UKQCD Review

Nicolas Garron

University of Liverpool

Dirac Day, Edinburgh 8^{th} of September 2016

Outline

- UKQCD
- Standard Model and new Physics
- Lattice QCD and Standard Model results
- Beyond the Standard Model
- Finite Temperature and density

UKQCD

According to
http://pyweb.swan.ac.uk/~allton/ukqcd/web/information.html

The list of member institutions is

- Cambridge
- Edinburgh
- Glasgow
- Liverpool
- Oxford
- Plymouth
- Southampton
- Swansea

UKQCD collaborations

- HPQCD (UK: Cambridge-Glasgow-Plymouth; Canada, Spain, US)
- QCDSF-UKQCD (UK: Edinburgh, Liverpool; Australia, Germany)
- RBC-UKQCD (UK: Edinburgh, Liverpool, Southampton; Canada, China, Japan, US, ...)
- Hadron Spectrum Collaboration (UK: Cambridge; Ireland, US)
- + unnamed collaborations

UKQCD Physics Topics

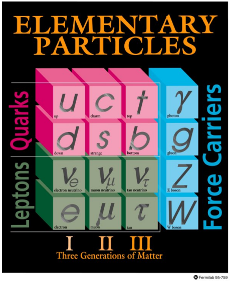
Theoretical Particle Physics using large-scale numerical simulations

- QCD, Flavour physics, precision tests of the Standard Model
- Beyond the Standard Model and Non-QCD studies
- Finite Temperature and Finite Density

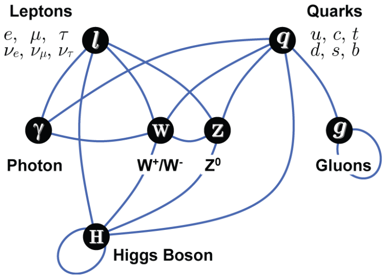
Standard Model: a beautiful theory

- Common description (Lagrangian) of electromagnetism, strong and weak interaction.
- Based on symmetry principles, combines Einstein's special relativity and quantum mechanics.
- Only a few free parameters (19, if we don't take neutrinos masses into account)
- Extremely accurate description over a large range of phenomena.

  Example: muonic anomalous magnetic moment $g_\mu - 2 = 11659208.0(5.4)(3.3)[6.3]\,10^{-10}$
- 2012: Observation of a Higgs-like particle $\rightarrow$ last missing piece of the puzzle ?



$\longrightarrow$



Why do look for new physics ?

- No gravity : the SM is not a "theory of everything"
- Cannot explain Matter-antimatter asymmetry in the universe (CP violation)
- Dark matter and dark energy
- Hierarchy problem(s), . . .
- Mathematically not well defined in the strong regime

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A lattice discretisation is the only way to define the theory properly

Need for Lattice simulations

- BSM effects very hard to detect, need to have all errors under control
- The strong force (which binds the quarks together) is strong
- In the hardonic regime, Perturbation theory does not make sense
- Need non-perturbative method,

$\Rightarrow$ Numerical simulations of Lattice of Quantum- Chromo- Dyanmics

- Allows for *ab-inito* computations (model-independent)
- Theoretically well-defined

QCD and Particle Physics Phenomenology

QCD and Phenomenology

For example, compute the free parameters of the Standard Model

- Quark masses (RBC-UKQCD, HPQCD)
- Coupling constant (QCDSF-UKQCD, HPQCD)

Or the ones related to quark flavour mixing (CKM matrix): UKQCD

Light and heavy quarks

The light quark sector (u,d,s) is "mature"

- Ab-inito simulations,
- Simulations with physical quark masses, various lattice spacings
- Several discretisations

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- $b-$ sector: Most of the results traditionally use "effective theory"
- Fewer available discretisations
- However the situation is evolving quickly

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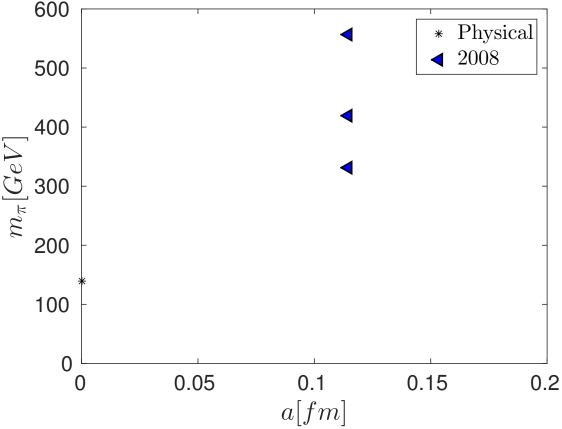
For the charm sector, we are an intermediate situation

There is an impressive effort by the lattice community, both for the c and the b

Going light

RBC-UKQCD $N_f = 2 + 1$ DWF - Landscape (since 2008)



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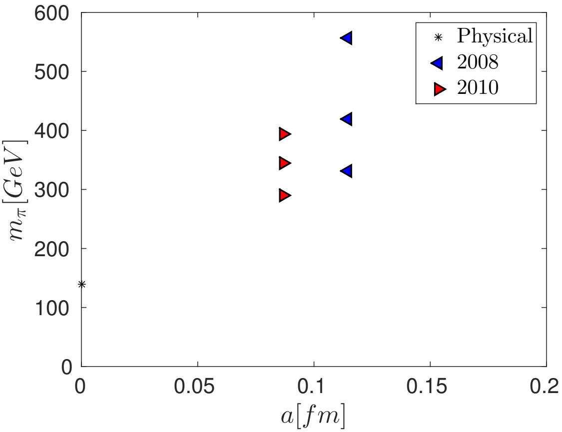

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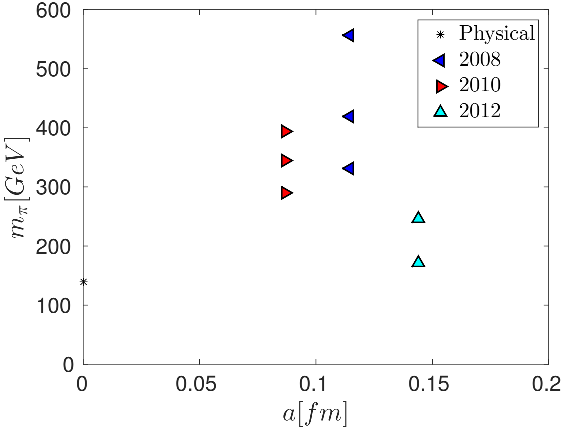

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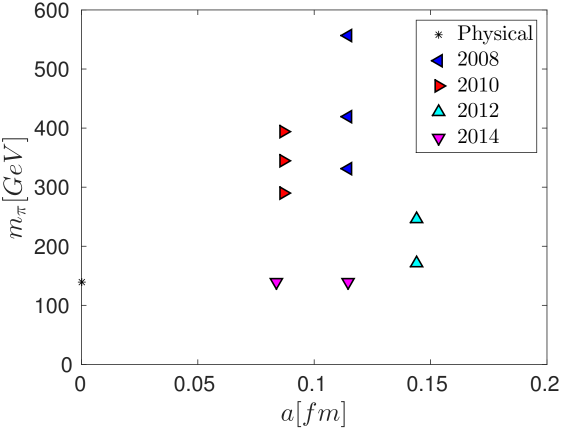

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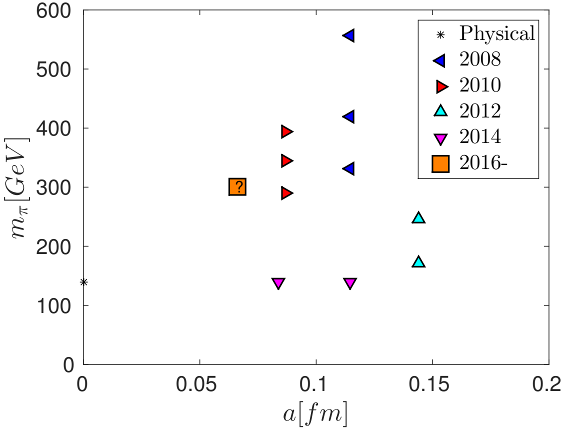


Light quarks - Kaon physics

RBC-UKQD has a broad Kaon project, very successful thanks to DiRAC

- $K \to \pi\pi$: Matter-Antimatter asymmetry in the Standard Model

  $\Rightarrow$ First every realistic computation of a decay amplitude
- Kaon semi-leptnoic decay: Determination of V_{us}
- Rare kaon decays: New strategy, important sensitivity to New Physics
- ...

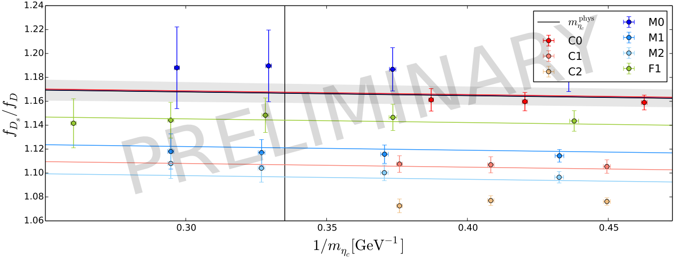
Very important impact in phenomenology !

D mesons

Decay constant of the $D\,(c,\bar{d})$ and the $D_s(c,\bar{s})$

RBC-UKQCD

P. Boyle, L. Del Debbio, A. Jüttner, A. Khamseh, M. Marinković, F. Sanfilippo, T. Tsang



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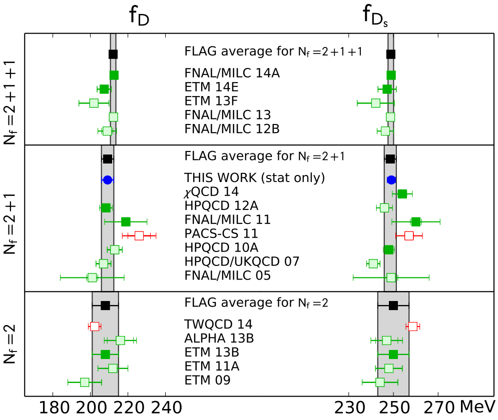

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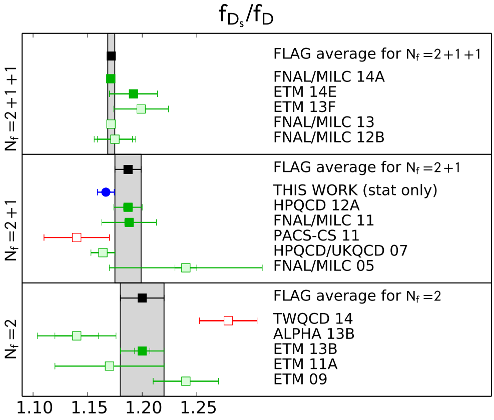

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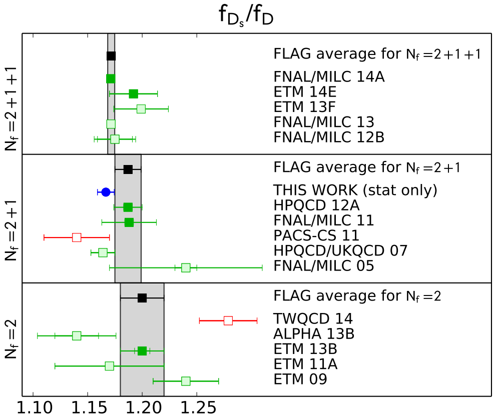

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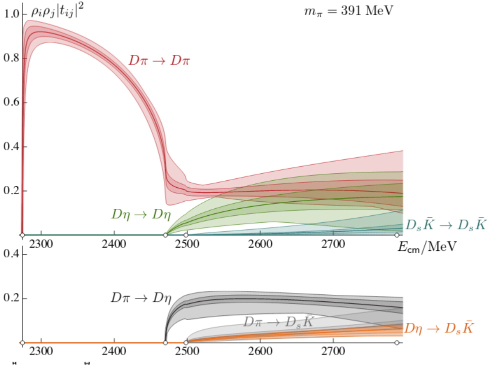
Scattering and spectra

Hadron Spectrum Collaboration

G Moir, M Peardon, S M Ryan, C E Thomas, D J Wilson



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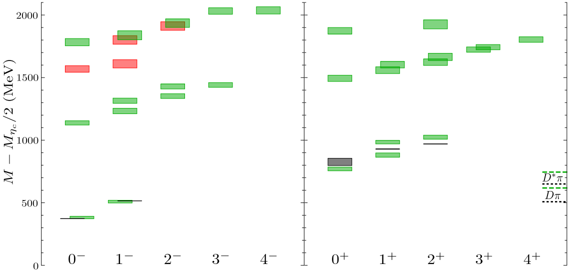

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B mesons

HPQCD A Lytle, B Colquhoun, C Davies, J Koponen, C McNeile
See talk by A. Lytle at B-physics conference 2016

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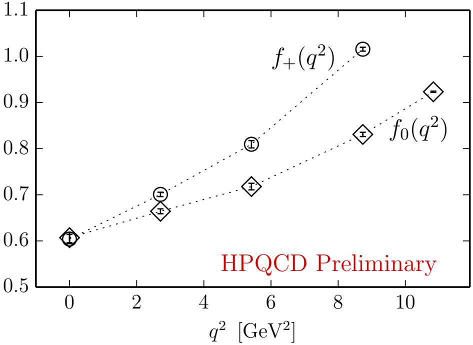

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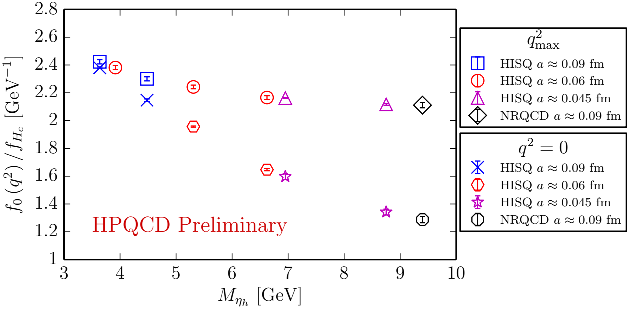

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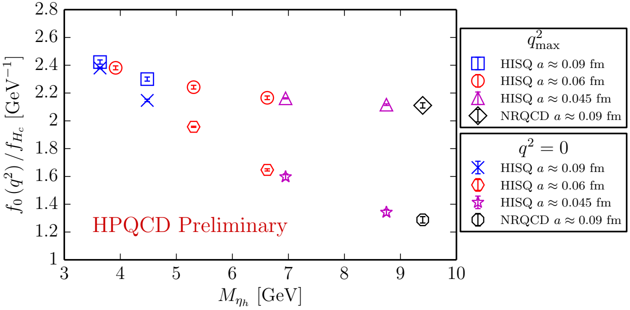

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J. M. Flynn, A. Jüttner, E. Lizarazo, O. Witzel

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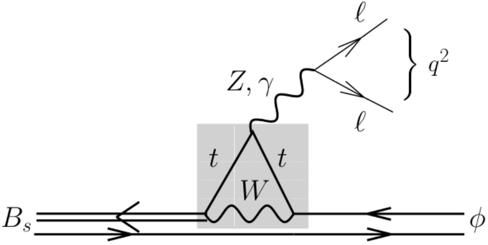

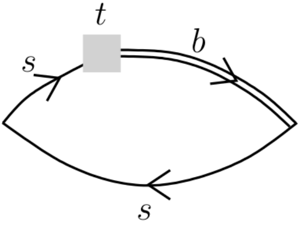

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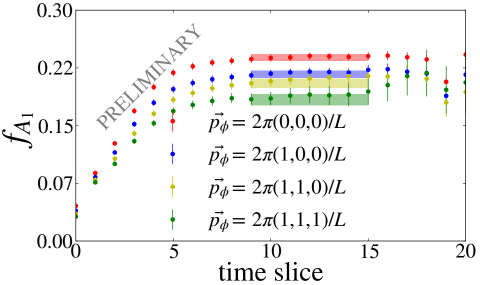

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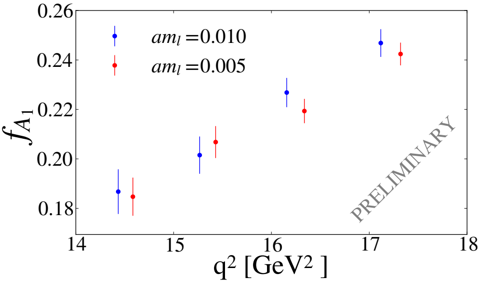

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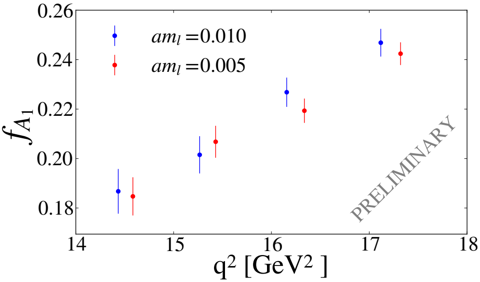


See Poster by Oliver Witzel

Internal structure of the proton

Internal structure of the nucleon

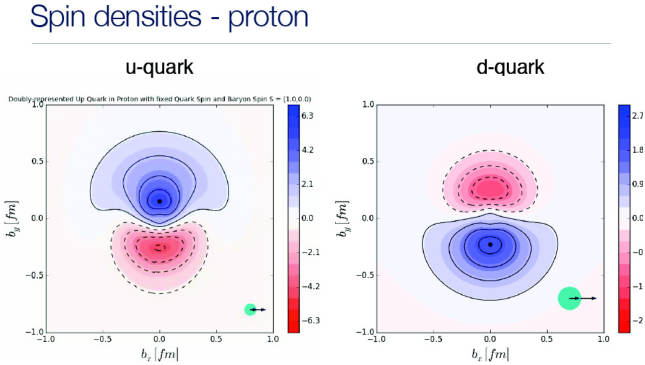
Proton and neutron have spin, what is the contribution of the quarks ?

Internal structure of the nucleon

QCDSF-UKQCD

Bickerton, Horsley, Nakamura, Rakow, Schierholz, Shanahan, Young, Zanotti

See talk by J. Zanotti at lattice 2016



Courtesy of Roger Horsley

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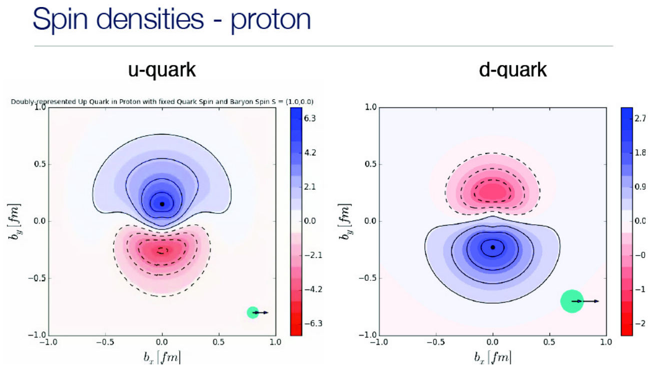

See Poster by Roger Horsley

Anomalous magnetic moment of the muon

Anomalous magnetic moment of the muon

An elementary particle of spin $1/2$, of spin angular momentum $\vec{S}$, charge e, mass m has a magnetic moment $\vec{\mu} = g\frac{e}{2m}\vec{S}$,

g is the gyromagnetic ratio, for the muon μ the classical value is $g_\mu = 2$

The anomalous moment is a the relative deviation from this value

$$a_\mu = \frac{g_\mu - 2}{2}$$

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$$a_\mu = \frac{g_\mu - 2}{2}$$

Known very precisely both experimentally and theoretically

$$\begin{aligned} a_\mu^{exp} &= 0.001\,165\,920\,91(54)(33) \\ a_\mu^{the} &= 0.001\,165\,918\,03(49) \end{aligned}$$

The numbers agree up to 10^{-8}, however there is a steady $\sim 3 - 4\sigma$ deviation

Anomalous magnetic moment of the muon

- We are dealing with “small” quantum effects which are very sensitive to new physics
- This quantity can be computed at an impressive level of precision
- New experiment coming up should decrease the experimental error by a factor 4 after a year of running

Anomalous magnetic moment of the muon

Contributions to a_μ PDG, 2015

Contribution	$a_\mu \times 10^{11}$	Uncertainty
QED (5-loop)	116584718.95	0.08
Electroweak (2-loop)	153.6	1.0
LO hadronic (HVP)	6923	42
NLO hadronic	7	26
Theory Total	116591803	49.4
Experiment Total	116592091	63.3

Courtesy of Matt Spraggs

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Anomalous magnetic moment of the muon

A lot of work is done with DiRAC, recently:

- HPQCD B. Chakraborty, C. T. H. Davies, P. G. de Oliviera, J. Koponen, G. P. Lepage,
- B. Chakraborty, C. T. H. Davies, J. Koponen, G. P. Lepage, M. J. Peardon, S. M. Ryan, PRD'16
- Eric B. Gregory & Craig McNeile
- RBC-UKQCD

  T. Blum, P.A. Boyle, L. Del Debbio, R.J. Hudspith, T. Izubuchi, A. Juttner, C. Lehner, R. Lewis, K. Maltman, M. Krstić Marinković, A. Portelli, M. Spraggs, JHEP'16

  T. Blum, P.A. Boyle, T. Izubuchi, L. Jin, A. Jüttner, C. Lehner, K. Maltman, M. Marinkovic, A. Portelli, M. Spraggs, PRL'16
- . . .

See talk by Christine Davies.
2pm

Beyond the Standard Model

Beyond the Standard Model (BSM)

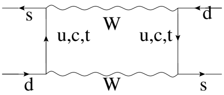
Different applications, approaches

- New physics effects are important at high energy, but QCD remains a valid description of the strong interaction at low energy. New interaction (at high energy) is visible at low energy though new "effective" operators (e.g. new four-quark operators)
- Lattice simulations can be used to simulate other non-perturbative theory (not QCD), composite Higgs model and Electroweak Symmetry Breaking, strongly interacting Dark Matter ... For example, work by UKQCD-BSM

Neutral kaon mixing

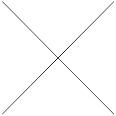
Indirect CP violation related to neutral kaon oscillations

in the SM this occurs though box diagrams with W exchange



$\mu \ll \overrightarrow{M_W}$

OPE

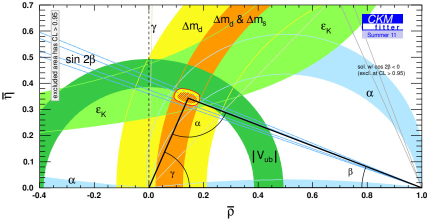


Factorise the non-perturbative contribution into

$$\langle \overline{K}^0 | \mathcal{O}_{LL}^{\Delta S=2}(\mu) | K^0 \rangle = \frac{8}{3} F_K^2 M_K^2 B_K(\mu) \qquad \text{w/ } \mathcal{O}_{LL}^{\Delta S=2} = (\bar{s}\gamma_\mu(1-\gamma_5)d)(\bar{s}\gamma^\mu(1-\gamma_5)d)$$

Related to ε via CKM parameters, schematically

$$\varepsilon \sim \text{ known factors} \times V_{\mathrm{CKM}} \times C(\mu) \times B_K(\mu)$$



[CKMfitter'11]

In the SM, neutral kaon mixing occurs through W-exchanges $\rightarrow$ $(V-A)$

$$O_1^{\Delta s=2} = (\bar{s}\,(V-A)\,d)\,(\bar{s}\,(V-A)\,d)$$

Beyond the SM, other Dirac structure appear in the generic Hamiltonian $H^{\Delta s=2} = \sum_{i=1}^{5} C_i(\mu)\, O_i^{\Delta s=2}(\mu)\,.$

We express them in terms of Lorentz matrices Vector, Axial, Scalar, Pseudo-scalar, Tensor

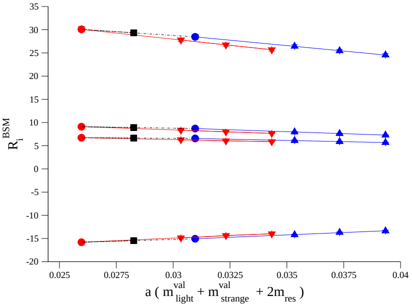
$$\begin{array}{l} (V-A)\times(V+A) \\ (S-P)\times(S+P) \\ (S-P)\times(S-P) \\ TT\times TT \end{array}$$

$\Rightarrow$ On the lattice, we compute $\langle \bar{K}^0 | O_i^{\Delta s=2} | K^0 \rangle$ in a model independent way

Results

- I show the ratios

$$R_i^{\rm BSM} \sim \frac{\langle \bar{K}^0 | O_i | K^0 \rangle}{\langle \bar{K}^0 | O_1 | K^0 \rangle} \sim {\rm BSM/SM}$$



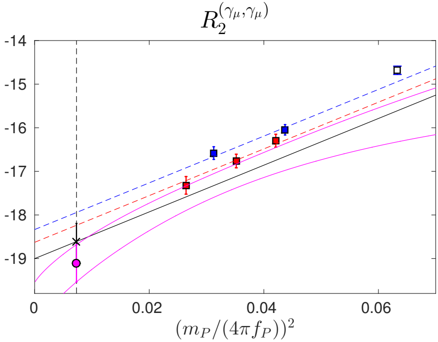
$$R_i^{\rm BSM} \sim O(10)$$

$\Rightarrow$ combined with experimental values of Δm_K and ε, provides important constraints on BSM theories.

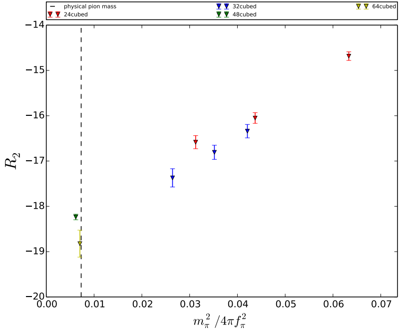
RBC-UKQCD

N.G., Hudspith, Lytle

Current work



Work in progress
See poster by Julia Kettle at Lattice 2016



Courtesy of Julia Kettle

Energy Momentum Tensor

EMT

UKQCD-BSM

F Capponi, L Del Debbio, A Patella, A Rago

See talk by F Capponi at lattice 2016

The renormalization of the Energy Momentum Tensor plays a crucial role in many aspects of non perturbative physics, from the thermodynamics of strongly interacting theories to the study of BSM models.

Thermodynamic quantities

$$\langle \epsilon - 3p \rangle_T = -\left\langle \hat{\mathcal{T}}_{\mu\mu} \right\rangle_T \quad ; \quad \langle s \rangle_T = \left(-\left\langle \hat{\mathcal{T}}_{00} \right\rangle_T + \sum_{i=1}^{3} \left\langle \hat{\mathcal{T}}_{ii} \right\rangle_T \right) / T$$

Transport coefficients

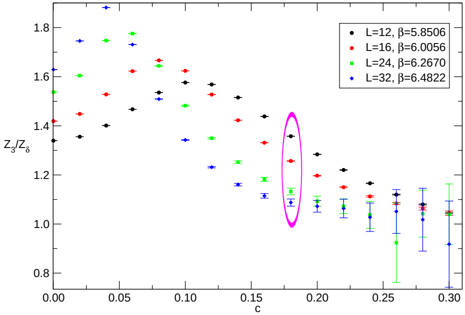
$$\eta = \pi \lim_{\omega \to 0} \mathrm{Im} \left\{ \left[i \int_0^\infty dt e^{i\omega t} \int d^3x \left\langle \hat{\mathcal{T}}_{12}(t,x) \hat{\mathcal{T}}^{12}(0,0) \right\rangle_T \right] \right\}$$

Study of conformal field theories:
$\langle \mathcal{T}^{\mu}_{\mu}(x) \rangle$ as order parameter

UKQCD-BSM

F Capponi, L Del Debbio, A Patella, A Rago

See talk by F Capponi at lattice 2016

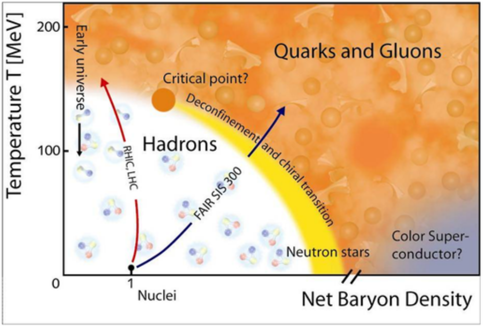


Courtesy of Francesco Capponi

QCD under extreme conditions

QCD phase diagram

So far I have only dsicussed $T = \mu = 0$, but the phase diagrm is rich



QCD under extreme conditions

For $T, \mu \neq 0$, standard MonteCarlo methods fail (sign-problem)

Recent development using DiRAC

- Complex Langevin (Swansea, ...)
- Density of states (Liverpool, Plymouth, Swansea)

Conclusions and outlook

Lattice QCD plays a crucial role in our understanding of Particle Physics

Thanks to DiRAC, the UK has massive impact in this field !

- Precision phenomenology
- New strategies, new observables
- Not only traditional QCD, but also BSM and QCD under extreme conditions

BACKUP SLIDES

Enter at your own risks

BSM kaon mixing - Results

	ETM 12	ETM 15	RBC − UKQCD 12	SWME 15
	RI − MOM	*RI − MOM*	*RI − MOM*	1 − *loop*
B_2	0.47(2)	0.46(3)	0.43(5)	0.525(1)(23)
B_3	0.78(4)	0.79(5)	0.75(9)	0.772(5)(35)
B_4	0.75(3)	0.78(5)	0.69(7)	0.981(3)(61)
B_5	0.60(3)	0.49(4)	0.47(6)	0.751(8)(68)

$\Rightarrow$ Important discrepancy for B_4 and B_5

BSM kaon mixing - Results

	ETM 12	ETM 15	RBC − UKQCD 12	SWME 15
	RI − MOM	*RI − MOM*	*RI − MOM*	1 − *loop*
B_2	0.47(2)	0.46(3)	0.43(5)	0.525(1)(23)
B_3	0.78(4)	0.79(5)	0.75(9)	0.772(5)(35)
B_4	0.75(3)	0.78(5)	0.69(7)	0.981(3)(61)
B_5	0.60(3)	0.49(4)	0.47(6)	0.751(8)(68)

⇒ Important discrepancy for B_4 and B_5

New RBC-UKQCD results [N.G., R.Hudspith, A.T. Lytle] (in preparation)

	RBC − UKQCD 16(prelim.)	
	RI − SMOM	*RI − MOM*
B_2	0.488(7)(17)(2)	0.417(6)(2)(2)
B_3	0.743(14)(64)(3)	0.655(12)(44)(2)
B_4	0.920(12)(12)(4)	0.745(9)(28)(3)
B_5	0.707(8)(34)(3)	0.555(6)(53)(2)

Difference seems to come from the renormalisation procedure

Heavy-dense QCD

Based on [NG & Langfeld, 1605.02709]

Moment expansion