Physics Beyond the Standard Model / **205**

Discrete β-function of the SU(3) gauge theory with 10 massless domain-wall fermions

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I present the updated results of the discrete β-function of the $SU(3)$ gauge theory with $N_f = 10$ massless optimal domain-wall fermions in the fundamental representation.
The renormalized coupling is obtained by the finite-volume gradient flow scheme on L^4 lattices, for seven lattice sizes: $L/a = 8, 10, 12, 16, 20, 24, 32$;
and each with $11 - 17$ different lattice spacings parametrized by $6/g_0^2$.
The discrete β-function is extrapolated to the continuum limit
using four lattice pairs $(L, 2L)/a = (8, 16), (10, 20), (12, 24)$ and $(16, 32)$.
This provides stronger evidence of the infrared fixed point at $g_c^2 \simeq 7$,
which was first reported in arXiv:1603.08854, based on the continuum extrapolation
of the discrete β-function obtained with three lattice pairs.

Poster / **27**

Discussion of the Loop Formula for the fermionic determinant

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A formula expressing the fermionic determinant as an infinite product of smaller determinants is here derived and discussed. These smaller determinants are of a fixed size, independent of the size of the lattice and are indexed by loops of increasing length. The application of the formula requires convergence considerations.

Algorithms and Machines / **361**

Domain Wall Fermion Simulations with the Exact One-Flavor Algorithm

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As algorithmic developments have driven down the cost of simulating degenerate light quark pairs the relative cost of simulating single quark flavors with the Rational Hybrid Monte Carlo (RHMC) algorithm has become more expensive. TWQCD has proposed an exact one-flavor algorithm (EOFA) that allows for HMC simulations of a single quark flavor without taking a square root of the fermion determinant. We have independently implemented EOFA for Shamir and M\"{o}bius domain wall fermions, and begun to optimize and test our implementation against RHMC. In this talk we will discuss the derivation of the EOFA action, our tests of its equivalence to RHMC, and the current state of our implementation and optimization.

Algorithms and Machines / 152

Domain decomposition and multilevel integration for fermions I

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The numerical computation of many hadronic correlation functions is exceedingly difficult due to the exponentially decreasing signal-to-noise ratio with the distance between source and sink. Multilevel integration methods, using independent updates of separate regions in space-time, are known to be able to solve such problems but have so far been available only for pure gauge theory.

We present first steps into the direction of making such integration schemes amenable to theories with fermions, by factorizing a given observable via an approximated domain decomposition of the quark propagator. This allows for multilevel integration of the (large) factorized contribution to the observable, while its (small) correction can be computed in the standard way.

Algorithms and Machines / 150

Domain decomposition and multilevel integration for fermions II

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The numerical computation of many hadronic correlation functions is exceedingly difficult due to the exponentially decreasing signal-to-noise ratio with the distance between source and sink. Multilevel integration methods, using independent updates of separate regions in space-time, are known to be able to solve such problems but have so far been available only for pure gauge theory.

We present first steps into the direction of making such integration schemes amenable to theories with fermions, by factorizing a given observable via an approximated domain decomposition of the quark propagator. This allows for multilevel integration of the (large) factorized contribution to the observable, while its (small) correction can be computed in the standard way.

Hadron Structure / 156

Double Parton Distributions of the Pion

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The effects of double hard interactions are no longer negligible at energy scales reached at the LHC. Double parton scattering (DPS) processes are often described by taking the product of two single parton scattering processes assuming that interference effects are very small. We calculate four point functions (4pt-functions), which appear in the the DPS cross section, employing lattice techniques. We consider a pion at rest and test the validity of the afore-mentioned factorization assumption by convoluting two pion form factors and comparing the result to the 4pt data. For our calculations we use a $N_f = 2$ gauge ensemble on a $40^3 \times 64$ lattice, with lattice spacing $a = 0.071\text{fm}$ and pion mass $m_\pi = 288.8\text{MeV}$.

Nonzero Temperature and Density / 278

Effective Polyakov Loop Models for QCD-like Theories at Finite Density

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We study the heavy quark limit of QCD-like theories by using a three-dimensional Polyakov theory. This theory can be derived from the full QCD-like theory by a combined strong coupling and hopping expansion. In particular we investigate the cold and dense regime of the phase diagram where we expect to find the Silverblaze property realized as Bose-Einstein-condensation of diquarks or a fist order liquid-gas transition depending on the gauge group of the theory. We find evidence for the Silverblaze property when the quark chemical potential μ reaches half the diquark mass. For even higher μ we find a the rise of the Polyakov loop as well as the quark number density.

Physics Beyond the Standard Model / 14

Effective action for pions and a dilatonic meson - foundations

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Recent simulations suggest the existence of a very light singlet scalar in QCD-like theories that may be lying just outside the conformal window. Assuming that the lightness of this scalar can be explained by an approximate dilatation symmetry, we develop an effective field theory framework for both the pions and this light scalar, the "dilatonic meson." We argue that a power counting exists that puts this effective field theory on a systematic footing.

Physics Beyond the Standard Model / 11

Effective action for pions and a dilatonic meson - results

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We consider applications of a recently developed effective field theory for a dilatonic meson and pions. We contrast the leading-order behavior of masses with that in a theory with only pions, comment on next-to-leading order, and argue that the effective theory breaks down at the sill of the conformal window, as it should.

Vacuum Structure and Confinement / 166

Effects of magnetic fields on quark-antiquark interactions

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I will discuss some recent results obtained in the study of the strong quark-antiquark interaction in the presence of intense external magnetic fields. At zero temperature the external field induces anisotropies in the static quark potential, that affect both the spectrum and the decays of the heavy mesons. In the quark-gluon plasma phase the screening masses do not show significant anisotropies but display a non-trivial dependence on the magnetic field.

Hadron Structure / 215

Electromagnetic Form Factors through Parity-Expanded Variational Analysis

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Variational analysis techniques in lattice QCD are powerful tools that give access to the full spectrum of QCD. At zero momentum, these techniques are well established and can cleanly isolate energy eigenstates of either positive or negative parity.

In order to compute the form factors of a single energy eigenstate, we must perform a variational analysis at nonzero momentum. When we do this with baryons, we run into issues with parity mixing, as boosted baryons are not eigenstates of parity. I present the parity-expanded variational analysis (PEVA) technique, a novel method for ensuring the successful and consistent isolation of boosted baryons. This is achieved through a parity expansion of the operator basis used to construct the correlation matrix.

Nucleon form factor calculations using this new technique are presented, showing the improvement over conventional methods.

Weak Decays and Matrix Elements / 313

Electromagnetic corrections to leptonic decay rates of charged pseudoscalar mesons: finite volume effects.

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In Ref.[1] we proposed a method for calculating leptonic (and semileptonic) decay rates of pseudoscalar mesons including $O(\alpha)$ electromagnetic corrections. Because of the presence of infrared divergences, this requires the calculation of contributions with both virtual and real photons. We have shown that the real photon contribution, by integrating up to photon momenta of the order of 20-30 MeV, can be calculated by treating the meson as a point-like particle. The corrections to this approximation are negligible because a very soft photon cannot resolve the internal structure of the hadron.

For the virtual contribution we need to integrate over all photon momenta and the point-like effective theory is not a valid approximation. For this reason we proposed to compute the virtual contribution by a non-perturbative lattice simulation. The logarithmic infrared divergences are properly regulated by the finite volume and are cancelled by subtracting from the non-perturbative lattice results the virtual decay rate calculated in the point-like approximation.

In this talk we discuss two main analytic results. First we give the explicit analytical expression of the finite volume virtual decay rate in the point-like approximation, necessary for the cancellation of the infrared divergences. We also show explicitly that the $O(1/L)$ finite volume corrections (FVC) to the virtual decay rate are universal, i.e. they are the same in the full theory and in the point-like effective theory. They therefore cancel in the difference of the non-perturbative decay rate and that in the point-like approximation. Structure dependent terms start to contribute to the FVC at $O(1/L^2)$ only.

With the theoretical results discussed in this talk all the ingredients are now in place to compute the decay rates at $O(\alpha)$. The numerical results from an exploratory non-perturbative lattice calculation will be presented by S. Simula in a companion talk.

[1]. N. Carrasco et al., Phys. Rev. D91 (2015) 074506.

Weak Decays and Matrix Elements / 253

Electromagnetic corrections to the leptonic decay rates of charged pseudoscalar mesons: lattice results

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Electromagnetic effects on the leptonic decay rates pi+ -> mu+ nu and K+ -> mu+ nu are evaluated for the first time on the lattice.
Following a method recently proposed in Ref. [1] the emission of virtual photons at leading order in the e.m. coupling is evaluated on the lattice with the subtraction of the infrared divergence computed for a point-like meson at finite lattice volume.
The physical decay rate is then obtained by adding the emission of real photons regularized with a photon mass.
Using the gauge ensembles produced by ETMC with Nf=2+1+1 dynamical quarks the feasibility of the lattice approach is demonstrated and preliminary results for the decay rates of charged pion and kaon will be presented.

[1]. N. Carrasco et al., Phys. Rev. D91 (2015) 074506.

Hadron Structure / 204

Electromagnetic pion form factor near physical point in $N_f = 2+1$ lattice QCD

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We present preliminary result of the electromagnetic form factor of the pion
at $m_\pi = 0.145$ GeV on the large volume corresponding to $L = 8.1$ fm
using stout-smearing Wilson clover quark action and Iwasaki
gauge action at $a^{-1} = 2.333$ GeV. The mean square charge radius
is estimated from the results at small space-like momentum transfer
with the NLO formula in SU(2) chiral perturbation theory.
Our preliminary result of the charge radius is compared with the experiment
and previous lattice calculations.

Plenary Session / 29

Energy-momentum tensor on the lattice: recent developments

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It is conceivable that the construction of the energy-momentum tensor in lattice field theory enlarges our ability in lattice field theory and also deepens our understanding on the energy-momentum tensor in the non-pertubative level. In this talk, I will review recent developments in this enterprise.

Nonzero Temperature and Density / 201

Equation of state in (2+1)-flavor QCD with gradient flow

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The energy-momentum tensor and the equation of state are studied in finite-temperature (2+1)-flavor QCD with improved Wilson quarks, using the gradient flow method proposed by Makino and Suzuki. Although the up and down quarks are heavy yet ($m_{\rm PS}/m_V \approx 0.63$), we obtain reasonable results, suggesting that the method works well. We also report on the results on the chiral condensate and its susceptibility with the gradient flow method.

Hadron Structure / 384

Estimating excited-state contamination in nucleon correlators using experimental data

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Excited-state contamination is one of the dominant uncertainties in lattice calculations of nucleon charges and form factors. To estimate this uncertainty one needs the finite-volume energy spectrum as well as the finite-volume matrix elements that determine the coefficients of excited state exponentials. In this work we use experimental data, supplemented by chiral perturbation theory (ChPT), to estimate these quantities. We first use the Lüscher quantization condition, extended to spin-half particles, to calculate finite-volume $N\pi$ states from $N\pi$ scattering phase shifts. We then study the excited state coefficients using an extension of the Lellouch-Lüscher formalism. This gives a relation between finite- and infinite-volume matrix elements. Both matrix elements of the axial current and the nucleon interpolating fields arise. While the former can be constrained experimentally, the latter are generally unknown and depend on the details of the lattice calculation. We examine various scenarios and find that excited-state contamination can be larger than previous ChPT studies suggest.

Weak Decays and Matrix Elements / 298

Extraction of the bare form factors for the semi-leptonic B_s decays

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Co-author(s): Debasish Banerjee [2] ; Felix Bahr [1] ; Hubert Simma [1] ; Rainer Sommer [3]

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The extraction of bare ground-state matrix elements for $B_s \to K\ell\nu$ decay at 2% precision poses a significant numerical challenge. Especially the B-sector, treated in HQET, is problematic due to large contamination by excited states combined with the signal-to-noise problem. The numerical setup that we use provides access to all time separations for both the two-point and three-point correlation functions of interest, for several different smearings. Using this data, we show how the extraction is achieved using two different techniques - the combined fits to two- and three-point correlation functions, as well as the ratio method (where we compare different possible ratio definitions, including summed ratios).

Theoretical Developments / 181

Fermion bags, topology and index theorems

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In this talk we argue that the fermion bag formulation extends the concepts of topology and index theorems associated with non-Abelian gauge theories, to simple lattice fermion field theories. Through such a connection we learn that fermion masses can arise in at least two different ways:(1) a conventional way where some lattice symmetry of the action is spontaneously, explicitly or anomalously broken and (2) an unconventional way where all lattice symmetries are preserved. We argue for these two scenarios by considering simple examples of lattice field theories formulated with staggered fermions.

Poster / 5

Fermions with long-range interactions using a matrix-product-states approach

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The long-range t-V model of fermions on a lattice is known to exhibit a transition between a Luttinger liquid phase and a Mott insulator phase [1]. At insulating densities, one can tailor the potential energy of the model in such a way that one forces a quantum phase transition to either another insulating charge-density-wave phase, a bond-order phase or a Luttinger liquid [2]. We show how to construct a matrix product operator representation of the Hamiltonian of the t-V model and we present phase diagrams calculated using the matrix-product-states approach [3]. We compare these phase diagrams with results obtained in the atomic limit.

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Physics Beyond the Standard Model / 142

Finite Size Scaling of the Higgs-Yukawa Model near the Gaussian Fixed Point

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We study the scaling property of Higgs-Yukawa models. Using the technique of Finite-Size Scaling, we are able to derive formulae to describe the behaviour of the observables near the Gaussian fixed point. The renormalisation procedure is discussed in this talk. A feasibility study of our strategy is performed for pure scalar theory. In addition, we test the formulae with lattice data obtained in the weak-coupling regime for the Higgs-Yukawa model. These formulae can be used to investigate the universality classes of the observed phase transitions, and thus play an essential role in further investigations of Higgs-Yukawa models.

Applications Beyond QCD / 300

Finite size and infra-red effects in QCD plus QED

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When QED is added to QCD simulations we have to consider the effects of massless degrees of freedom (the photons), which bring new problems which we did not have to worry about in simulations of pure QCD. Related to this, we have questions about the boundary conditions - how can we reconcile periodic boundary conditions with Gauss's Law? What is the best way of treating zero modes of the photon field?

`We combine data from our lattice simulations with perturbative calculations in the infra-red r`

Chiral Symmetry / **64**

First Experiences with Overlap Fermions based on the Brillouin Kernel

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First experiences are reported with overlap fermions which employ the Brillouin action as a kernel. After discussing the dispersion relations of both the kernel and the resulting chiral action, some of the physics features are addressed on quenched backgrounds. We find that the overlap with Brillouin kernel is much better localized than the overlap with Wilson kernel. Also a preliminary account is given of the cost of the formulation, in terms of CPU time and storage.

Hadron Structure / **55**

First Lattice QCD Study of Gluonic Transversity

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We present the first lattice QCD study of the double-helicity-flip leading-twist gluonic structure function Δ(x,Q2). In particular, we calculate its leading moment in a φ meson and find a robust signal. This quantity is particularly interesting since, unlike the unpolarised and helicity gluon distributions, the double-helicity-flip density is a clean measure of gluonic degrees of freedom as it only mixes with quark distributions at higher twist.
We also explore the gluon structure of the φ meson in more general terms, including the first investigation of the direct gluonic analogue of the Soffer bound for transversity which relates the helicity flip and non-flip gluon distributions. We find that the first moment of this bound in a φ meson (at the unphysical light quark masses used in this work and subject to caveats regarding renormalisation and the continuum limit) is saturated to approximately

the same extent as the first moment of the isovector quark Soffer bound for the nucleon as determined in a previous lattice simulation.
This constitutes a proof-of-feasibility of lattice QCD calculations of complicated aspects of the gluon structure of hadrons. Our investigations can be extended to light nuclei where Δ(x,Q2) provides a measure of 'exotic glue' (gluons in the nucleus not associated with individual nucleons), as well as to off-forward gluon transversity matrix elements in the nucleon.

Physics Beyond the Standard Model / 238

Flavor singlet mesons in QCD with varying number of flavors

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Flavor singlet pseudoscalar and scalar mesons are importat objects for both SM-QCD and technicolor models. The study utilizes the handle of the number of flavors in the many-flavor QCD simulations, which has been performed by LatKMI collaboration. Through this, implications to both SM-QCD and technicolor, which could help understand the dynamics of flavor singlet sector, are anticipated. We report on the on-going study towatds this direction with high-statitics HISQ configurations mainly with $N_f = 8$ and 4.

Poster / 368

Flux Tubes at Finite Temperature

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We show the flux tubes produced by static quark-antiquark,
quark-quark and quark-gluon charges at finite temperature.
The sources are placed in the lattice with fundamental and adjoint Polyakov loops.
We compute the square densities of the chromomagnetic and chromoelectric fields above and below the phase transition.
Our results are gauge invariant and produced in pure gauge SU(3).
The codes are written in CUDA and the computations are performed with GPUs.

Vacuum Structure and Confinement / 58

Flux Tubes in QCD with (2+1) HISQ Fermions

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We investigate the transverse profile of the chromoelectric field
generated by a quark-antiquark pair in the vacuum of (2+1) flavor QCD.
Monte Carlo simulations are performed adopting the HISQ/tree action
discretization, as implemented in the publicly available MILC code,
suitably modified to measure the chromoelectric field.
We work on the line of constant physics, with physical strange quark mass
m_s and light to strange mass ratio m_l/m_s = 1/20.

Hadron Structure / 302

Form factors from moments of correlation functions

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Momentum-space derivatives of matrix elements can be related to their coordinate-space moments through the Fourier transform. We derive these expressions as a function of momentum transfer Q^2 for asymptotic in/out states consisting of a single hadron. We calculate corrections to the finite volume moments by studying the spatial dependence of the lattice correlation functions. This method permits the computation of not only the values of matrix elements at momenta accessible on the lattice, but also the momentum-space derivatives, providing *a priori* information about the Q^2 dependence of form factors. As a specific application we use the method, at a single lattice spacing and with unphysically heavy quarks, to directly obtain the slope of the isovector form factor at various Q^2, whence the isovector charge radius. The method has potential application in the calculation of any hadronic matrix element with momentum transfer, including those relevant to hadronic weak decays.

Weak Decays and Matrix Elements / 260

Form factors in the $B_s --> Kl\nu$ decays using HQET and the lattice

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We report on a recent computation of the form factors in semi-leptonic decays of the B_s using Heavy Quark Effective Theory (HQET) formalism applied on the lattice. The connection of the form factors with the 2-point and 3-point correlators on the lattice is explained, and the subsequent non-perturbative renormalization of HQET and it's matching to $N_f = 2$ QCD is outlined. The results of the (static) leading-order calculation in the continuum limit is presented. Preliminary results on extending the leading-order computation by including the $1/m$ effects (where m is the heavy-quark mass) are mentioned.

Applications Beyond QCD / 293

Four-Fermion Theories with Exact Chiral Symmetry in Three Dimensions

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We investigate a class of quantum field theories of fermions interacting by a quartic coupling.
This includes well-known models like the Gross-Neveu model and the Thirring model.
In three spacetime dimensions, these models are used to describe properties of solid state systems like high temperature superconductors and graphene.
Additionally, they are interesting as toy models to study chiral symmetry breaking.

The Gross-Neveu model always has a broken and a symmetric phase, while the existence of a broken phase in the Thirring model depends on the number of fermion flavours.
The critical number of fermion flavours for chiral symmetry breaking is still subject of ongoing discussion.
Using SLAC fermions, we are able to simulate the Thirring model with exact chiral symmetry, but the chiral condensate is not obtainable on a finite lattice without explicit breaking.

The talk presents approaches to circumvent this problem.
We use Fierz identities to transform the Thirring model into other four-fermion models, where the chiral condensate does not vanish.
These models show a sign problem, which is not present in the original Thirring model.
We present an algorithm inspired by fermion bags, which may overcome this short coming.
As a second approach, the chiral symmetry breaking of a larger class of four-fermion models is studied.

Plenary Session / 39

From C to Parton Sea: Bjorken-x dependence of the PDFs

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Studying the structure of nucleons is not only important to understanding the strong interactions of quarks and gluons, but also to improving the precision of new-physics searches.

Since a broad class of experiments, including the LHC and dark-matter detection, require Standard-Model backgrounds with parton distribution functions (PDFs) as inputs for disentangling SM contributions from potential new physics.
For a long time, lattice calculations of the PDFs (as well as many hadron structures) has been limited to the first few moments.
In this talk, we present a first direct calculation of the Bjorken-x dependence of the PDFs using Large-Momentum Effective Theory (LaMET). An exploratory study of the antiquark/sea flavor asymmetry of these distributions will be discussed. This breakthrough opens an exciting new frontier calculating more complicated quantities, such as gluon structure and transverse-momentum dependence, which will complement existing theoretical programs for the upcoming Electron-Ion Collider (EIC) or Large Hadron-Electron Collider (LHeC).

Plenary Session / 409

From Spin Models to Lattice QCD – the Scientific Legacy of Peter Hasenfratz

Urs Wenger[1]

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From Spin Models to Lattice QCD – the Scientific Legacy of Peter Hasenfratz

Public Lecture / 411

From the Origins of Mass to the Stability of Matter: Lattice QCD and Supercomputers

Laurent Lellouch[1]

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The origin of mass is mysterious. In our everyday experience, the mass of an object is the sum of the mass of its parts. However, in the world of subatomic particles such as quarks and gluons, this everyday assumption is no longer true and even very small mass differences can have cosmic consequences. After an introduction to the subatomic world and the mechanisms by which mass emerges, I will describe how supercomputers are being used to compute from first principles the interactions between elementary particles in order to reveal the origins of mass and to explain the stability of the matter which constitutes us and the visible universe.

Tickets for this public lecture can be booked via Eventbrite http://latticeqcd.eventbrite.co.uk/ .

Nonzero Temperature and Density / 93

Functional Fit Approach (FFA) for Density of States method: SU(3) spin system and SU(3) gauge theory with static quarks

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We study new developments for the Density of States (DoS) method to simulate systems affected by the complex action problem. In particular we use the functional fit approach (FFA). It consists of a restricted Monte Carlo simulation with an additional Boltzmann factor, which allows one to explore the DoS for a given part of the spectrum. We fit the simulation data with a known function to obtain the parameters of the DoS.
We apply the approach to two model systems: 1) The SU(3) spin system with a chemical potential; 2) The SU3 gauge theory with static quarks. We discuss the technical challenges and the potential of FFA DoS.

Poster / **350**

Further Study of BRST-Symmetry Breaking on the Lattice

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We evaluate the so-called Bose-ghost propagator in minimal Landau gauge, for the SU(2) case in four dimensions. We consider lattice volumes up to 120^4 and physical lattice extents up to 13.5 fm. We investigate discretization effects, as well as the infinite-volume and continuum limits. A nonzero value for this quantity provides direct evidence of BRST-symmetry breaking, related to the restriction of the functional measure to the first Gribov region.

Nonzero Temperature and Density / **225**

Gauge cooling for the singular-drift problem in the complex Langevin method - an application to finite density QCD

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The complex Langevin method is a promising approach to complex action systems, which suffer from the sign problem. In particular, the use of gauge cooling enabled the studies of finite density QCD either in the deconfined phase or in the heavy dense limit. In the confined phase with light quarks, however, the method does not work as it is due to the singularities in the fermion drift term caused by small eigenvalues of the Dirac operator with the quark mass. In a previous paper, we proposed that this singular-drift problem can be overcome by the gauge cooling with different criteria for choosing the complexified gauge transformation, and showed that the method works in chiral Random Matrix Theory even at small quark mass.

Here, we apply the same idea to QCD at finite density with light quarks
and present some preliminary results.

Hadron Spectroscopy and Interactions / 264

Glueball spectrum from $N_f = 2$ lattice QCD study on anisotropic lattices

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The glueball spectrum is investigated through a $N_f = 2$ lattice QCD study. The gauge configurations are generated with two degenerate flavors of quarks on anisotropic lattices. At two pion masses, say, $m_\pi = 580$ MeV and 920 MeV, we obtain the masses of the scalar, the tensor glueballs, which are in agreement with the results from the previous quenched and unquenched lattice QCD studies. For the pseudoscalar channel, we can get a state of mass roughly 2.4-2.5 GeV by the use of the gluonic lattice operators whose continuum counterparts are $\epsilon_{ijk}B_i^a(D_jB_k)^a$. This state is compatible with the pseudoscalar glueball from the previous quenched lattice QCD studies. We do not observe a clear quark mass dependence of the masses of these states. We also calculate the correlation functions of the topological charge density adopting the gradiant flow smearing scheme. We can seemingly observe a state with a mass around 1 GeV, but fail to obtain a definite result owing to our coarse and small lattices. This state might be the isoscalar $q\bar{q}$ pseudoscalar meson, the $SU(2)$ counterpart of the $SU(3)$
flavor singlet η'.

Poster / 261

Gradient flow observables and boundary O(a) improvement of the Schroedinger functional

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The gradient flow provides a new class of renormalized observables which can be measured with high precision in lattice simulations. In principle this allows to improve lattice actions a la Symanzik by requiring such observables to take their continuum values already at finite lattice spacing. At lowest order of perturbation theory we here try to identify such improvement conditions for the O(a) counterterm at the Schroedinger functional boundaries. We study the action density, E(t,x), separately

for colour electric and magnetic components and with different discretizations of the observable and the flow.

Physics Beyond the Standard Model / 153

Gradient flow running coupling in SU(2) with 6 flavors

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We present preliminary results of the gradient flow running coupling in SU(2) gauge theory with 6 massless fundamental representation fermion flavours. We use the Schrödinger functional boundary conditions, which allows us to also measure the mass anomalous dimension. Our results, using the HEX-smeared Wilson-clover action, are consistent with perturbative running on the weak coupling region and diverge towards a possible infrared fixed point at strong coupling.

Poster / 122

Ground state charmed meson and baryon spectra for $N_f = 2+1+1$

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We present a study of the charmed meson and baryon ground state spectra on the electrically neutral subset of the BMW $N_f = 2+1+1$ gauge configurations that utilise the 3-HEX smeared clover action. The analysis focuses on a systematic evaluation of the hyperfine mass splittings of the doubly charmed J/ψ and η_c mesons and the singly charmed D_s^* and D_s mesons, with the aim to understand the significant cut-off effects that can accompany Wilson type fermion measurements.

Hadron Structure / 379

Hadron Matrix Elements and the Feynman-Hellman Theorem

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Motivated by the Feynman-Hellman Theorem, we develop an improved method for computing matrix elements of external currents utilizing only two-point correlation functions.
The contamination from excited states is shown to be Euclidean-time dependent allowing for a significantly improved ability to reliably determine and control the systematics.
We demonstrate the utility of our method with a calculation of the nucleon axial-charge, performed at a single lattice spacing and a moderate unphysical pion mass.
The Feynman-Hellman Theorem can be derived from the long Euclidean-time limit of correlation functions determined with functional derivatives of the partition function.
This elucidates the generic applicability of our new method: one can determine matrix elements of any external current by computing only two-point correlation functions, including non-zero momentum transfer and flavor-changing matrix elements.

Plenary Session / 118

Hadron Structure

Sara Collins[1]

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Recent calculations of hadron structure observables and related technical and theoretical advances are reviewed. A wealth of information on the properties of hadrons can be provided by lattice methods such as their wavefunctions, response to electromagnetic, weak or beyond the Standard Model probes and their internal dynamics in terms of the contributions from quarks and gluons. Progress in the evaluation of benchmark quantities which are well determined from experiment will be discussed, along with the control of systematics before highlighting recent calculations of more challenging and less well known observables.

Hadron Structure / 287

Hadron Structure from the Feynman-Hellmann Theorem

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Although hadron structure calculations in lattice QCD have improved greatly in recent years, many problems still remain. Various techniques for determining fermion line disconnected contributions to matrix elements have produced exciting and promising results, but rely on complicated analyses. Additionally, calculations of electromagnetic form factors at high momentum transfers remain limited by low signal-to-noise ratios.

In this talk we present results from Feynman-Hellmann motivated approaches to determinations of these quantities. We find disconnected contributions to $\Delta\Sigma$ consistent with stochastic calculations, and are able to access significantly higher momentum transfers for electromagnetic form factors than have previously been feasible. In conjunction with experimental data, these results may reveal interesting information regarding the possibility of a zero crossing in the ratio of electric and magnetic form factors in the nucleon.

Hadron Spectroscopy and Interactions / 105

Hadron scattering and resonances

Raul Briceno[1]

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In this talk, I present recent progress towards the determination of resonant systems via lattice QCD. The truncation of the volume – necessary for lattice QCD calculations – significantly alters the analytic structure of the theory. For scattering processes involving two-hadron states, this can be circumvented by utilizing formalism to map finite-volume quantities obtained onto the desired infinite-volume observables. I illustrate the power of these techniques by highlighting some important examples in the light sector of QCD.

Hadron Structure / 305

Hadronic contribution to the muon magnetic moment at the physical point

Taichi Kawanai[1]

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Recent phenomenological and lattice determinations of the anomalous magnetic moment of the muon a_μ hint at beyond the Standard Model physics on the 3-4 sigma level. Here we present lattice results for the leading order hadronic contribution of a_μ obtained from 2+1+1 flavor, staggered quark simulations at the physical point. The various quark flavor contributions, together with their systematics, will be discussed. The results are compared to existing ones in the literature.

Plenary Session / 31

Hadronic contributions to the muon $g-2$ from lattice QCD

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The overall accuracy of the Standard Model prediction of the anomalous magnetic moment of the muon is currently limited by hadronic effects. I review the status of lattice QCD calculations, aimed at providing precise estimates for the hadronic vacuum polarisation and hadronic light-by-light scattering contributions, respectively. In the case of the leading hadronic vacuum polarisation contribution I will focus on systematic effects in current lattice simulations and outline the progress made in computing the contributions from quark-disconnected diagrams. For the hadronic light-by-light scattering contribution the different computational and conceptual strategies employed by various groups will be reviewed.

Hadron Spectroscopy and Interactions / 335

Heavy and light spectroscopy near the physical point, Part I: Charm and bottom baryons

Anthony Francis[1] ; Kim Maltman[1] ; Randy Lewis[1] ; Renwick J. Hudspith[1]

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We present results of the hadron spectrum using $n_f = 2+1$ ensembles with pion masses as low as 156(4) MeV, we place particular emphasis on measurements of the singly and doubly heavy charm and bottom baryons.
Using the Tsukuba tuning for relativistic charm and NRQCD for the bottom quarks we perform measurements of both light and heavy mesons as well as spin-1/2 and spin-3/2 baryons for all possible flavor combinations. Our subsequent analysis yields masses with an accuracy below the 1%-level and therefore splittings with good statistical precision. All results are extrapolated to the physical pion mass via a tightly controlled, short, chiral extrapolation.

Hadron Spectroscopy and Interactions / 334

Heavy and light spectroscopy near the physical point, Part II: Tetraquarks

Anthony Francis[1] ; Kim Maltman[1] ; Randy Lewis[1] ; Renwick J. Hudspith[1]

[1] *York University*

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Having introduced the ensembles and basic spectrum in Part I, we focus on results for a doubly heavy tetraquark candidate, $qq\bar{Q}\bar{Q}$. Based on phenomenological observations regarding heavy baryon

systems, we motivate two possible lattice interpolating operators: a diquark-anti diquark and a meson-meson. We show these operators exhibit good behaviour both in terms of lattice QCD and their phenomenological interpretation. In particular we study the $qq\bar{b}\bar{b}$, $qq\bar{c}\bar{b}$ and $qq\bar{c}\bar{c}$ with $qq = ud, us$ flavor combinations and analyze their binding. In the chiral limit, at finite lattice spacing, we find strong indications for binding of the $qq = ud$ tetraquark candidates. We comment on possible search windows for experimental confirmation.

Plenary Session / 304

Heavy flavor physics

ran zhou[1]

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Heavy meson decays are used to extract the fundamental parameters
in Standard Model such as CKM matrix elements and probe new physics
beyond the Standard Model. Lattice QCD provides a non-perturbative
method to calculate the matrix elements in these processes. In this talk, I
will review recent progress in the study of B and D meson
decay constants, semileptonic decay form factors, B and D meson mixing.
In addition, I will present the impact of lattice-QCD results
on phenomenology and compare the latest Standard Model predictions
with the experimental results.

Plenary Session / 76

Heavy flavours in quark-gluon plasma

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Heavy quark system offers opportunities and challenges for theoretical (and experimental) investigations on the properties of Quark-Gluon Plasma (QGP). Here, recent progresses in the studies of heavy quarks and quarkonia in QGP are discussed. In particular, the results from the calculation of heavy quark kinetic/chemical equilibration in QGP and those from the studies of quarkonia behaviors at non-zero temperature are discussed.

Weak Decays and Matrix Elements / 132

Heavy-heavy current improvement for calculation of $\bar{B} \to D^{(*)}\ell\bar{\nu}$ semi-leptonic form factors using the Oktay-Kronfeld action – 1

Jaehoon Leem[1] ; Jon Bailey[1] ; Sungwoo Park[1] ; Weonjong Lee[1] ; Yong-Chull Jang[2]

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The Oktay-Kronfeld action is a highly improved version of the Fermilab action and systematically reduces heavy quark discretization effects through $\mathcal{O}(\lambda^3)$ in HQET power counting, for the heavy-light meson spectrum. To calculate $\bar{B} \to D^{(*)}\ell\bar{\nu}$ semi-leptonic form factors using Oktay-Kronfeld heavy quarks, we need to improve the heavy quark currents to the same level. We report our progress in calculating the improvement coefficients for currents composed of bottom and charm quarks.

Poster / **131**

Heavy-heavy current improvement for calculation of $\bar{B} \to D^{(*)}\ell\bar{\nu}$ semi-leptonic form factors using the Oktay-Kronfeld action – 2

Jaehoon Leem[1] ; Jon Bailey[1] ; Sungwoo Park[1] ; Weonjong Lee[1] ; Yong-Chull Jang[2]

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The Oktay-Kronfeld action is a highly improved version of the Fermilab action and systematically reduces heavy quark discretization effects through $\mathcal{O}(\lambda^3)$
in HQET power counting, for the heavy-light meson spectrum. To calculate $\bar{B} \to D^{(*)}\ell\bar{\nu}$ semi-leptonic form factors using Oktay-Kronfeld heavy quarks, we need to improve the heavy quark currents to the same level.
We report our progress in calculating the improvement coefficients
for currents composed of bottom and charm quarks.

Poster / **184**

Hierarchically deflated conjugate residua

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Hierarchically deflated conjugate residual

We present a new class of multigrid solver algorithm suitable for the solution of 5d chiral fermions such as Domain Wall fermions
and the Continued Fraction overlap. Unlike HDCG \cite{arXiv:1402.2585}, the algorithm
works directly on a nearest neighbour fine operator. The fine operator used is Hermitian indefinite, for example $\Gamma_5 D_{dwf}$,
and convergence is achieved with an indefinite matrix solver such as outer iteration based on conjugate residual.
As a result coarse space representations of the operator remain nearest neighbour, giving an 8 point stencil rather than the 81 point stencil used in HDCG.
It is hoped this may make it viable to recalculate the matrix elements of the little Dirac operator in an HMC evolution.

Hadron Spectroscopy and Interactions / 324

Hindered M1 Radiative Decays

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Throughout the literature, phenomenological models have been unsuccessful in pinning down the heavy quarkonia hindered M1 radiative transitions (i.e., those radiative transitions between states with different principal quantum numbers that require one of the quarks to flip-spin) and yield predictions that are spread over a vast range.

In this talk, we will learn how to accurately and precisely predict these classes of decays by utilising lattice NRQCD, compare to the phenomenological calculations, and then show how this work is relevant for the experimental hyperfine splitting.

Theoretical Developments / 194

How to make a quantum black hole with ultra-cold gases

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We argue that a small, quantum black hole can be made from atoms and lasers.

The holographic principle claims that the quantum gravitational systems, e.g. superstring theory, is equivalent to non-gravitational quantum systems, e,g. super Yang-Mills theory. Here the 'equivalence' means two theories cannot be distinguished even in principle. Therefore, if the holographic principle is true, then by engineering the non-gravitational systems by using an optical lattice, one can create actual quantum black holes.

In this presentation, we consider the simplest example: the Sachdev-Ye-Kitaev (SYK) model.
We design a an experimental scheme for creating the SYK model with use of ultra-cold fermionic atoms.

This presentation is based on a paper "Creating and probing the Sachdev-Ye-Kitaev model with ultracold gases: Towards experimental studies of quantum gravity," arXiv:1606.02454 with Ippei Danshita (Yukawa Institute for Theoretical Physics, Kyoto University) and Masaki Tezuka (Deptartment of Physics, Kyoto University).

Weak Decays and Matrix Elements / 72

Hypercubic effects in semileptonic $D \to \pi$ decays on the lattice

Author(s): Vittorio Lubicz[1]

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We present lattice results of the form factors relevant for semileptonic $D \to \pi \ell \nu$ decays, using the gauge ensembles produced by the European Twisted Mass Collaboration with Nf=2+1+1 flavors of dynamical quarks, at three values of the lattice spacing and pion masses as low as 210 MeV.
We have computed the matrix elements of both the vector and scalar weak currents for several kinematic configurations corresponding to moving parent and child mesons. The lattice data exhibit the presence of hypercubic effects. Our preliminary results for the momentum dependence of the form factors and for the vector form factor at zero-momentum transfer, f+(0), are obtained by removing such lattice effects.

Hadron Spectroscopy and Interactions / **269**

Impact of dynamical charm quarks

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We investigate the influence of dynamical charm quarks on various observables. For observables without explicit charm-quark dependence, decoupling applies and the effects are expected to be small. However, we also study quantities with explicit charm-quark dependence, like the charmonium mass spectrum, where decoupling does not apply.

Our study puts an emphasis on careful continuum extrapolations, which require very small lattice spacings when heavy quarks are present in the action. Since our precision goals cannot be currently met in full QCD, we carry our investigations out in a model without light quarks; quenched QCD is compared to QCD with two dynamical heavy quarks.

Plenary Session / **32**

Impact of lattice QCD on CKM phenomenology

Monika Blanke[1]

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In this talk I review the implications of recent lattice QCD results on the phenomenology of flavour and CP-violating meson decays. Precise lattice QCD results for hadronic matrix elements, decay constants and form factors play a crucial role in the determination of CKM matrix elements and in the identification of possible new physics contributions to flavour violating observables. I also highlight some possible future directions for lattice QCD calculations which would have a big impact on flavour phenomenology.

Hadron Spectroscopy and Interactions / 307

Importance of closed quark loops for lattice QCD studies of tetraquarks

Abdou Abdel-Rehim[1] ; Constantia Alexandrou[1] ; Jacob Finkenrath[2] ; Joshua Berlin[3] ; Marc Wagner[4] ; Mario Gravina[5] ; Mattia Dalla Brida[6] ; Theodoros Leontiou[1]

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To investigate the light scalar tetraquark candidate $a_0(980)$ (quantum numbers $J^P = 0^+$), a correlation matrix including a variety of two- and four-quark interpolating operators has to be computed. We discuss efficient techniques to compute the elements of this correlation matrix. In particular we present numerical results for diagrams with closed quark loops and present evidence that such diagrams are not negligible, i.e. that their contribution is essential to obtain physically meaningful results.

Hadron Spectroscopy and Interactions / 100

Including heavy spin effects in a lattice QCD study of static-static-light-light tetraquarks

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In previous works we predicted the existence of a $\bar{b}\bar{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$ using the static approximation for the $\bar{b}$ quarks and neglecting heavy spin effects. Since the binding energy is of the same order as expected for these heavy spin effects, it is essential to include them in the computation. Here we present a corresponding method and show evidence that binding is only slightly weakened and that the $\bar{b}\bar{b}ud$ tetraquark persists.

Applications Beyond QCD / 220

Infrared features of dynamical QED+QCD simulations

Ross Young[1]

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Using dynamical lattice simulations of the coupled theory of QED and QCD we explore some particular aspects of the periodic boundary conditions. We observe that the finite volume effects in spectroscopy are dependent upon the precise implementation of the gauge-fixing condition. We also report on the finite-volume dependence of the charge renormalisation.

Physics Beyond the Standard Model / 200

Infrared properties of a prototype pNGB model for beyond-SM physics

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We construct a prototype BSM model where the Higgs boson is a pseudo
Nambu-Goldstone boson by combining 4 light (massless) flavors and 8
heavy flavors. In the infrared, the SU(4) chiral symmetry is spontaneously broken , while in the ultraviolet it exhibits the properties of the $N_f = 12$ conformal fixed point. The running coupling of this system "walks" and the energy range of walking can be tuned by the mass of the heavy flavors. At the same time, renormalization group considerations predict the spectrum of such a system to show hyperscaling i.e. hadron masses in units of F_π are independent of the heavy mass. Hyperscaling is present for bound states made-up of light, heavy, or heavy and light flavors. This observation is supported by numerical observations and makes the model strongly predictive.

Physics Beyond the Standard Model / 60

Interacting ultraviolet completions of four-dimensional gauge theories

Andrew Bond[1]

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We will discuss some of the recent developments in understanding ultraviolet completions of gauge-Yukawa theories beyond traditional asymptotic freedom.

Algorithms and Machines / 359

Introduction to the Quantum EXpressions (QEX) framework

Author(s): James Osborn[1]

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We present a new lattice field theory software framework designed with ease of use, flexibility, efficiency and portability in mind. The framework is written using the Nim programming language which offers many of the features one would find in a high-level scripting language, while in fact being a strongly-typed language with full control over low-level optimizations. This allows us to present a simple expression-based language to the end user that can be transformed into highly optimized code for a particular architecture. We will discuss the features of the QEX framework, performance results and development plans.

Hadron Structure / 331

Isospin-breaking effects for meson masses and HVP, from Lattice QCD + quenched QED

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Lattice calculations of the leading-order hadronic contribution to the muon g-2, from the hadronic vacuum polarisation, are approaching sub-percent level precision. At this level, it becomes important to consider corrections from isospin-breaking. Here, we include quenched QED in our simulations by stochastically generating U(1) gauge configurations and combining these with existing SU(3) gauge configurations. We will present some first results for meson masses and HVP using this method, obtained on a 24^3 x 64, N_f=2+1 ensemble using domain wall fermions. This calculation will be directly compared to the perturbative approach presented by Vera Gülpers.

Poster / 69

Isovector Axial Charge with Current Improvement

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We employ dimension 4 operators to improve the local vector and axial vector currents, as the leading order approximation of the lattice conserved current, and then calculate the nucleon iso-vector axial coupling g_A^3 using overlap valence on Domain Wall Fermion sea. Using the equality of g_A^3 from A_i and A_4 components of the axial-vector current as a normalization condition in addition to axial Ward identity, we find two to three percent increase of g_A^3 towards the experimental value. The excited state contamination has been taken into account with three time separations between the source and sink.
The improved axial charges $g_A^{IM}(24I) = 1.188(7)$, $g_A^{IM}(32I) = 1.177(9)$ are obtained on $24^3 \times 64$ and $32^3 \times 64$ lattices at the unitary point where the pion masses are 330 MeV and 300 MeV respectively.

Hadron Spectroscopy and Interactions / 344

Kaon Kaon scattering at maximal isospin from $N_f = 2+1+1$ twisted mass lattice QCD

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We present results for the interaction of two Kaons at maximal isospin. The calculation is based on 2+1+1 flavour gauge configurations generated by the ETM Collaboration featuring pion masses ranging from about 230 MeV to 450 MeV at three values of the lattice spacing. The elastic scattering length a_0 is calculated at several values of the bare strange quark and light quark masses. Chiral extrapolations to the physical point are presented and compared to other lattice results.

Weak Decays and Matrix Elements / 148

Kaon semileptonic decays with $N_f = 2+1+1$ HISQ fermions and physical light quark masses

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We present an update of our calculation of the $K_{\ell 3}$ form factor $f_+^{K\pi}(0)$, with added statistics and the inclusion of new ensembles with smaller lattice spacing. In addition, we now also include a study of finite volume effects using a version of staggered ChPT that includes the effects of twisted boundary conditions.We also examine the implications for the unitarity of the CKM matrix in the first row by combining these improved results together with $N_f = 2+1+1$ MILC results for light decay constants.

Hadron Spectroscopy and Interactions / 96

Lambda-Nucleon and Sigma-Nucleon interactions from lattice QCD with physical masses

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We present our recent study on baryon-baryon (BB) interactions from lattice QCD with almost physical quark masses corresponding to $(m_\pi, m_K) \approx (146, 525)$ MeV and large volume $(La)^4 = (96a)^4 \approx$ (8.2 fm)^4. In order to make better use of large scale computer resources, a large number of BB interactions from NN to $\Xi\Xi$ are calculated simultaneously. In this contribution, we focus on the strangeness $S = -1$ channels1 of the hyperon interactions by means of HAL QCD method. More recent results will be presented which include ΛN$-\Sigma$N coupled-channel potential comprising the tensor force as well as increasing the Monte Carlo samples than shown in the past1.

References:
1 H. Nemura, et al., arXiv:1604.08346 [hep-lat].
enter link description here

Nonzero Temperature and Density / 133

Landau Levels in Lattice QCD

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The spectrum of the two-dimensional continuum Dirac operator in the presence of a uniform background magnetic field consists of Landau levels, which are degenerate and separated by gaps. On the lattice the Landau levels are spread out by discretization artefacts, but a remnant of their structure is clearly visible (Hofstadter butterfly). If one switches on a non-Abelian interaction, the butterfly structure will be smeared out, but the lowest Landau level will still be separated by a gap from the rest of the spectrum. In this talk we discuss how the eigenmodes of the four-dimensional QCD Dirac operator are built out of the two-dimensional eigenmodes of the Dirac operator diagonalized on each slice at fixed (z,t). In particular, starting from this decomposition, we consider how well certain physical

quantities are approximated by using only the two-dimensional eigenmodes belonging to the lowest Landau level.

Vacuum Structure and Confinement / 351

Landau gauge gluon vertices from Lattice QCD

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In lattice QCD the computation of one-particle irreducible (1PI) Green's functions with a large number (> 2) of legs is a challenging task. Besides tuning the lattice spacing and volume to reduce finite size effects, the problems associated with the estimation of higher order moments via Monte Carlo methods and the extraction of 1PI from complete Green's functions are limitations of the method. Herein, we address these problems revisiting the calculation of the three gluon 1PI Green's function, with emphasis in the infrared region and providing a first look at the four gluon vertex.

Physics Beyond the Standard Model / 292

Large mass hierarchies from strongly-coupled dynamics

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Motivated by tentative signals of new physics at the LHC, which seems to imply the presence of large mass hierarchies, we investigate the theoretical possibility that these could arise dynamically in new strongly-coupled gauge theories extending the standard model of particle physics. To this purpose, we study lattice data on non-Abelian gauge theories in the (near-)conformal regime—specifically, $\mathrm{SU}(2)$ with $N_\mathrm{f} = 1$ and 2 dynamical fermion flavours in the adjoint representation. We focus our attention on the ratio R between the masses of the lightest spin-2 and spin-0 resonances, and draw comparisons with a simple toy model in the context of gauge/gravity dualities. For models in which large anomalous dimensions arise dynamically, we show indications that this mass ratio can be large, with $R > 5$. Moreover, our results suggest that R might be related to universal properties of the IR fixed point. Our findings provide an interesting step towards understanding large mass ratios in the non-perturbative regime of quantum field theories with (near) IR conformal behaviour.

Physics Beyond the Standard Model / 177

Latest results from lattice N=4 supersymmetric Yang–Mills

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I will present results from numerical studies of maximally supersymmetric Yang–Mills theory, focusing on the scaling dimension of the Konishi operator. Working with a lattice formulation that exactly preserves one supersymmetry at non-zero lattice spacing, we employ an improved action developed in 2015 that dramatically reduces lattice artifacts. Using this new improved action we are exploring a range of 'tHooft couplings for two-, three- and four-color gauge theories, to bridge the perturbative regime and the onset of strong-coupling AdS/CFT duality in the large-N limit. Among the various quantities we are investigating the Konishi operator is particularly significant as the simplest conformal operator with a non-trivial anomalous dimension.

Theoretical Developments / 172

Lattice Conformal Field theory on Curved Manifolds

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A Quantum Finite Element (QFE) Lagrangian is formulated for a general simplicial complex approximation to a smooth Euclidean Riemann manifold. The construction is applied to Wilson Dirac fermions with the appropriate lattice spin connection and to phi 4th-theory with QFE counter terms required for these theories to converge in the continuum limit. Numerical tests are given for the Wilson-Fisher fixed point in 2D with comparison to the exact solution of the Ising CFT on the two sphere and for the 3D phi 4th-theory in radial quantization. Potential future applications to more general 3D conformal field theories and 4D Beyond the Standard Model (BSM) gauge theories near the conformal window are suggested.

Plenary Session / 404

Lattice QCD at nonzero temperature and density

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I will review some recent selected results from Lattice QCD computations at nonzero temperature and density.

Weak Decays and Matrix Elements / 312

Lattice QCD calculation of form factors for $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ decays

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Experimental results for mesonic $b \to s\mu^+\mu^-$ decays show a pattern of deviations from Standard-Model predictions. These deviations could be due to new fundamental physics or due to an insufficient understanding of hadronic effects. Complementary information on the $b \to s\mu^+\mu^-$ transition can be obtained from Λ_b decays. This was recently done using the process $\Lambda_b \to \Lambda\mu^+\mu^-$, where the Λ is the lightest strange baryon. A further interesting channel that is being analyzed by LHCb is $\Lambda_b \to p^+K^-\mu^+\mu^-$, where the p^+K^- final state receives contributions from multiple higher-mass Λ resonances. The narrowest and most prominent of these is the $\Lambda(1520)$, which has $J^P = \frac{3}{2}^-$. We discuss our progress toward a lattice QCD calculation of the relevant $\Lambda_b \to \Lambda(1520)$ form factors.

Theoretical Developments / 309

Lattice QCD on non-orientable manifolds - part I

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A common problem in lattice QCD simulations on the torus is the extremely long autocorrelation time of the topological charge, when one approaches the continuum limit. The reason is the suppressed tunneling between topological sectors. The problem can be addressed by replacing the torus with a different manifold. Here we propose to use a non-orientable manifold, and show how to define and simulate lattice QCD on it. Part I focuses on the motivation and general introduction of our construction.

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Lattice QCD on non-orientable manifolds - part II

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A common problem in lattice QCD simulations on the torus is the extremely long autocorrelation time of the topological charge, when one approaches the continuum limit. The reason is the suppressed tunneling between topological sectors. The problem can be addressed by replacing the torus with a different manifold. Here we propose to use a non-orientable manifold, and show how to define and simulate lattice QCD on it. Part II focuses on special issues like the implementation of fermions on a non-orientable manifold.

Hadron Spectroscopy and Interactions / 322

Lattice QCD searches for tetraquarks containing charm quarks

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We present searches for tetraquarks in lattice QCD with quark content $cc\bar{q}\bar{q}$ and isospin-1 $c\bar{c}q\bar{q}$ which are especially of relevance to the experimentally observed charged Z_c states. Utilising the variational method, we employ a large bases of operators consisting of diquark-antidiquark and meson-meson operators. We show the spectra determined across a range of channels. We discuss extending our study to the isospin-0 $c\bar{c}q\bar{q}$ sector.

Theoretical Developments / 8

Lattice QCD simulation of the Berry curvature

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The Berry curvature is a fundamental concept describing topological order of quantum systems.
While it can be analytically tractable in non-interacting systems, numerical simulations are necessary in interacting systems.
We present a formulation to calculate the Berry curvature in lattice QCD.

Hadron Spectroscopy and Interactions / 104

Lattice QCD study of heavy-heavy-light-light tetraquark candidates

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We study $\bar{b}\bar{b}ud$ and $\bar{b}bu\bar{d}$ four-quark systems using lattice QCD. The heavy b quarks are treated either in the static approximation or by using NRQCD. Both for $\bar{b}\bar{b}ud$ (quantum numbers $I(J^P) = 0(1^+)$) and for $\bar{b}bu\bar{d}$ (quantum numbers of Z_b, $I(J^P) = 1(1^+)$) our results indicate the existence of a four-quark bound state, i.e. a tetraquark.

Hadron Structure / 348

Lattice calculation of the pion transition form factor $\pi^0 \to \gamma^*\gamma^*$

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We report on the lattice QCD calculation of the $\pi^0 \to \gamma^*\gamma^*$ form factor using two flavors of O(a)-improved Wilson fermions with photon virtualities in the range $Q^2 \in [0 - 1.5]$~GeV^2. Different lattice spacings and pion masses are used to extrapolate our result to the physical point.
First, we check that our results, once extrapolated to the chiral and continuum limit, are compatible with the chiral anomaly. Then, the shape of the form factor is compared to different phenomenological models proposed in the literature and to experimental data in the single-virtual case when one photon is on-shell. From a phenomenological point of view, this form factor determines the π^0 pole contribution to hadronic light-by-light (HLbL) scattering in the muon $g-2$,thought to be dominant.

Hadron Spectroscopy and Interactions / 47

Lattice operators for scattering of particles with spin

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The operators for simulating the scattering of two hadrons with spin will be presented. Three methods give consistent operators for PN, PV, VN and NN scattering, where P, V and N denote pseudoscalar, vector and nucleon. Explicit expressions for all irreducible representations and few lowest momenta will be shown as an example. Correct transformation properties will be demonstrated.

Hadron Structure / 183

Lattice simulations of vector mesons in strong magnetic field

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We have explored ground state energies of the light vector mesons on the base of the $SU(3)$ lattice gauge theory. This study was performed without dynamical quarks. We have observed the energies spliting depending on the value of the spin projections on an external magnetic field. The ground state energy of neutral mesons with the $s_z = 0$ diminishes with the increase of the field, while the energy of charged one increases according to the theoretical expectation. The neutral mesons energies with non-zero spins $s_z = -1$ and $+1$ increase with the value of the magnetic field.
The Landau level describes the energy of a charged point-like particle in a magnetic field , while in our calculations we took into account the quark structure of a particle and introduced the term with magnetic polarizability:
\begin{equation}
E^2=p^2_z+m^2+|qH|-gs_zqH-4\pi m \beta_m H^2, \ \ H=eB,
\end{equation}
where E is the ground state energy of a particle, g is the magnetic dipole moment of the particle in $\frac{e}{2m_\rho}$ units, q is its charge, $m = E(H = 0)$ is the mass of the particle, s_z is the spin projection on the external magnetic field, β is the magnetic polarizability. We have observed the agreement of the Landau level picture with our data for the magnetic field values below $0.6\ GeV^2$.

The background magnetic field enables to calculate the magnetic polarizabilities and the magnetic dipole moments of the hadrons. We measured the energy of a meson as a function of the uniform abelian field.
In our calculations external magnetic field is constant and it's values vary from 0 up to $2.5\ GeV^2$. The magnetic dipole moment of the charged ρ meson has been defined for various quark masses more precisely then in our previous work. This value is in good agreement with the experimentally obtained value. We have also estimated the magnetic dipole moment of the K^* meson.

The study of the internal structure of hadrons in external fields is important and relevant in connection with ongoing experiments at JLAB, CERN(COMPASS), SLAC. Currently there exist significant discrepancies between the theoretical predictions, different phenomenological models and experimentally obtained data. For most mesons the magnetic polarizability and g-factor has not been found experimentally yet. There still exist large uncertainties in determination of the electric and magnetic polarizabilities. According to the chiral perturbation theory magnetic and electric polarizabilities are interrelated, what stresses the importance of calculating magnetic polarizability.

Hadron Structure / 326

Leading electromagnetic corrections to meson masses and the HVP

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We present a strategy to calculate the leading order electromagnetic corrections to meson masses and the hadronic vacuum polarization. These corrections are computed directly through a QED perturbative expansion of the QCD+QED correlation functions. We will show some first results obtained using $N_f = 2 + 1$ Domain Wall fermions. This calculation will be directly compared to the stochastic approach presented by James Harrison.

Nonzero Temperature and Density / 40

Lefschetz-thimble approach to the Silver Blaze problem of one-site fermion model

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Path integral on Lefschetz thimbles gets much attention in the context of the sign problem, because of its usefulness in order to study the system with the complex classical action nonperturbatively. After giving its brief introduction, it is applied for studying the sign problem of the one-site Hubbard model. This model has a severe sign problem, which looks quite similar to that of the finite-density QCD at low temperatures. We present the analytical study of the sign problem using the Lefschetz-thimble method, and also discuss the failure of the complex Langevin method. Furthermore, we give a speculation about the early-onset problem of the baryon number density, called the baryon Silver Blaze problem, based on similarity between the sign problems of one-site Hubbard model and of finite-density QCD.

Weak Decays and Matrix Elements / 115

Leptonic decay-constant ratio f_K/f_π from clover-improved $N_f = 2+1$ QCD

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The leptonic decay-constant ratio f_K/f_π is calculated from lattice-QCD simulations using $N_f = 2+1$ dynamical fermion flavors in the clover-improved formulation and 2-HEX smearing. The simulations were performed at a range of mass-degenerate light quarks including the physical point and at various lattice couplings and volumes, allowing to quantify all relevant sources of systematic uncertainties for our final number of the decay-constant ratio. Utilizing input from ChPT, we also quote the charged decay-constant ratio $f_{K^\pm}/f_{\pi^\pm}$. With further input from super-allowed nuclear β-decays, eventually we obtain an estimate for the CKM-matrix element V_{us}.

Physics Beyond the Standard Model / 392

Light Isosinglet Scalar in Eight Flavor QCD

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The LSD Collaboration has recently completed a study of the light hadron spectrum in SU(3) gauge theory with eight light, degenerate flavors. We have observed that the lightest isosinglet scalar meson, also called the sigma, remains essentially degenerate with the pions even when the (pi,sigma) multiplet mass scale falls below half the rho meson mass as a function of the input quark mass. This is clearly quite different from QCD with two light flavors. However, we also observe behavior consistent with the vector meson dominance (VMD) hypothesis, which is quite similar to QCD with two light flavors. Finally, we discuss how the presence of a light sigma in the spectrum affects the standard methodology of lattice gauge theory calculations.

Hadron Structure / 94

Light and strange axial form factors of the nucleon at pion mass 317 MeV

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A lattice QCD calculation of the light and strange axial form factors G_A and G_P of the nucleon will be reported. Disconnected diagrams were calculated using hierarchical probing, and a clear nonzero signal was obtained. We pay special attention to renormalization, which we determined nonperturbatively, including the mixing between light and strange quarks. This calculation was done on a single ensemble with 2+1 flavours of stout-smeared Wilson-clover fermions at pion mass 317 MeV and near-physical strange quark mass.

Hadron Structure / 240

Light-cone distribution amplitudes of the baryon octet

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We present results of the first ab initio lattice QCD calculation of the normalization constants and first moments of the leading twist distribution amplitudes of the full baryon octet, corresponding to the small transverse distance limit of the associated S-wave light-cone wave functions. The P-wave (higher twist) normalization constants are evaluated as well. The calculation is done using $N_f = 2 + 1$ flavors of dynamical (clover) fermions on lattices of different volumes and pion masses down to 222 MeV. Significant SU(3) flavor symmetry violation effects in the shape of the distribution amplitudes are observed.

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Light-cone distribution amplitudes of the rho meson

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We present preliminary results of the RQCD collaboration for the lowest moments of the distribution amplitudes of the rho meson obtained from simulations with 2 degenerate flavours of clover fermions. The quark masses are chosen such that we have rho masses below the decay threshold as well as above threshold. Treating the rho as a stable particle, we find results for small quark masses which seem to follow the chiral extrapolation of results obtained above the decay threshold region.

Physics Beyond the Standard Model / 125

Lines of Constant Physics in a 5-d Gauge-Higgs Unification Scenario

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We report on the progress in the study of a five-dimensional SU(2) Gauge-Higgs Unification model. In the non-perturbative study, the Higgs mechanism is triggered by the spontaneous breaking of a global symmetry. In the same region of the phase diagram, we observe both dimensional reduction and the ratio of Higgs and Z boson masses to take the value known from experiment.

We present the first results on the construction of a line of constant physics in this region, including the prediction for the mass scale of the first excited states of the Higgs and gauge bosons.

Nonzero Temperature and Density / 41

Locating the critical end point of QCD

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I will give an overview on our recent results for the phase diagram of QCD with Nf=2+1 and Nf=2+1+1 flavors. We use a combination of lattice and Dyson-Schwinger methods to determine the chiral and deconfinement order parameters at finite temperature and chemical potential. In a recent exploratory study we also give a first estimate on the influence of baryon effects on the location of the critical end-point. As a result we find a critical end-point at large chemical potential in the vicinity of the chiral critical line extrapolated from lattice QCD.

Poster / 349

Long-Distance Properties of Landau Gluon and Ghost Propagators and Deconfinement

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We investigate numerically the long-distance properties of gluon and ghost propagators in Landau gauge on the lattice, for the SU(2) case. By considering electric and magnetic gluon propagators at nonzero temperature, we extract Debye screening masses and look for signs of deconfinement around the critical temperature. Our results are related to the zero-temperature behavior of infrared propagators for comparison.

Poster / 24

Looking forward to new lattice inputs for flavour phenomenology

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We review the current status of HQE predictions for neutral meson mixing and related observables. A comparison with most recent data shows a confirmation of the HQE, but also leaves sizeable space for new physics effects. We also point out what improved lattice inputs might be most useful for unambiguously identifying new physics in mixing observables.

Hadron Spectroscopy and Interactions / 117

Luescher's finite volume test for two-baryon systems with attractive interactions

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Since the energy shift of two-baryon system due to the finite volume is negative for the attractive interaction, the Lueshcer's finite volume formula gives the phase shift at negative squared momentum, $k^2 < 0$, for the ground state. The phase shift at $k^2 < 0$ is not physical in the infinite volume where k^2 are all positive except for bound states, but it corresponds to the analytic continuation of the phase shift form $k^2 > 0$ to a real but negative k^2 in the infinite volume.

In this talk, using the Lueshcer's finite volume formula for the phase shift, we reexamine behaviors of the phase shifts at $k^2 < 0$ from previous lattice studies on various volumes. We have found that data, based on which existences of the bound states are claimed, give the phase shifts at $k^2 < 0$ which seems incompatible with the naive expectation predicted by the effective range expansion (ERE).
We therefore conclude that either of the following possibilities should hold.

(1). The naive ERE badly breaks down for these systems.

(2). Volumes are too small for the Luescher's formula to apply.

(3). Lattice data, most of which are obtained with the smeared source, are incorrect.

We have also applied the same analysis to our recent lattice data, which gave inconsistent conclusions between two sources on the existence of bound states for same two-baryon systems, an absence (wall source) or a presence (smeared source).
We have shown that behaviors of the phase shift at $k^2 < 0$ from the wall source seem consistent with the ERE, while those from the smeared source are incompatible with the ERE.
This result indicates that the smeared source result is less reliable, and therefore it favors the possibility (3) in the above.

Algorithms and Machines / 354

MILC Staggered Conjugate Gradient Performance on Intel KNL

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We review our work done to optimize the staggered conjugate gradient(CG) algorithm in the MILC code for use with the Intel Knights Landing (KNL) architecture. KNL is the second generation Intel Xeon Phi processor. It is capable of massive thread parallelism, data parallelism and high on-board memory bandwidth, and is being adopted in supercomputing centers for scientific research. The CG solver consumes the majority of time in production running, so we have spent most of our effort on it. We compare performance of an MPI+OpenMP baseline version of the MILC code with a version incorporating the QPhiX staggered CG solver, for both one-node and multi-node runs.

Plenary Session / 306

Machines and Algorithms

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I will discuss the evolution of architectures for QCD with a focus
on the interplay between architecture, engineering, data motion and algorithms.
I also discuss recent progress in performance programming strategies and algorithms.

Poster / 270

Mass anomalous dimension of SU(2) using the spectral density method

Author(s): Joni Suorsa[1]

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We study the mass anomalous dimension of SU(2) with $N_f = 6$ and $N_f = 8$ in both massless and massive quark cases for a range of gauge coupling values. In the massless case we find behaviour consistent with results obtained using the Schrödinger functional method.

Weak Decays and Matrix Elements / 255

Masses and decay constants of D *(s) and B *(s) mesons in Lattice QCD with Nf=2+1+1 Twisted fermions

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We present the results of a Lattice QCD determination of the heavy-light vector mesons masses and decay constants. The vector decay constants are relevant hadronic parameters that, for instance, can provide phenomenologically good descriptions of non-leptonic decay rates within the factorization approximation.
Our calculation is based on the gauge configurations generated by the European Twisted Mass Collaboration with Nf = 2+1+1 dynamical quarks. These are particularly suitable for charm physics, as the strange and charm quark masses are close to their physical values. The extension to the beauty-sector requires an extrapolation for which the ETMC ratio method has been applied.

Hadron Structure / 355

Matching issue in quasi parton distribution approach

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In recent years, the quasi parton distribution has been introduced to extract the parton distribution functions by the lattice QCD simulation. The quasi and standard distribution share the same collinear IR singularity and the quasi distribution can be factorized into the standard distribution with perturbative matching factor. The quasi parton distribution is known to have power-law UV divergences, which is quite different from the standard distribution. We discuss the UV renormalization scheme in the matching. We also show an example of perturbative matching of the quasi quark distribution between continuum and lattice.

Theoretical Developments / 92

Meson masses and decay constants at large N

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Meson masses and decay constants in the large N limit of SU(N) gauge theory is estimated from the twisted space-time reduced model. To this end, we introduce a new smearing method which enables us to obtain reliable values for these quantities.

Algorithms and Machines / 366

Metadynamics Remedies for Topological Freezing

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Metadynamics is a class of powerful algorithms in which the time evolution of a system is modified introducing a history-dependent potential associated with the past values of observables of choice. This has the effect of driving the system away from previously occupied states, ultimately speeding up the evolution of the system.
These methods are widely used in biochemistry and computational physics, and are especially suitable for solving problems in which the free energy presents a many-minima landscape. In this talk I will show a successful application of Metadynamics to the critical slowing down of the topological charge in CP(N-1) models, discussing the scaling of the performances with volume and lattice spacing, limitations and future improvements, and giving also a first glance of applications to lattice QCD.

Hadron Structure / 337

Moments of the hadron vacuum polarization at the physical point

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The low, euclidean momentum behavior of the hadron vacuum polarization (HVP) is critical for determining, amongst other quantities, the anomalous magnetic moments of the electron and the muon. Here we present lattice QCD results for the first few moments of the HVP obtained from 2+1+1 flavor, staggered-quark simulations at the physical point. The various quark-flavor contributions, together with their systematics, will be discussed.

Poster / 185

Momentum smearing

Author(s): Bernhard Lang[1] ; Gunnar Bali[1]

Co-author(s): Andreas Schäfer [1] ; Bernhard Musch [1]

[1] *University Regensburg*

Hadrons in lattice QCD are usually created employing smeared interpolators.

We introduce a new quark smearing that allows us to maintain small statistical errors

and good overlaps of hadronic wavefunctions with the respective ground states, also

at high spatial momenta. We test this method for various physical observables see

also arXiv:1602.05525v2 [hep-lat].

Algorithms and Machines / 17

Monte Carlo methods in continuous time for lattice Hamiltonians

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We solve a variety of sign problems for models in lattice field theory using the Hamiltonian formulation, including Yukawa models and simple lattice gauge theories. The solutions emerge naturally in continuous time and use the dual representation for the bosonic fields. These solutions allow us to construct quantum Monte Carlo methods for these problems. The methods could provide an alternative approach to understanding non-perturbative dynamics of some lattice field theories.

Algorithms and Machines / 391

Monte Carlo simulation of ϕ_2^4 and $O(N)\,\phi_3^4$ theories

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We report lattice simulations of ϕ_2^4 and $O(N)\,\phi^4$ models, performed by means a Monte Carlo method based on the all-order strong coupling expansion (worm algorithm). The investigation of the non–perturbative features of the ϕ^4 continuum limit in two dimensions lead us to the result $g/\mu^2 = 11.15 \pm 0.06_{stat} \pm 0.03_{syst}$ for the critical coupling. Furthermore we present a study of the scaling behaviour of worm and loop size in two-dimensional $O(N)$ model (non-linear σ-model) and three-dimensional $\phi^4\,O(N)$ model.

Hadron Spectroscopy and Interactions / 265

Near threshold states $D_{s0}^*\,(2317)$ and $D_{s1}\,(2460)$

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Early theoretical studies and lattice simulations predicted the charmed-strange mesons $D_{s0}^*(2317)$ and $D_{s1}(2460)$ to be broad states lying above the thresholds, DK and D^*K, respectively. Experiments found narrow states below threshold. We present results of a high statistics $Nf = 2$ study with a lattice spacing of approximately 0.071 fm, taking explicitly into account the thresholds by including four quark operators. We find a lowering of the meson's masses relative to the two-quark operator results. Two pion masses with multiple volumes were employed, $Lm_\pi = 2.5, 3.4, 4.2$ and 6.7 at $m_\pi = 289$ MeV and $Lm_\pi = 2.8$ and 3.5 at $m_\pi = 150$ MeV. The volume dependence of the resulting spectrum is investigated according to Luescher's formula.

Physics Beyond the Standard Model / 389

Near-conformal composite Higgs or PNGB with partial compositeness?

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Based on recent analysis of the LatHC collaboration I will review critical features of a minimal composite Higgs model close to the conformal window. Challenging problems of the near-conformal paradigm will be compared with PNGB based partial compositeness.

Plenary Session / 369

Neutrinoless double beta decay from lattice QCD

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While the discovery of non-zero neutrino masses is one of the most important accomplishments by physicists in the past century, it is still unknown how and in what form these masses arise. Lepton number-violating neutrinoless double beta decay is a natural consequence of Majorana neutrinos and many BSM theories, and several experimental efforts are involved in the search for these processes. Understanding how neutrinoless double beta decay would manifest in nuclear environments is key for understanding any observed signals. In this talk I will present an overview of a set of one- and two-body matrix elements relevant for experimental searches for neutrinoless double beta decay, along with preliminary lattice QCD results.

Poster / 13

New Noise Subtraction Methods in Lattice QCD

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Lattice QCD calculations of quark loop operators are extremely time-consuming to evaluate. To calculate these diagrams we use stochastic noise methods, which employ a randomly generated set of noise vectors to project out physical signals. This is done with linear equation solvers like GMRES-DR (Generalized Minimum RESidual algorithm-Deflated and Restarted) for the first noise, and GMRES-Proj (similar algorithm projected over eigenvectors) for remaining noises. In this context, we are attempting to employ matrix deflation algorithms to reduce statistical uncertainty in these time-consuming lattice calculations. In addition, we are developing noise suppression algorithms using polynomial subtraction techniques, as well as combining deflation and polynomial methods in an original way.

Poster / 249

New extended interpolating fields for hadron correlation functions

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We introduce new extended interpolating operators made of quenched three dimensional fermions propagating in the timeslices. Such non-local operators are well behaved under renormalisation.

The mass of the three 3D fermions can be tuned in a controlled way to find a better overlap of the extended operators with the states of interest. We test these operators for baryon two-point functions and compare to point sources and Jacobi smearing.

Theoretical Developments / 284

New polynomially exact integration rules on U(N) and SU(N)

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In lattice QFT, we are often presented with integrals over polynomials of coefficients of matrices in $U(N)$ or $SU(N)$ with respect to the Haar measure. In some physical situations, e.g., in presence of a chemical potential, these integrals are, however, numerically very difficult since they are highly oscillatory which manifests itself in form of the sign problem. In these cases, Monte Carlo methods often fail to be adequate, rendering such computations practically impossible.

In this talk, we will propose a new class of polynomially exact integration rules on $U(N)$ and $SU(N)$ which are derived from polynomially exact rules on spheres. We will examine these quadrature rules and their efficiency at the example of a $0+1$ dimensional QCD for a non-zero quark mass and chemical potential. In particular, we will demonstrate the failure of Monte Carlo methods in such applications but that we can obtain arbitrary precision results using the new polynomially exact integration rules.

Nonzero Temperature and Density / 291

New results for QCD at non-vanishing chemical potentials from Taylor expansion

Edwin Laermann[1]

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We present recent results for QCD at non-vanishing chemical potentials for baryon number, electric charge and strangeness.
The results are obtained from Taylor expanding the QCD partition function up to sixth order in these potentials.
The numerical simulations for two light and one strange quark have been carried out on the basis of the Highly Improved Staggered Quark (HISQ) discretization scheme at lattice spacings which in the vicinity of the chiral transition temperature correspond to temporal extents of Nt = 6, 8 and 12, and at mass values which correspond to a physical Kaon mass and pion Goldstone masses around the physical value of 140 MeV.
The results on, for instance, the equation of state are obtained as function of the three different chemical potentials and can thus also easily be adjusted to experimental conditions met in heavy ion colliders.

Plenary Session / 330

New simulation strategies for lattice QCD

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Despite the numerous successful applications of lattice QCD in nuclear and particle theory, fundamental algorithmic challenges remain. Among those, relevant for numerical studies of QCD on a space time torus, is topological freezing–a form of critical slowing down, which becomes particularly severe for lattice spacing less than 0.05 fm. In this talk, I will highlight several recently proposed simulation strategies for ameliorating the problem of topological freezing, discussing both the advantages and disadvantages of such approaches. Then, I will turn focus toward strategies for addressing critical slowing down in a more general context.

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No talk

Standard Model Parameters and Renormalization / 82

Non perturbative renormalization of flavor singlet quark bilinear operators in lattice QCD

Stefano Piemonte[1]

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We report on our studies of the renormalization of flavor singlet quark bilinear operators in lattice QCD. The renormalization constants are determined non-perturbatively using gauge field ensembles with Nf=2 dynamical clover improved fermions. The renormalization is performed in the RI-MOM

and RI-SMOM schemes. The difference between flavor singlet and non-singlet quark bilinear operators is a disconnected contribution, which has to be evaluated by stochastic estimators. We compare our results with perturbation theory.

Nonzero Temperature and Density / 239

Non-Local effective SU(2) Polyakov loop model from inverse Monte-Carlo methods

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The strong coupling expansion of the lattice gauge action leads to a Polyakov loop model that effectively describes the gluodynamic at low temperatures and together with the hopping expansion of the fermion determinant allows for insights into the QCD phase diagram at finite density and low temperatures, although the accessible pion masses are rather large.
At high temperatures the strong coupling expansion breaks down and it is expected that the interaction of Polyakov loops becomes non-local.
Therefore we use inverse Monte-Carlo methods to map pure SU(2) gluodynamic to different non-local Polyakov models . We take into account Polyakov loops in higher representations and gradually add interaction terms at larger distances to investigate how well we can describe the full theory. Particularly we are interested in the behaviour of those models when extrapolating the dependency of non-local terms and higher represenations, especially in the large volume limit. We try to find connections between the strength of the coupling of the non-local terms (with respect to the interaction distance) and the correlation length of the full theory at a given value of the gauge coupling in order to compare our results to existing proposals for non-local effective actions.

Standard Model Parameters and Renormalization / 217

Non-Perturbative Renormalization of Nucleon Charges with Automated Perturbative Subtraction

Author(s): Georg von Hippel[1]

Co-author(s): Hartmut Wittig [1] ; Linus Wrang [2] ; Maxwell Hansen [1] ; Parikshit Junnarkar [3] ; Tim Harris [3]

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We report on the determination of the renormalization factors of quark bilinears which are required among others in order to determine the nucleon scalar and tensor charges from the CLS $N_f = 2$ configurations. Working in the RI'-MOM scheme, we eliminate all lattice artifacts at one-loop order using a combination of analytical results near the continuum limit and numerical calculations in automated lattice perturbation theory. The latter will allow for a ready generalization to the renormalization factors required for the average momentum fraction and other operators beyond local bilinears.

Standard Model Parameters and Renormalization / 111

Non-equilibration of topological charge and its effects

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[MILC collaboration}

In QCD simulations at small lattice spacings the topological charge Q evolves very slowly, and if this quantity is not properly equilibrated it could lead to incorrect results for physical quantities, or incorrect estimates of their errors. We use the known relation between the dependence of masses and decay constants on the QCD vacuum angle θ and the squared topological charge Q^2 together with chiral perturbation theory results for the dependence of masses and decay constants on θ to estimate the size of these effects and suggest strategies for dealing with them. For the partially quenched case, we sketch an alternative derivation of the known χPT results of Aoki and Fukaya, using the nonperturbative correct chiral theory worked out by Golterman, Sharpe and Singleton. With the MILC collaboration's ensembles of lattices with four flavors of HISQ dynamical quarks, we measure the Q^2 dependence of masses and decay constants and compare to the χPT forms. The observed agreement gives us some confidence that we can reliably estimate the errors from slow topology change, and even correct for its leading effects.

Standard Model Parameters and Renormalization / 137

Non-perturbative determination of improvement coefficients using coordinate space correlators in Nf=2+1 lattice QCD

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We determine quark mass dependent order a improvement terms of the form b_J am for non-singlet scalar, pseudoscalar, vector and axialvector currents, using correlators in coordinate space. We use a set of CLS ensembles comprising non-perturbatively improved Wilson Fermions and the tree-level Luescher-Weisz gauge action at $\beta = 3.4, 3.46, 3.55$ and $\beta = 3.7$, corresponding to lattice spacings a in [0.05,0.09] fm. We report the values of the b_J improvement coefficients which are proportional to non-singlet quark mass combinations and also discuss the possibility of determining the $\bar{b}_J$ coefficients which are proportional to the trace of the quark mass matrix.

Standard Model Parameters and Renormalization / 273

Non-perturbative matching of HQET heavy-light axial and vector currents in N_f=2 lattice QCD

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Based on a non-perturbative matching strategy between Heavy Quark Effective Theory (HQET) at O(1/m) and finite-volume QCD, we report on our determination of the effective theory parameters of all components of the HQET heavy-light axial and vector currents in two-flavour lattice QCD. These parameters, which can be fixed by matching conditions between suitable QCD and HQET observables evaluated through numerical simulations, are required to absorb the power divergences of lattice HQET, as, for instance, encountered in
an effective theory computation of form factors for semi-leptonic decays of B- and B_s-mesons.

Standard Model Parameters and Renormalization / 339

Non-perturbative running of quark masses in three-flavour QCD

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We present our results for the computation of the non-perturbative running of renormalized quark masses in $N_f = 3$ QCD, between the electroweak and hadronic scales, using standard finite-size scaling techniques. The computation is carried out to very high precision, using massless $\mathcal{O}$(a) improved Wilson quarks. Following the strategy adopted by the ALPHA Collaboration for the running coupling, different schemes are used above and below a scale $\mu_{\rm swi} \sim m_b$, which differ by using either the Schrödinger Functional or Gradient Flow renormalized coupling. We discuss our results for the running in both regions, and the procedure to match the two schemes.

Plenary Session / 401

Nuclear Physics

Martin Savage[1]

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Lattice QCD is making good progress toward calculating the structure and properties of light nuclei and the forces between nucleons. These calculations will ultimately
refine the nuclear forces, particularly in the three- and four-nucleon sector and the
short-distance interactions of nucleons with electroweak currents, and allow for a reduction of uncertainties in nuclear many-body calculations of nuclei and their reactions. After highlighting their importance, particularly to the Nuclear Physics and High-Energy Physics experimental programs, I will discuss the progress that has been made toward achieving these goals and the challenges that remain.

Poster / 397

Nucleon EDM from Chromo EDM using Domain-Wall Fermion

Hiroshi Ohki[1] ; Michael Abramczyk[2] ; Sergey Syritsyn[3] ; Thomas Blum[2]

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[2] *University of Connecticut*

[3] *Jefferson Lab*

We present a progress report on the study of the CP violation effects on the nucleon from the quark chromoelectric dipole moment (cEDM) operator using $N_f = 2+1$ dynamical Domain-Wall fermions. Details of the calculation and preliminary results for $m_\pi = 170$ and 250 MeV will be reported.

Hadron Structure / 65

Nucleon Matrix Elements at Physical Point and Cost Comparison

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I shall report on calculations of isovector matrix elements of the nucleon, such as g_A, g_s, and $\langle x \rangle$ on the $48^3 \times 96$ lattice with pion mass at 139 MeV and lattice size of 5.5 fm. We employ overlap valence fermion on the 2+1 flavor DWF configurations for the calculation. Also reported will be the strange quark momentum fraction and its magnetic moment from this lattice.

`A comparison of the cost of such calculations with those of the twisted mass fermion, clover fermion`

Hadron Structure / 358

Nucleon Vector and Axial-Vector Form Factors

Author(s): Yong-Chull Jang[1]

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We present the status of the calculation of the nucleon iso-vector axial and vector form factor using the MILC $N_f = 2{+}1{+}1$ HISQ ensembles with lattice spacings $a = 0.12, 0.09$, and 0.06 fm and three values of light quark masses corresponding to pion masses $310, 220, 130$ MeV. Valence quarks are simulated with the clover action. A number of techniques to increase the statistics cost effectively, such as the AMA (all-mode-averaging) method, will be discussed.

Hadron Structure / 196

Nucleon charges and form factors from clover-on-clover and clover-on-HISQ simulations

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High precision estimates of the iso-vector nucleon charges g_A, g_S and g_T, electric, magnetic and axial form factors measured on four ensembles of 2+1 flavor clover fermions will be presented and compared with those from clover-on-HISQ calculations. An analysis of systematic uncertainties due the lattice volume, lattice spacing, quark mass and renormalization will also be presented for both sets of calculations. Phenomenological implications and constraints on novel scalar and tensor interactions at the TeV scale will be discussed.

Hadron Structure / 162

Nucleon electromagnetic and axial form factors with $\mathbf{N_f = 2}$ twisted mass fermions at the physical point

Christos Kallidonis[1] ; Constantia Alexandrou[2] ; Giannis Koutsou[1] ; Karl Jansen[3] ; Kyriakos Hadjiyiannakou[4] ; Martha Constantinou[1]

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The nucleon electromagentic and axial form factors are presented using an N_f=2 twisted mass fermion ensemble with pion mass of 135 MeV. Dipole masses for the momentum dependence of the form factors are extracted and compared to experiment, as is the nucleon magnetic moment and charge and magnetic radii.

Hadron Structure / 280

Nucleon form factors and couplings with $N_\mathrm{f} = 2{+}1$ Wilson fermions

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We present updated results on the isovector electromagnetic form factors and axial coupling of the nucleon calculated using the CLS ensembles with $N_\mathrm{f} = 2{+}1$ flavours of Wilson fermions. Systematic effects are investigated by covering a range of lattice spacings and pseudoscalar masses. Efficient variance reduction is achieved with the truncated solver method. The strategy to renormalize nucleon matrix elements with the Rome-Southampton method is discussed.

Hadron Structure / 198

Nucleon form factors near the physical point in 2+1 flavor QCD

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We present preliminary results for nucleon form factors including the axial charge and the Dirac radius in 2+1 flavor QCD at the almost physical pion mass on a 96^4 lattice with the lattice spacing of 0.084 fm. The configurations are generated with the stout-smeared $O(a)$-improved Wilson quark action and the Iwasaki gauge action at beta=1.82. A large spatial volume of (8.1fm)^3 allows us to investigate the form factors at small momentum transfer region. We discuss analyses of the momentum dependence of the form factors.

Hadron Structure / 161

Nucleon spin and quark content at the physical point

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The quark contributions to the spin and mass of the nucleon are computed using $N_f = 2$ twisted mass fermions with a physical value of the pion mass. We use improved methods to obtain accurate results for
the disconnected contributions involved in the evaluation of the axial charge and quark momentum fraction as well as the light, the strange and the charm σ-terms.

Hadron Structure / 136

Nucleon structure from 2+1-flavor dynamical DWF ensembles

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Nucleon isovector vector- and axialvector-current form factors and some low moments of isovector structure functions will be reported with improved statistics from four recent RBC+UKQCD 2+1-flavor dynamical drain-wall fermions ensembles: Iwasaki gauge 24^3x64 at 1.78-GeV momentum cut off and pion mass of 432 ans 330 MeV and Iwasaki times DSDR gauge 32^3x64 at 1.38 GeV momentum cut off and pion mass of 250 and 172 MeV.

Physics Beyond the Standard Model / 73

Numerical Analysis of Discretized $\mathcal{N} = (2,2)$ SYM on Polyhedra

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We investigate the two-dimensional $\mathcal{N} = (2,2)$ supersymmetric
Yang-Mills (SYM) theory on the discretized curved space both from theoretical and numerical points of view.
We first show that the number of the supersymmetry of the continuum $\mathcal{N} = (2,2)$ SYM theory on any curved manifold is enhanced to two by considering an appropriate $U(1)$ gauge backgrounds associated with the $U_V(1)$ symmetry.
We then show that the generalized Sugino model, which was proposed in our previous work,
can be identified to the discretization of the SUSY enhanced theory,
where one of the supersymmetries is kept and the other one is restored in the continuum limit.
The $U_A(1)$ anomaly of the continuum theory is maintained also in the discretized theory as an unbalance of the number of the fermions.
We study the discretized supersymmetric model based on the numerical Monte-Carlo simulation.

In the process, we propose a novel phase-quenched approximation, which we call the “anomaly-phase-quench approximation”.
We find that the Ward-Takahashi (WT) identity expected from the analytical study realizes in the model and there is no sign-problem by adopting the anomaly-phase-quench method.
The result is the first numerical observation for the supersymmetric lattice model on the curved space with generic topologies.

Standard Model Parameters and Renormalization / 4

Numerical determination of the Λ-parameter in SU(3) gauge theory from the twisted gradient flow coupling

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We calculate the Λ-parameter in $\overline{\mathrm{MS}}$ scheme for SU(3) pure gauge theory with the twisted gradient flow method non-perturbatively. Using the Schrödinger functional scheme as an intermediate scheme, we numerically evaluate the Λ-parameter ratio $\frac{\Lambda_{\overline{\mathrm{MS}}}}{\Lambda_{\mathrm{TGF}}} = \frac{\Lambda_{\overline{\mathrm{MS}}}}{\Lambda_{\mathrm{SF}}} \cdot \frac{\Lambda_{\mathrm{SF}}}{\Lambda_{\mathrm{TGF}}}$. We also estimate $\Lambda_{\mathrm{TGF}}/\sqrt{\sigma}$ and $r_0\Lambda_{\mathrm{TGF}}$ from $a\sqrt{\sigma}$ and a/r_0 available in the literature. Our final values $\Lambda_{\overline{\mathrm{MS}}}/\sqrt{\sigma}$ and $r_0\Lambda_{\overline{\mathrm{MS}}}$ are consistent with the known results, which demonstrates the validity of the present method.

Applications Beyond QCD / 66

Numerical simulation of Dirac semimetals

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Dirac semimetals are recently discovered materials with low energy spectrum similar to the massless two flavour 3+1D Dirac fermions. The interaction between quasiparticles in Dirac semimetals is instantaneous Coulomb with large effective coupling constant \alpha\sim 1. In this report we present the result of study of the phase diagram of Dirac semimetals within lattice simulation with rooted staggered fermions. In particular, calculate the chiral condensate as a function of effective coupling constants and thus determine the position of semimetal-insulator transition in Dirac semimetals.

Theoretical Developments / 67

O(3) model with Nienhuis action

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We study the O(3) sigma model on a D=2 lattice with a Boltzmann weight linearized in β on each link.
While the spin formulation now suffers from a sign-problem the equivalent loop model remains positive and
becomes particularly simple. By studying the transfer matrix and by performing MC simulations in the loop form
we study the mass gap coupling in a step scaling analysis. The question addressed is, whether or not such a
simplified action still has the right universal continuum limit. If the answer is affirmative this would be
helpful in widening the applicability of worm algorithm methods.

Poster / 199

O(4) scaling analysis in two-flavor QCD at finite temperature and density with improved Wilson quarks

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We study scaling behavior of a chiral order parameter in the low density region, performing a simulation of two-flavor lattice QCD with improved Wilson quarks. It have been confirmed that the scaling behavior of the chiral order parameter defined by a Ward-Takahashi identity agrees with the scaling function of the three-dimensional O(4) spin model at zero chemical potential. We discuss the scaling properties of the chiral phase transition at finite density, applying the reweighting method and calculating derivatives of the chiral order parameter with respect to the chemical potential. In the comparison between the scaling functions of the O(4) spin model and QCD at low density, there is a fit parameter which can be interpreted as the curvature of the chiral phase transition curve in the QCD phase diagram with respect to temperature and chemical potential. We determine the curvature of the phase boundary by the fitting. The physical scale is set by the gradient flow.

Nonzero Temperature and Density / 79

On complex Langevin dynamics and zeroes of the determinant

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In the complex Langevin approach to lattice simulations at nonzero density, zeroes of the fermion determinant lead to a meromorphic drift and hence a need to revisit the theoretical justification. In this talk we discuss how poles in the drift affect the formal justification of the approach and then explore the various possibilities in simple models. The implications of the findings for heavy dense QCD and full QCD are discussed.

Standard Model Parameters and Renormalization / 263

On the accuracy of perturbation theory in QCD

Alberto Ramos[1] ; Mattia Dalla Brida[2] ; Patrick Fritzsch[3] ; Rainer Sommer[4] ; Stefan Sint[5] ; Tomasz Korzec[6]

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A collaborative effort to determine the Λ-parameter in 3-flavour QCD by the ALPHA collaboration is currently being finalized. The strategy involves 2 finite volume schemes for the coupling, both defined with Schroedinger functional (SF) boundary conditions. I here discuss the scale evolution from an intermediate scale $1/L_0$ of about 4 GeV to scales of O(100) GeV using the traditional SF coupling and a 1-parameter family of close relatives. Our precise continuum extrapolated data allows for stringent tests of perturbation theory, which is then used to extract $L_0 * \Lambda$ with an error below 3 per cent. To quote such a small error with confidence, non-perturbative data is required around alpha_s = 0.1. In particular, we have evidence that the apparent precision reached with data around alpha_s = 0.2 can be misleading.

(cf. related talks by A. Ramos and R. Sommer)

Nonzero Temperature and Density / 242

On the condition for correct convergence in the complex Langevin method

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The complex Langevin method (CLM) is a promising way to perform the path integral with a complex action based on a stochastic equation for complexified dynamical variables. It is known, however, that the CLM gives wrong results in some cases, while it works, for instance, in finite density QCD in the deconfinement phase or in the heavy dense limit. In this talk, we revisit this issue starting with a finite Langevin step-size. We find that there is a subtlety in taking the zero step-size limit, although the previous argument used a continuous time from the beginning. Also there is a subtlety in using the time-evolved observables, which play a crucial role in the argument. These subtleties require that the probability distribution of the drift term should be suppressed exponentially at large magnitude. We demonstrate our claim in some examples including chiral Random Matrix Theory and show that our criterion is indeed useful in judging whether the results obtained by the CLM are trustable or not.

Hadron Structure / 77

On the nature of an excited state

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In many lattice simulations with dynamical quarks, radial or orbital excitations of hadrons lie near multihadron thresholds: it makes the extraction of excited states properties more challenging and cqn introduce some systematics difficult to estimate without an explicit computation of correlators using interpolating fields strongly coupled to multihadronic states. In a recent study of the strong decay of the first radial excitation of the B^* meson, this issue has been investigated and we have clues that a diquark interpolating field $\bar{b}\gamma^i q$ is very weakly coupled to a $B\pi$ P-wave state while the situation is quite different if we consider an interpolating field of the kind $\bar{b}\nabla^i q$, where $\vec{\nabla}$ is a covariant derivative: those statements are based on examining the charge density distribution.

Nonzero Temperature and Density / 316

Open charm correlators and spectral functions at high temperature

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We present results for correlators and spectral functions of open charm mesons using 2+1 flavours of clover fermions on anisotropic lattices. The D mesons are found to melt close to the deconfinement

crossover temperature T_c. Our preliminary results suggest a shift in the thermal D meson mass below T_c.

Algorithms and Machines / 317

Optimization of the Domain Wall Dslash Kernel in Columbia Physics System

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We present updated strategies and results of combining hand-tuning with the R-Stream source-to-source auto-parallelizing compiler to transform the serial implementation of the domain wall fermion Dslash kernel in CPS into an efficient parallel code targeting the Intel Xeon CPUs. The R-Stream compiler performs preliminary optimizations of the input Dslash code, including a novel iteration space compression scheme, while the SIMD optimization is done with a data layout transformation and compiler intrinsics. Tuning for the OpenMP and MPI scaling will also be discussed.

Algorithms and Machines / 385

Overcoming strong metastabilities with the LLR method

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It has been shown that the recently proposed LLR method is very efficient at overcoming strong metastabilities that arise near first-order phase transition points. Here we present a systematic study of the performance of the algorithm near (pseudo)critical points on q-state Potts models for q as large as 20, in two and three dimensions. In particular, we shall focus our study on the ergodicity of the replica exchange step and the underlying physical mechanism. Our results for thermodynamic observables (including interface tensions at criticality) are also discussed.

Nonzero Temperature and Density / 314

Parity doubling in two-color and two-flavor gauge theory at high temperature

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Recently the two-color gauge theory with two flavors of fundamental fermions has received considerable attention in BSM model building, as it provides a minimal template for a composite Higgs theory that includes dark matter candidates. In this work, we consider the two-color model with two flavors of Wilson fermions at non-zero temperature. For a more reliable investigation of meson correlation functions at high temperature, we perform simulations on anisotropic lattices with a target anisotropic factor of a_s/a_t=6.3. The tuning of bare parameters was carried out using the pseudo-scalar dispersion relation and Wilson loop ratios. We present our preliminary results for the identification of parity doubling from the temporal and spacial correlation functions of vector and axial-vector mesons.

Nonzero Temperature and Density / 84

Parity doubling of nucleons and Delta baryons across the deconfinement phase transition

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At zero temperature nucleons and their parity partners have non-degenerate
masses due to spontaneous breaking of chiral symmetry.
However, chiral symmetry is expected to be restored at sufficiently high temperature,
in particular when going from the hadronic to the quark-gluon plasma (QGP) phase,
implying that the parity partners should become degenerate.
We study the nucleon (spin 1/2) and Delta (spin 3/2) baryons in both
parity sectors for a range of temperatures in the confined and QGP phases.
Using anisotropic $N_f = 2 + 1$ flavour simulations, we analyse the correlation functions and the spectral functions
using respectively exponential fits and the Maximum Entropy Method.
We find a clear sign of parity doubling for both baryons in the QGP phase:
the parity state masses become degenerate and
their corresponding correlators become essentially identical.

Hadron Structure / 134

Partially conserved axial vector current and applications

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A partially conserved axial vector current that satisfies the chiral Ward identity is defined nonperturbatively for improved Wilson fermions. A first application to the nucleon axial vector coupling is presented.

Poster / 80

Perturbative calculation of Z_q and Z_m at the one-loop level using improved staggered quarks

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We present results of matching factors for Z_q and Z_m calculated perturbatively at the one loop level with improved staggered quarks. We calculate Z_q and Z_m with HYP-smeared staggered quarks. Final results of Z_q and Z_m at $\mu = 2$ GeV and 3 GeV in the $\overline{\text{MS}}$ scheme are given in tables.

Poster / 141

Perturbative running of the twisted Yang-Mills coupling in the gradient flow scheme

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We present our ongoing computation of the running of the twisted Yang-Mills coupling using gradient flow techniques. In particular, we use the gradient flow equation with twisted boundary conditions to perform a perturbative expansion of the expectation value of the Yang-Mills energy density up to fourth order at finite flow time, and regularise the respective resulting sums and integrals. Additionally, we show our ongoing computation of the aforementioned integrals in the particular case of a two-dimensional twist.

Nonzero Temperature and Density / 188

Phase diagram of the O(3) model from dual lattice simulations

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We simulated the asymptotically free two-dimensional O(3) model at nonzero chemical potential through dual variables free of the sign problem. The system undergoes a quantum phase transition when mu reaches the particle mass (generated dynamically similar to QCD). The density follows a square root universal for repulsive bosons in one spatial dimension. We have also measured the spin stiffness, known to be sensitive to the spatial correlation length, in different scaling trajectories to zero temperature and infinite size. It points to a dynamical critical exponent z=2, which can be explained by particle worldlines. Comparisons to thermodynamic Bethe ansaetze are shown as well.

Theoretical Developments / 116

Phase structure analysis of CP(N-1) model using Tensor renormalization group

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We investigate the phase structure of the lattice CP(N-1) model in two dimensions by using the tensor renormalization group (TRG) method. The TRG method has no sign problem even though the action is complex. We focus on the case N=2 and compare the numerical result of the TRG method with that of the strong-coupling analysis in the presence of the theta term.

Plenary Session / 408

Phenomenology of Heavy Ions and LQCD

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Phenomenology of Heavy Ions and LQCD

Physics Beyond the Standard Model / 189

Phenomenology of a composite Higgs model: lessons for the lattice.

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We study the phenomenology of a specific model of strongly interacting dynamics beyond the Standard Model, and derive the current bounds on the low-energy constants that describe the large-distance behaviour of the model.

We deduce from these bounds the required accuracy for lattice simulations to have an impact on searches for new physics beyond the Standard Model.

Physics Beyond the Standard Model / 3

Physical spectra and the limits of perturbative estimates in a theory with a Higgs

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The spectacular success of perturbation theory in electroweak physics hinges on the validity of the Froehlich-Morchio-Strocchi mechanism. This mechanism allows the determination of the spectrum of physical, gauge-invariant states using perturbation theory if a Brout-Englert-Higgs effect is present. For this mechanism to work two preconditions have to be met. One is the structural requirement that the perturbative multiplet structure can be mapped to the physical one. The other requires that dynamically the pole structure of gauge-dependent correlation functions is not qualitatively altered. To assess the validity of perturbation theory to describe the spectrum in beyond-the-standard model calculations requires to understand when these conditions are fulfilled.

The second condition will be investigated in the Yang-Mills-Higgs case on the lattice. It is found that it depends crucially on the parameters whether this condition is fulfilled. Even in cases where perturbation theory should be expected to work well it turns out that it does not. Various possibilities for a criterion for this breakdown will be discussed. As a side-effect the physical spectrum of the theory in a wide range of the phase diagram is uncovered, which is also valuable for several other research directions.

Hadron Structure / 272

Pion structure from twisted mass lattice QCD down to the physical pion mass

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We present an investigation of pion structure based on ETMC $N_f = 2$ and $N_f = 2+1+1$ twisted mass configurations at maximal twist. We compute the first two moments of the quark momentum fraction of the pion and the electromagnetic form factor.
For the latter, momentum is injected using twisted boundary conditions and $F_\pi(Q^2)$ is calculated at the physical pion mass. We find that our data is consistent with vector meson dominance and experimental data in the region of momentum transfer $Q^2 > 0.01\ \mathrm{GeV}^2$.

Poster / **282**

Platform Independent Profiling of a QCD Code

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The supercomputing platforms available for high performance computing based research evolve at a great rate. However, this rapid development of novel technologies requires adaptations and optimizations of the existing codes for each new machine architecture. In such context, minimizing time of efficiently porting the code on a new platform is of crucial importance. A possible solution is to use coarse grain simulations of the application that can assist in detecting performance bottlenecks. We present a procedure of implementing the intermediate profiling for openQCD code that will enable the global reduction of the cost of profiling and optimizing this code commonly used in the lattice QCD community. Our approach is based on well-known SimGrid simulator, which allows for fast and accurate performance predictions of the codes on HPC architectures. Additionally, accurate estimations of the program behavior on some future machines, not yet accessible to us, are anticipated.

Hadron Structure / **83**

Polarizability of pseudoscalar mesons from the lattice calculations

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We explore the ground state energy of pseudoscalar charged and neutral mesons as a function of external magnetic field in SU(3) lattice gauge theory. We calculate the dipole magnetic polarizabilities and hyperpolarizabilities of charged and neutral pseudoscalar pi and K mesons. It was found that the magnetic polarizability of charged pion agrees with the experimental prediction of COMPASS collaboration.

Hadron Structure / **248**

Position-space approach to hadronic light-by-light scattering in the muon $g-2$ on the lattice

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The anomalous magnetic moment of the muon currently shows a more than 3σ discrepancy between the experimental value and recent Standard Model predictions. The theoretical uncertainty is

dominated by the hadronic vacuum polarization and the hadronic light-by-light (HLbL) scattering contributions, where the latter has so far only been fully evaluated using different models. To pave the way for a lattice calculation of HLbL, we present an expression for the HLbL contribution to $g-2$ that involves a multidimensional integral over a position-space QED kernel function in the continuum and a lattice QCD four-point correlator. We describe our semi-analytic calculation of the kernel and test the approach by evaluating the π^0-pole contribution in the continuum.

Standard Model Parameters and Renormalization / 107

Precision determination of the strong coupling at the electroweak scale

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The ALPHA-collaboration computation
of the three-flavor Lambda-parameter and the determination of $\alpha(m_Z)$
consists of the steps:
Running from beyond the Z-mass to 4 GeV in the SF scheme,
matching to the GF scheme,
running from 4GeV to small energy in the GF scheme,
determining the smallest energy scale ($\approx$ 200 MeV) in
physical units with the help of the CLS simulations.
We summarize the first steps and discuss the last one in detail.
We then present our final result for $\Lambda^{(3)}_{\overline{\mathrm{MS}}}$ with its error budget.
Finally, the connection of the three-flavor theory to the five-flavor
$\alpha(m_Z)$ uses decoupling and high order perturbation theory in the $\overline{\mathrm{MS}}$ scheme.

Nonzero Temperature and Density / 59

Precision test of the gauge/gravity duality in two-dimensional N=(8,8) SYM

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We present a precision test of the gauge gravity duality in two-dimensional N=(8,8) SYM. We employ the Sugino lattice action to perform lattice simulations of N=(8,8) SYM at finite temperature. We

show the evidence of validity of the duality conjecture by comparing lattice results with analytical predictions of the corresponding gravitational theory.

Poster / **323**

Prediction of positive parity Bs mesons and search for the X(5568)

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We use a combination of quark-antiquark and $B^{(*)}K$ interpolating fields to predict the mass of two QCD bound states below the B^*K threshold in the
quantum channels $J^P = 0^+$ and 1^+. The mesons correspond to the b-quark cousins of the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ and have not yet been observed in experiment, even though they are expected to be found by LHCb.
In addition to these predictions, we obtain excellent agreement of the remaining p-wave energy levels with the known $B_{s1}(5830)$ and $B^*_{s2}(5840)$ mesons. The results from our first principles calculation are compared to previous model-based estimates. More recently the D0 collaboration claimed the existence of an exotic resonance $X(5568)$ with exotic flavor content $\bar{b}s\bar{d}u$. If such a state with $J^P = 0^+$ exists, only the decay into $B_s\pi$ is open which makes a lattice search for this state much cleaner and simpler than for other exotic candidates involving heavy quarks. We conclude, however, that we do not find such a candidate in agreement with a recent LHCb result.

Plenary Session / **402**

Presentation of 2016 Kenneth Wilson Award

Algorithms and Machines / **362**

Progress Report on Staggered Multigrid

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As the push towards the exascale enables increasingly accurate lattice calculations, the inversion of the Dirac matrix becomes a superlinearly growing expense. Adaptive algebraic multigrid (AAMG) methods for all fermion discretizations are essential to address this phenomena of critical slowing

down. As a preconditioner, AAMG expedites Dirac matrix inversions with manageable start up costs. This is important for modern lattice measurements which require the efficient computation of an increasing number of Dirac propagators. In this talk we will discuss progress towards the development of an AAMG algorithm for staggered fermions based upon the successful implementation of Wilson-Clover multigrid. Optimal performance is being sought in the QUDA library on GPUs.

Weak Decays and Matrix Elements / 380

Progress in the calculation of epsilon' on the lattice

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We discuss recent progress by the RBC & UKQCD collaborations in the lattice calculation of the measure of Standard Model direct CP violation, \epsilon', with physical kinematics. We present results with improved systematic errors resulting from the use of step-scaling to
reduce the renormalization error, an analysis that also takes into account the one-loop-suppressed mixing with the G_1 two-quark operator. We also review our progress in decreasing the dominant statistical error on our result.

Weak Decays and Matrix Elements / 343

Progress on the lattice QCD calculation of rare kaon decays: K+ -> pi+ l+ l-

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The rare decays of a kaon into a pion and a lepton/antilepton pair proceed via a flavour changing neutral current and therefore first arise in the Standard Model only as a second order electroweak interaction. This natural suppression makes these decays sensitive to the effects of potential New Physics. However the rare decay channels K+ -> pi+ l+ l- are dominated by contributions from long-distance effects, where the two electroweak processes are separated by distances over which non-perturbative QCD effects play a significant role. In this talk I will provide an update on the progress of our exploratory calculations of the long-distance contributions to K+ -> pi+ l+ l- amplitudes, which make use of the Domain Wall Fermion ensembles of the RBC and UKQCD collaborations.

Weak Decays and Matrix Elements / 375

Progress on the lattice QCD calculation of the rare kaon decays: K+ -> pi+ nu nu-bar

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The rare kaon decays K+ -> pi+ nu nu-bar are highly suppressed in the standard model and thus provide an ideal place to search for new physics beyond the standard model. These decays are the principal objective of a new experiment, NA62 at CERN. Another new experiment to search for KL -> pi0 nu nu-bar is now underway at J-PARC. Given the goal of 10% precision by NA62, it is important to determine the long-distance contributions to the K+ -> pi+ nu nu-bar amplitude with a controlled uncertainty. In this talk I will report the progress on the lattice QCD calculation of the long-distance contributions to the K+ -> pi+ nu nu-bar decay amplitude, with an emphasis on the treatment of the short-distance divergence in the bilocal operator system.

Hadron Spectroscopy and Interactions / 193

Progress on three-particle quantization condition

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We report progress on extending the relativistic model-independent quantization condition for three particles to a broader class of theories, and in checking the formalism. Topics that will be touched on are: (i) the extension to include the possibility of 2->3 and 3->2 transitions and (ii) checks of the formalism by comparing to threshold expansions and to the energy shift of a three-particle Efimov-like bound state.

Hadron Spectroscopy and Interactions / 256

Properties of non-local wave function equivalent potential with generalized derivative expansion

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HAL QCD collaboration has mostly considered the lowest order potential of the derivative expansion so far based on the assumption that higher order terms yield minor correction in low energy region.
In this study, we aim at investigating the properties of HAL QCD's non-local potentials when the derivative expansion is explicitly performed to higher order.
We report the result of our model calculation in a 1+1 dimensional coupled-channel system.
We introduce a generalized version of the derivative expansion and show that the potential reproduces scattering phase shift quite well.
The generalized expansion has some favorable features which is also applicable to the actual lattice QCD calculations.
The possibility of improving the convergence of the expansion is also discussed in this framework.

Hadron Structure / **43**

Proton spin decomposition and its perturbative renormalization

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I shall report on the progress of the proton spin decomposition based on Ji's scheme and also the necessary perturbative calculation, to convert them from the lattice regularization to MS-bar scheme at 2 GeV.

Poster / **128**

Pseudo-scalar decay constants on three-flavour CLS ensembles with open boundaries

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We determine the masses and the pseudo-scalar decay constants of charmed mesons using non-perturbatively O(a) improved Wilson quarks.
Our analysis is based on the $N_{\mathrm{f}} = 2 + 1$ ensembles using open boundary conditions, generated within the CLS effort.
The status of results for 2 lattice spacings, $a \approx 0.086$ fm and

$a \approx 0.064$ fm, will be presented. The pion mass is varied from 420 to 220 MeV. This is part of a continuing analysis by the RQCD and ALPHA Collaborations, aiming at a stable continuum extrapolation using several lattice spacings. To extrapolate to the physical masses, we follow both, the $(2m_l + m_s) = \mathrm{const.}$ and $m_s = \mathrm{const.}$ line.

Chiral Symmetry / 158

QCD with Flavored Minimally Doubled Fermions

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I discuss QCD with Flavored Minimally Doubled Fermions as sea quarks.
Minimally Doubled Fermions are an ultra-local formulation that realizes a non-singlet chiral symmetry with only two real fermions at finite lattice cutoff, but break the hypercubic symmetry as well as some discrete space-time symmetries.
I show that the broken discrete space-time symmetries do not affect vacuum since the corresponding symmetry breaking terms cancel exactly in the fermion determinant.
With a non-singlet mass term, I introduce a well-controlled definition of flavor in the continuum limit which is consistent with the naturally emergent flavor structure of meson correlation functions at finite cutoff.

Nonzero Temperature and Density / 90

QCD with isospin chemical potential: low densities and Taylor expansion

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We investigate the phase diagram of QCD at finite isospin chemical potential using 2+1 flavours of staggered fermions with physical quark masses at different lattice spacings and volumes. In this talk we focus on the region of small isospin chemical potential below the phase boundary to the pion condensation phase and investigate the change of the transition temperature with the chemical potential. To investigate the convergence properties and the range of validity of the Taylor expansion method at a given order, we compare our results to the Taylor expansion for finite isospin chemical potential at 4 derivative order. This can serve as an important crosscheck for the Taylor expansion method at finite baryon chemical potential, where direct simulations are impossible due to the sign problem.

Nonzero Temperature and Density / 86

QCD with isospin chemical potential: pion condensation

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We study the QCD phase diagram at nonzero isospin chemical potential using 2+1 flavors of staggered fermions with physical quark masses at different lattice spacings and volumes. The talk focuses on the transition to the pion condensation phase at high chemical potentials. This phase is characterized by a proliferation of low modes that slow down the simulation considerably and necessitate the use of an infrared regulator. We discuss a novel strategy to determine the pion condensate in the limit of vanishing regulators.

Plenary Session / 400

QED Corrections to Hadronic Observables

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When aiming at a percent precision in hadronic quantities calculated by means of lattice simulations, isospin breaking effects become relevant. These are of two kinds: up/down mass splitting and electromagnetic corrections. In order to properly account for the latter, a consistent formulation of electrically-charged states in finite volume is needed. In fact on a periodic torus Gauss' law and large gauge transformations forbid the propagation of electrically-charged states. In this talk I will review methods that have been used or proposed so far in order to circumvent this problem, while highlighting practical as well as conceptual pros and cons. I will also review and discuss various methods to calculate electromagnetic corrections to hadron masses and decay rates in numerical simulations.

Physics Beyond the Standard Model / 197

Quark Chromoelectric Dipole Moment Contribution to the Neutron Electric Dipole Moment

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The quark chromo-electric dipole moment operator and the pseudo-scalar fermion bilinear with which it mixes under renormalization can both be included in a calculation of the electromagnetic form factor of the nucleon using the Schwinger source method. A preliminary calculation of these operators using clover quarks on HISQ lattices generated by MILC collaboration will be presented showing the quality of the signal in the correlators necessary for calculating the neutron electric dipole moment.

Nonzero Temperature and Density / 70

Quark Mass Dependence of the QCD Critical End Point in the Strong Coupling Limit

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Strong coupling lattice QCD in the dual representation allows to study the full mu-T phase diagram, due to the mildness of the sign problem. This has been done in the chiral limit. Here we extend the phase diagram to finite quark masses. We present our results on the quark mass dependence of the QCD critical end point obtained by Monte Carlo via the worm algorithm. We compare our simulations which are performed on 4^3x4, 6^3x4, 8^3x4, 12^3x4, 16^3x4 lattices with mean field results.

Vacuum Structure and Confinement / 78

Quark confinement to be caused by Abelian or non-Abelian dual superconductivity in the $SU(3)$ Yang-Mills theory

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Standard Model Parameters and Renormalization / 138

Quark masses and strong coupling constant with Highly-Improved Staggered Quarks

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We present new results on the charm and bottom quark masses as well as the strong coupling constant in 2+1-flavor QCD
using Highly Improved Staggered Quark action and gauge configurations generated by HotQCD Collaboration.
Our approach is based on calculating the moments of meson correlators and we use a wide range of lattice spacing up to $a^{-1} \sim 4.9$ GeV in our study.
The ratios of quark masses m_c/m_s and m_b/m_c are obtained from the combinations of the pseudoscalar and vector meson masses and found to be $m_c/m_s = 11.871(96)$ and $m_b/m_c = 4.528(57)$ in

the continuum limit.
The lattice results of the hyper-fine splitting of the charmonium can reproduce the experimental value in the continuum.
We also perform the determination of the strong coupling constant in the $\overline{\mathrm{MS}}$ scheme from the moments of pseudo-scalar charmonium correlators and find $\alpha_s(\mu = m_c) = 0.3697(56)$, which is the determination of α_s
at lowest energy scale so far.
For the charm quark mass we obtain $m_c(\mu = m_c) = 1.2668(10)$ GeV.

Hadron Structure / 15

Quark orbital dynamics in the nucleon - from Ji to Jaffe-Manohar orbital angular momentum

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Quark orbital angular momentum (OAM) in the nucleon can be evaluated directly by employing a Wigner function embodying the simultaneous distribution of parton transverse position and momentum. This distribution can be accessed via a generalization of the nucleon matrix elements of quark bilocal operators which have been used previously in the lattice evaluation of transverse momentum dependent parton distributions (TMDs). By supplementing these matrix elements with a nonzero momentum transfer, mixed transverse position and momentum information is generated. In the quark bilocal operators, a gauge connection between the quarks must be specified; a staple-shaped gauge link path, as used in TMD calculations, yields Jaffe-Manohar OAM, whereas a straight path yields Ji OAM. A lattice calculation at a pion mass of 518 MeV is presented which demonstrates that the difference between Ji and Jaffe-Manohar OAM can be clearly resolved. The obtained Ji OAM is confronted with traditional evaluations utilizing Ji's sum rule. Jaffe-Manohar OAM is enhanced in magnitude compared to Ji OAM.

Poster / 140

RG scaling at chiral phase transition in two-flavor QCD

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We investigate the nature of the chiral phase transition using the RG improved gauge action and the Wilson quark action
with two degenerate quarks on $32^3 \times 16$, $24^3 \times 12$, and $16^3 \times 8$ lattices.

We introduce RG scaling relations for both the time direction and the spacial effective masses of mesons at the chiral phase transition point.

Numerical results of effective masses at the chiral phase transition on the three sizes of lattices are excellently on the universal limiting curves for the pseudo-scalar meson and vector meson, respectively, except for three data points at short distance of each lattice.
The results imply the effective masses of pion and vector meson vanishes as $1/N$ in the continuum limit with $N\,a =$ constant.
The fact that the scaling relations are satisfied and the effective masses becomes zero in the continuum limit strongly implies the transition is of second order.
When the quark is massive at the chiral phase transition in the deconfining side,
the hyper-scaling is verified with $\gamma^* \simeq 0.5$.

Physics Beyond the Standard Model / 126

Radiative contribution to the effective potential in a composite Higgs model

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The SU(4) gauge theory with two flavors of Dirac fermions in the sextet representation shares features of a candidate for a composite Higgs model. The analogue of the Higgs multiplet of the Standard Model lives in the Goldstone manifold resulting from spontaneous breaking of the global symmetry SU(4) to SO(4). The Higgs potential arises from interaction with the particles of the Standard Model. We have computed the gauge boson contribution to the Higgs potential, using valence overlap fermions on a Wilson-clover sea. The calculation is similar to that of the electromagnetic mass splitting of the pion multiplet in QCD.

Chiral Symmetry / 271

Real-time simulations of anomaly induced transport in external magnetic field

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One of the macroscopic manifestations of the Chiral anomaly in a matter with Dirac fermions is a large negative magnetoresistivity in strong magnetic fields, which is common feature of Weyl- and Dirac semimetals and QCD. However, most of previous studies have been done in the linear response approach in non-interacting theory. We study Magnetoresistivity in a model of Dirac semimetal using Wilson-Dirac lattice fermions with on-site four-fermion interactions in the background of magnetic field in the framework of mean-field theory and classical-statistical real-time simulations with arbitrary external electric fields. We investigate the phase diagram of the model and discuss the fate of dynamically generated chiral imbalance in the system, as well as manifestations of dynamical axion field.

Nonzero Temperature and Density / 169

Relative weights approach to dynamical fermions at finite densities

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The relative weights method is applied to extract the effective Polyakov line action corresponding to SU(3) gauge theory with dynamical staggered fermions, and this theory is solved, at finite chemical potential and a few sample temperatures, quark masses, and couplings, by a mean field technique. The effective Polyakov line action is highly non-local, and in at least one case we encounter very long-lived metastable states in the numerical simulation.

Poster / **211**

Relaxation time of the fermions in the magnetic field (I) - the case for relativistic fermions -

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The chiral magnetic effect (CME) is the quantum anomaly related electric charge transport phenomenon along the external magnetic field, which appears in various systems possessing chiral fermions, such as the quark-gluon plasma, condensed matter physics and astrophysics.

The magnetic field dependence of the relaxation time is needed to compare the theory and experiments quantitatively. However, the model calculation of the relaxation time has been made by Argyres and Adams only for the non-relativisitic fermion with the strong magnetic field limit.
In this poster, we extend the work by Argyres and Adams and compute the relaxation time for the relativistic fermions in the magnetic field.

Poster / **214**

Relaxation time of the fermions in the magnetic field (II) - away from strong magnetic field limit -

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The relaxation time for the fermions in the magnetic field is needed for estimate the chiral magnetic effect. However, it has been estimated only in the strong magnetic field. We discuss the relaxation time away from the strong magnetic field limit.

Theoretical Developments / 373

Renormalisation of the scalar energy-momentum tensor with the Wilson flow

Antonin Portelli[1] ; Antonio Rago[2] ; Francesco Capponi[2] ; Luigi Del Debbio[3] ; Roberto Pellegrini[1] ; Susanne Ehret[4]

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The Wilson flow is a promising tool to study strongly coupled theories. Its remarkable renormalisation properties allow for a meaningful formulation of the energy-momentum tensor on the lattice. The non-perturbative computation of the latter can in turn be used to study the scaling behaviour of quantum field theories. We extent recent studies on the renormalisation of the energy-momentum tensor in 4-dimensional gauge theory to the case of a 3-dimensional scalar theory to investigate its intrinsic structure and numerical feasibility on a more basic level. In this talk, we introduce the Wilson flow for scalar theory, discuss Ward identities, and present our results for the renormalisation constants of the scalar energy-momentum tensor.

Theoretical Developments / 68

Renormalization constants of the lattice energy momentum tensor using the gradient flow

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We present an update about our program for the non perturbative renormalization of the energy momentum tensor. Our strategy consists in probing suitable lattice Ward identities with observables computed along the gradient flow. This set of identities exhibits many interesting qualities, arising from the UV finiteness of flowed composite operators, and can be used to measure the renormalization constants of the energy momentum tensor. We show how this method is applied in a SU(3) Yang-Mills theory on the lattice, and report our numerical results.

Hadron Structure / 297

Renormalization of three-quark operators for baryon distribution amplitudes

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Octet baryon distribution amplitudes are non-perturbative objects of phenomenological interest parametrizing the momentum distribution within the corresponding Fock states. Their normalization and their moments can be calculated using lattice QCD, and such results require renormalization. However, the MS-bar scheme, i.e., the renormalization scheme used in phenomenological applications, necessitates a perturbative approach in non-integer spacetime dimension and is therefore not well suited for lattice calculations. Instead, we renormalize the lattice results non-perturbatively in a RI'/SMOM scheme and carry out the conversion to the MS-bar scheme in continuum perturbation theory. Using group theoretical and symmetry considerations we have constructed optimized three-quark operator bases for the renormalization procedure in order to minimize mixing.

Plenary Session / 340

Resonances in Coupled-Channel Scattering

David Wilson[1]

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Excited states in hadron physics are seen as resonances in the scattering of lighter stable hadrons like π, K and η. Many decay into multiple final states necessitating coupled-channel analyses. Recently it has become possible to obtain coupled-channel scattering amplitudes from lattice QCD. Using large diverse bases of operators it is possible to obtain reliable finite volume spectra at energies where multiple channels are open. Utilising the finite volume formalism proposed by L\"uscher and extended by several others, scattering amplitudes can be extracted from the finite volume spectra. Recent applications will be discussed where the energy dependence of scattering amplitudes is mapped out in several quantum numbers. These are then continued to complex energies to extract resonance poles and couplings.

Nonzero Temperature and Density / 252

Results on the heavy-dense QCD phase diagram using complex Langevin

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Complex Langevin simulations have been able to successfully reproduce results from Monte Carlo methods in the region where the sign problem is mild and make predictions when it is exponentially hard. We present here our study of the QCD phase diagram in the limit of heavy and dense quarks (HDQCD) for 3 different lattice volumes and the boundary between the hadronic phase and the quark-gluon plasma. We also briefly discuss instabilities encountered in our simulations.

Theoretical Developments / 16

Retrieving the optical potential from a Lattice simulation.

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We propose a method for the direct extraction of the complex hadron-hadron optical potential (or, equivalently, the phase shift and inelasticity in a given channel) on the lattice, which does not require the use of the multi-channel Lüscher formalism, but the knowledge of a tower of energy levels only.

The approach works for any multi-particle states and tested explicitly on a set of synthetic data for the $\pi\eta - K\bar{K}$ system. Further, we show how a sufficiently large number of energy eigenvalues can be obtained utilizing partial twisting.

Plenary Session / 49

Review on Hadron Spectroscopy

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I review the recent lattice results on spectroscopy and resonances in the past years.
For the conventional hadron spectrum computations,
focus has been put on the isospin breaking effects, QED effects, and simulations near the physical point. I then go through several single-channel scattering studies
using Luescher formalism which has matured over the past years.
The topics cover light hadrons and also the charmed mesons, with the latter
case intimately related to the recently discovered exotic XYZ particles.
Other possible related formalisms that are available on the market are also discussed.

Nonzero Temperature and Density / 124

Reweighting trajectories from the complex Langevin method

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We introduce the reweighted complex Langevin method, which enlarges the applicability range of the complex Langevin method by reweighting the complex trajectories. In this reweighting procedure both the auxiliary and target ensembles have a complex action. We validate the method by applying it to a random matrix model for QCD and to two-dimensional strong-coupling QCD, both at nonzero chemical potential, and observe that it gives access to mass regions that could otherwise not be reached with the complex Langevin method.

Physics Beyond the Standard Model / 120

Rho meson decay width in SU(2) gauge theories with 2 fundamental flavours.

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SU(2) gauge theories with two quark flavours in the fundamental representation are among the most promising theories of composite dynamics describing the electroweak sector. Three out of five Goldstone bosons in these models become the longitudinal components of the W and Z bosons giving them mass. Like in QCD we expect a spectrum of excitations which appear as resonances in vector boson scattering, in particular the vector resonance corresponding to the rho-meson in QCD.

In this talk I will present the preliminary results of the first calculation of the rho-meson decay width in this theory, which is analogous to rho to two pions decay calculation in QCD. The results presented were calculated using 2 moving frames on s single ensemble. Future plans include using 3 moving frames on a larger set of ensembles to extract the resonance parameters more reliably and also take the chiral and continuum limits.

Plenary Session / 399

Richard Feynman, Data-Intensive Science and the Future of Computing

Tony Hey[1]

[1] *STFC*

This talk will discuss three current trends in computing: quantum computers; data-intensive computing and the recent resurgence in AI and Machine Learning; Exascale computing and the end of Moore's Law. Although Richard Feynman is famous for his Nobel Prize for QED and his Feynman Diagrams, and for his three volume set of Lectures on Physics, it is not so well-known that he gave lectures on computing for the last five years of his life. In these lectures he was first to propose building a quantum computer. After an introduction to Feynman's ideas on quantum computing, the 'Big Data' revolution in science will be discussed. The analysis of PetaBytes of CERN LHC data to find the Higgs Boson is one example but the explosion of experimental data is now impacting almost every field of science. We then briefly look at 'Big Data' applications outside of science and the emergence of 'smart technologies' in many aspects of everyday life. Finally, we end with a look at Exascale computing and some of the implications of the coming end of Moore's Law.

Nonzero Temperature and Density / 21

Roberge-Weiss periodicity and confinement-deconfinement transition

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We propose a new determination of the confinement-deconfinement transition by using the imaginary chemical potential. The imaginary chemical potential can be interpreted as the Aharonov-Bohm phase and then an analogy of the topological-order suggests that the Roberge-Weiss endpoint would define the deconfinement temperature. Based on the topological property, we can construct a new quantity which describes the confinement-deconfinement transition. This quantity is defined as the integral of the quark number susceptibility along the closed loop of θ where θ is the dimensionless imaginary chemical potential. Expected behavior of it at finite temperature is discussed and its asymptotic behaviors are shown.

Nonzero Temperature and Density / 159

Roberge-Weiss transition in Nf=2 QCD with staggered fermions and Nt=6

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The QCD phase diagram at imaginary chemical potential exhibits a rich structure and studying it can constrain the phase diagram at real values of the chemical potential. Moreover, at imaginary chemical potential standard numeric techniques based on importance sampling can be applied, since no sign problem is present.

In the last decade, a first understanding of the QCD phase diagram at imaginary chemical potential has been developed, but it is so far based on investigations on coarse lattices ($N_t = 4,\ a = 0.3$ fm).
Considering the $N_f = 2$ case, at the Roberge-Weiss critical value of the imaginary chemical potential,
the chiral/deconfinement transition is first order for light/heavy quark masses
and second order for intermediate values of the mass: there are then two tricritical masses, whose position strongly depends on the lattice spacing and on the discretisation. On $N_t = 4$, we have the chiral
$m_\pi^{\text{tric.}} \simeq 400$ MeV with unimproved staggered fermions and $m_\pi^{\text{tric.}} \simeq 900$ MeV with unimproved pure Wilson fermions.

Employing finite size scaling we investigate the change of this tricritical point between $N_t = 4$ and $N_t = 6$
as well as between Wilson and staggered discretisations.

Standard Model Parameters and Renormalization / 228

Running coupling from Wilson flow for three quark flavors

Gerrit Schierholz[1]

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The running coupling constant $\alpha_s(Q^2)$ is computed from the Wilson flow for three quark flavors on multiple volumes and a wide range of lattice spacings, which allows for a continuum extrapolation. Of particular interest is the behavior at small Q^2 and the question of an infrared fixed point.

Physics Beyond the Standard Model / 390

Running coupling of twelve flavors

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Numerical results are reported on the discrete β-function of $SU(3)$ gauge theory with $N_f = 12$ fundamental fermions in the gradient flow scheme. Controlled continuum extrapolation is performed for $s = 2$ scale change with $c = \sqrt{8t}/L = 0.2$ targeting 3 tuned values of the renormalized coupling, approximately $g^2 = 6.0,\ 6.2$ and 6.4. Contrary to a previous claim, no evidence is found for a zero of the continuum β-function.

Physics Beyond the Standard Model / 71

S-duality in lattice N=4 super Yang-Mills

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Formulations of lattice supersymmetry over the last decade have been able to significantly reduce the amount of fine-tuning necessary in order to obtain the correct continuum limit. In the case of N=4 super Yang-Mills, the approach that has emerged as the best path forward is based on a topological twisting of the theory. Montonen and Olive found evidence that a duality could exist in Yang-Mills with adjoint scalars. In this scheme, the 't Hooft-Polyakov monopole is dual to the W boson,leading to a theory equivalent to the original one, but with magnetic charge replacing electric charge. The duality is believed to be realized in N=4 super-Yang-Mills. We are pursuing numerical, nonperturbative evidence for this S-duality using our lattice formulation. The various tricks that are necessary for doing this will be described.

Physics Beyond the Standard Model / 103

SUNny gluonia as DM

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We investigate the possibility that the dark matter candidate is from a pure non-abelian gauge theory of the hidden sector, motivated in large part by its elegance and simplicity. The dark matter is the lightest bound state made of the confined gauge fields, the hidden glueball. We point out this simple setup is capable of providing rich and novel phenomena in the dark sector, especially in the parameter space of large N. They include self-interacting and warm dark matter scenarios, Bose-Einstein condensation leading to massive dark stars possibly millions of times heavier than our sun giving rise to gravitational lensing effects, and indirect detections through higher dimensional operators as well as interesting collider signatures. Non-perturbative relevant studies to further our understandings of these uniquely simple non-abelian gauge theories are suggested. This talk is based on arXiv:1602.00714 [to appear in Phys. Rev. D] with Yue Zhang [CIT] and more in progress with him.

Nonzero Temperature and Density / 157

Scalar QCD at nonzero density

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We study scalar QCD at nonzero density in the strong coupling limit.
It has a sign problem which looks structurally similar to the one in QCD.
After introducing dual variables by integrating out the SU(3) gauge links
we find that we need at least 3 flavors for a nontrivial dependence on the
chemical potential.
In this dual representation there is no sign problem remaining.
The dual variables are partially constrained,
thus we use a hybrid approach for the updates:
For unconstrained variables we use local updates,
while for constrained variables we use updates based on the worm algorithm.

Hadron Spectroscopy and Interactions / 360

Scaling and properties of 1/a = 1 GeV, 2+1 flavor Mobius Domain Wall Fermion ensembles

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The RBC and UKQCD Collaborations have used 2+1 flavor
Domain Wall Fermion ensembles, generated with the Iwasaki gauge
action plus the Dislocation Suppressing Determinant Ratio (DSDR),

for a variety of calculations, including our ongoing G-parity calculation of $K \to \pi\pi$ matrix elements. These calculations have been done with 1/a = 1.35 GeV. With the HotQCD Collaboration, zero and finite temperature ensembles at even coarser lattice spacings, 1/a = 1 GeV, have been produced. These coarse, zero temperature ensembles have been included in global fits for light hadronic observables and show scaling errors of a few percent for them. Large physical volume ensembles at 1/a = 1 GeV are being generated for a variety of measurements and our ongoing investigation of their properties will be presented.

Theoretical Developments / 97

Sea quark QED effects and twisted mass fermions

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We show that maximally twisted mass fermions can be employed to regularize on the lattice the fully unquenched QCD+QED theory with vanishing theta-term. We discuss how the critical mass of the up and down quarks can be conveniently determined beyond the electroquenched approximation by imposing that certain symmetries of continuum QCD+QED, which are broken by Wilson terms, are restored (up to cutoff effects). A mixed action setup is sketched that allows to extend the computation of the leading isospin breaking corrections to physical observables via the RM123 method beyond the electroquenched approximation by using ETMC (pure QCD) gauge configurations with N_f=2+1+1 dynamical quark flavours, with only O(a^2) lattice artifacts.

Theoretical Developments / 191

Search for a continuum limit of the PMS phase

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Previous studies of a simple four-fermion model with staggered fermions in 3d have shown the existence of an exotic quantum critical point, where one may be able to define a continuum limit of the Paramagnetic Strong Phase (or the PMS phase). We believe the existence of the critical point suggests a new mechanism for generating fermion masses. In this work we begin the search for this quantum critical point in 4d by extending the 3d model to 4d.
Unlike in 3d, now we do find evidence for an intermediate spontaneously broken phase (FM phase) and are able compute the phase boundaries accurately. In terms of the bare coupling, the width of the intermediate region appears to be quite small.

Hadron Spectroscopy and Interactions / 254

Searching for evidence of diquark states using lattice QCD simulations

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In recent years, exotic hadrons called X, Y, Z
which cannot be explained by the quark model have been found one after another.
For example, the tetraquark state, which is one of the typical scenarios to interpret the exotic state, is based on the existence of a diquark state.
The discovery of a pentaquark state at CERN in July last year
also makes a diquark state even more important.
It is well known that an attraction between two quarks
can be enhanced in the color anti-triplet, flavor anti-symmetric,
spin singlet, positive parity channel and this diquark is called good diquark.
Our main subject is to check
if a lattice QCD simulation with 2 flavor Wilson fermions actually supports this statement.
For this objective,
we calculate diquark mass diference between good diquark and other diquarks
and also analyze density distribution of diquarks
through calculation of density-density correlators.

Physics Beyond the Standard Model / 192

Selected new results from the spectroscopy of the sextet BSM model

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We will present results on important spectroscopy problems of the sextet composite Higgs model selected from the light scalar spectrum, vector resonances, the eta' particle of the axial anomaly, and spectroscopy analysis using a mixed action with restored chiral symmetry of valence fermions.

Weak Decays and Matrix Elements / 321

Semi-leptonic B decays with charming final state

Andreas Juettner[1] ; Edwin Lizarazo[1] ; Jonathan Flynn[1] ; Oliver Witzel[2]

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First results for our calculation of semi-leptonic B decays with charmed-mesons in the final state are presented. Our work is based on RBC-UKQCD's 2+1 flavor domain-wall fermion and Iwasaki gauge field configurations, We calculate the form factors by simulating the b quarks using the relativistic heavy quark action, create light u/d and s quarks with standard domain-wall kernel, and use optimised Möbius domain-wall fermions for charm quarks.

Weak Decays and Matrix Elements / 299

Semi-leptonic form factors for rare B decays

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We present an update on our calculation of short distance contributions
to semi-leptonic form factors for rare B decays. Results for $B_s \to \phi\ell^+\ell^-$ at three lattice spacings of $a^-1 = 1.78$, 2.38, and
2.76 GeV are shown. Our calculations are based on RBC-UKQCD's $N_f = 2+1$ domain-wall fermion and Iwasaki gauge field ensembles. The heavy
b-quarks are simulated using the relativistic heavy quark action and
domain-wall fermions are used for the light quarks.

Physics Beyond the Standard Model / 119

Sextet Model with Wilson Fermions

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We present new results from our ongoing study of the SU(3) "sextet model" with two flavors in the 2-index symmetric representation of the gauge group. The simulations use unimproved Wilson fermions and to address the issue of whether or not the model is inside the conformal window, we measure the meson and baryon spectrum. To better understand the overall behavior of the lattice model we map out the bare parameter space, which reveals a non-trivial phase structure. At strong bare coupling, a first order phase transition is observed as a function of the bare mass, whereas closer to the continuum limit this first order transition disappears. Our study also shows that the behavior of mass spectrum (as a function of the quark mass) changes significantly when moving away from the bulk phase and into the weak coupling phase.

Nonzero Temperature and Density / 329

Sign problem in heavy-dense QCD from a density-of-states perspective

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We investigate QCD at finite densities of heavy quarks from a density-of-state perspective. Using the LLR approach, we can compute the phase-factor expectation value in the strong sign problem regime with unprecedented precision due to its inherent exponential error suppression.
We use our findings to draw conclusions on the approach using phase cumulants.

Nonzero Temperature and Density / 276

Simulating low dimensional QCD on Lefschetz thimbles

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Non-perturbative lattice QCD calculations at non-vanishing baryon number density are hampered by the sign problem. The path integral becomes highly oscillating and standard Monte Carlo techniques seize working. One possible solution is the Lefschetz thimble approach. It requires a deformation of the original integration domain into a manifold embedded in complex space. For properly chosen integration manifolds ("thimbles") the sign problem is drastically alleviated. For some bosonic and fermionic models this approach has been shown to work. In this talk we will discuss aspects of the thimble discretization of low dimensional QCD.

Nonzero Temperature and Density / 130

Simulating thimble regularization of lattice quantum field theories (including LGT)

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Monte Carlo simulations of lattice quantum field theories on Lefschetz thimbles are non trivial. We discuss a new Monte Carlo algorithm based on the idea of computing contributions to the functional integral which come from complete flow lines. The latter are the steepest ascent paths attached to

critical points, i.e. the basic building blocks of thimbles. The measure to sample is thus dictated by the contribution of complete flow lines to the partition function. The algorithm is based on a heat bath sampling of the gaussian approximation of the thimble: this defines the proposals for a Metropolis-like accept/reject step. The effectiveness of the algorithm has been tested on a few models, e.g. the chiral random matrix model. We also discuss thimble regularization of gauge theories, and in particular the successfull application to 0+1 dimensional QCD and the status and prospects for Yang-Mills theories.

Poster / 236

Simulation of SU(2) gauge theory with improved domain-wall fermions

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In this work, we study SU(2) gauge theory with many flavors using the improved domain-wall fermions, which is realized by the stout-HYP link smearing and the optimal domain-wall formulation.
In contrast to the standard domain-wall fermions used in the previous studies, it enables us to investigate the small fermion mass region due to the much suppressed residual mass.
With the improved domain-wall fermions, the spectrum and the residual mass are examined on previously generated configurations as well as in dynamical simulations.
We also discuss the extension to simulations of the epsilon-regime.

Physics Beyond the Standard Model / 186

Simulations of N=1 supersymmetric Yang-Mills theory with three colours

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We report on our recent results regarding numerical simulations of the four dimensional, N=1 Supersymmetric Yang-Mills theory with SU(3) gauge symmetry and light dynamical gluinos.

Theoretical Developments / 226

Six-dimensional regularization of chiral gauge theories on a lattice I

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Co-author(s): Ryo Yamamura [2] ; Shota Yamamoto [1] ; Tetsuya Onogi [1]

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We propose a 6-dimensional lattice regularization of chiral gauge theories.
In our formulation, Weyl fermions are localized on the junction of two
different domain-walls. One domain-wall naturally exhibits the
Stora-Zumino chain of the anomaly descent equations. Another domain-wall mediates a similar inflow of the global anomalies. The anomaly free condition is equivalent to requiring the measure of the 6-dimensional Dirac fermions to cancel the axial U(1) and parity anomalies. "Localizing" the gauge fields on the 4-dimensional junction using
the Yang-Mills gradient flow, as proposed by Grabowska and Kaplan, we non-perturbatively define the 4-dimensional path integral of the target chiral gauge theory.

In the first talk, we present the basic idea of our formulation,
emphasizing on why the 6-th dimension is needed for the global anomalies.
In the second talk, we explain our lattice set-up in details.

Theoretical Developments / 227

Six-dimensional regularization of chiral gauge theories on a lattice II

Author(s): Ryo Yamamura[1]

Co-author(s): Hidenori Fukaya [2] ; Shota Yamamoto [1] ; Tetsuya Onogi [2]

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We propose a 6-dimensional lattice regularization of chiral gauge theories. In our formulation, Weyl fermions are localized on the junction of two different domain-walls. One domain-wall naturally exhibits the Stora-Zumino chain of the anomaly descent equations. Another domain-wall mediates a similar inflow of the global anomalies. The anomaly free condition is equivalent to requiring the measure of the 6-dimensional Dirac fermions to cancel the axial U(1) and parity anomalies. "Localizing" the gauge fields on the 4-dimensional junction using the Yang-Mills gradient flow, as proposed by Grabowska and Kaplan, we non-perturbatively define the 4-dimensional path integral of the target chiral gauge theory.

In the first talk, we present the basic idea of our formulation, emphasizing on why the 6-th dimension is needed for the global anomalies. In the second talk, we explain our lattice set-up in details.

Poster / 106

Some Statistics on Women in Lattice QCD

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We present a sampling of analyses concerning the gender ratio of plenary speakers during the years 2000-2016 and make comparisons with other conferences, such as the APS April meeting. Please stop by to discuss ideas for how to make our field more accessible to women and minorities. We are preparing for an in-depth survey of the lattice field and welcome any ideas or suggestions. To leave post-conference comments and read about news affecting women in our field, see our Facebook page: https://www.facebook.com/WLQCD

Hadron Spectroscopy and Interactions / 383

Spectroscopy of charmed mesons from lattice QCD

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Charmed meson spectroscopy with data generated by the Hadron Spectrum Collaboration is presented, using two ensembles with different light sea-quark masses to investigate the effect of the sea quark mass on the spectrum. Initial results from an investigation of the contribution of the disconnected quark-line diagram on the charmonium hyperfine splitting will be presented, including a comparison with quenched data.

Physics Beyond the Standard Model / 295

Spectroscopy of two dimensional N=2 Super Yang Mills theory

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Albeit the standard model is the most successful model of particles physics, it still has some theoretical shortcomings, for instance the hierarchy problem, the absence of dark matter, etc. . Supersymmetric extensions of the standard model could be a possible solution to these problems.

One of the building blocks of these supersymmetric models are supersymmetric gauge theories. It is expected that they exhibit interesting features like confinement, chiral symmetry breaking, magnetic monopoles and the like.
We present new results on N=2 Super Yang Mills theory in two dimensions. The lattice action is derived by a dimensional reduction of the N=1 Super Yang Mills theory in four dimensions. By

preserving the R symmetry of the four dimensional model we can exploit Ward identities to fine tune our parameters of the model to obtain the chiral and supersymmetric continuum limit. This allows us to calculate the mass spectrum at the physical point and compare these results with effective field theories.

Physics Beyond the Standard Model / **357**

Spectrum and mass anomalous dimension of SU(2) gauge theories with fermions in the adjoint representation: from $N_f = 1/2$ to $N_f = 2$

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In this work I will summarize our results concerning the spectrum and mass anomalous dimension of SU(2) gauge theories with a different number of fermions in the adjoint representation, where each Majorana fermion corresponds effectively to half a Dirac flavour N_f. The most relevant examples for the extensions of the standard model are supersymmetric Yang-Mills theory ($N_f = 1/2$) and minimal walking technicolour ($N_f = 2$). In addition to these theories I will also consider the cases of $N_f = 1$ and $N_f = 3/2$.
The results will contain the particle spectrum of glueballs, triplet and singlet mesons, and possible fractionally charged spin half particles.
In addition I will discuss our recent results for the mass anomalous dimension.

Physics Beyond the Standard Model / **308**

Spectrum of a prototype model with the Higgs as pNGB

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We present our results for the spectrum and other observables of an SU(3) gauge theory with 4 light fermions and 8 fermions of heavier mass, built on an IR fixed point. Our numerical data validate hyperscaling and, while our model does not presume to be a complete theory of EW symmetry breaking, it exhibits many of the features that would be expected of a realistic theory where the Higgs emerges as a pNGB.

Nonzero Temperature and Density / 209

Spontaneous symmetry breaking induced by complex fermion determinant — yet another success of the complex Langevin method

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In many interesting systems, the fermion determinant becomes complex and its phase plays a crucial role in the determination of the vacuum. For instance, in finite density QCD at low temperature and high density, exotic fermion condensates are conjectured to form due to such effects. When one applies the complex Langevin method to such a complex action system naively, one cannot obtain the correct results because of the singular-drift problem associated with the appearance of small eigenvalues of the Dirac operator. Here we propose to add a fermion bilinear term to the action to avoid this problem and extrapolate its coefficient to zero. We test this idea in an SO(4)-invariant matrix model with a Gaussian action and a complex fermion determinant, whose phase is expected to induce the spontaneous breaking of the SO(4) symmetry. Our results agree well with the previous results obtained by the Gaussian expansion method.

Vacuum Structure and Confinement / 268

Squared width and profile of the confining fluxtube in the U(1) LGT in 3D

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The dual formulation of the compact U(1) lattice gauge theory in three spacetime dimensions allows to finely study the squared width and the profile of the confining fluxtube on a wide range of physical interquark distances. The results obtained in Montecarlo simulations are compared with the predictions of the effective bosonic-string model and with the dual superconductor model. While the former fails at describing the data from a quantitative point of view, the latter is in good agreement with it. An interpretation of these results is proposed in light of the particular features of the U(1) LGT in 3D and a comparison with non-Abelian gauge theories in four spacetime dimensions is discussed.

Chiral Symmetry / 283

Staggered domain wall fermions

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We construct domain wall fermion operators with a staggered kernel and investigate their spectral and chiral properties numerically in the Schwinger model. In some relevant cases we see an improvement of chirality by more than an order of magnitude compared to standard domain wall fermions.

Nonzero Temperature and Density / 245

Static and non-static vector screening masses

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Thermal screening masses associated to the conserved vector current are calculated both in a weak-coupling and a lattice QCD approach. The inverse of a screening mass can be understood as the length scale over which an external electric field is screened in a QCD medium. The comparison of screening masses in the zero and non-zero Matsubara frequency sectors shows good agreement of the perturbative and the lattice results. Moreover, at $T \approx 508$MeV the lightest screening mass lies above the free result $(2n\pi T)$, in agreement with the $\mathcal{O}(g^2)$ weak-coupling prediction, whereas this was not the case in a previous study at $T \approx 254$MeV.

Poster / 224

Status report on ε_K with lattice QCD inputs

Author(s): Weonjong Lee[1]

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We present results of the indirect CP violation parameter in the neutral kaon system, ε_K calculated using lattice QCD inputs including $\hat{B}_K$, ξ_0, V_{us}, and V_{cb}.

Standard Model Parameters and Renormalization / 48

Step scaling in X-space: running of the quark mass

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We perform a benchmark study of the step scaling procedure for the ratios of renormalization constants extracted from position space correlation functions. We work in the quenched approximation and consider the pseudoscalar, scalar, vector and axial vector bilinears. The pseudoscalar/scalar cases allow us to obtain the non-perturbative running of the quark mass over a wide range of energy scales - from around 15 GeV to nearly 1 GeV - which agrees well with the 4-loop prediction of continuum perturbation theory. We find that step scaling is feasible in X-space and we discuss its advantages and potential problems.

Nonzero Temperature and Density / 121

Stochastic approaches to extract spectral functions from Euclidean correlators

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The spectral functions provide us the knowledge to understand the in-medium hadron and transport properties of the QCD medium. For instance, quantities like thermal dilepton production and photon emission rates of QGP can be obtained from the vector spectral functions. Though spectral functions are important, they can not be obtained directly from Euclidean lattice QCD calculations. Analytic continuations to real time are needed to extract spectral functions from Euclidean correlation functions. Currently the most commonly used method is the Maximum Entropy Method (MEM). To investigate the systematic uncertainties in spectral function reconstructions we study two stochastic approaches, i.e. Stochastic Optimization Method (SOM) and Stochastic Analytical Inference (SAI). SOM has advantage that it does not need any prior information. SAI is more generalized method, which reduces to the MEM in the mean-field limit. We compare results obtained from these two methods with those from MEM by investigating various model correlation functions.

Nonzero Temperature and Density / 370

Stochastic reconstruction of charmonium spectral functions at finite temperature

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We study charmonium spectral functions at finite temperature by using stochastic reconstruction methods. Our quenched lattice QCD simulations are performed with the standard plaquette gauge and the $O(a)$-improved Wilson fermion actions on $192^3 \times N_\tau$ lattices with N_τ = 96–32, which corresponds to temperatures from $0.73T_c$ to $2.2T_c$. To reconstruct the charmonium spectral functions for the Euclidean time correlators we apply two different stochastic methods called Stochastic Analytical Inference (SAI) and Stochastic Optimization Method (SOM), where the former is based on the Bayes' theorem similar to commonly used Maximum Entropy Method (MEM) while the latter does not rely on any prior information. We carefully estimate systematic uncertainties by comparing results among SAI, SOM and also MEM. With the given spectral functions we discuss melting temperatures of charmonia as well as the heavy quark diffusion coefficient.

Poster / **52**

Strange Quark Magnetic Moment and Charge Radius of the Nucleon at Physical Point

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Co-author(s): Jian Liang [2] ; Keh-Fei Liu [2] ; Terrence Draper [2] ; YIBO Yang [3]

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We present a lattice QCD calculation of the strange quark contribution to the proton's magnetic moment and the charge radius at the physical pion mass. The finite lattice spacing and finite volume corrections are included in a global fitting on three lattices with different lattice spacings, different volumes, and three sea quark masses. We obtain the strange magnetic moment $G_M^s(0) = -0.073(17)\,\mu_N$ and strange charge radius $\langle r_s^2 \rangle_E = -0.0047(22)\,\mathrm{fm}^2$. Additionally, we present our results of the disconnected u, d-quarks contribution to the proton's electromagnetic form factors.

Nonzero Temperature and Density / **232**

Strangeness at finite temperature

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We give a lattice-based description of QCD thermodynamics in the hadronic phase from staggered simulations of up to $N_t = 16$. Using generalized quark number susceptibilities we obtain the free energy in various strangeness sectors and compare it with the expectations from the hadron resonance gas model. We use the findings to disambiguate between various

spectrum tables. Thus we constrain the abundance of strange mesons and baryons using finite temperature data

Physics Beyond the Standard Model / 19

Strings on the lattice and AdS/CFT

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String sigma-models relevant in AdS/CFT are highly non-trivial two-dimensional field theories whose perturbative analysis is being crucially used to verify various conjectures, among which their integrability. I will discuss significant progress on how to address the extraction of information at finite values of the string effective tension via the use of lattice-based methods.

Plenary Session / 102

Strongly Coupled Composite Dark Matter

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Models of composite dark matter, originating from a new strongly coupled dark sector, have a very interesting phenomenology.
To make robust predictions in these models one often needs to investigate non-perturbative effects due to the strong self interactions.
Lattice field theory methods and numerical simulations are well suited for this task and contribute to a solid uncertainty quantification.
In this talk I review recent works in this direction,comparing lattice results for composite dark matter interactions to experimental bounds.

Nonzero Temperature and Density / 112

Study of the phase diagram of dense QC_2D with $N_f = 2$ within lattice simulation

Aleksandr Nikolaev[1] ; Alexander Molochkov[2] ; Andrey Kotov[1] ; Ernst-Michael Ilgenfritz[3] ; Victor Braguta[1]

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In this talk we present our results on the low-temperature scan of the phase diagram of dense two-color QCD with $N_f = 2$ quarks. The study is conducted using lattice simulation with rooted staggered quarks. At small chemical potential we observe the hadronic phase, where the theory is in a confining state, chiral symmetry is broken, the baryon density is zero and there is no diquark condensate. At the critical point $\mu = m_\pi/2$ we observe the expected second order transition to Bose-Einstein condensation of scalar diquarks. In this phase the system is still in confinement in conjunction with non-zero baryon density, but the chiral symmetry is restored in the chiral limit. We have also found that in the first two phases the system is well described by chiral perturbation theory. For larger values of the chemical potential the system turns into another phase, where the relevant degrees of freedom are fermions residing inside the Fermi sphere, and the diquark condensation takes place on the Fermi surface. In this phase the system is still in confinement, chiral symmetry is restored and the system is very similar to the quarkyonic state predicted by SU(N_c) theory at large N_c.

Nonzero Temperature and Density / 174

Study of the sign problem in canonical approach

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Canonical approach is one of the powerful tools to approach the QCD phase diagram. We calculate the canonical partition function instead of the grand canonical one in the canonical approach. However, it is known that the sign problem emerges as a complex phase of the canonical partition function.

Thanks to multi-precision calculations with the canonical approach we obtained the canonical partition function even for large baryon numbers. In this talk, we will argue the origin of this "phase", and study some behavior of its temperature and baryon number dependence.

Physics Beyond the Standard Model / 406

Studying the Low Energy Effective Theory of Eight Flavor QCD

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In recent years, lattice studies of multi-flavor gauge theories near and inside the conformal window have provided strong evidence for the existence of light 0++ states in their spectra, which has led to a renewed interest in strong dynamics as a solution to the Higgs hierarchy problem. An additional requirement to realize a UV complete composite Higgs sector is that observables of low energy scattering be in close agreement with the linear sigma model. We will compute the momentum dependence of the scalar form factor of the pion and of the scattering phase shift of I=2 pi-pi scattering. These quantities will be compared to the linear sigma model and other low energy effective theories. We will also study the vector form factor to test the ansatz of vector meson dominance and to compare to I=1 scattering in a future study. This talk reports on the current progress.

Physics Beyond the Standard Model / 377

Supergravity from Gauge Theory

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Gauge/gravity duality is the conjecture that string theories have dual descriptions as gauge theories. Weakly-coupled gravity is dual to strongly-coupled gauge theories, ideal for lattice calculations.
I will show precision lattice calculations that confirm large-N continuum D0-brane quantum mechanics correctly reproduces the leading-order supergravity prediction for a black hole's internal energy—the first leading-order test of the duality—and constrains stringy and quantum corrections.

Hadron Spectroscopy and Interactions / 113

Systematic study of operator dependence in nucleus calculation at large quark mass

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Recently it was raised a possibility that calculation of the nucleus correlation functions suffers from a significant systematic error due to excited state contributions depending on the choice of the source operator.
In order to investigate the operator dependence of the nucleus correlation functions,
we have performed a high precision calculation employing the exponential smeared and
wall operators at 0.7 GeV pion mass in 2+1 flavor QCD, and 0.8 GeV pion mass
in quenched QCD.
We present preliminary results and discuss the systematic errors caused by the choice of the source operator.

Nonzero Temperature and Density / 413

Talk withdrawn

Nonzero Temperature and Density / 54

Temperature dependence of shear viscosity in SU(3)-gluodynamics

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This report is devoted to the study of temperature dependence of shear viscosity in SU(3)-gluodynamics. To calculate shear viscosity we measured the correlation function of the energy-momentum tensor T_{12}T_{12} for a set of temperatures in the region T/T_c \in (0.9, 1.5). The measurements were carried out using multilevel algorithm which considerably improves the accuracy of the data. The results of the calculation allow to determine temperature dependence of the ratio of shear viscosity to the entropy density {\eta}/s.

Nonzero Temperature and Density / 207

Temperature dependence of topological susceptibility using gradient flow

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Topological susceptibility brings important information of the QCD vacuum and contributes to a production of the axion. The temperature dependence of the topological susceptibility plays a crucial role in its production rate in the early universe.
It is a test whether the axion can be an appropriate candidate of the dark matter.
In this talk we report our recent study on the topological susceptibility in the finite temperature QCD with Nf=2+1 flavors.
The topological susceptibility is given by applying the gradient flow to the finite temperature system.
We cover a wide range of temperature region $174 \leq T \leq 697$ MeV.
The ud quark mass is rather heavy $m_\pi/m_\rho = 0.63$ and s quark mass is set to almost the physical value.

Theoretical Developments / 179

Tensor RG calculations and quantum simulations near criticality

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We reformulate the Ising model, the O(2) model with a chemical potential and the Abelian Higgs model on a 1+1 space-time lattice using the
Tensor Renormalization Group (TRG) method. The reformulation allows exact blocking and connects smoothly the classical Lagrangian approach to the quantum Hamiltonian approach. We discuss the linearization of the TRG for the Ising model near the critical point.
We calculate the entanglement entropy in the superfluid phase of the O(2) model and show that it obeys the Cardy scaling (c/3)*Ln(L).
We calculate the Polyakov loop in the Abelian Higgs model and discuss the possibility of a deconfinement transition at finite volume.
We propose Bose-Hubbard Hamiltonians with two species implementable on optical lattices as quantum simulators.

Plenary Session / 235

Tensor networks

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In this talk, I will review the recent progress of tensor network approaches;
Hamiltonian/Hilbert-space approach and Lagrangian/path-integral approach,
whose striking feature is free of the sign problem.
As examples, I will show some results of CP(N-1) model including theta-term and other models.
Finally, I will address outstanding problems and discuss future prospects.

Theoretical Developments / 296

Tensor renormalization group approach to higher dimensional fermions

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We apply the higher order tensor renormalization group to two and three dimensional lattice fermion systems. To deal with the tensor network including Grassmann numbers, higher order Grassmann tensor renormalization group (HOGTRG) is introduced. Because of its deterministic property, HOGTRG is perfectly free of the sign problem. We analyze the well-known systems such as the GrossNeveu model using HOGTRG, and test the validity of the new algorithm.

Nonzero Temperature and Density / 151

Testing dynamic stabilization in complex Langevin simulations

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Complex Langevin methods have been successfully applied in theories that suffer from a sign problem such as HDQCD. We present and illustrate a novel method that ensures that Complex Langevin simulations stay close to the SU(3) manifold, which lead to correct and improved results in the framework of HDQCD and pure gauge simulations. Applying the same technique in fully dynamical QCD simulations shows great potential to allow the determination of the phase diagram from first principles.

Hadron Spectroscopy and Interactions / 182

Testing the hadro-quarkonium model on the lattice

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Recently the LHCb experiment found evidence for the existence of two exotic resonances consisting of $c\bar{c}uud$ quarks. Among the possible interpretations there is the hadro-charmonium model, in which charmonium is bound "within" a hadron. We test this idea on CLS n_f=2+1 lattices using the static formulation for the heavy quarks. We find that the static potential is modified by the presence of a hadron. It becomes more attractive and the effect is of the order of few MeV.

Nonzero Temperature and Density / 95

The CP(2) Model at Nonzero Chemical Potential

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CP(N-1) quantum field theories in (1+1)-d share important features with (3+1)-d QCD, such as asymptotic freedom, a dynamically generated mass gap and topological sectors. In the low energy limit the (2+1)-d SU(3) spin system undergoes spontaneous symmetry breaking and hence dimensional reduction to the (1+1)-d CP(2) model. By performing Monte Carlo simulations of (2+1)-d SU(3) spin systems at non-zero chemical potential we have gained access to the (1+1)-d CP(2) model at non-zero chemical potential. The theory which underpins our calculation will be reviewed and numerical results for the magnetisations and correlation functions as a function of the chemical potentials will be discussed.

Hadron Structure / 139

The Calculation of Parton Distributions from Lattice QCD

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Although parton distribution functions are the fundamental objects describing the inner structure of hadrons, they were so far not calculated from first principles.
In the past, lattice QCD has successfully been employed for the computation of hadronic spectra and form factors. Yet calculations of quark distributions are still missing, since they are given by light-cone correlation functions and light-like distances are not accessible on an Euclidean lattice.

This could possibly be overcome by a recent proposal which allows the light-cone distributions to be extracted from purely spatial correlations, being thus accessible to lattice methods. In order to test the feasibility of this method, we present the latest results of our effort to perform a lattice calculation of the non-singlet combination for the momentum, helicity and transversity distributions of the nucleon using twisted mass fermions.

We will also give first results for the application of a newly proposed momentum improved smearing, which has the potential to reach higher nucleon momenta as required for a save matching procedure to the physical distribution functions.

Algorithms and Machines / 246

The DDalphaAMG solver library

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In this talk we report on the publication of the DDalphaAMG solver library. We describe its features, show examples of its application and give an overview of future developments.

Vacuum Structure and Confinement / 28

The Dark Side of the Propagators: analytical approach to QCD in the infrared of Minkowski space.

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Since most of the non-perturbative approaches to QCD rely on numerical calculations in the *Euclidean* space, many important dynamical information cannot be easily extracted because of the ill-defined problem of analytic continuation for a limited set of data points.
On the other hand, by a shift of the expansion point, a perturbative approach has been developed[1,2] that has the nice feature of providing one-loop analytical functions for the propagators that are in perfect agreement with the data of lattice simulations in the Euclidean space. These functions are generally analytic and can be studied in Minkowski space, yielding a direct proof of positivity violation and confinement.

The expansion has been extended to full QCD [3], including a set of chiral quarks, in order to give a unified description of dynamical mass generation and chiral symmetry breaking, yielding new insights on the coupled quark, gluon and ghost propagators in the infrared of Minkowski space, that is still basically unexplored.

While dealing with the exact Lagrangian, the modified expansion is based on *massive* free-particle propagators, is safe in the infrared and is equivalent to the standard perturbation theory in the UV [2,3]. By dimensional regularization, all diverging mass terms cancel exactly without including spurious mass counterterms that would spoil the gauge and chiral symmetry of the Lagrangian. If optimized, the *massive* expansion provides a variational tool disguised to look like a perturbative method, without any phenomenological parameter, from first principles.

Among the main findings, universal scaling properties are predicted for the inverse dressing functions and shown to be satisfied by the lattice data. Complex conjugated poles are found for the gluon propagator, in agreement with the *i-particle* scenario. No complex poles are found for the quark propagators but the positivity constraints of the spectral functions are badly violated by the explicit presence of
negative-norm multiparticle states below the two-particle threshold.

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1 F. Siringo, *Perturbative study of Yang-Mills theory in the infrared*, arXiv:1509.05891.

[2] F. Siringo, *Analytical study of Yang-Mills theory in the infrared from first principles*, Nucl.Phys.B907, 572 (2016); arXiv:1511.01015.

[3] F. Siringo, *Analytic structure of QCD propagators in Minkowski space*, arXiv:1605.07357

Poster / 206

The Hadronic Vacuum Polarisation contribution to the anomalous magnetic moment of the muon

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We report on the HPQCD calculation of the u/d HVP contribution to a_mu, discussed in arXiv:1601.03071.
This allows us to obtain a total HVP contribution from u, d, s and c quarks and including an estimate of disconnected pieces and QED and isospin effects of 666(6)(12) x 10^{-10}.
Our result implies a discrepancy between the experimental determination of a_mu and the Standard Model of 3 sigma.
We discuss prospects for improvements to this calculation underway with the MILC and Fermilab Lattice Collaborations.

Standard Model Parameters and Renormalization / 251

The Nf=3 gradient flow coupling running from 4GeV to 200MeV

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A fundamental step in the ALPHA collaboration efforts to determine the fundamental parameters of $N_f = 3$ QCD at the electroweak scale in terms of hadronic quantities is the connection of an intermediate scale $\sim 4\text{GeV}$ with a hadronic scale. In this talk we will show that using the Gradient Flow running coupling this task can be achieved with a very high precision. Our analysis will pay special attention to the continuum limit of flow quantities and reach a precision below 2% in the scale factor for a change of the coupling from $g^2 = 13$ to $g^2 = 2.5$.

Nonzero Temperature and Density / 367

The Nuclear and Chiral Transition in the Strong Coupling Regime of Lattice QCD

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Lattice QCD in the strong coupling limit with staggered quarks gives rise to a dual representation. Here, the sign problem is mild enough to study the phase diagram at finite density. In the strong coupling limit, the first order nuclear and chiral transition at low temperatures coincide due to Pauli saturation.

Away from the strong coupling limit, incorporating higher order gauge corrections, both transitions are expected to split, with an intermediate phase of nuclear matter where chiral symmetry is still broken.

We show numerical evidence from Monte Carlo simulations in the dual representation that indicate this splitting.

Hadron Structure / 371

The Nucleon Axial Form Factor from HISQ

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The nucleon axial form factor is a dominant contribution to errors in neutrino oscillation studies. Lattice calculations have the potential to make an impact on controlling theory errors by disentangling the effects of nuclear corrections and nucleon form factors. In this talk, I will present preliminary results on a blinded calculation of g_A and the axial form factor using HISQ staggered baryons with 2+1+1 flavors of sea quarks. Calculations are done using physical light quark masses and are absolutely renormalized. Results are fit using the model-independent z-expansion parameterization and systematic errors are quantified.

Nonzero Temperature and Density / 160

The QCD deconfinement critical point as a function of N_t with N_f=2 flavours of unimproved Wilson fermions

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QCD at zero baryon density in the limit of infinite quark mass undergoes a first order deconfinement phase transition at a critical temperature T_c corresponding to the breaking of the global centre symmetry.
In the presence of dynamical quarks the global centre symmetry is explicitly broken. Lowering the

quark mass the first order phase transition weakens and terminates in a second order Z(2) point. Beyond this line confined and deconfined regions are analytically connected by a crossover transition. As the continuum limit is approached (i.e. the lattice spacing is decreased) the region of first order transitions expands towards lower masses. We study the deconfinement critical point with standard Wilson fermions and N_f=2 flavours. Therefore we simulate several kappa values on N_t=8 and various aspect ratios in order to extrapolate to the thermodynamic limit, applying finite size scaling. We estimate if and when a continuuum extrapolation is possible.

Nonzero Temperature and Density / 319

The QCD equation of state at finite density from analytical continuation

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An efficient way to study the QCD phase diagram at small finite density is to extrapolate thermodynamical observables from imaginary chemical potential. In this talk we present results on several observables for the equation of state to order (muB/T)^6. The observables are calculated along the isentropic trajectories in the (T, muB) plane corresponding to the RHIC Beam Energy Scan collision energies. The simulations are performed at the physical mass for the light and strange quarks. muS was tuned in a way to enforce strangeness neutrality to match the experimental conditions; the results are continuum extrapolated using lattices of up to Nt = 16 temporal resolution.

Hadron Spectroscopy and Interactions / 187

The Rho Resonance from Twisted Mass Lattice QCD

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We present new results for $I = 1$ $\pi\pi$ scattering with twisted mass fermions utilizing the sLapH method. The breaking of rotational symmetry on the lattice is fully taken into account at multiple moving frames. Our previous calculation is extended by more single and multi-hadron operators and by utilising more irreducible representations.

Nonzero Temperature and Density / 165

The Roberge-Weiss endpoint in $N_f = 2 + 1$ QCD at the physical point

Claudio Bonati[1] ; Francesco Negro[2] ; Francesco Sanfilippo[3] ; Marco Mariti[4] ; Massimo D'Elia[2] ; Michele Mesiti[5]

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In this talk I will report on our recent results about the determination of the position and the nature of the Roberge-Weiss endpoint. Our study is performed in $N_f = 2 + 1$ QCD, with physical quark masses, making use of stout-improved staggered fermions and of the tree level Symanzik improvement for the gauge action. We study the theory at 4 different lattice spacings, corresponding to $N_t = 4, 6, 8$ and 10, and at different spatial sizes. The finite size scaling analysis performed on $N_t = 4$ and 6 lattices indicates that the Roberge-Weiss transition at the endpoint is of the 2nd order kind, in the 3D Ising universality class, while the continuum limit of the critical temperature is found to be $T_{RW} = 208(5)$ MeV.

Theoretical Developments / 101

The Slab Method to Measure the Topological Susceptibility

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In simulations of a model with topological sectors, algorithms which proceed in small update steps tend to get stuck in one sector, especially on fine lattices. This distorts the numerical results; in particular it is not straightforward to measure the topological susceptibility chi_t.
Here we test a method to measure chi_t even if configurations from only one sector are available. It is based on the topological charges in sub-volumes, which we denote as ‘’slabs”. Under suitable circumstances, this enables the evaluation of chi_t, as we demonstrate with numerical data for non-linear sigma-models and 2-flavor QCD.

Nonzero Temperature and Density / 143

The chiral phase transition from non-integer flavour numbers with staggered fermions

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The attempt at clarifying the order of the thermal transition in the chiral limit of QCD at zero chemical potential, with two dynamical flavours of quarks, by progressively decreasing the simulated pion mass has proven to be inconclusive because of the increasing costs of the simulations as the pion mass is lowered.

An alternative way to approach this question is to consider the path integral as a function of continuous Nf . If the transition is first order for Nf ⊠ 3 , a second order transition for Nf = 2 requires a tricritical point in between.

The simulation of non-integer numbers of fermion flavours is easily achievable within the staggered fermion discretization. First simulations at μ = 0 and Nf = 2.8, 2.6, 2.4, 2.2 , on coarse Nτ = 4 lattices, show a continuous variation of the critical mass mapping out a critical line in the m − Nf plane.

Hadron Structure / 381

The connected and leading disconnected diagrams of the hadronic light-by-light contribution to muon $g-2$

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We report our recent lattice calculation of hadronic light-by-light contribution to muon $g-2$ using our recent developed moment method. The connected diagrams and the leading disconnected diagrams are included. The calculation is performed on a $48^3 \times 96$ lattice with physical pion mass and 5.5 fm box size. We expect sizable finite volume and finite lattice spacing corrections to the results of these calculations which will be estimated in calculations to be carried out over the next 1-2 years.

Hadron Spectroscopy and Interactions / 213

The coupled channel approach to the Lambda_c N - Sigma_c N system in lattice QCD

Takaya for HAL QCD Collaboration Miyamoto[1]

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We investigate the 2-baryon system with the isospin 1/2
including one charm quark, namely, $\Lambda_c N$ and $\Sigma_c N$.

Although this system is similar to the ΛN and ΣN system,
the interaction of this charmed 2-baryon system above $\Sigma_c N$ threshold
might be quite different from its hyperon counter part, due to the smaller mass splitting
between Σ_c and Σ_c^* than Σ and Σ^*,
which is consequence of the heavy quark spin symmetry.
To explore this possibility, we calculate the coupled channel potential
for charmed 2-baryon system using the HAL QCD method in lattice QCD.
To avoid the discretization error coming from the heavy quark mass, we employ
the Relativistic Heavy Quark (RHQ) action for the charm quark.
The purpose of this talk is to present our latest results and to discuss
the nature of the interaction in the charmed 2-baryon system including
a possibility on the existence of bound or resonance states.

Theoretical Developments / 233

The gradient flow coupling from numerical stochastic perturbation theory

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The perturbative calculation of gradient flow observables is technically challenging.
Current results are in fact limited to a few quantities and, in general, to low perturbative orders. Numerical stochastic perturbation theory is a potentially powerful tool that may be applied in this context. Precise results using these techniques, however, require control over both statistical and systematic uncertainties. In this talk we discuss how the recent algorithmic developments of these methods substantially ameliorate the cost for such precise computations. As an illustration we then present results for the two-loop matching of the gradient flow coupling in finite volume with Schroedinger functional boundary conditions and the $\overline{\mathrm{MS}}$ coupling.

Hadron Spectroscopy and Interactions / 229

The isospin-0 pion-pion scattering length from twisted mass lattice QCD

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We present results for the $\pi\pi$ isospin-0 scattering length calculated in twisted mass lattice
QCD. We use a set of $N_f = 2 + 1 + 1$ ensembles with pion mass

varying in the range of 230MeV - 510MeV at three different values of lattice spacing and two $N_f = 2$ ensembles with one pion mass at its physical value and one at 250MeV.
The quark disconnected diagrams are computed with sufficient precision by using the stochastic Laplacian Heaviside quark smearing method. For the first time we extrapolate our lattice results to the physical pion mass and continuum limit.

Vacuum Structure and Confinement / 325

The large N limit of the topological susceptibility of Yang-Mills gauge theory

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We present a precise computation of the topological susceptibility χ of SU(N) Yang–Mills theory in the large-N limit. The computation is done on the lattice, using high-statistics Monte Carlo simulations of the SU(N) Yang-Mills theories, with $N = 3, 4, 5, 6$ and three different lattice spacings. Two major improvements allowed us to go to finer lattice spacing and larger N compared to previous works. First, the topological charge is implemented through the gradient flow definition; and second, open boundary conditions in the time direction are employed in order to avoid the freezing of the topological charge. Our results allow us to extrapolate the dimensionless quantity $t_0^2\chi$ to the continuum and large-N limits with confidence. The accuracy of our final result represents a new quality in the verification of large-N scaling.

Hadron Structure / 258

The leading order hadronic contribution of the anomalous magnetic moment of the muon with O(a)-improved Wilson fermions with Pade approximants from fits and time moments

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We present results of our lattice QCD study of the hadronic vacuum polarization (HVP) function with O(a)-improved $N_\mathrm{f} = 2$ Wilson fermions with twisted boundary conditions. We discuss the extraction of the leading order hadronic contribution to the anomalous magnetic moment of the muon $\left(a_\mu^{\mathrm{HLO}}\right)$ via the
hybrid method involving two steps: (i) To describe the low Q^2 range, we construct Pade approximants obtained either from correlated fits to the HVP or from time moments, which we obtain from derivatives of the current-current correlator.(ii) For the large Q^2 range we use a numerical integration. We estimate systematic uncertainties of the continuum and chiral extrapolations with the extended frequentist method. Preliminary results for u, d, s and c valence quarks at the physical point for a_μ^{HLO} will be presented.

Theoretical Developments / 53

The multi-flavor Schwinger model with chemical potential - Overcoming the sign problem with Matrix Product States

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During recent years there has been quite some interest in applying Matrix Product States and more general tensor networks to lattice gauge theories in the Hamiltonian formulation. Previous work already demonstrated the power of this approach by computing the mass spectrum and thermal sates for the Schwinger model, and also real-time dynamics for abelian and non-abelian gauge models have been successfully addressed in the meantime.

In this talk we present ground state calculations for the two-flavor Schwinger model with finite chemical potential using Matrix Product States. While the conventional Monte Carlo approach suffers from the sign problem, our numerical simulations with Matrix Product States reliably reproduce analytic results for the massless case by Narayanan [Phys. Rev. D 86, 125008 (2012)] and readily extend to the massive case, where no analytic prediction is available.

Physics Beyond the Standard Model / 22

The physical spectrum of a partially Higgsed gauge theory

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The description of electroweak physics using perturbation theory is highly successful. Though not obvious, this is due to a subtle field-theoretical effect, the Fröhlich-Morchio-Strocchi mechanism, which links the physical spectrum to that of the elementary particles. This works because of the special structure of the standard model, and it is not a priori clear whether it works for structurally different theories.
Candidates for conflicts are, e.g., partially Higgsed gauge theories. We study this situation in an $SU(3)$ gauge theory with one fundamental Higgs field and a breaking pattern $SU(3) \to SU(2)$. We determine the leading order predictions for the gauge invariant spectrum in this theory and discuss the results from lattice simulations.

Physics Beyond the Standard Model / 218

The scalar sector of $SU(2)$ gauge theory with $N_F = 2$ fundamental flavours

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We present a non perturbative study of SU(2) gauge theory with two fundamental Dirac flavours.
This theory provides a minimal template which is ideal for a wide class of Standard Model extensions featuring novel strong dynamics.
After reviewing our findings for the Goldstone bosons and spin-1 spectrum, we present our new results for the sigma and eta states.
We evaluate the relevant disconnected contributions and obtain benchmark results that are crucial input for model building.

Vacuum Structure and Confinement / 51

The spectra of (closed) confining flux tubes in D=3+1 and D=2+1 SU(N) gauge theories.

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We summarise the most striking features of the spectra of closed confining flux tubes, for the flux in the fundamental
and some other representations. We compare to recent theoretical predictions. In $D = 2 + 1$ we present results for the continuum string tensions for theories ranging from SU(2) to SU(16) and we determine the leading correction to the N-dependence of k-strings.

Hadron Structure / 394

The strange and charm contributions to a_μ with physical quark masses using M\"obius domain wall fermions

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I present our work on the leading strange and charm quark-connected contributions to the muon anomalous magnetic moment using RBC/UKQCD physical point domain wall fermion ensembles.

Nonzero Temperature and Density / 405

Thermalisation properties of various field theories

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Motivated by the hadronization properties of heavy-ion and p-p collisions, we study the thermalisation properties of field theories.
First of all, we present our recent observations regarding the local energy-density and momentum distributions in the classical Phi^4 theory.
As this theory exhibits interesting features regarding these questions, we continue the research by the MC simulation of the SU(3) Yang-Mills theory and we intend to investigate further in more complicated theories.

Nonzero Temperature and Density / 180

Thermodynamics of strongly interacting plasma with high accuracy

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The thermodynamic properties of the $SU(3)$ Yang-Mills theory are investigated from the confining phase up to 250 T_c. Results for the temperature dependence of the entropy density, energy density and pressure are presented with an accuracy of about 0.5%. The framework of shifted boundary conditions is considered where the entropy density is related to the expectation value of the off-diagonal components of the energy-momentum tensor. The pressure and the energy density are then obtained by numerical integration. A comparison with data collected by other groups is discussed.

Nonzero Temperature and Density / 347

Thermodynamics of strongly-coupled lattice QCD in the chiral limit

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In the strong coupling limit, n-point functions in lattice QCD with staggered fermions can be rewritten exactly as traces over constrained configurations of monomers, dimers, and baryon loops covering the spacetime lattice. Worm algorithms provide efficient global sampling methods over such ensembles, and are particularly efficient in the chiral limit. We study the thermodynamics of strongly-coupled U(3) and SU(3) lattice QCD with one massless staggered fermion using such methods, and compare the results with the relativistic pion gas.

Nonzero Temperature and Density / 274

Thermodynamics with continuum extrapolated overlap fermions

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We study the QCD transition with dynamical overlap fermions. A continuum extrapolation is carried out using lattices up to N_t=12. We use a fixed topology approach and study its effect on our observables.

Nonzero Temperature and Density / 363

Thermodynamics with physical mass staggered quarks

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Finite temperature lattice QCD is investigated with four flavor physical mass staggered quarks using lattices upto N_t=20. Results for the equation of state and the low-lying modes of the Dirac-operator are presented with a focus on lattice artefacts.

Vacuum Structure and Confinement / 281

Theta dependence in the large N limit

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Studies of the large N behaviour of the topological properties of gauge theories typically focused on the large N scaling of the topological susceptibility. A much more difficult task is the study of the behaviour of higher cumulants of the topological charge in the large N limit, which up to now remained elusive. We will present first results confirming the expected large N scaling of the coefficient commonly denoted by b_2, related to the kurtosis of the topological charge.

Physics Beyond the Standard Model / 168

Towards Partial Compositeness on the Lattice: Baryons with Fermions in Multiple Representations

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We describe our recent lattice study of SU(4) gauge theory with dynamical Wilson-clover fermions in the fundamental and sextet representations. In this theory, a unique type of baryon consists of quarks in both representations. The spectrum of these “chimera baryons” turns out to have enlightening interpretations in terms of large-N expansion and the non-relativistic quark model. We also discuss the relevance of these results for so-called “partially composite” models of physics beyond the Standard Model.

Weak Decays and Matrix Elements / 129

Towards a determination of the ratio of the kaon to pion decay constants

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The SU(3) flavour symmetry breaking expansion in up, down and strange quark masses is extended from hadron masses to meson decay constants. This allows a determination of the ratio of kaon to pion decay constants in QCD. Furthermore when using partially quenched valence quarks the expansion is such that SU(2) isospin breaking effects can also be determined. It is found that the lowest order SU(3) flavour symmetry breaking expansion (Gell-Mann-Okubo) works very well. Simulations are performed for 2+1 flavours of clover fermions at 4 lattice spacings.

Weak Decays and Matrix Elements / 346

Towards a non-perturbative calculation of the weak Hamiltonian Wilson coefficients

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Perturbation theory plays a significant role in some lattice calculations, in particular in those related to weak processes. Here we discuss the possibility to calculate the Wilson Coefficients of the leading order electro-weak effective Hamiltonian of the Standard model to all order in the strong coupling constant, using lattice simulations.

Plenary Session / **23**

Towards a theory of the QCD string

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I will review recent advances in describing the dynamics of the QCD string (confining flux tube) both on theoretical and on lattice sides. I will argue that combined efforts of theorists and lattice practitioners may result in a dramatic progress in our understanding of the world sheet theory of the QCD string in the nearest future.

Poster / **222**

Towards extracting the timelike pion form factor on CLS 2-flavour ensembles

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Results are presented from an ongoing study of the ρ resonance. We use the LapH-smearing approach in order to create correlator matrices involving ρ and $\pi\pi$ interpolators. The study is done in a centre-of-mass frame and several moving frames. We are able to extract effective-energy levels by solving the GEVP of those correlator matrices. The initial exploratory study is being done on a CLS 2-flavour lattice with a pion mass of $451\ \mathrm{MeV}$ using $\mathcal{O}(a)$ improved Wilson fermions. One aim of this work is to extract the timelike pion form factor after applying the Lüscher formalism. We also have all the ingredients ready which allow us to integrate this study with the existing Mainz programme for the calculation of the hadronic vacuum polarization contribution to the muon $g-2$. We plan to extend our study to lower pion masses and larger lattices in the future, including ensembles with $2+1$ flavours.

Hadron Spectroscopy and Interactions / 237

Towards radiative transitions in charmonium

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We present preliminary calculations towards radiative transitions in charmonium using Nf = 2+1 dynamical ensembles generated by the Hadron Spectrum Collaboration. A crucial ingredient in this work is the use of variationally optimised interpolating operators which allow for a reliable determination of the three-point correlation functions needed. Using these operators, we perform first calculations of relevant three-point correlation functions before discussing future directions"

Hadron Spectroscopy and Interactions / 109

Towards the continuum limit with improved Wilson fermions employing open boundary conditions. Part 1.

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We present results obtained by RQCD on various observables, obtained from simulations of $N_f = 2+1$ flavours of non-perturbatively order-a improved Wilson fermions, employing open boundary conditions in time, that were created within the CLS (Coordinated Lattice Simulations) effort. Configurations at five different values of the lattice spacing, ranging from 0.086 fm down to below 0.04 fm exist and many quark mass combinations, in particular along a line of an (almost) constant sum of quark masses and a constant renormalized strange quark mass have been generated. Several key observables, mostly meson and baryon masses have been computed, and these results will be presented. In some cases a precise and controlled extrapolation to the continuum limit has become possible.

Hadron Spectroscopy and Interactions / 99

Towards the continuum limit with improved Wilson fermions employing open boundary conditions. Part 2.

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We present results obtained by RQCD on various observables, obtained from simulations of $N_f = 2+1$ flavours of non-perturbatively order-a improved Wilson fermions, employing open boundary conditions in time, that were created within the CLS (Coordinated Lattice Simulations) effort. Configurations at five different values of the lattice spacing, ranging from 0.086 fm down to below 0.04 fm exist and many quark mass combinations, in particular along a line of an (almost) constant sum of quark masses and a constant renormalized strange quark mass have been generated. Several key observables, mostly meson and baryon masses have been computed, and these results will be

presented. In some cases a precise and controlled extrapolation to the continuum limit has become possible.

Hadron Structure / 243

Transverse spin densities of octet baryons

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Fourier transforms of electromagnetic form factors provide valuable insights into the spatial distribution of quarks/charge within a hadron. When combined with form factors arising from non-forward matrix elements of the tensor operator, we are able to unlock fascinating information into the distribution of transversely polarised/unpolarised quarks within a transversely polarised/unpolarised hadron. Here we present results from the QCDSF collaboration for simulations in Nf=2+1 QCD for the form factors of the octet baryons and their resulting transverse spin densities. Particular attention is paid to SU(3) flavour breaking effects in the octet baryons as we move away from the SU(3)-symmetric point towards the physical point.

Vacuum Structure and Confinement / 286

Triple-gluon and quark-gluon vertex from lattice QCD in Landau gauge

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We report on new results for the triple-gluon and the quark-gluon vertex in Landau gauge. Our results are based on two-flavor and quenched lattice QCD calculations for different quark masses, lattice spacings and
volumes. We will focus on the momentum dependence of the different tensor structures.

Poster / 212

Tuning of hopping parameters in Oktay-Kronfeld action for heavy quarks on the $N_f = 2+1+1$ MILC HISQ ensemble.

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We determine hopping parameters of the Oktay-Kronfeld (OK) action for charm and bottom quarks. We use $N_f = 2 + 1 + 1$ MILC HISQ ensembles (with $a \approx 0.12$fm, $am_l = 0.0102$, $am_s = 0.0509$ and $am_c = 0.635$). As a key ingredient, we compute the masses of pseudoscalar and vector mesons B_s^*, D_s^* and their hyperfine splittings; the valence light quark is simulated with HISQ action. We also monitor the inconsistency parameters to confirm the improvement.

Nonzero Temperature and Density / 149

Two-colour QCD at finite density with two flavours of staggered quarks

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Lattice simulations of two-colour QCD can be performed at finite density without sign problem and by now have a long history already. The physics of the bosonic diquark baryons is believed to be fairly well understood and qualitatively resembles QCD at finite isospin density with pion condensation. There is good guidance from effective field theory predictions and model studies of the BEC-BCS crossover inside the condensed phase. We have revisited the question how well this can all be described with rooted staggered quarks. A potential problem thereby is the proximity of the bulk phase. We therefore use an improved gauge action and lattice couplings that somewhat larger than those of the early studies with N f =8 and 4 flavours.
This implies that we have to worry about additive renormalization in the chiral condensate before we can compare our results with the effective field theory predictions. We also confirm that the Polyakov-loop does not appear to respond to the finite density in the staggered formulation, and we perform some basic meson and diquark spectroscopy at finite density.

Hadron Spectroscopy and Interactions / 9

Two-flavor simulations of the rho(770) and the role of the KKbar channel

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The $\rho(770)$ meson is the most extensively studied resonance in lattice QCD
simulations in two ($N_f = 2$) and three ($N_f = 2 + 1$) flavors. We
analyze all available phase shifts from $N_f = 2$ simulations using unitarized Chiral Perturbation
Theory, allowing not only for the extrapolation in mass but also in flavor,

$N_f = 2 \to N_f = 3$. The flavor extrapolation requires information from a global fit to $\pi\pi$ and πK phase shifts from experiment. The $K\bar{K}$ channel has a significant effect and leads to $\rho(770)$ masses surprisingly close to the experimental one. Chiral extrapolations of $N_f = 2+1$ simulations are also presented.

Standard Model Parameters and Renormalization / 320

Up and down quark masses and corrections to Dashen's theorem from lattice QCD and quenched QED

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We present a determination of the corrections to Dashen's theorem and of the individual up and down quark masses from a lattice calculation based on quenched QED and $N_f = 2+1$ QCD simulations with 5 lattice spacings down to 0.054 fm. The simulations feature lattice sizes up to 6 fm and average up-down quark masses all the way down to their physical value. For the parameter which quantifies violations to Dashens's theorem we obtain $\epsilon = 0.73(2)(5)(17)$, where the first error is statistical, the second is systematic, and the third is an estimate of the QED quenching error. For the light quark masses we obtain, $m_u = 2.27(6)(5)(4)$ MeV and $m_d = 4.67(6)(5)(4)$ MeV in the $\bar{M}S$ scheme at 2 GeV and the isospin breaking ratios $m_u/m_d = 0.485(11)(8)(14)$, $R = 38.2(1.1)(0.8)(1.4)$ and $Q = 23.4(0.4)(0.3)(0.4)$. Our results exclude the $m_u = 0$ solution to the strong CP problem by more than 24 standard deviations.

Poster / 230

Update on Nf=3 finite temperature QCD phase structure with Wilson-Clover fermions

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We will present an update on analysis of the phase structure for finite temperature QCD with 3-flavor non-perturbatively O(a) improved Wilson-Clover fermions and Iwasaki gauge action.
In our previous study, it was shown that the value of kurtosis of quark condensate at the critical point tends to deviate from that of 3D Z_2 universality class when increasing the temporal lattice sizes N_T=8 and 10,
while the values at smaller N_T=4 and 6 are consistent with that of Z_2 .
We will discuss possible sources of this phenomenon and present results of new analysis.

Nonzero Temperature and Density / 374

Using Wilson flow to study the deconfinement transition

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We use the Wilson flow to study the deconfinement transition. We construct renormalized observables sensitive to the deconfinement transition. In particular, behavior of renormalized operators associated with the Polyakov loop are investigated for both quenched and two-flavor QCD. We also investigate the behavior of various thermodynamic quantities across the transition.

Hadron Spectroscopy and Interactions / 311

Using a new analysis method to extract excited states in the scalar meson sector

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We present an alternative method to the Generalized Eigenvalue Problem (GEVP) for extracting excited states.
The method is based on statistically sampling the space of possible set of parameters according to the χ^2-value of each set of values.
This method is particularly suited when one has noisy data as is the case for some correlators at large times
such as in the scalar light qqbar channel. We will apply this method to the analysis of the $J^P = 0^+$ channels used in the search for
the a_0 particle and compare the results to the standard GEVP approach, pointing out
advantages and disadvantages of the method compare to the GEVP approach.

Hadron Spectroscopy and Interactions / 336

Utilising optimised operators and distillation to extract scattering phase shifts

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Distillation is a method of smearing that allows for the efficient computation of correlation functions on the lattice. It vastly reduces the number of operations needed to calculate correlation functions with large bases of operators and all-to-all propagators. In this investigation, we provide a comprehensive comparison of the quality of extracted energy spectra with different amounts of distillation smearing for the isospin-1 $\pi\pi$, ρ like channel. Results are demonstrated in the determination of the mass spectra and also the scattering phase shift and mass and width of the resonant ρ via the Luscher method.

Nonzero Temperature and Density / 250

Viscosity of the pure SU(3) gauge theory revisited

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We give a preliminary estimate of the shear viscosity and the sound attenuation length in a pure SU(3) gluon plasma, using an improved anisotropic gauge action. We use Wilson-flow for anisotropy tuning, shifted boundary conditions for renormalization, and a multilevel algorithm
for the measurement of the energy-momentum tensor correlators. We also look at the continuum limit of the momenta of the spectral function by using $N_t = 10, 12, 16$ lattices.

Theoretical Developments / 216

Volume reduction through perturbative Wilson loops

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We derive the perturbative expansion of Wilson loops to order g^4 in a SU(N) lattice gauge theory with twisted boundary conditions. Our expressions show that the thermodynamic limit is attained at infinite N for any number of lattice sites and allow to quantify the deviations from volume independence at finite large N as a function of the twist. The effect of adjoint Wilson fermions will be briefly described.

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Vus from inclusive determinations based on hadronic tau data

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We discuss the current status of the determination of V_us based on flavor-breaking finite energy sum rule analyses of non-strange and strange hadronic tau decay data, highlighting the role of lattice input in providing a means of investigating the reliability of the OPE representation for the relevant flavor-breaking polarization combination employed in this analysis, and in quantifying the associated theoretical errors on V_us. We present results for V_us based on an new implementation this approach motivated by continuum and lattice studies and show that this resolves the long-standing problem of V_us values more than 3 sigma low compared to 3-family unitarity expectations obtained in earlier implementations of this approach. We also discuss the practical limitations of this new implementation given what near-term improvements are likely in the experimental strange decay distributions, and, motivated by these limitations, propose a new method for obtaining V_us which involves dispersive analyses of the strange hadronic tau decay data alone in which lattice results for the relevant combination of the flavor us J=0 and 1 vector and axial vector polarizations can be used in place of the OPE. Details of the practical implementation of this approach, as well as preliminary results for V_us, will be presented in the accompanying talk by Hiroshi Ohki.

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Vus from inclusive strange tau decay data and lattice HVP

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We present a novel approach to determining Vus which employs inclusive strange hadronic tau decay data and hadronic vacuum polarization functions (HVPs) computed on the lattice. The experimental and lattice data are related through dispersion relations which employ a class of weight functions which are products of factors having poles at Euclidean Q^2.

Implementing this approach using lattice data generated by the RBC/UKQCD collaboration, we show examples of weight functions which allow the combination of lattice HVPs required for this analysis to be determined with good accuracy while at the same time strongly suppressing spectral integral contributions from the region where experimental data either have large uncertainties or do not exist.

Preliminary results for Vus obtained using this approach will be presented and shown to be in good agreement with those obtained from analyses of kaon physics and 3-family CKM unitarity.

Related background, details of the experimental data employed and the current status of the conventional flavor-breaking sum rule tau V_us puzzle, as well as an outline of the advantages of the new approach over the conventional sum rule analysis will be discussed in the talk by Kim Maltman. Some related studies, involving applications to the running of alpha_QED and the Weinberg angle, and a possible application to muon g-2 will also be discussed, as time permits.

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Welcome

Nonzero Temperature and Density / 290

What we can learn from two-dimensional QCD-like theories at finite density

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Theoretical knowlegde about the nonperturbative aspects of the phase diagram of QCD is of utmost importance for the design of future collider experiments or the understanding of cold and dense neutron stars.

Since lattice QCD suffers from a severe sign problem at finite density, QCD-like theories are useful to understand the phase diagram
of baryonic matter at finite density. Most QCD-like theories (two-color QCD, G_2-QCD or adjoint QCD) contain bosonic baryons, for example diquarks, or other more exotic types of matter.
It is important to understand the interactions of these particles with ordinary fermionic baryons present in QCD.

Simulations of these theories, for instance G_2-QCD, reveal an interesting and rich phase diagram at zero temperature. Many open questions arise, partly due to the lack of high precision or large volume/continuum data. This is the reason why we study two-dimensional QCD-like theories. In the talk we shall discuss
differences between QCD-like theories at baryon chemical and isospin chemical potential. Furthermore we present simulation results on the phase diagram and spectroscopy at finite density for G_2- and two-color-QCD and compare it to free lattice fermions. Finally we give an outlook to our ongoing simulations in four dimensions.

Poster / 50

Zero-momentum SU(2) gluon correlator at various boundary conditions

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We make simulations of the zero-momentum $SU(2)$ Landau gauge gluon correlator both for periodic and zero-field boundary conditions at varying β and $L_t * L_s^3$ lattice sizes.

Physics Beyond the Standard Model / **202**

dark matter from one-flavor SU(2) gauge theory

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SU(2) gauge theory with a single fermion in the fundamental representation is a minimal non-Abelian candidate for the dark sector. Having only a single flavor provides a natural mechanism for stabilizing dark matter on cosmological timescales. Preliminary lattice results will be presented and discussed in the context of dark matter phenomenology.

Weak Decays and Matrix Elements / **407**

long distance part of ϵ_K from lattice QCD

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We demonstrate the lattice QCD calculation of the long distance contribution to ϵ_K. Due to the singular, short-distance structure of $epsilon_K$, we must perform a short-distance subtraction and introduce a corresponding subtraction term determined from perturbation theory, which we calculate at Next Leading Order (NLO). We perform the calculation on a $24^3 \times 64$ lattice with a pion mass of 329 MeV. This work is a complete calculation, which includes all connected and disconnected diagrams.

Poster / **57**

pMR: A high-performance communication library

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On many parallel machines, the time LQCD applications spend in communication is a significant contribution to the total wall-clock time, especially in the strong-scaling limit.
We present a novel high-performance communication library that can be used as a de facto drop-in replacement in existing software.
Its lightweight nature that avoids some of the unnecessary overhead introduced by MPI allows us to improve the communication performance of an application without any algorithmic or complicated implementation changes.
As a first real-world benchmark, we make use of the library in the coarse grid solve of the DD-\alphaAMG algorithm.
On realistic lattices, we see an improvement of a factor 2x in pure communication time and total time savings of up to 20%.