Lattice calculations
&
DiRAC facility

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Outline

- Overview
- Selected physics highlights
  - Flavour physics
  - Muon magnetic moment
  - QCD spectrum
- DiRAC computing facility

Lattice QCD

- Use methods of effective field theory and renormalization to turn a ***quantum physics*** problem into a ***statistical physics*** problem

- ***Quarks*** propagating through strongly interacting QCD ***glue*** + ***sea*** of quark-antiquark bubbles

- Numerically evaluate path integrals using Monte Carlo methods: ***importance sampling*** & ***correlation functions***

- Numerical challenge: solving $M x = b$ where M is big and has a ***diverging condition number*** as $am_q \to 0$ (vanishing lattice spacing × light quark mass)

UKQCD consortium

- 24 faculty at 8 UK institutions
- Membership/Leadership in several international collaborations (e.g. HPQCD, RBC-UKQCD, HadSpec, QCDSF, FastSum)
- Broad range of physics: quark flavour, hadron spectrum, hot/dense QCD; BSM theories of EWSB, dark matter
- Widespread impact: LHC, BES-III, Belle, JLab, J-PARC, FAIR, RHIC, NA62

Image credit: CIA World Factbook

Selected highlights

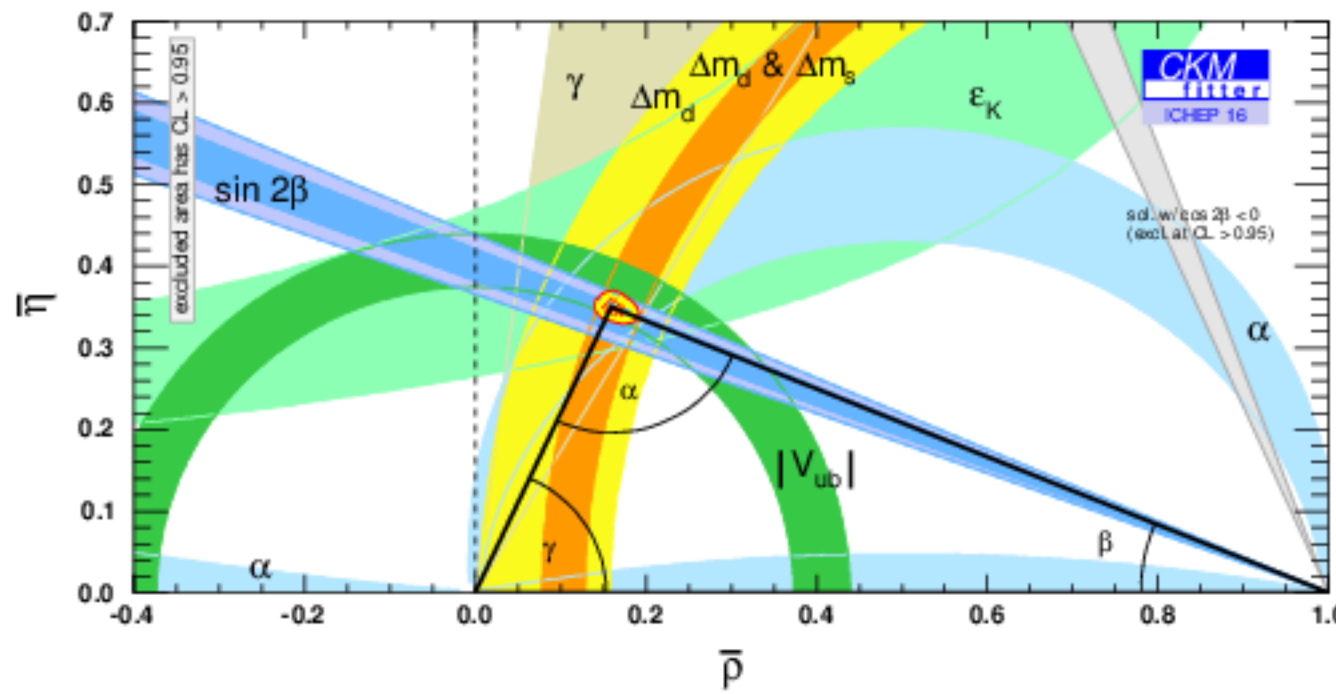
Apologies for all the interesting work not mentioned here due to time.

Quark flavour physics

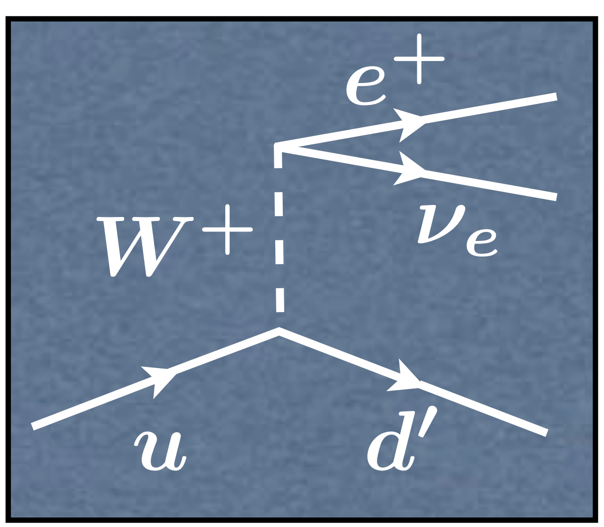
CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



CKM Fitter



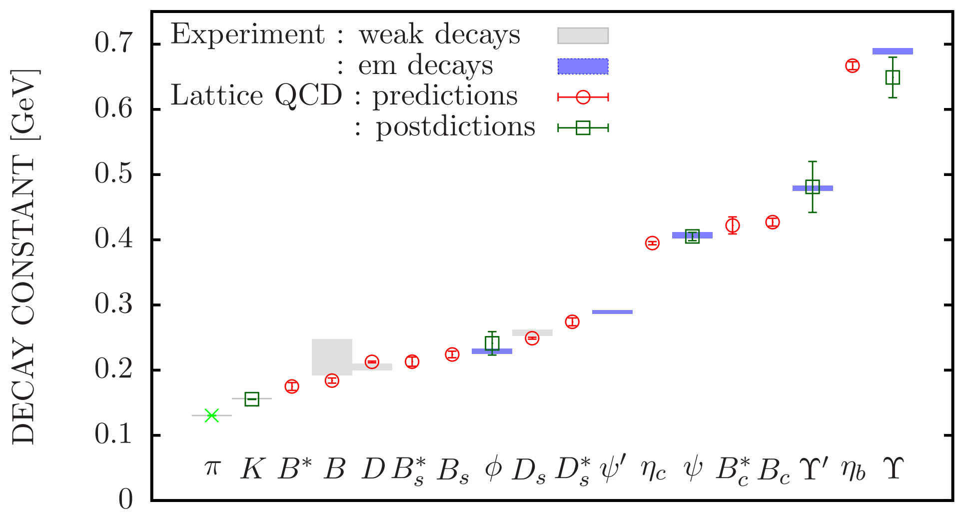
tree

$$K \to \pi \ell \nu \qquad B \to \pi \ell \nu$$

$$D \to \pi \ell \nu \quad D \to K \ell \nu \quad B_{(s)} \to D^{(*)}_{(s)} \ell \nu$$

$$B^0_{(s)} - \bar{B}^0_{(s)} \quad B_c \to J/\psi\, \ell \nu$$

Quark flavour physics

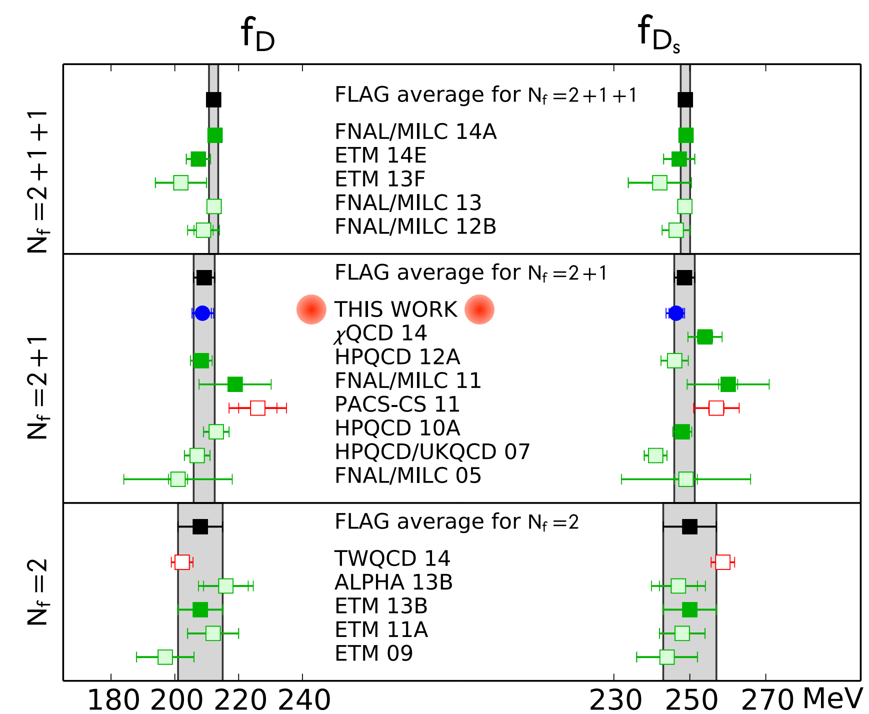


Colquhoun et al., (HPQCD), arXiv:1503.05762

Decay constants

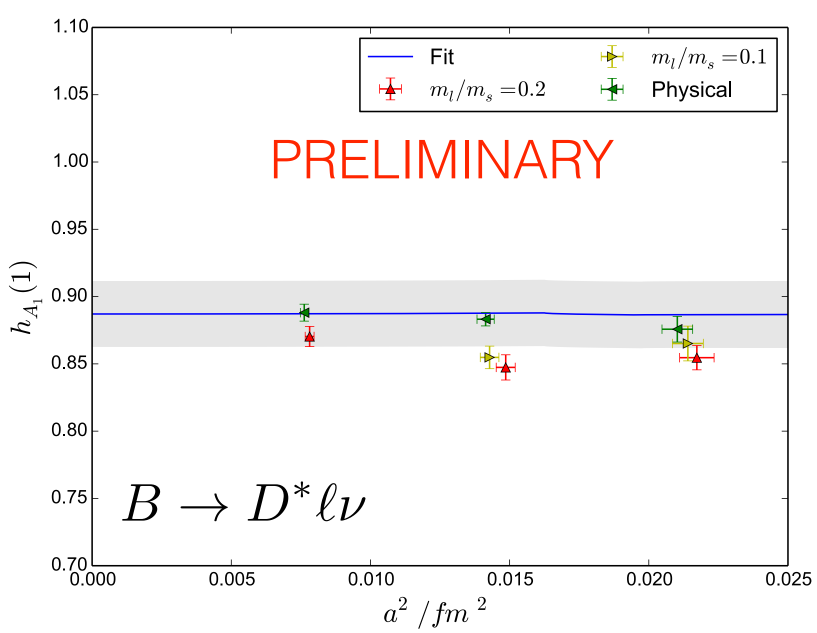
Weak (or EM) annihilation

$$\langle 0_{\mathrm{QCD}}|J_\mu|H\rangle$$



Boyle et al, (RBC-UKQCD), arXiv:1701.02644

zero recoil



Harrison et al, (HPQCD), in preparation

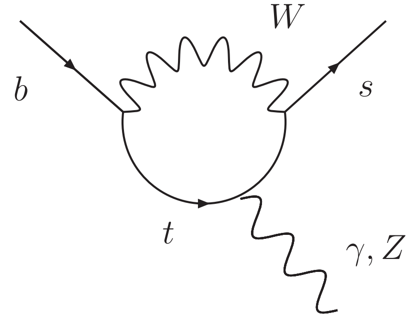
Form factors

Weak decay

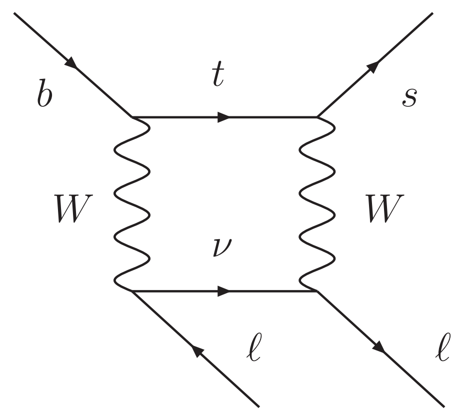
$$\langle D^*(k)|J_\mu|B(p)\rangle$$

Quark flavour physics

Flavour changing neutral decays



penguin



box

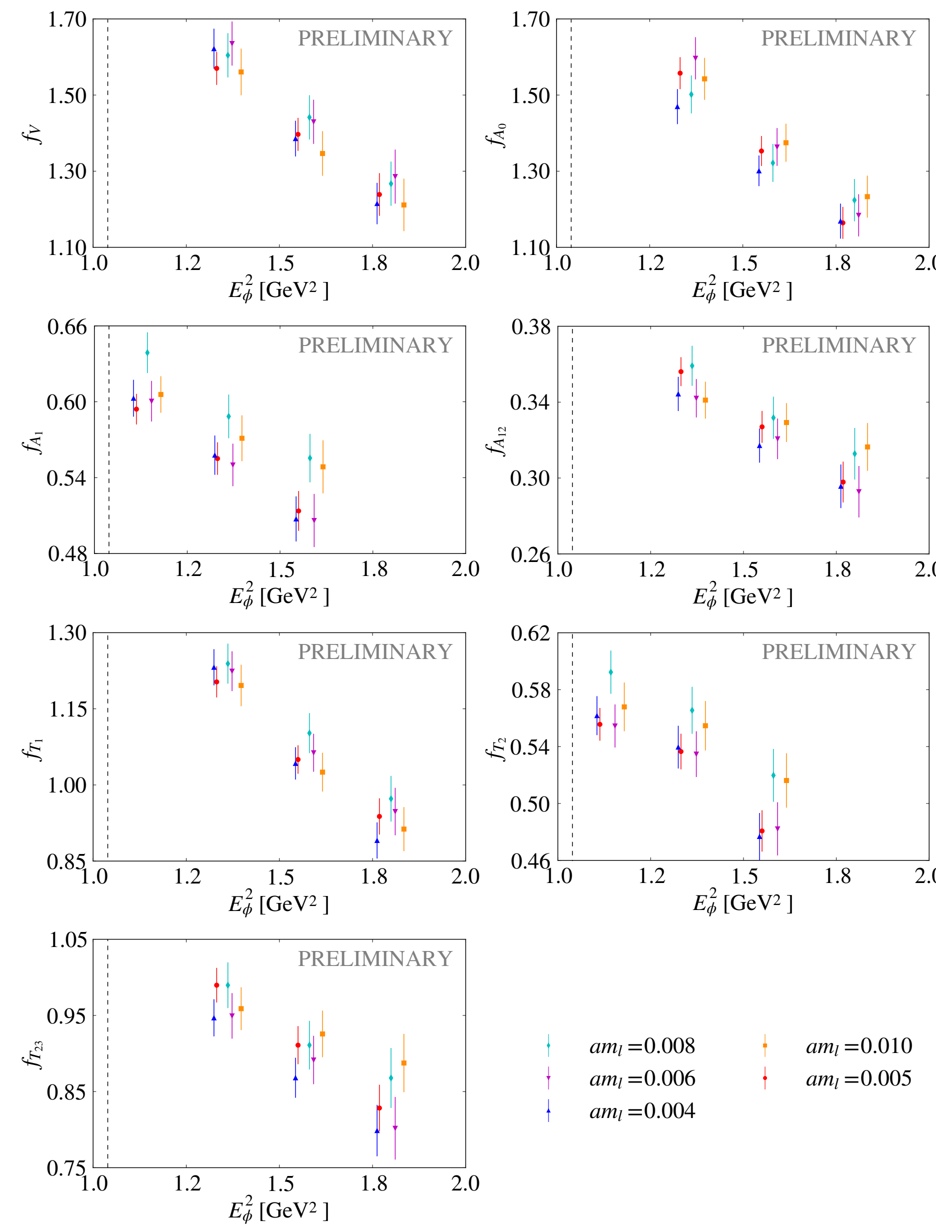
$B \to K^* \ell^+ \ell^-$ $\quad B_s \to \phi \ell^+ \ell^-$

Horgan et al., (HPQCD) arXiv:1310.3722, arXiv:1310.3887

Also rare K decays

$K \to \pi\, l\, l$: Christ et al., (RBC-UKQCD), arXiv:1608.07585
$K \to \pi\, \nu\nu$: Bai et al., (RBC-UKQCD), arXiv:1701.02858

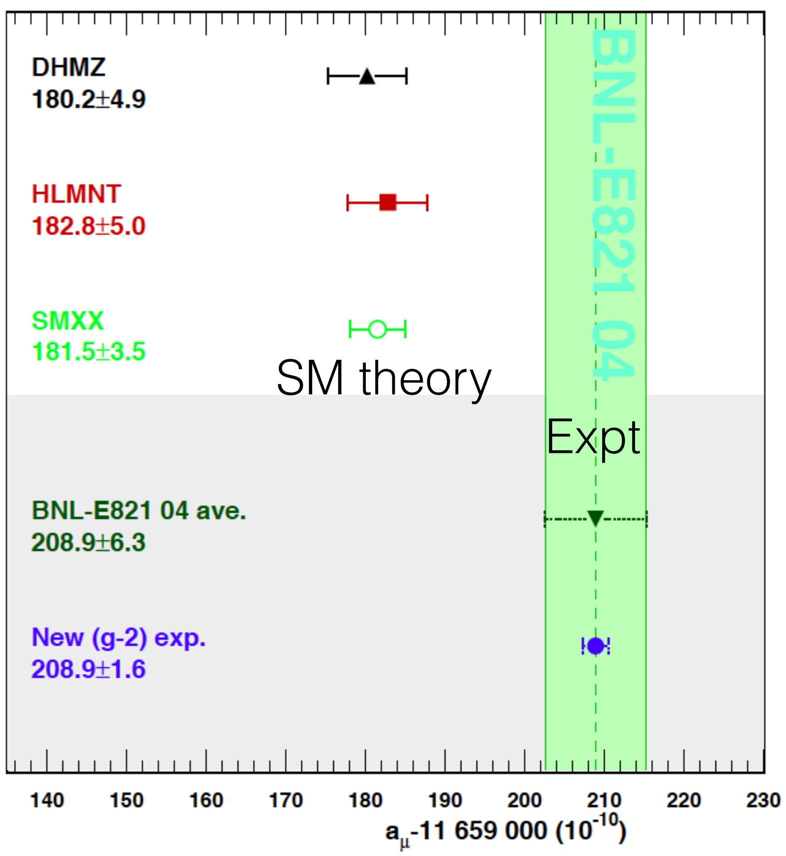
$B_s \to \phi \ell^+ \ell^-$



Flynn et al, (RBC-UKQCD), arXiv:1612.05112(C)

μ magnetic moment

$$a_\mu = \frac{1}{2}(g-2)_{\mathrm{muon}}$$

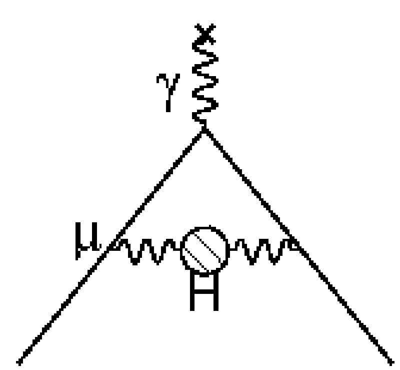


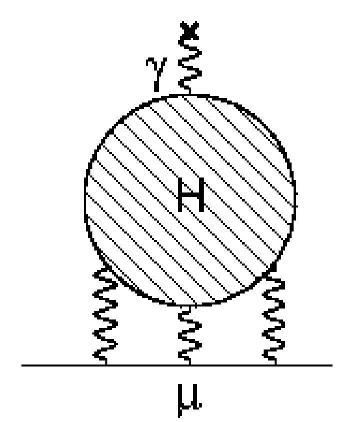
Standard model contributions

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

Blum et al., arXiv:1311.2198

Hadron Vacuum Polarization (HVP)

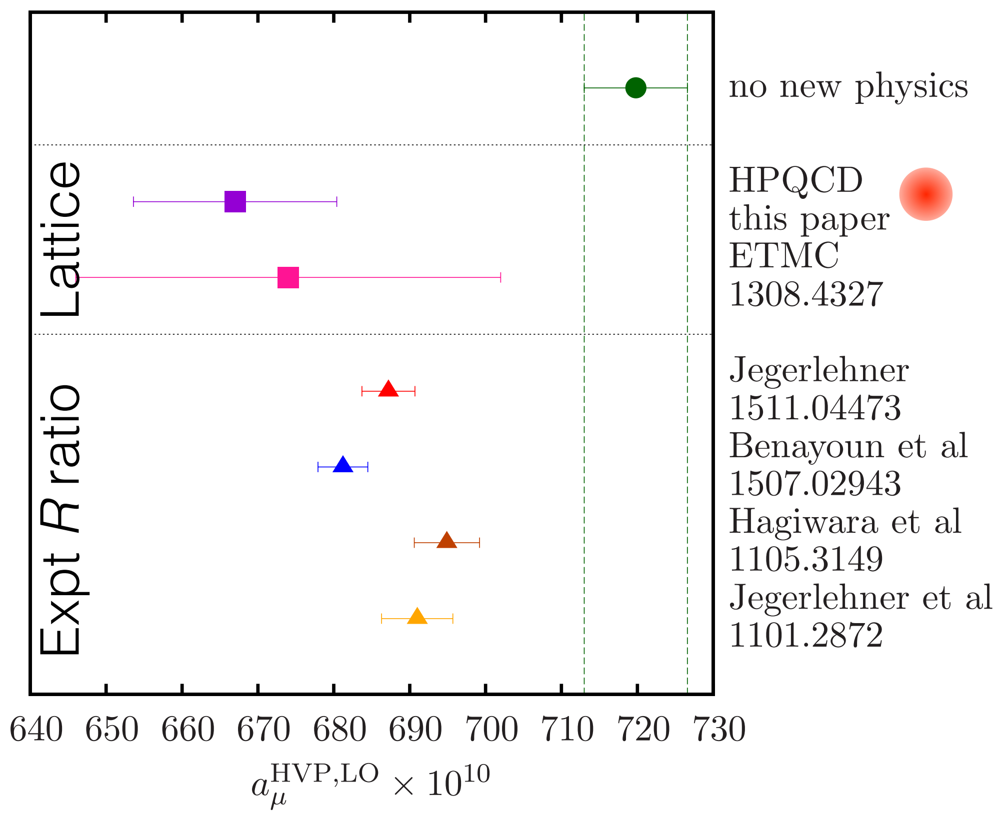




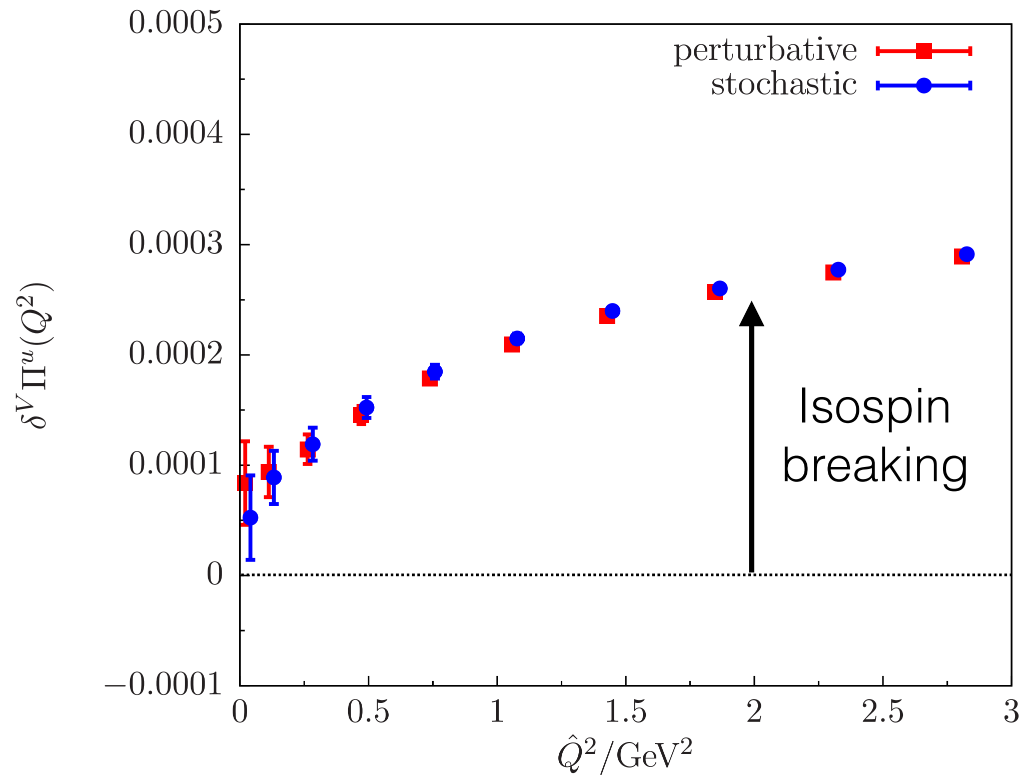
Hadronic Light-by-Light scattering (HLbL)

μ magnetic moment

HVP in SM



Isospin breaking effects
[exploratory study]



Chakraborty et al., (HPQCD), arXiv:1601.03071

Boyle et al, (RBC-UKQCD), arXiv:1706.05293

Aim for 1% precision in lattice HVP in the next couple years

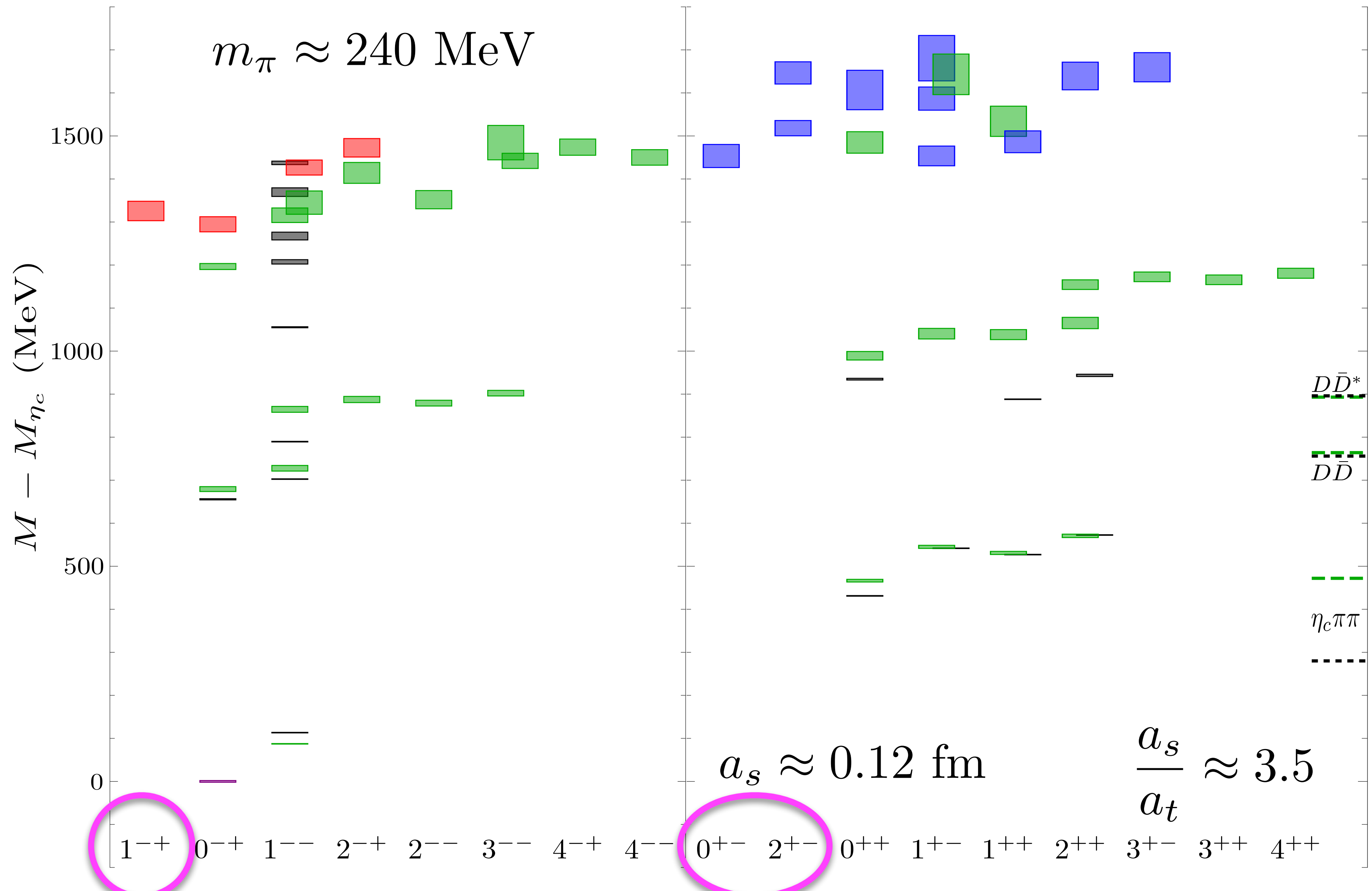
+ first LQCD efforts to estimate HLbL and quark-disconnected contributions.

Spectroscopy

- Experimental discovery of “puzzling” hadronic resonances
- X, Y, Z states: defy usual quarkonium description (e.g. exotic quantum numbers; some are charged)
- Scalar $D_{s0}^{*}(2317)$ and axial vector $D_{s1}(2460)$ much narrower and lighter than expected from quark model
- Lattice QCD can be used to study excited state spectrum, distinguishing bound states and determining scattering properties
- Great care must be taken to correctly investigate resonance structure, then control systematic errors

Charmonium (narrow)

Green (■): Good overlap w/ $q\bar{q}$ operators
Red (■) & blue (■): Hybrid mesons; Black (■): Expt

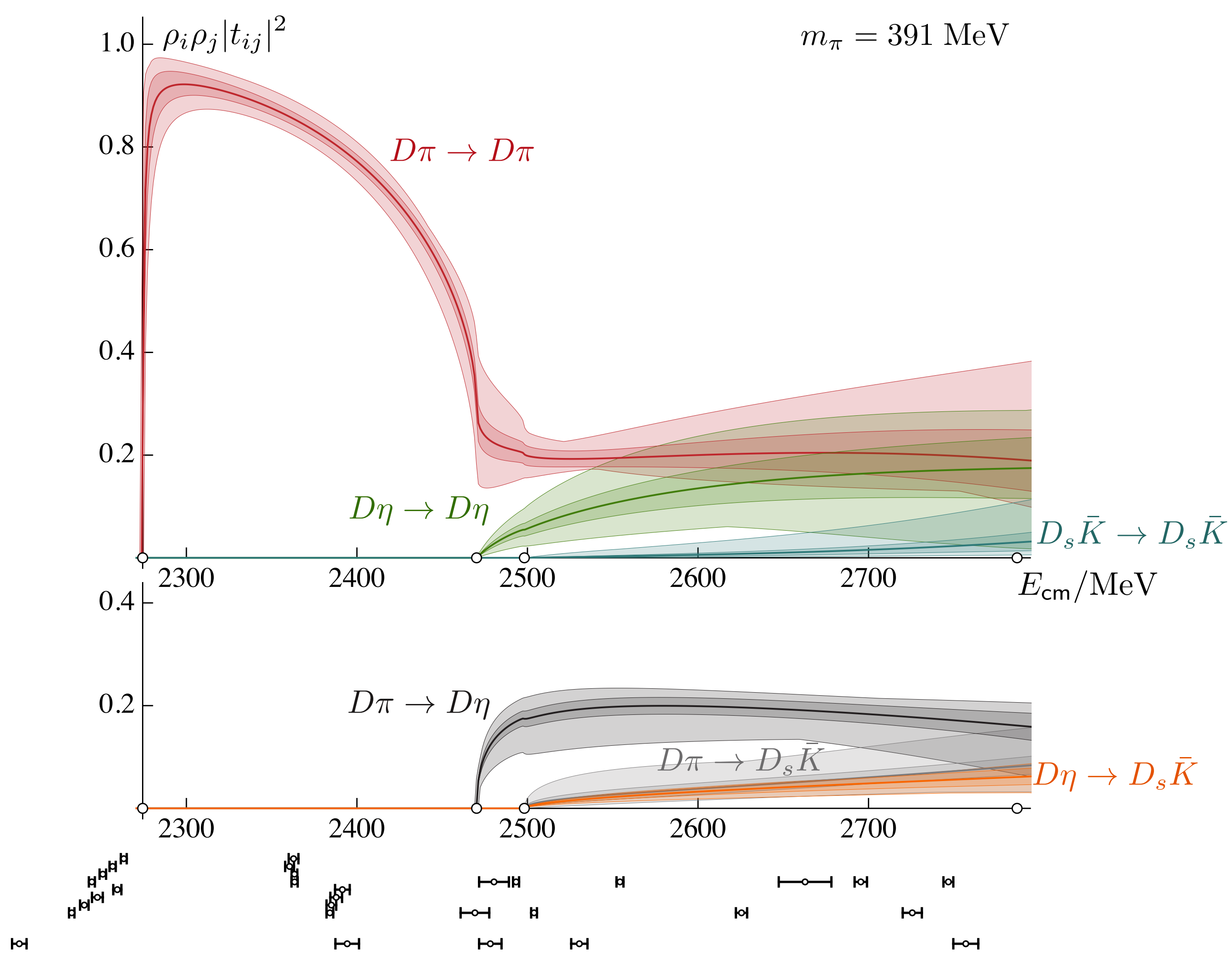


Cheung et al. (HadSpec), arXiv:1610.01073

Scattering amplitudes

- Finite volume ⇒ discrete energy levels
- Need to reconstruct full scattering amplitude
- Groundbreaking results, exploring new, sophisticated methods
- Long programme to then control systematic uncertainties

$I = \frac{3}{2}$ — 3 coupled channels!



Moir et al. (HadSpec), arXiv:1607.07093

DiRAC computing facility

DiRAC 2

- 2011: £15M BIS investment in national distributed HPC facility for particle & nuclear physics, cosmology, & theoretical astrophysics. Recurrent costs funded by STFC

- 2012: 5 systems deployed:
    - **Extreme scaling**:1.3 Pflop/s Blue Gene/Q (Edinburgh)
    - **Data Analytic/Data Centric/Complexity**: 3 tightly-coupled clusters with various levels of interconnectivity, memory, and fast I/O (Cambridge, Durham, Leicester)
    - **Shared Memory System** (**SMP**) (Cambridge)

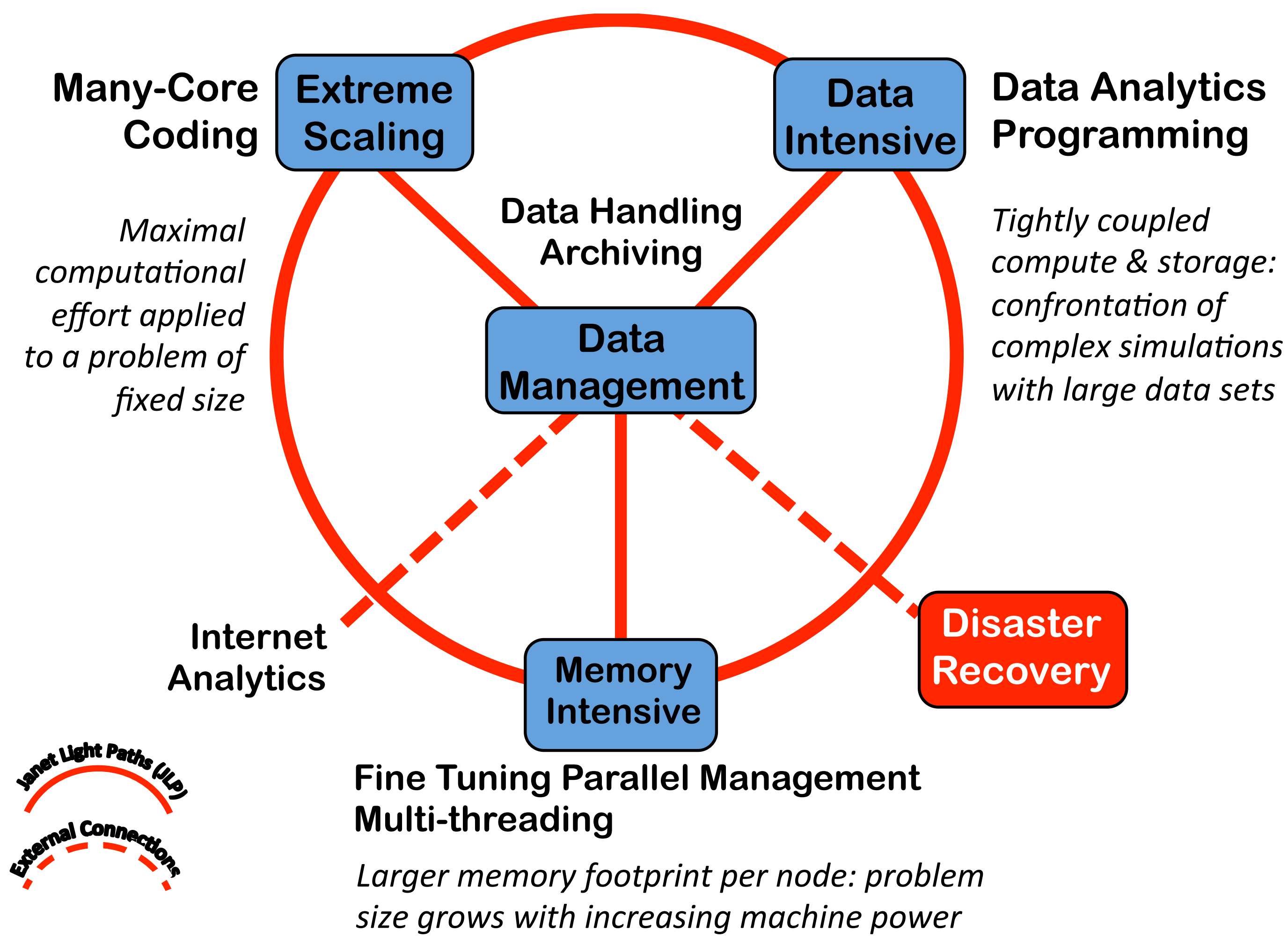
- Service started 1 December 2012

DiRAC 2 outputs

- 106 lattice publications, with 1977 citations (as of 20/7/2017)
- 765 publications in a broad scientific range (PPAN) — 35,365 citations (as of 20/7/2017)
- Gravitational waves, cosmology, galaxy & planet formation, exoplanets, MHD, particle pheno, nuclear physics
- Valuable resource for PDRA's & PhD students
- Scientific results, training in high performance computing

DiRAC 3

- Continued success requires continued investment
- Seek approx £25M capital investment to upgrade DiRAC-2 x10
- Running costs for staff and electricity
- Improve exploitation of research and HPC training impact with PDRA and PhD support (Big Data CDTs)
- Part of RCUK's <u>e-Infrastructure roadmap</u>



2011/12

DiRAC 2

Stop-gap funding:

2016/17 DiRAC 2.5

2017 DiRAC 2.5x

2018/19

DiRAC 3

DiRAC 2.5

After £1.67M capital injection

- **Extreme Scaling 2.5**: 1.3 Pflop/s Blue Gene/Q
- **Data Analytic 2.5**: Share of Peta5 system + continued access to Sandybridge system
  - Shared EPSRC/DiRAC/Cambridge: 25K Skylake cores + 1.0 Pflop/s GPU + 0.5 Pflop/s KNL service
- **Data Centric 2.5**: Over 14K cores, 128 GB RAM/node
- **Complexity 2.5**: 4.7K large-job cores + 3K small-job cores
- **SMP**: 14.8TB, 1.8K core shared memory service

DiRAC 2.5x

June 2017: £9M capital funding (BEIS), lifeline to DiRAC3:

- Planned investment
    - **Extreme scaling**: 1024-node, 2.5 Pflop/s system
    - **Memory intensive**: 144 nodes, 4.6K cores, 110 TB RAM
    - **Data analytic**: 128 nodes, 4K cores, 256GB/node; hierarchy of fat nodes (1-6 TB); NVMe storage for data intensive workflows
- Additional storage at all DiRAC sites
- Procurement procedure: November 2017
- Target for hardware availability: April 2018

Who we are

DiRAC

Project Board Chair: D Sijacki (Cambridge)
Project Board Co-chair: S Hands (Swansea)
Director: M Wilkinson* (Leicester)
Technical Director: P Boyle (Edinburgh)
Project Scientist: C Jenner (UCL)
Technical Manager: J Yates (UCL)

UKQCD

G Aarts (Swansea)
C Allton (Swansea)
C Bouchard (Glasgow)
P Boyle (Edinburgh)
C Davies (Glasgow)
L Del Debbio (Edinburgh)
J Flynn (Southampton)
S Hands (Swansea)
R Horgan (Cambridge)
R Horsley (Edinburgh)
A Jüttner (Southampton)
T Kennedy (Edinburgh)
R Kenway (Edinburgh)
K Langfeld (Liverpool)
B Lucini (Swansea)
C McNeile (Plymouth)
A Patella (Plymouth)
B Pendleton (Edinburgh)
A Rago (Plymouth)
P Rakow (Liverpool)
C Sachrajda (Southampton)
M Teper (Oxford)
C Thomas (Cambridge)
M Wingate (Cambridge)
+ PDRAs & PhD students

* Thanks to Mark Wilkinson for contributing to DiRAC slides presented here.

Summary

- UKQCD consortium: broad range of research, impact in addressing STFC's key scientific challenges

- DiRAC 2: Enabled UK lattice field theory to be internationally competitive

- DiRAC 2.5/x: Now in the preliminary stages of refreshing capital resources

- Looking forward to DiRAC 3!