Lattice QCD calculations for Muon g-2

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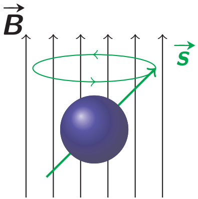
Magnetic Moment of the Muon

- magnetic moment $\vec{\mu}$ of the muon due to its spin $\vec{s}$ and electric charge e

$$\vec{\mu} = g \, \frac{e}{2m} \, \vec{s}$$

torque $\quad \vec{\tau} = \vec{\mu} \times \vec{B}$



- gyromagnetic-factor (g-factor) of the muon

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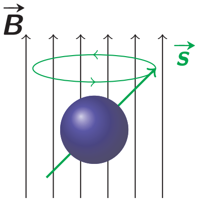
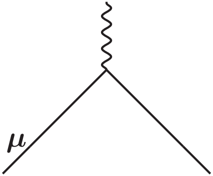


- gyromagnetic-factor (g-factor) of the muon

without quantum effects:

$$g = 2$$



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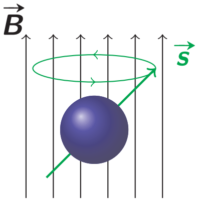


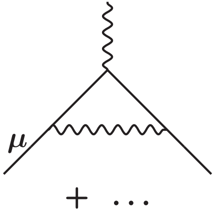
- gyromagnetic-factor (g-factor) of the muon

with quantum effects:

$$g = 2.00233\ldots$$

anomalous magnetic moment of the muon
"Muon g-2"

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

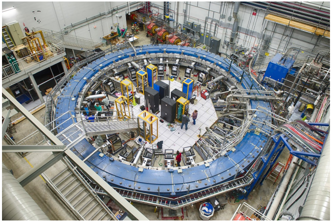


Muon g-2: Experimental measurement

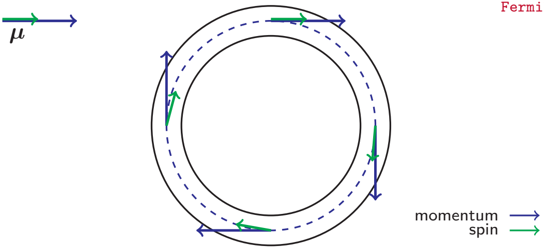
Previous: Muon g-2 @ BNL (2006)
[Phys.Rev. D73, 072003 (2006)]

New: Muon g-2 @ FNAL (2021, 2023)
[PhysRevLett.126.141801 (2021)]

measure precession frequency of muons in magnetic field:



[https://commons.wikimedia.org/wiki/File:Fermilab_g-2_(E989)_ring.jpg]



$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

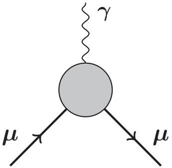
$$a_\mu(\text{exp}) = 11659205.9(2.2) \times 10^{-10}$$

[Phys. Rev. Lett. 131, 161802 (2023)]

Muon g-2: Standard Model Prediction

White Paper (2020) of the
Muon g-2 Theory initiative

[Phys.Rept. 887 (2020) 1-166]
[https://muon-gm2-theory.illinois.edu/]



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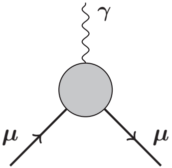

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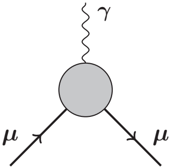
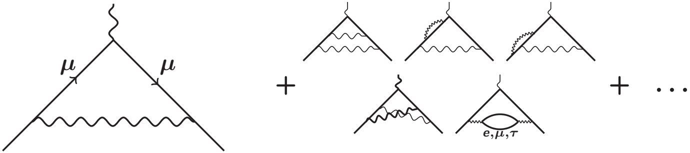


electro-magnetism

11658471.8931(104) $\times$ **10^{-10}**



$O(10^4)$ diagrams at $O(\alpha^5)$

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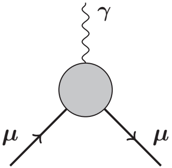
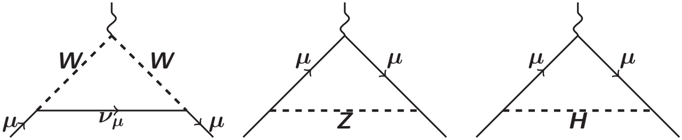


electro-magnetism **11658471.8931(104)** $\times$ $\mathbf{10^{-10}}$

weak **15.36(10)** $\times$ $\mathbf{10^{-10}}$



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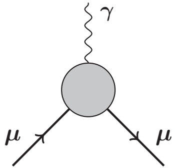
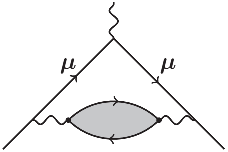


electro-magnetism	$\mathbf{11658471.8931(104)} \times 10^{-10}$
weak	$\mathbf{15.36(10)} \times 10^{-10}$
Hadronic Vacuum Polarisation (HVP)	$\mathbf{693.1(4.0)} \times 10^{-10}$



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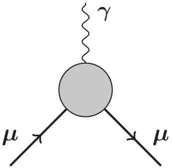

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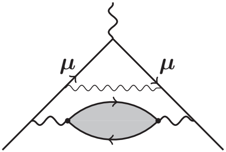
HVP(α^3,α^4)	$\mathbf{-8.59(7)} \times \mathbf{10^{-10}}$



$+ \ \ldots$

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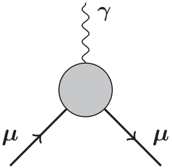

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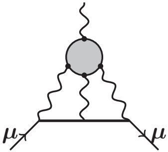
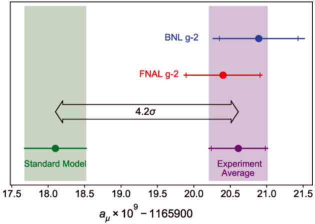
Hadronic light-by-light scattering	$\mathbf{9.2(1.8) \times 10^{-10}}$



Experiment vs Standard Model prediction

Muon g—2 Coll., Phys. Rev. Lett. 126, 141801



Exp ('23): $\boldsymbol{a_\mu = 0.00116592059(22)}$

Exp ('21): $\boldsymbol{a_\mu = 0.00116592061(41)}$

SM: $\boldsymbol{a_\mu = 0.00116591810(43)}$

- new physics?

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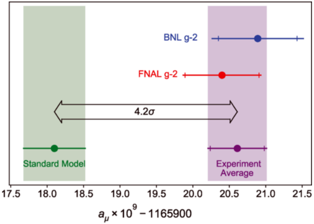

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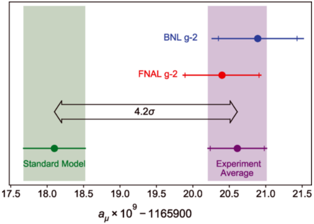
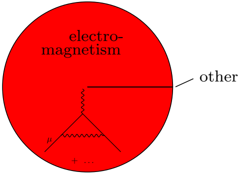
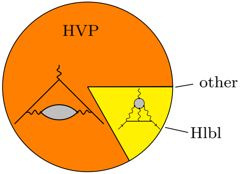


- new physics?
- FNAL to publish final result in 2025 (0.14 ppm), new upcoming experiment @JPARC
- Breakdown of Standard Model Prediction

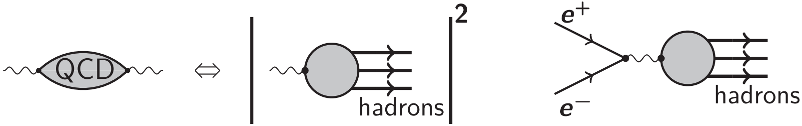
contribution to a_μ



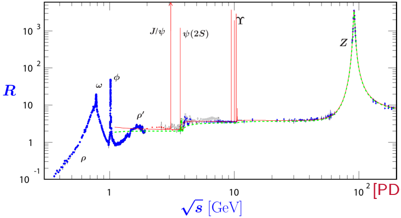
contribution to variance $\Delta^2 a_\mu$



The HVP from R-ratio



$$R(s) = \frac{\sigma(e^+ e^- \to \text{hadrons}, s)}{\sigma(e^+ e^- \to \mu^+ \mu^-, s)} \qquad a_\mu^{\text{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \mathrm{d}s \, \frac{R(s) K(s)}{s^2}$$



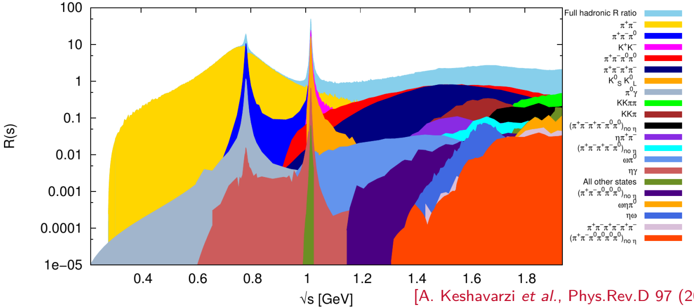
[PDG]

$a_\mu^{\text{hvp}} = 689.46(3.25)$ [Jegerlehner 18]
$a_\mu^{\text{hvp}} = 693.9(4.0)$ [DHMZ 19]
$a_\mu^{\text{hvp}} = 693.37(2.46)$ [KNT 18]

$a_\mu^{\text{hvp}} = 693.1(4.0)$ [white paper]

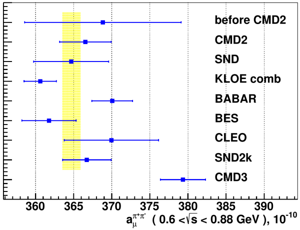
Tensions in R-ratio

- various channels contributing to ***R***-ratio



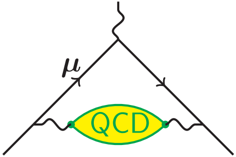
[A. Keshavarzi *et al.*, Phys.Rev.D 97 (2018) 11, 114025]

- 2023 results for $e^+e^- \to \pi^+\pi^-(\gamma)$ from CMD-3 disagree with KLOE and BABAR [CMD-3, arXiv:2302.08834]



Hadronic Vacuum Polarisation (HVP) from the lattice

- calculate hadronic part on the lattice



- vector two-point function

$$C_{\mu\nu}(t) = \sum_{\vec{x}} \langle J_\mu(t, \vec{x}) J_\nu(0) \rangle$$

- electromagnetic current

$$J_\mu = \frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d - \frac{1}{3}\overline{s}\gamma_\mu s \ + \ldots$$

- a_μ from $C(t)$ [T. Blum, Phys.Rev.Lett.**91**, 052001 (2003); Bernecker and Meyer, Eur.Phys.J.**A47**, 148 (2011)]

$$a_\mu^{\text{HVP}} = \sum_t w_t C_{ii}(t) \qquad \text{with kernel function } w_t$$

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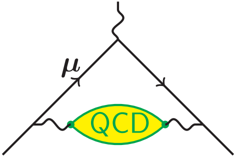

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- flavour decomposition (isospin symmetric QCD $u = d = \ell$)

$$C(t) = \frac{5}{9}C^\ell(t) + \frac{1}{9}C^s(t) + \frac{4}{9}C^c(t)$$

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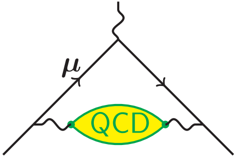

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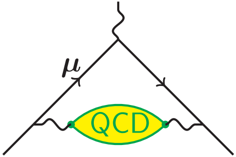

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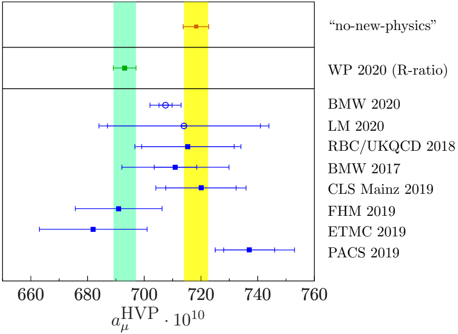
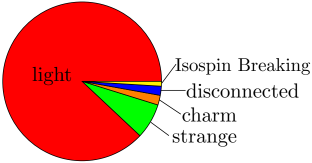
Lattice Calculations of HVP (2020 WP status)

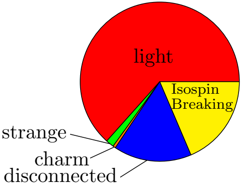
- White Paper lattice average $a_\mu^{\mathrm{HVP}}(\mathrm{lat}) = 711.6(18.4) \times 10^{-10}$



contributions to a^{HVP}



contributions to $\Delta a_\mu^{\mathrm{HVP}}$

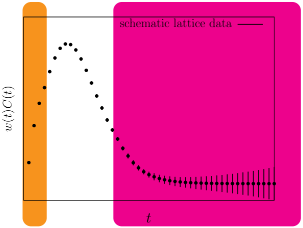


- BMW 2020

$$a_\mu^{\mathrm{HVP}}(\mathrm{BMW}) = 707.5(5.5) \times 10^{-10}$$

The window method

- main challenges:
  - statistical noise at large t
  - finite volume effects (largest at large t)
  - discetisation effects at small t



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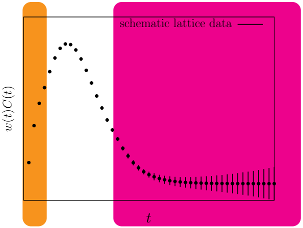
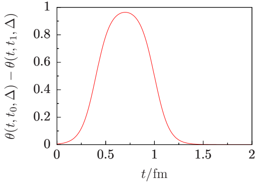
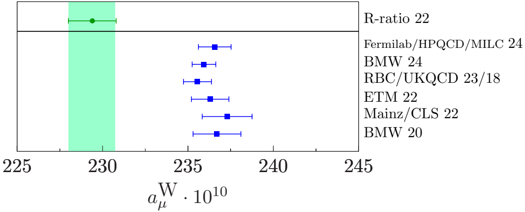


- window method

$$a_\mu = a_\mu^{SD} + a_\mu^{W} + a_\mu^{LD} \qquad a_\mu^{W} = \sum_t w_t C(t)[\theta(t,t_0,\Delta) - \theta(t,t_1,\Delta)]$$





The long distance contribution to the HVP

- tame **statistical noise** by using knowledge of the spectral representation of the vector correlator $C(t)$

$$C(t) = \frac{1}{3}\sum_j \sum_x \langle J_j(t,x) J_j(0)\rangle = \sum_i A_i^2 e^{-E_i t} \qquad \text{with} \qquad A_i^2 > 0$$

- lowest states: two pions with back-to-back momentum
- bounding method [S. Borsanyi *et al.*, (2017)], [T. Blum, VG, *et al.*, (2018)]

$$0 \leq C(t_c)\, e^{-E_{t_c}(t-t_c)} \leq C(t) \leq C(t_c)\, e^{-E_0(t-t_c)}$$

- explicitly reconstruct the lowest N states
- improved bounding method [A. Meyer, *et al.*, (2019)]

$\rightarrow$ bounding method for $C(t) - \sum_{i=1}^{N} A_i^2 e^{-E_i t}$

RBC/UKQCD collaboration

Boston University

Nobuyuki Matsumoto

BNL and BNL/RBRC

Peter Boyle
Taku Izubuchi
Christopher Kelly
Shigemi Ohta (KEK)
Amarjit Soni
Masaaki Tomii
Xin-Yu Tuo Shuhei Yamamoto

University of Cambridge

Nelson Lachini

CERN

Matteo Di Carlo
Felix Erben
Andreas Jüttner (Southampton)
Tobias Tsang

Columbia University

Norman Christ
Sarah Fields
Ceran Hu
Yikai Huo
Yong-Chull Jang
Joseph Karpie (JLab)
Erik Lundstrum
Bob Mawhinney
Bigeng Wang (Kentucky)

University of Connecticut

Tom Blum
Jonas Hildebrand
Luchang Jin
Vaishakhi Moningi
Anton Shcherbakov
Douglas Stewart
Joshua Swaim

DESY Zeuthen

Raoul Hodgson

Edinburgh University

Luigi Del Debbio
Vera Gülpers
Maxwell T. Hansen
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The long-distance window of the hadronic vacuum polarization for the muon $g-2$

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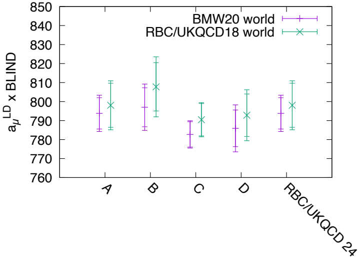
(RBC and UKQCD Collaborations)

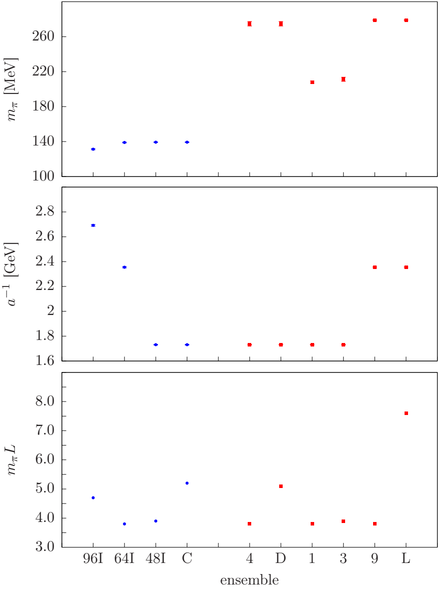
arXiv:2410.20590

RBC/UKQCD long distance result – computational details

- $N_f = 2 + 1$ Domain Wall Fermions
- four physical point ensembles
- three lattice spacings
- several volumes

- four groups
- blinding (overall factor)





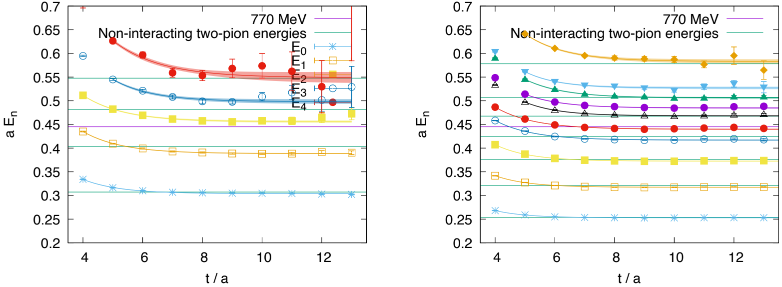
RBC/UKQCD long distance result – spectrum

- spectrum/overlaps of vector correlator using GEVP
  [M. Luscher and U. Wolff (1990); B. Blossier *et al* (2009)]

$$C^{ij}(t) = \left\langle O^i(t) O^j(t)^\dagger \right\rangle$$

- vector and two-pion operators with momenta up to $(2,0,0)$, or $(2,2,0)$ (96I, C), using distillation [M. Peardon *et al*, Phys. Rev. D 80, 054506 (2009)]

- spectrum ensembles 48I (left) and C (right)

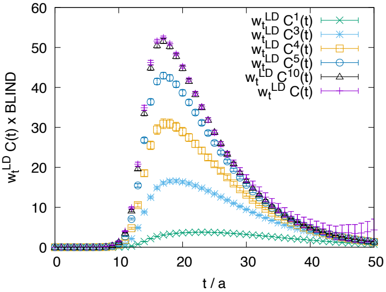


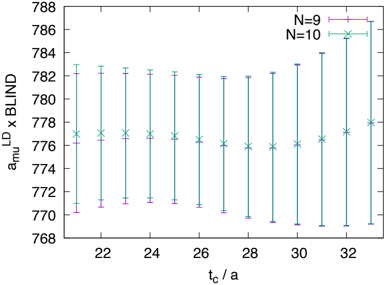
RBC/UKQCD long distance result – reconstruction

- long-distance a_μ from vector correlator $a_\mu^{\mathrm{LD}} = \sum_t w_t C(t)\theta(t, t_1, \Delta)$
- for large times $t > t_c$: use reconstruction

$$C^N(t) = \sum_{i=1}^{N} A_i^2 e^{-E_i t}$$

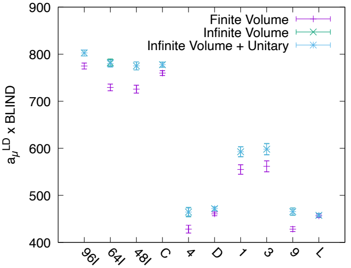
- Left: reconstruction for 96I
- Right: dependence of a_μ on t_c and number of states N for 96I



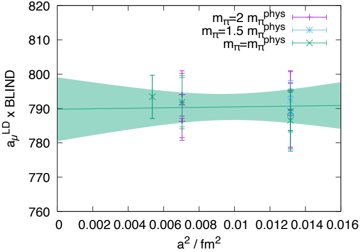


RBC/UKQCD long distance result – FV and continuum

- FV corrections using Hansen-Patella formalism [M. T. Hansen and A. Patella (2019), (2020)]
- ensembles that only differ by volume (48**I&**C, 4**&**D, 9**&**L) agree after FV corrections



- combined extrapolation: continuum and "physical" isospin-symmetric point
- continuum extrapolation: a^2-term
- two choices of Z_V



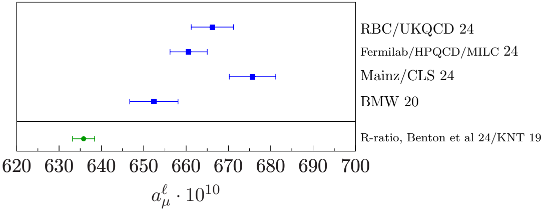
Comparison

- Final results (BMW isospin symmetric scheme):

$$a_\mu^{\mathrm{LD},\ell} = 411.4(4.3)(2.4) \times 10^{-10}$$
$$a_\mu^{\ell} = 666.2(4.3)(2.5) \times 10^{-10}$$

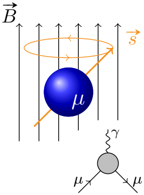
- systematic error domiated by choices of extrapolation (2.2×10^{-10})

- comparison with other (recent and precise) light-quark results



- good agreement between lattice calculations
- **Disclaimer:** not all results shifted to same IB symmetric point

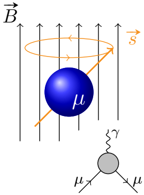
Summary



- Muon $g-2$ promising quantity for finding new physics
  $\rightarrow$ currently: $\mathbf{4.2\sigma}$ tension between experiment and theory
- Theory error dominated by Hadronic Vacuum Polarisation
  $\rightarrow$ R-ratio input: tensions between experiments
- precision of lattice calculations now competive with R-ratio, further improvements needed to match precision of FNAL experiment
- recent lattice calculations closer to experiment, in tension with R-ratio

- Are we about to find new physics with a_μ?

Summary



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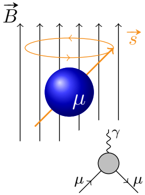
  Probably not.

Summary



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- Are we about to find new physics with $\boldsymbol{a_\mu}$?

Probably not.

Thank you!

Backup

Isospin symmetric schemes

- Decomposing into isospin symmetric and isospin breaking

$$X^{\phi} = \overline{X} + X_{SU(2)} + X_{\gamma} \qquad \hat{X} \equiv \overline{X} + X_{SU(2)}$$

X_{γ}: QED isospin breaking
$X_{SU(2)}$: strong isospin breaking
$\overline{X}$: isospin symmetric
X^{ϕ}: observable at the physical point

- observable at the physical point unambigously defined
- separation into $\overline{X}$, $X_{SU(2)}$ and X_{γ} requires separation scheme

  $\rightarrow$ define arbitrary values $\overline{\Pi}$ and $\hat{\Pi}$ for a set of quantities Π

- RBC/UKQCD long-distance calculation uses two schemes:
  - BMW20: $m_{\pi} = \mathbf{0.13497}$GeV, $m_{ss^*} = \mathbf{0.6898}$GeV , $w_0 = \mathbf{0.17236}$fm
  - RBC/UKQCD18: $m_{\pi} = \mathbf{0.135}$GeV, $m_K = \mathbf{0.4957}$GeV, $m_{\Omega} = \mathbf{1.67225}$GeV

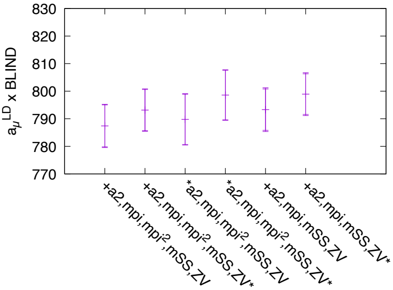
a_μ^{LD} combined extrapolation

- two fit-ansaetze (e.g., for BMW scheme):

$$f_+ = f_0 + f_1 a^2 + f_2\Big(w_0 m_\pi - (w_0 m_\pi)_{\mathrm{phys}}\Big) + f_3\Big(w_0 m_\pi - (w_0 m_\pi)_{\mathrm{phys}}\Big)^2 + f_4\Big(w_0 m_{ss*} - (w_0 m_{ss*})_{\mathrm{phys}}\Big)$$

$$f_* = f_0\Big(1 + f_1 a^2\Big)\Bigg(1 + f_2\Big(w_0 m_\pi - (w_0 m_\pi)_{\mathrm{phys}}\Big) + f_3\Big(w_0 m_\pi - (w_0 m_\pi)_{\mathrm{phys}}\Big)^2 + f_4\Big(w_0 m_{ss*} - (w_0 m_{ss*})_{\mathrm{phys}}\Big)\Bigg)$$

- either $f_3 = 0$ or $f_3 \neq 0$
- two different Z_V
- total: $\rightarrow$ 8 fit choices
  $\rightarrow$ model average



RBC/UKQCD window result – ensembles

- Möbius Domain Wall Fermions
- three lattice spacings at the physical point with $N_f = 2+1$

ID	a^{-1}/GeV	$L^3 \times T \times L_s$	m_π/MeV	m_K/MeV
48I	**1.7312(28)**	$48^3 \times 96 \times 24$	**139.32(30)**	**499.44(88)**
64I	**2.3549(49)**	$64^3 \times 128 \times 12$	**138.98(43)**	**507.5(1.5)**
96I	**2.6920(67)**	$96^3 \times 192 \times 12$	**131.29(66)**	**484.5(2.3)**

- additional "helper" ensembles at heavier masses

ID	a^{-1}/GeV	N_f	$L^3 \times T \times L_s$	m_π/MeV	m_K/MeV	m_{D_s}/GeV
1	**1.7310(35)**	2+1	$32^3 \times 64 \times 24$	**208.1(1.1)**	**514.0(1.8)**	–
2	**1.7257(74)**	2+1	$24^3 \times 48 \times 32$	**285.4(2.9)**	**537.8(4.6)**	–
3	**1.7306(46)**	2+1	$32^3 \times 64 \times 24$	**211.3(2.3)**	**603.8(6.1)**	–
4	**1.7400(73)**	2+1	$24^3 \times 48 \times 24$	**274.8(2.5)**	**530.1(3.1)**	–
5	**1.7498(73)**	2+1+1	$24^3 \times 48 \times 24$	**279.8(3.5)**	**539.1(5.3)**	**1.9902(69)**
7	**1.7566(81)**	2+1+1	$24^3 \times 48 \times 24$	**272.5(5.9)**	**523(10)**	**1.3882(57)**
A	**1.7556(83)**	2+1	$24^3 \times 48 \times 8$	**307.4(3.5)**	**557.3(5.7)**	–

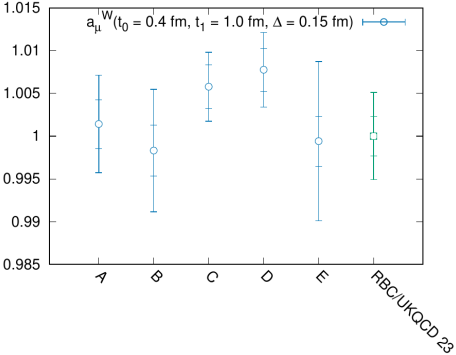
RBC/UKQCD window result – blinding

- blinded analysis, to avoid bias towards other results
- five different analysis groups
- vector two-point function blinded

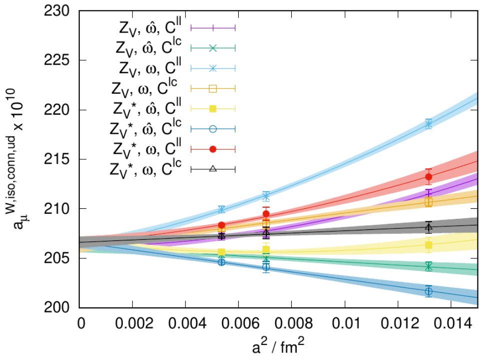
$$C_b(t) = (b_0 + b_1 a^2 + b_2 a^4) C_0(t)$$

with random coefficients b_0, b_1 and b_2 different for each group

- relative unblinding



RBC/UKQCD window result – continuum extrapolation



- isospin symmetric light-quark connected window

$$a_\mu^{\text{W, iso, conn, ud}} = \mathbf{206.36(44)(43)} \times \mathbf{10^{-10}}$$

- total window (using RBC/UKQCD 2018 results for other flavours)

$$a_\mu^{\text{W}} = \mathbf{235.56(65)(50)} \times \mathbf{10^{-10}}$$