Muon g-2: leading hadronic contribution from the lattice

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CERN Theory Retreat @LesHouches

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Before coming to CERN …

- 2003-2009 BSc/MSc at University of Belgrade, Serbia
- 2009-2013 PhD at Humboldt University, Berlin, Germany
- 2012-2014 Postdoc at the University of Southampton, UK

My current interests

- Hadronic vacuum polarisation from the lattice
- Isospin breaking corrections, QED+QCD
- Heavy quark physics
- Quantum simulation of gauge theories

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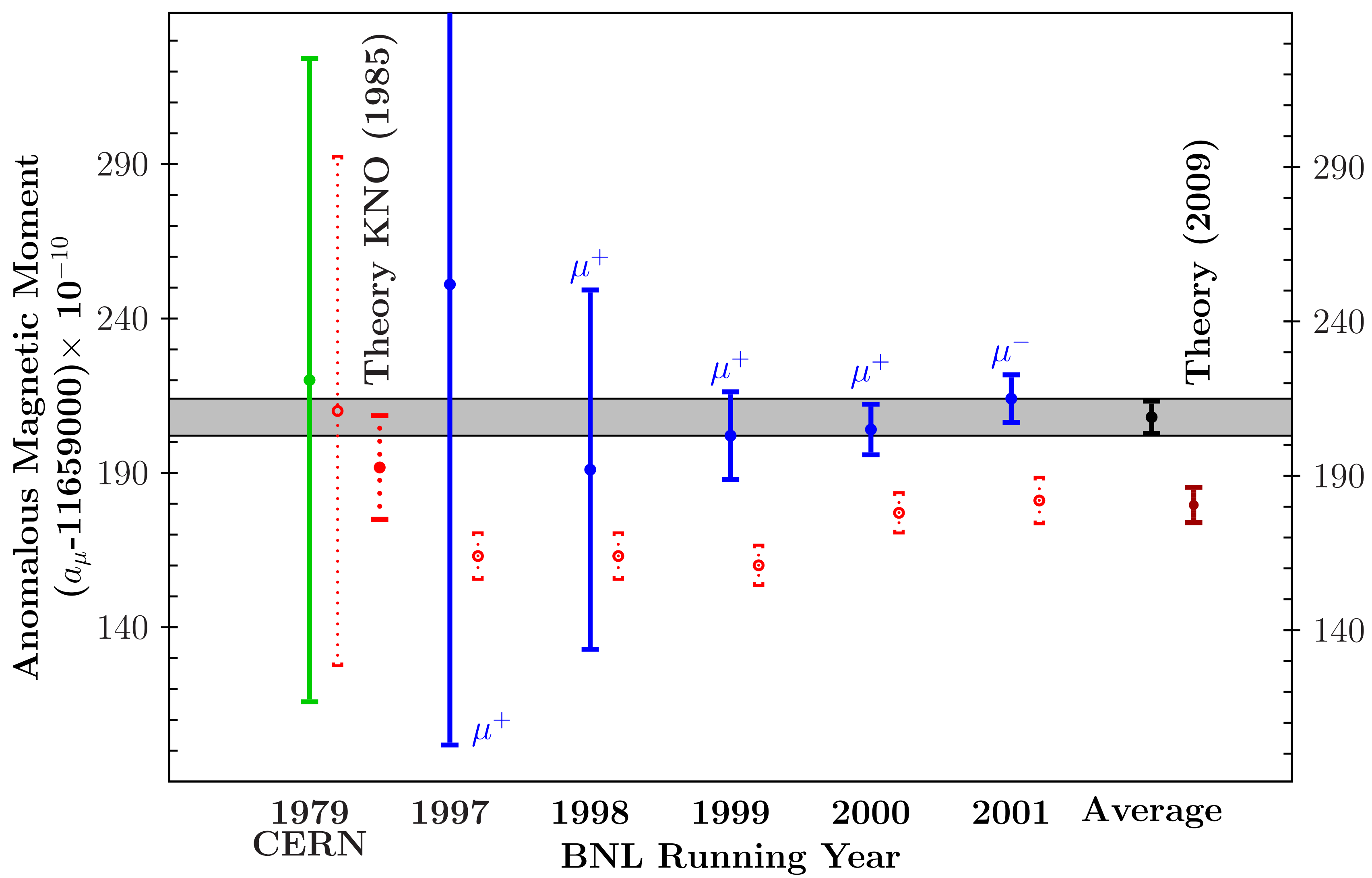
- Heavy quark physics (Southampton+KEK+Tsukuba…, theoretical explorations)
- Quantum simulation of gauge theories (initial discussions …)

a_μ as a stringent test of the SM

- Evolution of the (th - exp) tension [Jegerlehner, Nyffeler 0902.3360]



a_μ as a stringent test of the SM

- a_μ^{exp} = 11659208.0(6.3) × 10 $^{-10}$(0.54ppm) [BNL, 2006-2008]

- Current theoretical and experimental estimates:
  - ➡ discrepancy: 2.9- 3.6 stand. dev. discrepancy (e^+e^-, τ - data)
  - ➡ $a_\mu^{exp} - a_\mu^{th,SM}$ = 287(63)(51) × 10 $^{-11}$ [Jegerlehner, Nyffeler 0902.3360]

- New experiments (J-PARC, Fermilab E989) expected to perform 4× more precise measurement

- Improved precision of the theoretical estimates with dominating uncertainty required

a_μ as a stringent test of the SM

SM Contribution	Value ± Error ($\times 10^{11}$)	Ref
QED (5 loops)	116584718.951 ± 0.080	[Aoyama et al., 2012]
HVP LO	6923 ± 42	[Davier et al., 2011]
	6949 ± 43	[Hagiwara et al., 2011]
HVP NLO	-98.4 ± 0.7	[Hagiwara et al., 2011]
		[Kurz et al., 2014]
HVP NNLO	12.4 ± 0.1	[Kurz et al., 2014]
HLbL	105 ± 26	[Prades et al., 2009]
Weak (2 loops)	153.6 ± 1.0	[Gnendiger et al., 2013]
SM Tot (0.42 ppm)	116591802 ± 49	[Davier et al., 2011]
(0.43 ppm)	116591828 ± 50	[Hagiwara et al., 2011]
(0.51 ppm)	116591840 ± 59	[Aoyama et al., 2012]
Exp (0.54 ppm)	116592089 ± 63	[Bennett et al., 2006]
Diff (Exp − SM)	287 ± 80	[Davier et al., 2011]
	261 ± 78	[Hagiwara et al., 2011]
	249 ± 87	[Aoyama et al., 2012]

- Lattice provides *ab initio* setup for the computation of hadronic contribution(s)
- Completely independent from the current phenomenological determinations
- HVP leading order: largest uncertainty!
- HLbL next, very important to compute, requres QED

Hadronic contributions to a_μ from the lattice

- Computing hadronic vacuum polarisation(HVP) contribution as a part of RBC&UKQCD
- Computing leading isospin breaking correction (LIBE) to HVP
- Prospects: disconnected contribution, improving LIBE to HVP —> QED+QCD

The RBC & UKQCD collaborations

BNL and RBRC

Tomomi Ishikawa
Taku Izubuchi
Chulwoo Jung
Christoph Lehner
Meifeng Lin
Taichi Kawanai
Christopher Kelly
Shigemi Ohta (KEK)
Amarjit Soni
Sergey Syritsyn

CERN

Marina Marinkovic

Columbia University

Ziyuan Bai
Norman Christ
Xu Feng
Luchang Jin
Bob Mawhinney
Greg McGlynn
David Murphy
Daiqian Zhang

University of Connecticut

Tom Blum

Edinburgh University

Peter Boyle
Luigi Del Debbio
Julien Frison
Richard Kenway
Ava Khamseh
Brian Pendleton
Oliver Witzel
Azusa Yamaguchi

Plymouth University

Nicolas Garron

University of Southampton

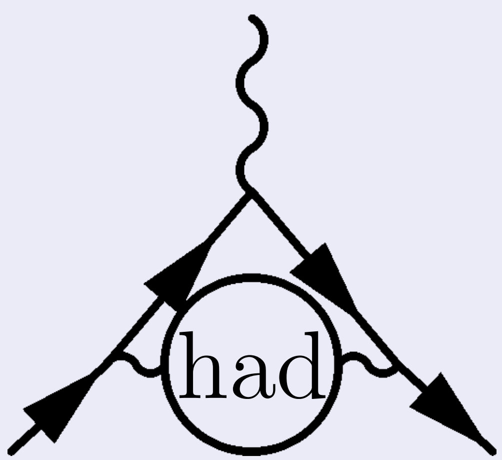
Jonathan Flynn
Tadeusz Janowski
Andreas Juettner
Andrew Lawson
Edwin Lizarazo
Antonin Portelli
Chris Sachrajda
Francesco Sanfilippo
Matthew Spraggs
Tobias Tsang

York University (Toronto)

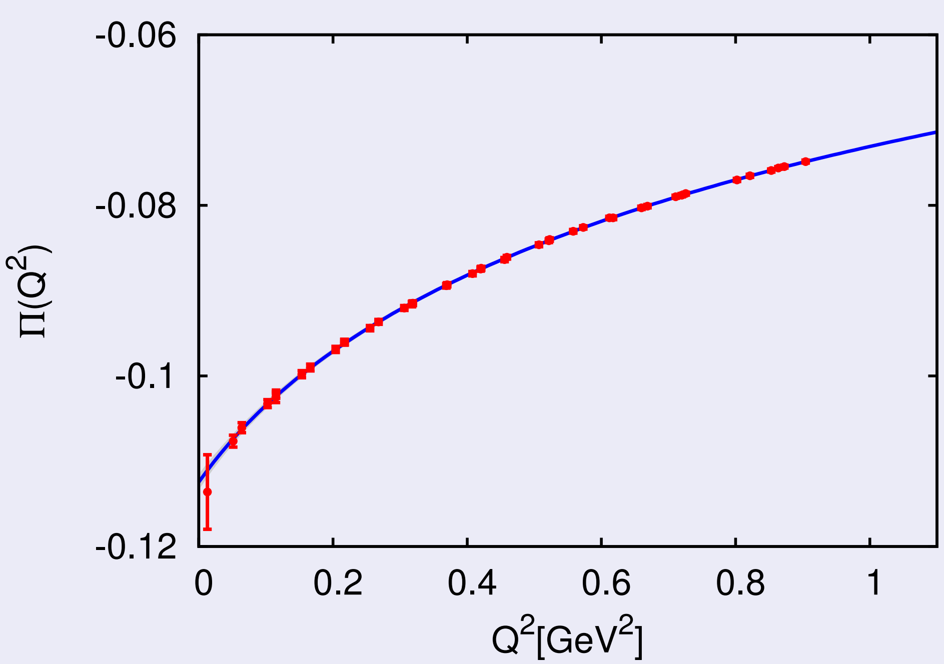
Renwick Hudspith

Hadronic vacuum polarisation

- Can be computed in Euclidean space-time [Blum, 2003; Lautrup et al., 1971]



- $a_\mu^{HLO} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2) \times \hat{\Pi}(Q^2)$
- $f(Q^2) = m_{\mu^2} Q^2 Z^3(Q^2) \frac{1 - Q^2 Z(Q^2)}{1 + m_\mu^2 Q^2 Z^2(Q^2)}$
- $Z(Q^2) = \left(\sqrt{(Q^2)^2 + 4 m_\mu^2 Q^2} - Q^2\right) / (2 m_\mu^2 Q^2)$



- $\hat{\Pi}(Q^2) = \Pi(Q^2) - \Pi(0)$
- $\Pi_{\mu\nu}(Q) = a^4 \sum_x e^{iQx} \langle J_\mu^{em}(x) J_\nu^{em}(0) \rangle$
- $\Pi_{\mu\nu}(Q) = (Q^2 \delta_{\mu\nu} - Q_\mu Q_\nu) \Pi(Q^2)$

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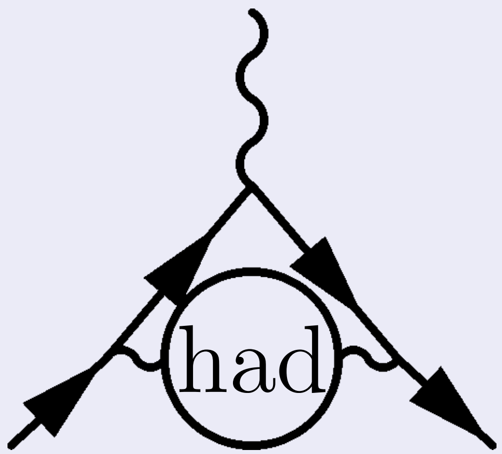

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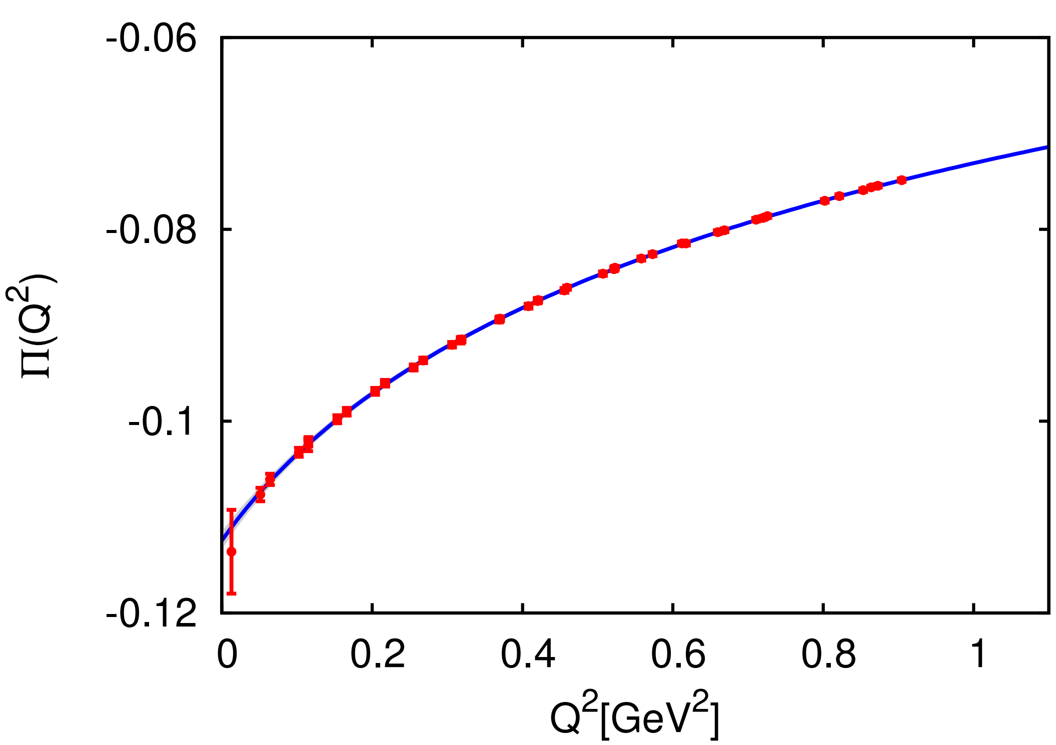
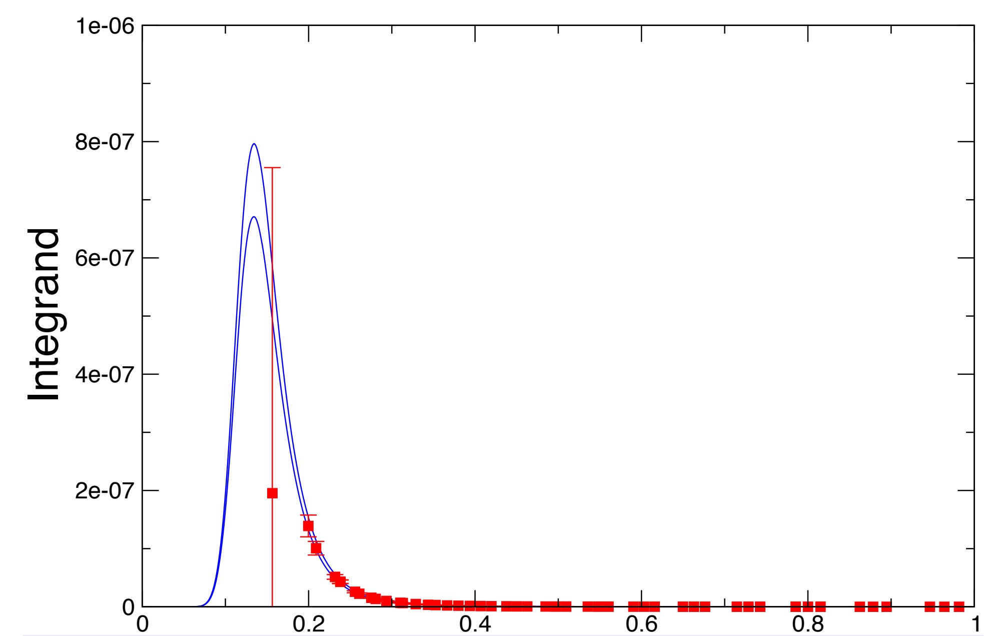
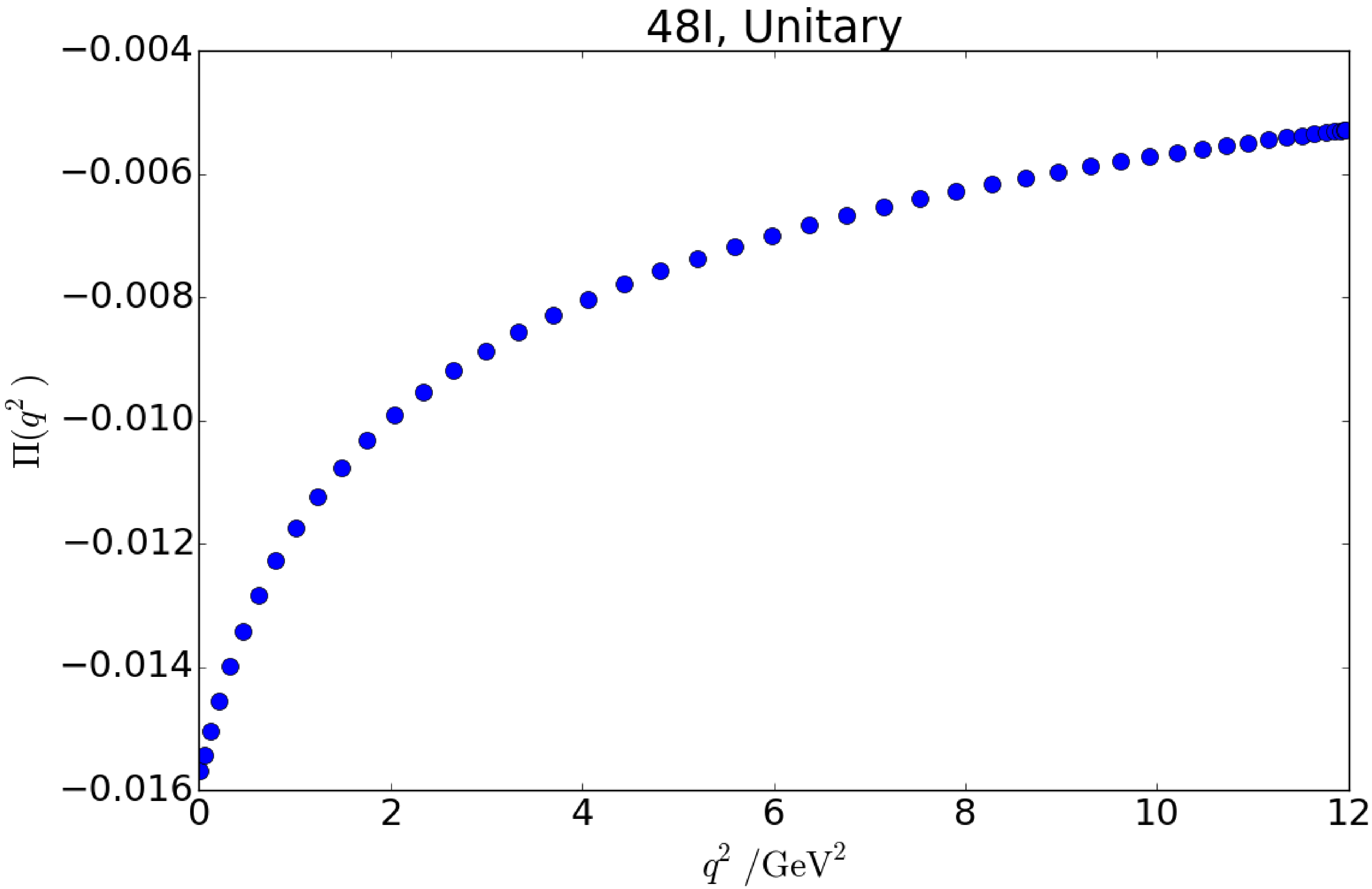




[RBC-UKQCD, Boyle et al. '12]

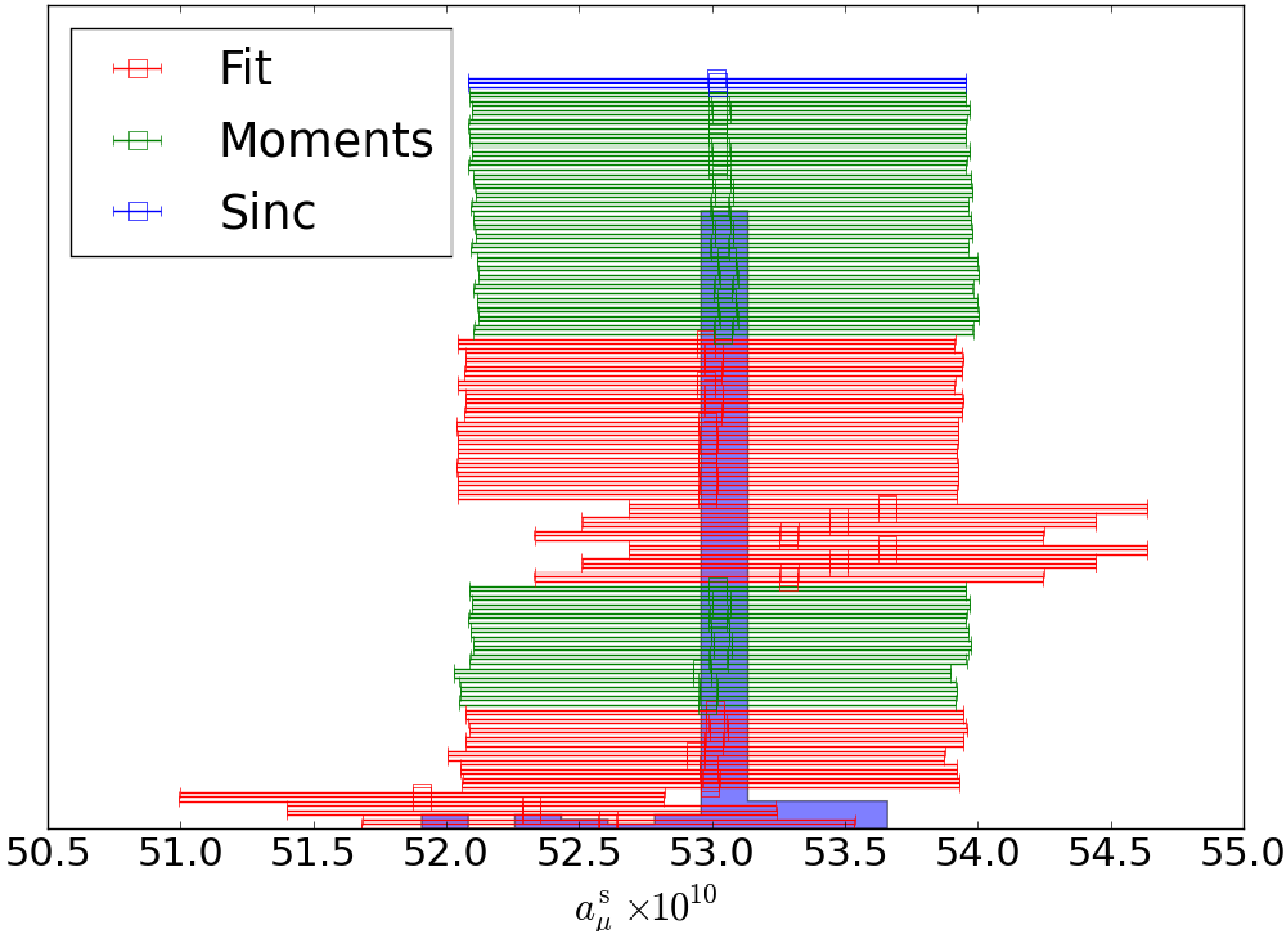
Strange HVP: Matt Spraggs's talk at Lattice 2015 [RBC/UKQCD 2015]

- Strange contribution to HVP, 2+1 flavor Möbius DWF, physical quark mass ensemble



Strange HVP: Matt Spraggs's talk at Lattice 2015 [RBC/UKQCD 2015]

Histogram of results from various strategies. Results insensitive



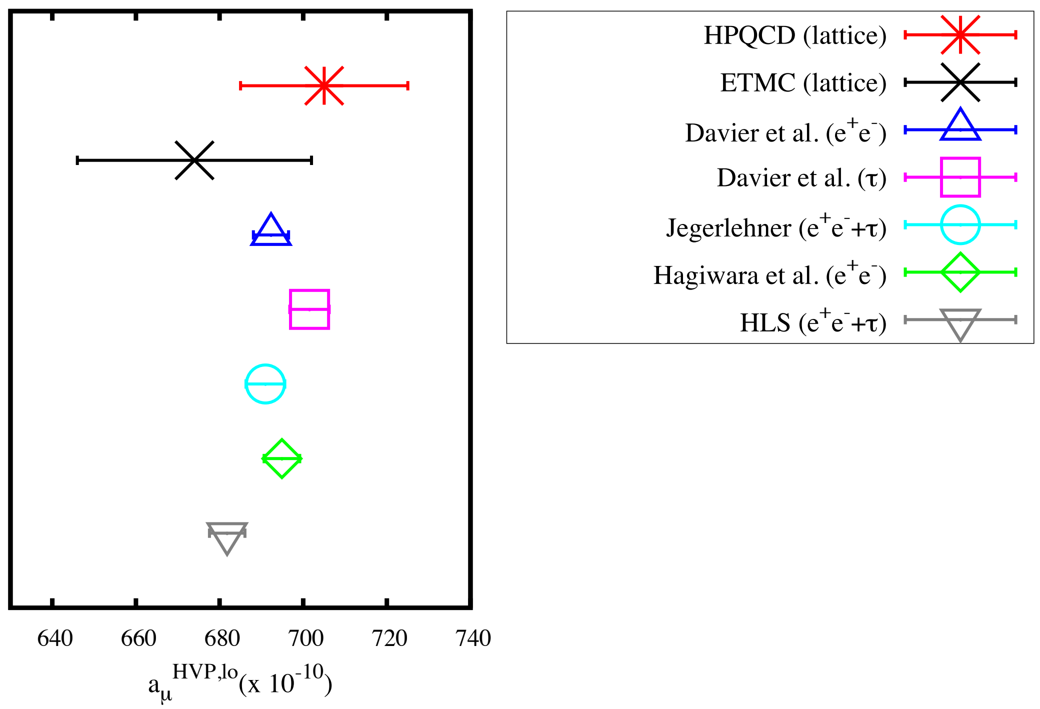
- remarkable agreement with HPQCD 2+1+1 staggered fermion result: 53.41(59)

Light HVP (u,d): needs quite a bit more work …

Computing IB correction to the HVP

- Once the aimed precision for the connected HVP from the lattice is achieved (in the isosymmetric theory) —> the effects we neglected so far might become important:
  - disconnected contribution,
  - isospin breaking corrections,
  - charm in the sea, …

- In the phenomenological determination of a_μ^{had} model calculation of [Jegerlehner,Szafron '11]
  - ➡ correctly applied IB correction reduced the discrepancy between e^+e^- and τ - estim.



[Plot: B. Chakraborty, LATTICE 2015]

- It would be good to have a model independent (non-perturbative) estimate of IB effects: lattice QCD+QED

Computing IB correction to the HVP

$$\Delta O = \left\{ e^2 \frac{\partial}{\partial e^2} + [g_s^2 - (g_s^0)^2] \frac{\partial}{\partial g_s^2} + [m_f - m_f^0] \frac{\partial}{\partial m_f} + [m_f^{cr} - m_0^{cr}] \frac{\partial}{\partial m_f^{cr}} \right\} O$$

[Gasser, Rusetsky, Scimemi '03, RM123 '13]

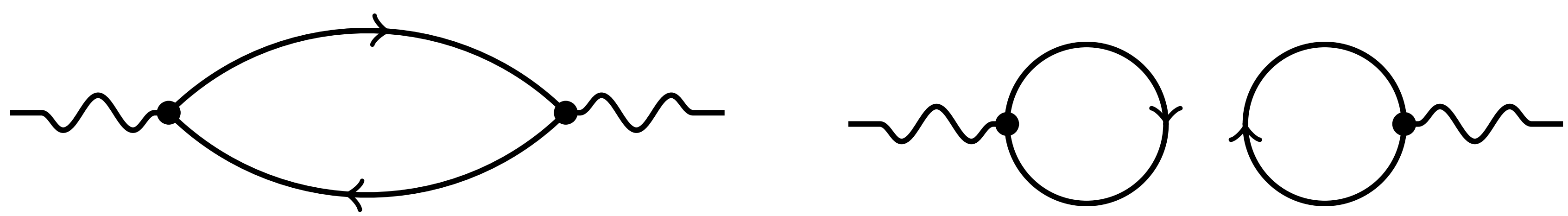
- RM123 method [arXiv:1303.4896] for computing leading isospin breaking corrections (LIBE)
  - ➡ Expanding an observable (in the isospin broken theory) with respect to the isosymmetric QCD result
- For a start: applying it to the connected part of the HVP
- Main advantage w. respect to simulating QED+QCD:
  - ➡ Diagrams obtained individually (before multiplying with $O(\alpha_{em})$, $O(m_u - m_d)$ coeff.)
  - ➡ No extrapolation in α_{em}
- Main disadvantage: one needs to compute many diagrams, mainly 3pt and 4pt functions
  - ➡ Can be overcome with careful organisations of the computation [DD-SCOR code, N.Tantalo]
  - ➡ Code base for lattice QCD with isospin breaking corrections

Prospects I: conceptual improvements

- Reducing finite volume effects - they are expected to be main source of systematics
- Currently: global zero mode subtracted: $A_\mu(k=0) \equiv 0$
  - ➡ Violates reflection positivity and does not have a well defined $T \to \infty$ limit [1406.4088]
- Removing the zero mode of the field on each time slice separately [Hayakawa, Uno '08]
  - ➡ this explicitly violates the hypercubic symmetry of the lattice -> no trace of the violation in the inf. vol limit [1406.4088]
- Charged particles in QED/QED+QCD with C* BCs —> FV effects for masses even smaller
  - ➡ [Alberto, Agostino, … arXiv:1509.01636]
- Eager to try this out for LIBE of HVP as well
- Getting the disconnected contributions (beyond el-quenched)

Prospects II: Disconnected contribution

- Connected and disconnected contribution to the HVP



- Disconnected:
  - Computationaly very demanding
  - ChPT estimate $\propto 10\%$ [Della Morte, Juettner '10]
  - Direct estimates from the lattice in progress [Guelpers et al. '14]
  - **Several other progress reports @ Lattice2015, Kobe**
  - **Together with postdoc@IST,Lisbon [N. Cardoso]: setting up evaluation of disconnected on GPUs**

Conclusions & outlook

- Lattice gives an independent theory prediction of hadronic contributions a_μ
- HVP front: strange contribution under control, light still needs work
- Phenomenologically - IB plays an important role in the th.-exp. discrepancy
- First attempt to extract the IB correction to the HVP from first principles
- Difficult task, but RM123 method should give good signal over noise ratio

- Other topics I am interested in:
  - ➡ **Heavy quark physics** from non-perturbative perspective
  - ➡ **Quantum simulations of gauge theories** motivated by the sign problem at finite μ

- Feel free to come and discuss any of these or sth. else further…
- And just one more thing …

Excited QCD 2016

Costa da Caparica, Lisbon, Portugal
6-12 March 2016

QCD at high temperatures & finite densities

- heavy-ion collisions, jets, diffraction, hadronisation
- quark-gluon plasma
- holography, colour-glass condensate
- compact stars, applications to astrophysics

QCD at low energies

- excited hadrons
- new resonances
- glueballs, multiquarks

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Robert Kaminski, IJF PAN, Krakow
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More information

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