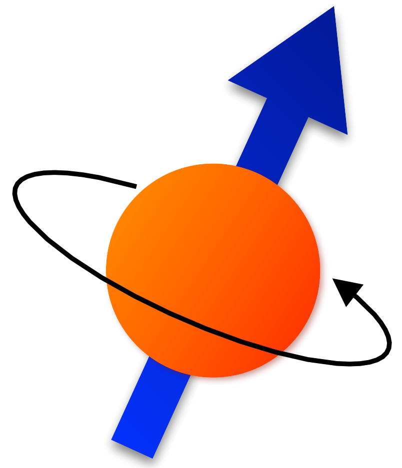
Muon g-2 in the SM: status and prospects

Aida X. El-Khadra
University of Illinois

ICISE QUY NHON VIETNAM

RENCONTRES DU VIETNAM

Outline



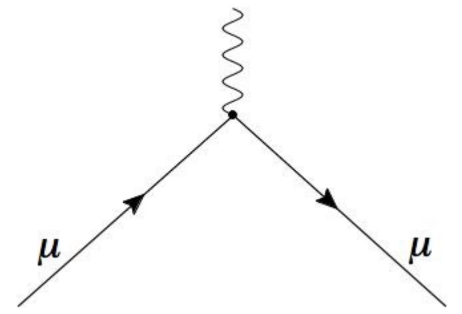
- Introduction
- Muon g-2 Theory Initiative
- Hadronic corrections in comparison
- HVP
  - puzzles
- HLbL
- Summary and Outlook
- Appendix

- ``The anomalous magnetic moment of the muon in the SM":
  1st White Paper published in 2020 (132 authors, 82 institutions) [T. Aoyama et al, arXiv:2006.04822, Phys. Repts. 887 (2020) 1-166.]
- ``Prospects for precise predictions of a_μ in the SM": 2022 Snowmass Summer Study, arXiv:2203.15810
- Summary statement on the status of Muon g-2 Theory in the SM: https://muon-gm2-theory.illinois.edu

Anomalous magnetic moment

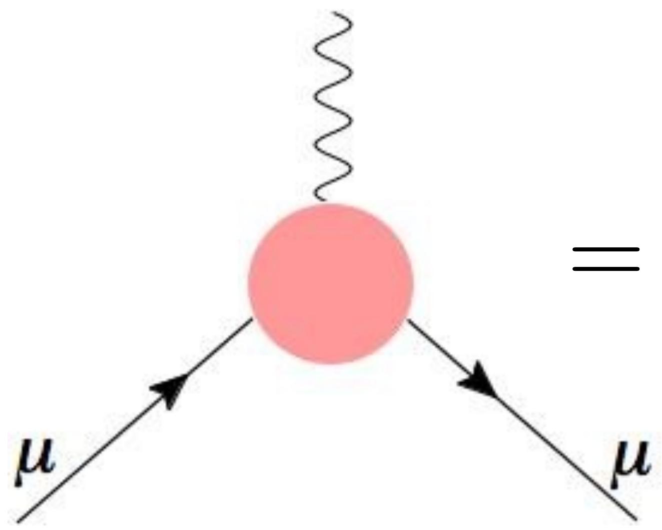
The magnetic moment of charged leptons (e, μ, τ): $\vec{\mu} = g\frac{e}{2m}\vec{S}$

Dirac (leading order): $g = 2$



$$= (-ie)\,\bar{u}(p')\gamma^{\mu}u(p)$$

Quantum effects (loops):



$$= (-i\,e)\,\bar{u}(p')\left[\gamma^{\mu}F_1(q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m}F_2(q^2)\right]u(p)$$

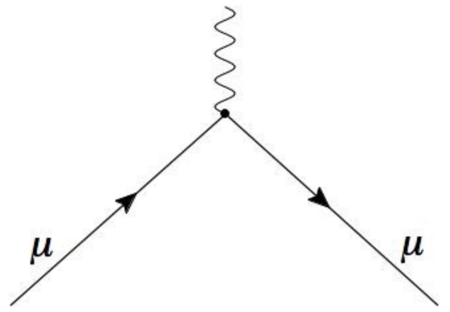
Note: $F_1(0) = 1$ and $g = 2 + 2\,F_2(0)$

Anomalous magnetic moment: $a \equiv \frac{g-2}{2} = F_2(0)$

Anomalous magnetic moment

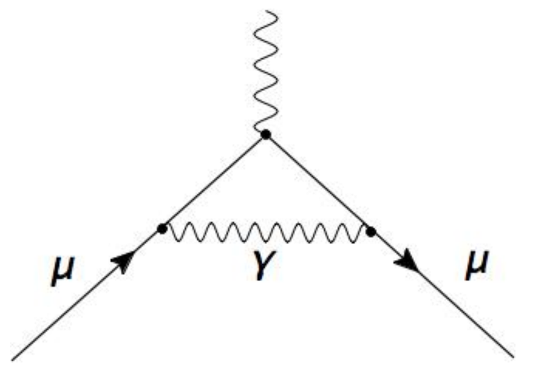
The magnetic moment of charged leptons (e, μ, τ): $\vec{\mu} = g \frac{e}{2m} \vec{S}$

Dirac (leading order): $g = 2$



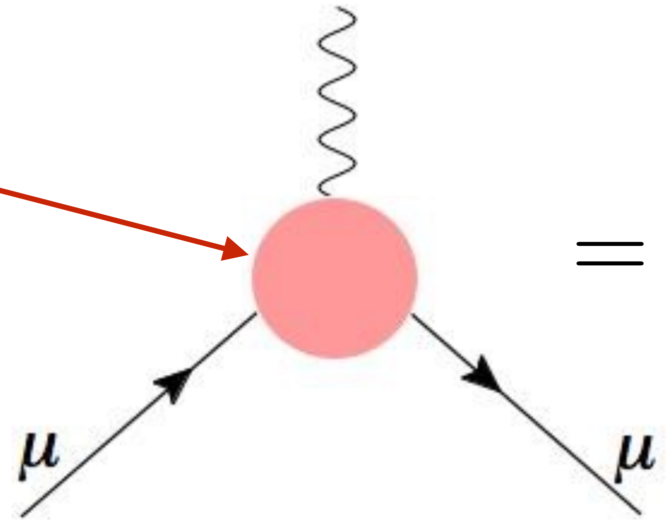
$$= (-ie)\, \bar{u}(p')\gamma^{\mu} u(p)$$

Quantum effects (loops):



$$\Rightarrow \quad g = 2\left(1 + \frac{\alpha}{2\pi}\right)$$

All SM particles contribute



$$= (-i\, e)\, \bar{u}(p') \left[\gamma^{\mu} F_1(q^2) + \frac{i\sigma^{\mu\nu} q_{\nu}}{2m} F_2(q^2) \right] u(p)$$

Note: $F_1(0) = 1$ and $\quad g = 2 + 2\, F_2(0)$

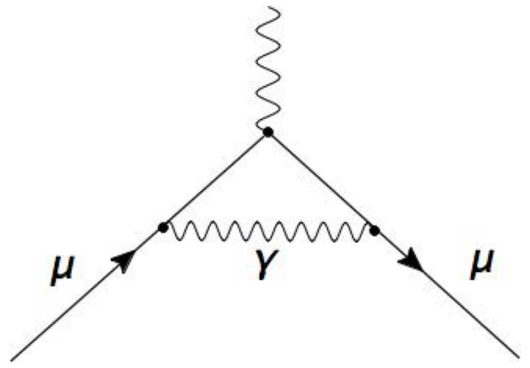
Anomalous magnetic moment: $a \equiv \frac{g-2}{2} = F_2(0)$ $= \frac{\alpha}{2\pi} + O(\alpha^2) + \ldots = 0.00116\ldots$

Muon g-2: SM contributions

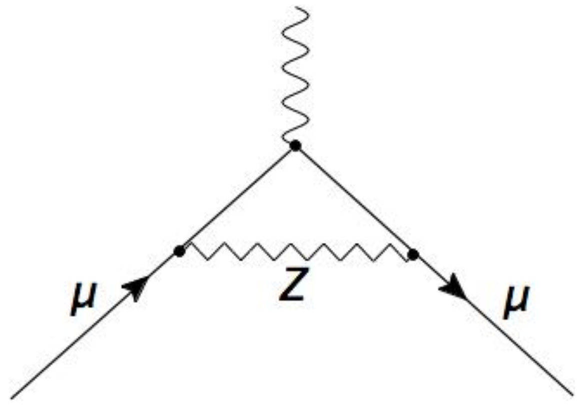
$$a_\mu = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{EW}) + a_\mu(\mathrm{hadronic})$$

Muon g-2: SM contributions

$$a_\mu = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{EW}) + a_\mu(\mathrm{hadronic})$$

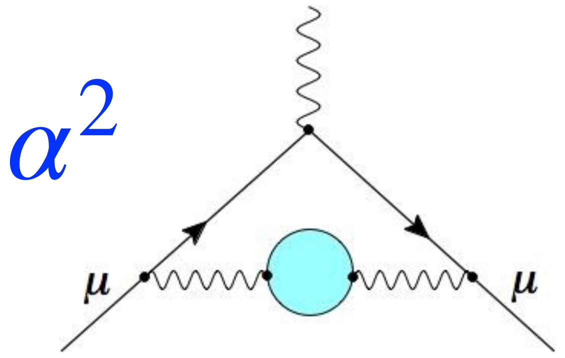
QED 

+… (5 loops) $116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

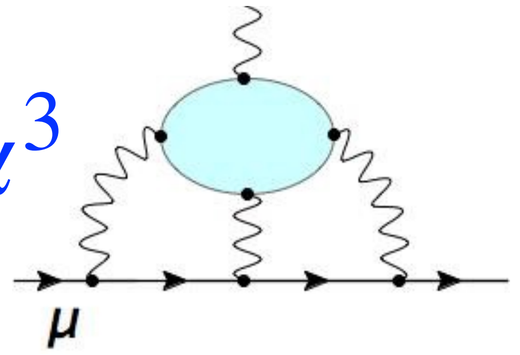
EW 

+… (2 loops) $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic corrections

HVP α^2 

+… (NNLO) $6845\,(40) \times 10^{-11}$ [0.6%] 0.34 ppm

HLbL α^3 

+… (NLO) $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

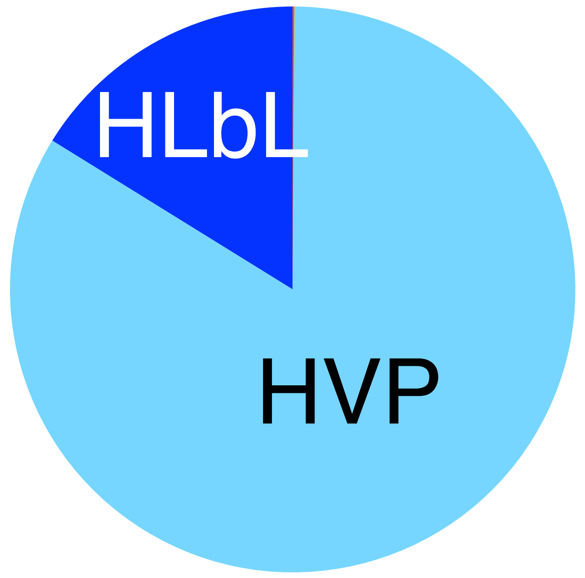
Muon g-2: SM contributions

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{EW}) + a_\mu(\text{hadronic})$$

contribution

- QED
- EW
- HVP
- HLbL

error²

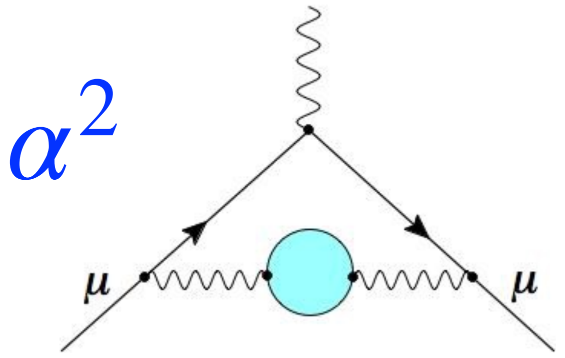


$116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

$153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

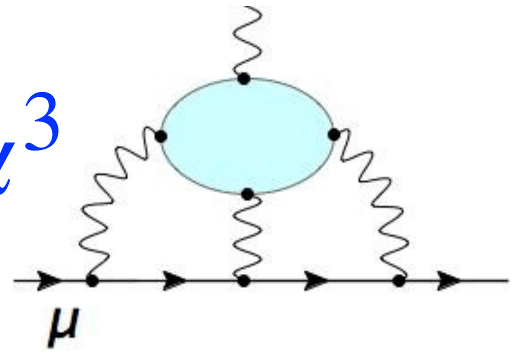
Hadronic corrections

HVP α^2



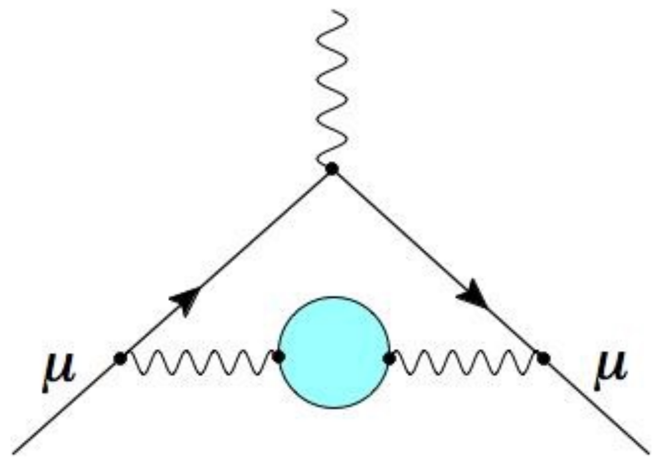
+… (NNLO) $6845\,(40) \times 10^{-11}$ [0.6%] 0.34 ppm

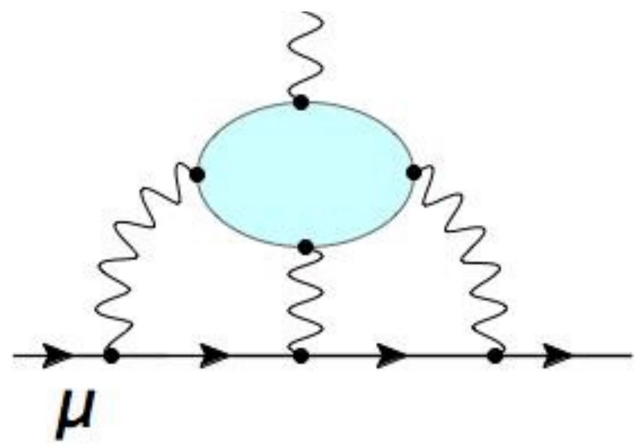
HLbL α^3



+… (NLO) $92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

Muon g-2: hadronic corrections



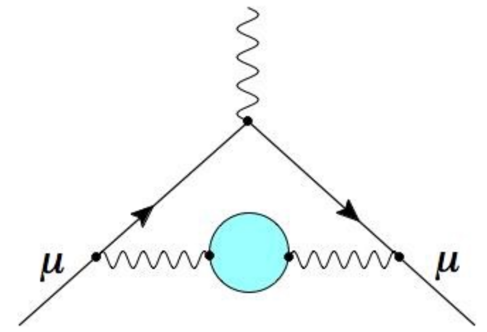


- Hadronic contributions are obtained by integrating over all possible virtual photon momenta, integral is weighted towards low q^2.
- Cannot use perturbation theory to reliably compute the hadronic bubbles
- Two-point & four-point functions:

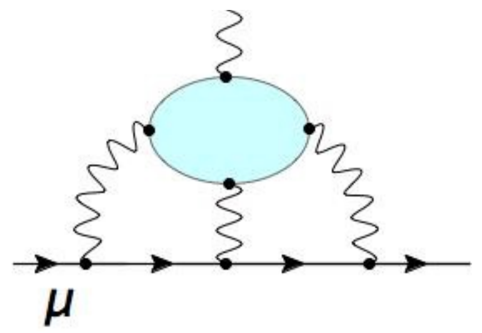
  HVP: $\langle 0 | T\{j_\mu j_\nu\} | 0 \rangle$ HLbL: $\langle 0 | T\{j_\mu j_\nu j_\rho j_\sigma\} | 0 \rangle$

Two independent approaches

1. Dispersive, data-driven
2. Lattice QCD



Hadronic Corrections

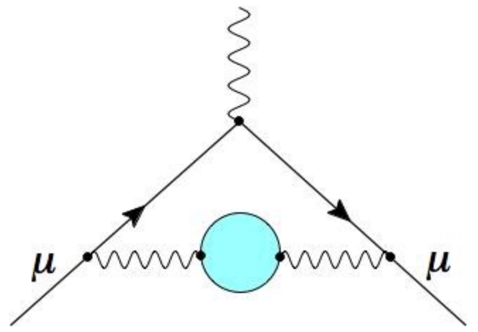


Two independent approaches:

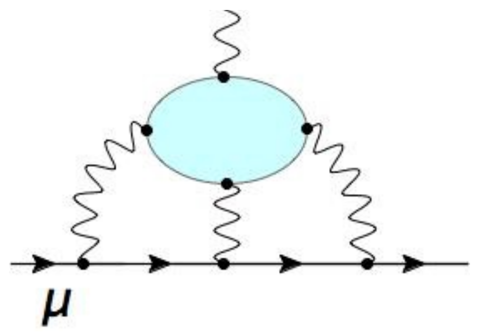
- **For HVP:** use dispersion relations to rewrite integral in terms of hadronic cross section:

Many experiments (over 20+ years) have measured the e^+e^-cross sections for the different channels over the needed energy range with increasing precision.

For HLbL: new dispersive approach

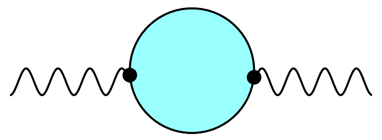
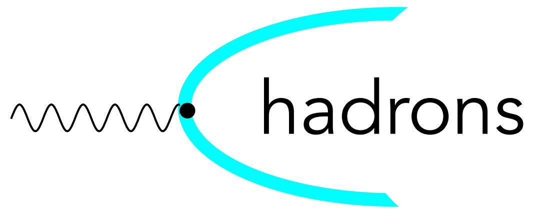


Hadronic Corrections



Two independent approaches:

- **For HVP:** use dispersion relations to rewrite integral in terms of hadronic cross section:

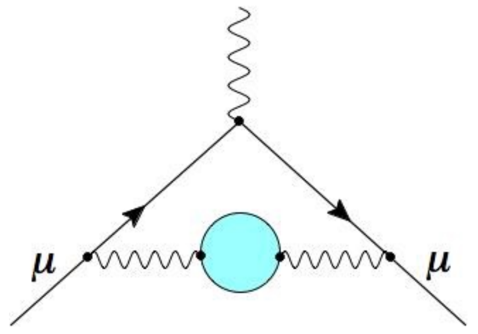
Im[] ~ | 

$|^2$ ➠

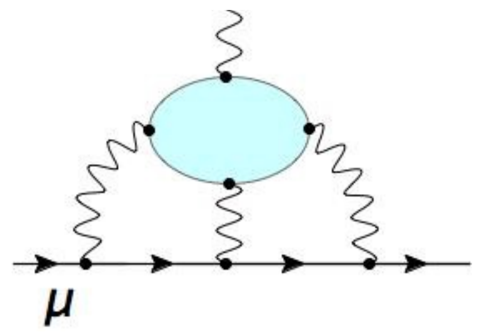
$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\,\hat{\Pi}(q^2) \;=\; \frac{m_\mu^2}{12\pi^3} \int ds \frac{\hat{K}(s)}{s}\,\sigma_{\mathrm{exp}}(s)$$

Many experiments (over 20+ years) have measured the e^+e^-cross sections for the different channels over the needed energy range with increasing precision.

For HLbL: new dispersive approach

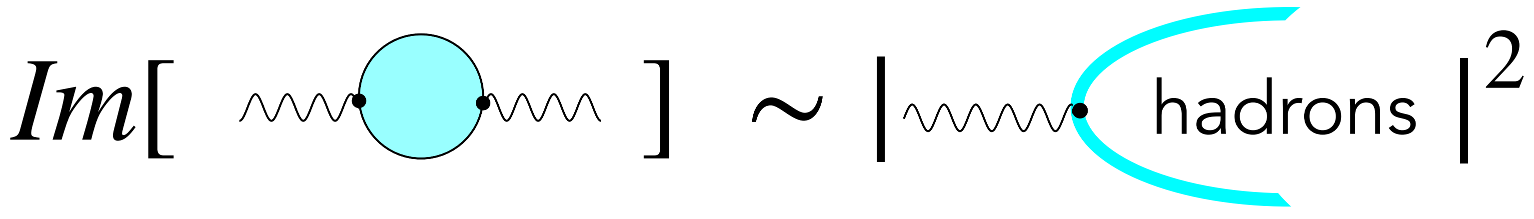


Hadronic Corrections



Two independent approaches:

- **For HVP:** use dispersion relations to rewrite integral in terms of hadronic cross section:

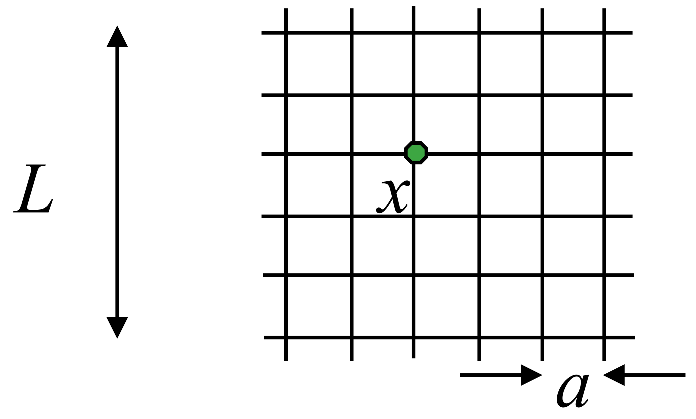


$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\,\hat{\Pi}(q^2) = \frac{m_\mu^2}{12\pi^3}\int ds \frac{\hat{K}(s)}{s}\sigma_{\mathrm{exp}}(s)$$

Many experiments (over 20+ years) have measured the e^+e^-cross sections for the different channels over the needed energy range with increasing precision.

For HLbL: new dispersive approach

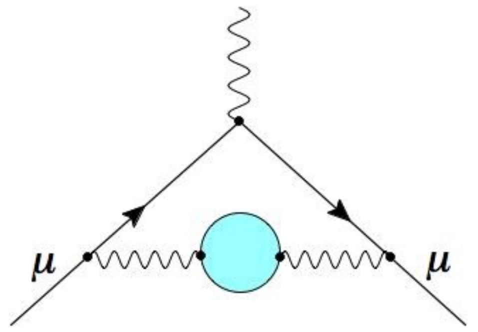
- Direct calculation using Euclidean Lattice QCD



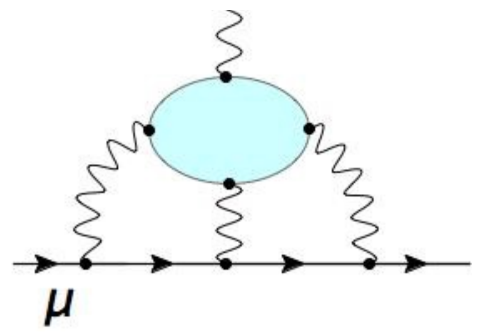
Approximations:
discrete space-time (spacing a)
finite spatial volume (L), and time extent (T)
…

  - *ab-initio* method to quantify QCD effects
  - already used for simple hadronic quantities with high precision
  - requires large-scale computational resources
  - allows for entirely SM theory based evaluations

Integrals are evaluated numerically using Monte Carlo methods.

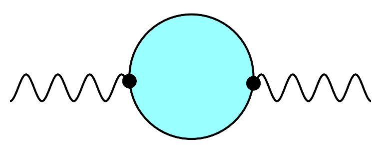
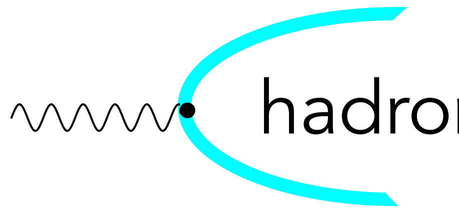


Hadronic Corrections



Two independent approaches:

- **For HVP:** use dispersion relations to rewrite integral in terms of hadronic cross section:

Im[] ~ | 

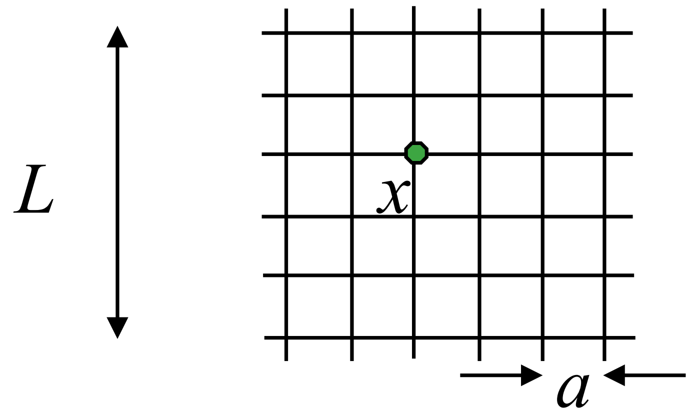
$|^2$ ➠ $a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2) = \frac{m_\mu^2}{12\pi^3} \int ds \frac{\hat{K}(s)}{s} \sigma_{\mathrm{exp}}(s)$

Many experiments (over 20+ years) have measured the e^+e^-cross sections for the different channels over the needed energy range with increasing precision.

For HLbL: new dispersive approach

- Direct calculation using Euclidean Lattice QCD ➠

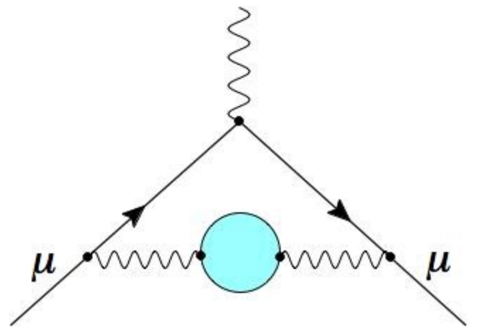
$$a_\mu^{\mathrm{HVP,LO}} = 4\,\alpha^2 \int_0^\infty dt\, C(t)\, \tilde{w}(t)$$



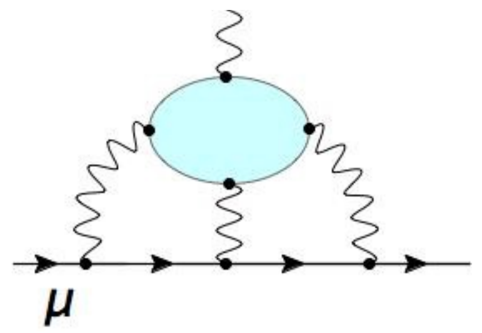
Approximations:
- discrete space-time (spacing a)
- finite spatial volume (L), and time extent (T)
- …

- *ab-initio* method to quantify QCD effects
- already used for simple hadronic quantities with high precision
- requires large-scale computational resources
- allows for entirely SM theory based evaluations

Integrals are evaluated numerically using Monte Carlo methods.

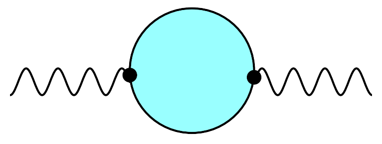
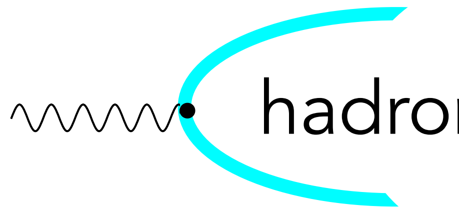


Hadronic Corrections



Two independent approaches:

- **For HVP:** use dispersion relations to rewrite integral in terms of hadronic cross section:

Im[] ~ |  |²

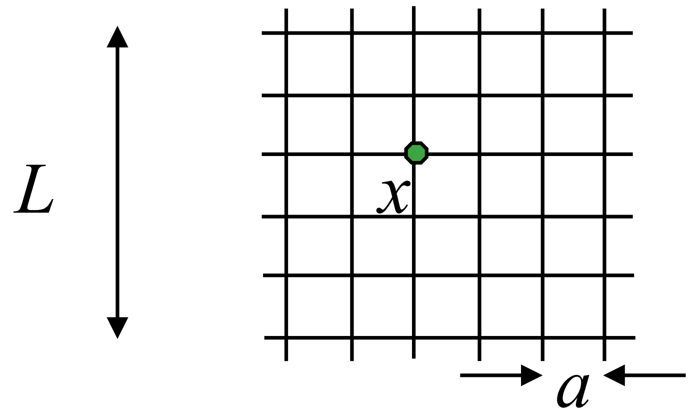
$$\Rightarrow \quad a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int dq^2 \omega(q^2)\, \hat{\Pi}(q^2) \;=\; \frac{m_\mu^2}{12\pi^3} \int ds \frac{\hat{K}(s)}{s} \sigma_{\exp}(s)$$

Many experiments (over 20+ years) have measured the e^+e^-cross sections for the different channels over the needed energy range with increasing precision.

For HLbL: new dispersive approach

- Direct calculation using Euclidean Lattice QCD

$$\Rightarrow \quad a_\mu^{\mathrm{HVP,LO}} = 4\,\alpha^2 \int_0^\infty dt\, C(t)\, \tilde{w}(t)$$



Approximations:
discrete space-time (spacing a)
finite spatial volume (L), and time extent (T)
…

- *ab-initio* method to quantify QCD effects
- already used for simple hadronic quantities with high precision
- requires large-scale computational resources
- allows for entirely SM theory based evaluations

Integrals are evaluated numerically using Monte Carlo methods.

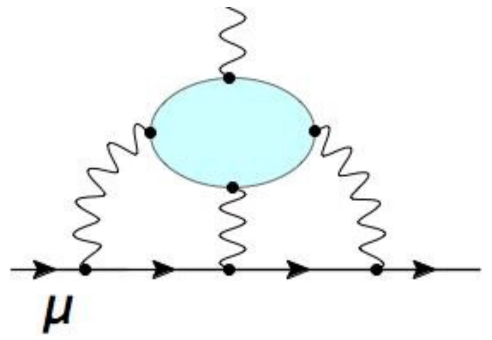
Muon g-2 Theory Initiative

Steering Committee

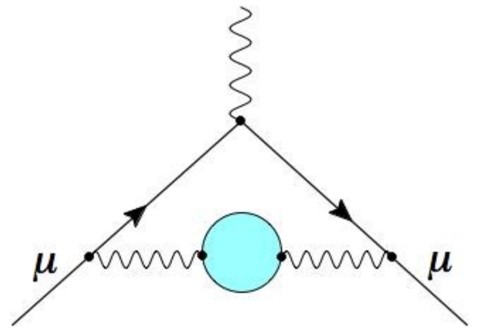
- Gilberto Colangelo (Bern)
- Michel Davier (Orsay) co-chair
- Aida El-Khadra (UIUC & Fermilab) chair
- Martin Hoferichter (Bern)
- Christoph Lehner (Regensburg University) co-chair
- Laurent Lellouch (Marseille)
- Tsutomu Mibe (KEK)
  J-PARC Muon g-2/EDM experiment
- Lee Roberts (Boston)
  Fermilab Muon g-2 experiment
- Thomas Teubner (Liverpool)
- Hartmut Wittig (Mainz)

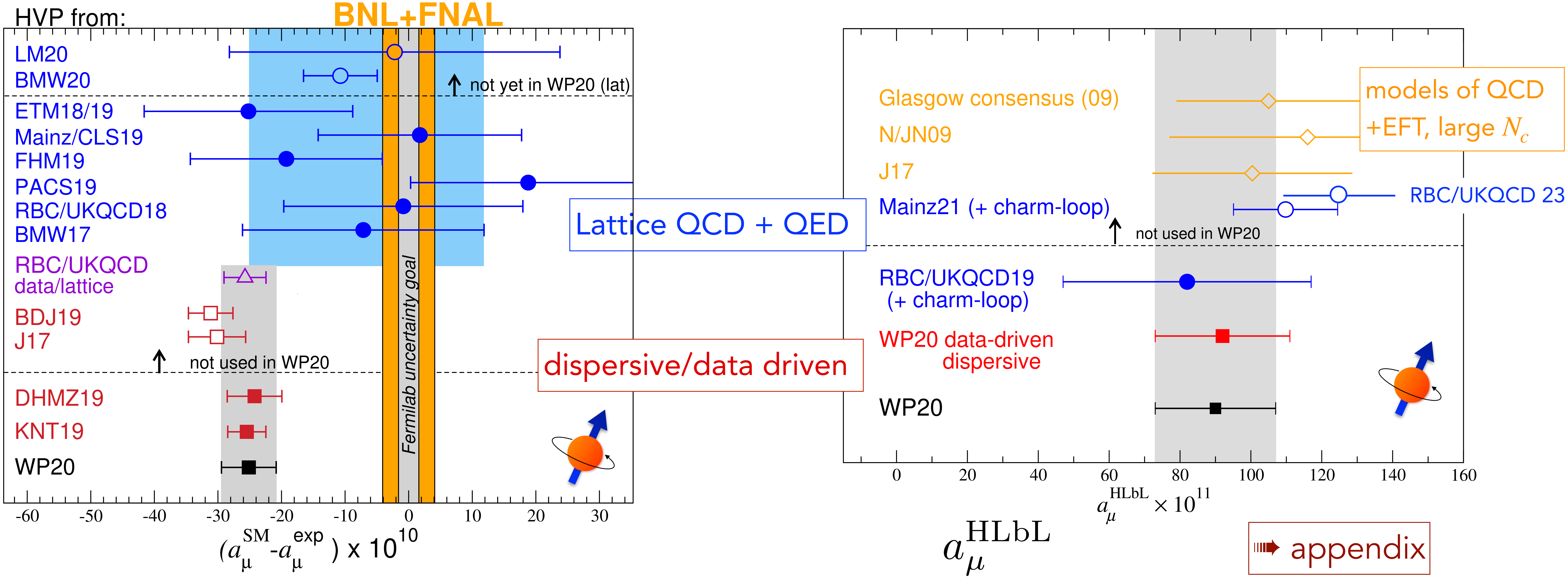
https://muon-gm2-theory.illinois.edu

- Maximize the impact of the Fermilab and J-PARC experiments
  ➠ quantify and reduce the theoretical uncertainties on the hadronic corrections
- summarize the theory status and assess reliability of uncertainty estimates
- organize workshops to bring the different communities together:
  First plenary workshop @ Fermilab: 3-6 June 2017
  HVP workshop @ KEK: 12-14 February 2018
  HLbL workshop @ U Connecticut: 12-14 March 2018
  Second plenary workshop @ HIM (Mainz): 18-22 June 2018
  Third plenary workshop @ INT (Seattle): 9-13 September 2019
  Lattice HVP at high precision workshop (virtual): 16-20 November 2020
  Fourth plenary workshop @ KEK (virtual): 28 June - 02 July 2021
  Fifth plenary workshop @ Higgs Centre (Edinburgh): 5-9 September 2022
  Sixth plenary workshop @ University of Bern: 4-8 September 2023
  Seventh plenary workshop @ KEK (Japan): June 2024
  Eight plenary workshop: 2025 in the US — seeking proposals

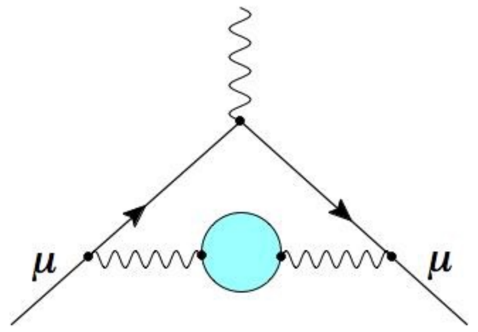


Hadronic Corrections: Comparisons



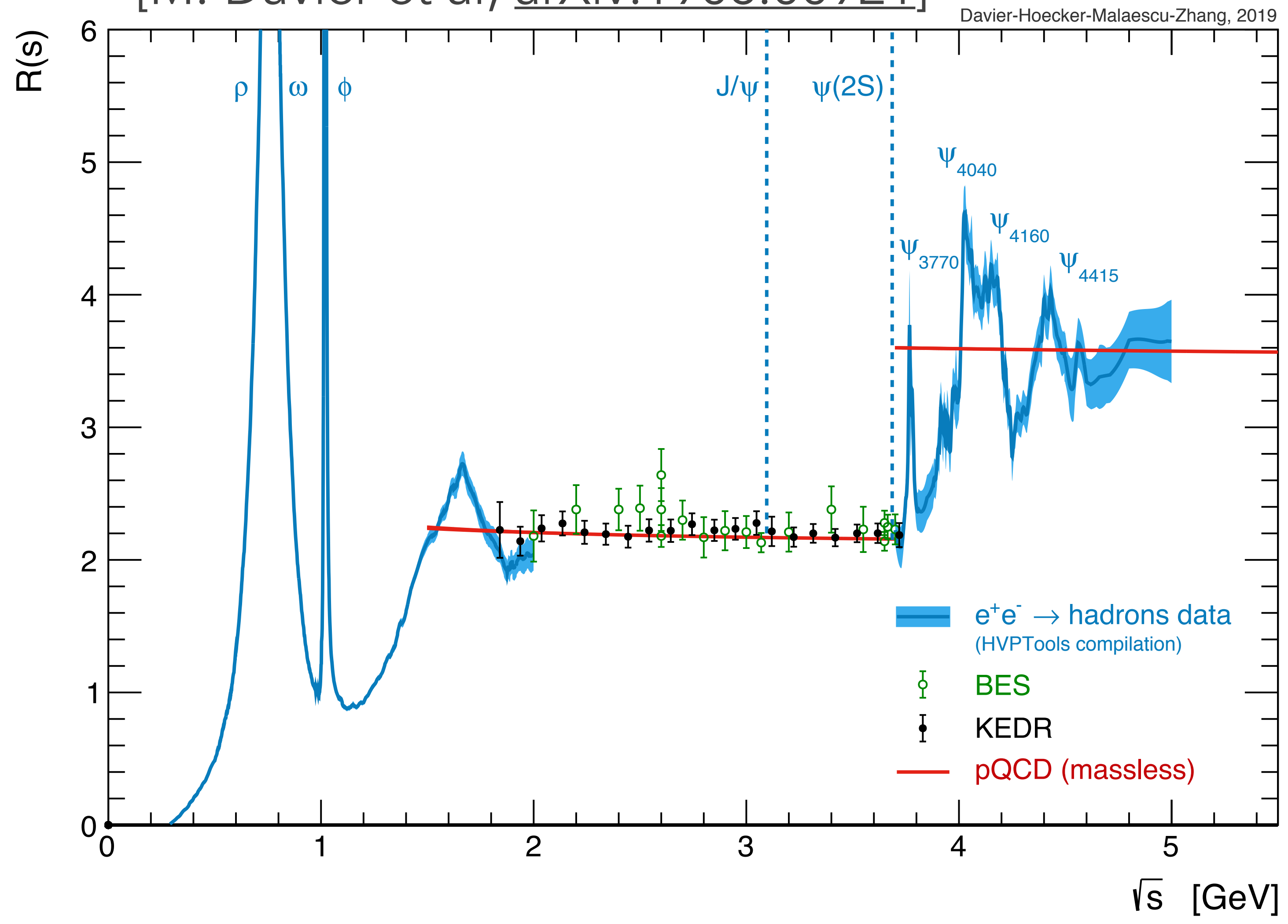


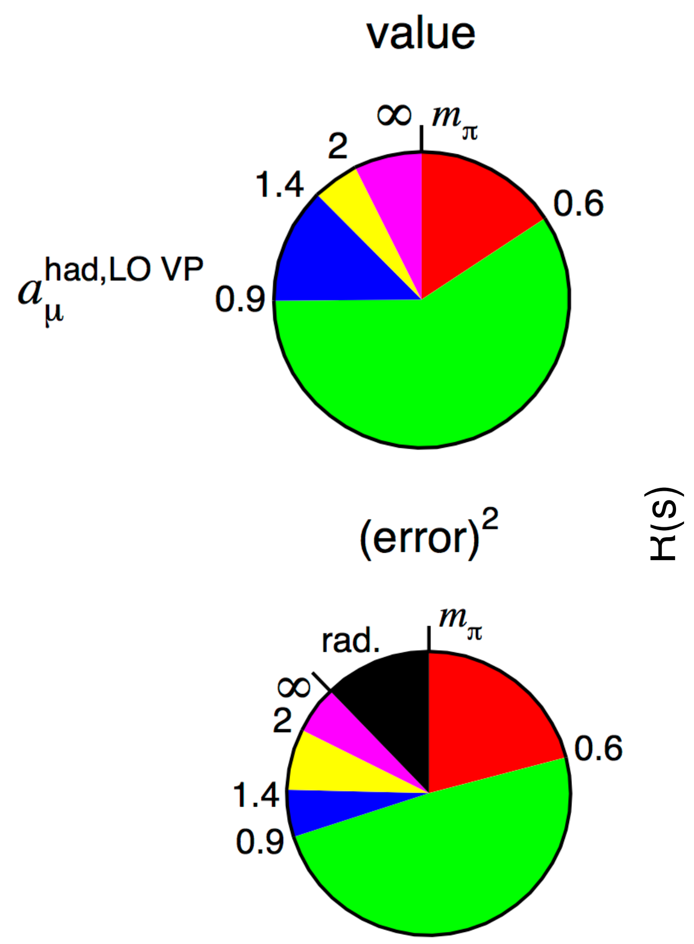
$$a_\mu^{\mathrm{SM}} \quad a_\mu^{\mathrm{HVP}} + \left[a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}\right]$$



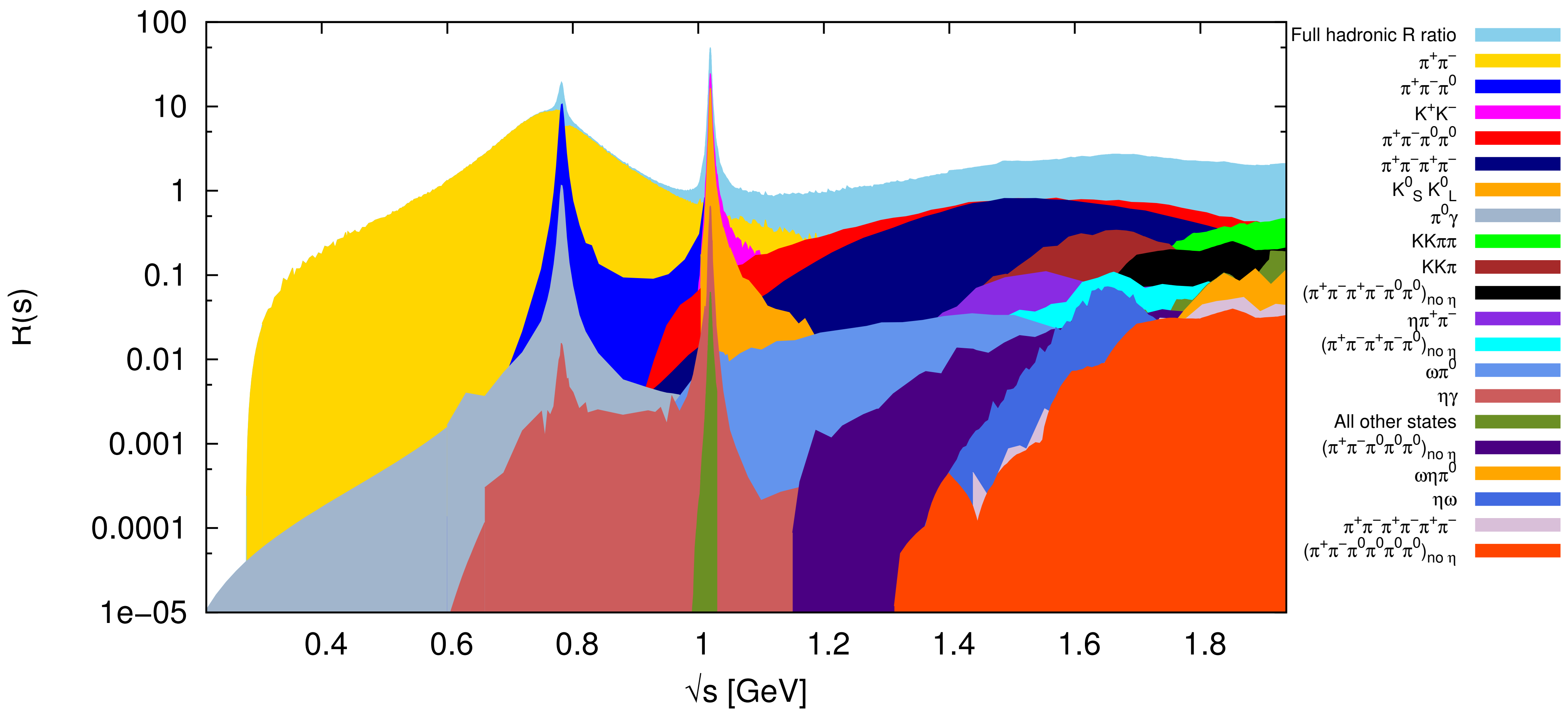
HVP: data-driven

[M. Davier et al, arXiv:1908.00921]





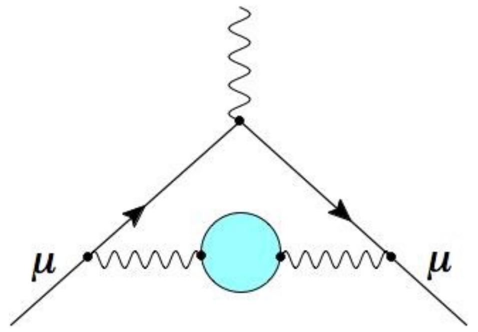
[A. Keshavarzi et al, arXiv:1802.02995]



- $\sigma_{\rm had}(s)$ defined to include real & virtual photons
- direct integration method: no modelling of $\sigma_{\rm had}(s)$, summing up contributions from all hadronic channels
- total hadronic cross section $\sigma_{\rm had}(s)$ from > 100 data sets in more than 35 channels summed up to $\sqrt{s} \sim 2\,{\rm GeV}$
- $\sqrt{s} > 2$ GeV: inclusive data + pQCD + narrow resonances
- two independent compilations (DHMZ, KNT) using the direct integration method

Tensions between BaBar and KLOE data sets:

- Cross checks using analyticity and unitarity relating pion form factor to $\pi\pi$ scattering
- Combinations of data sets affected by tensions
  ➠ conservative merging procedure



HVP: data-driven

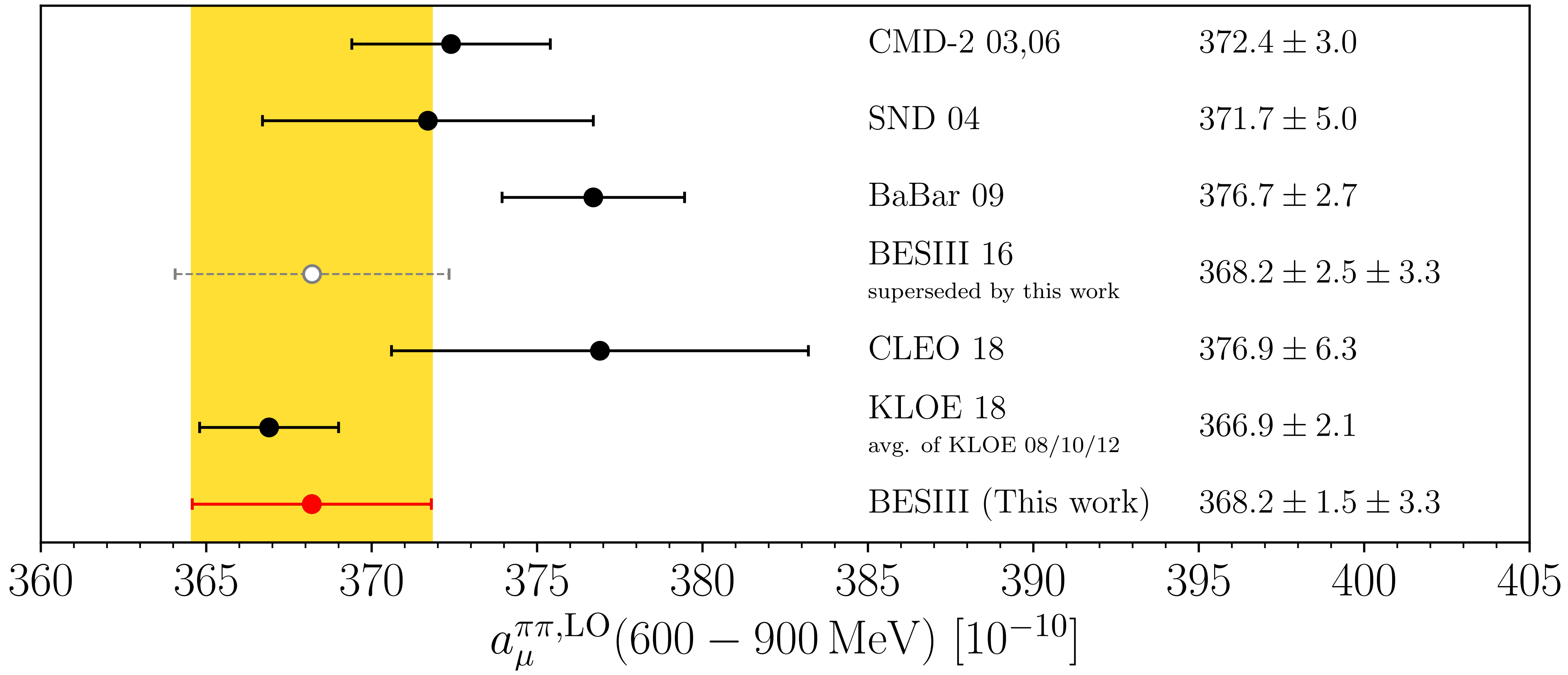
2020 White Paper [T. Aoyama et al, arXiv:2006.04822, Phys. Repts. 887 (2020) 1-166.]

Conservative merging procedure to obtain a realistic assessment of the underlying uncertainties:

- account for tensions between data sets
- account for differences in methodologies for compilation of experimental inputs and treatment of correlations between systematic errors
- include results using constraints from unitarity & analyticity in $\pi\pi$ and $\pi\pi\pi$ channels [Colangelo et al, 2018; Anantharayan et al, 2018; Davier et al, 2019; Hoferichter et al, 2019]
- Full NLO radiative corrections [Campanario et al, 2019]

$$a_\mu^{\rm HVP,LO} = 693.1\,(2.8)_{\rm exp}\,(0.7)_{\rm DV+pQCD}\,(2.8)_{\rm BaBar-KLOE} \times 10^{-10}$$
$$= 693.1\,(4.0) \times 10^{-10}$$

[M. Ablikim et al (BES III), arXiv:2009.05011]



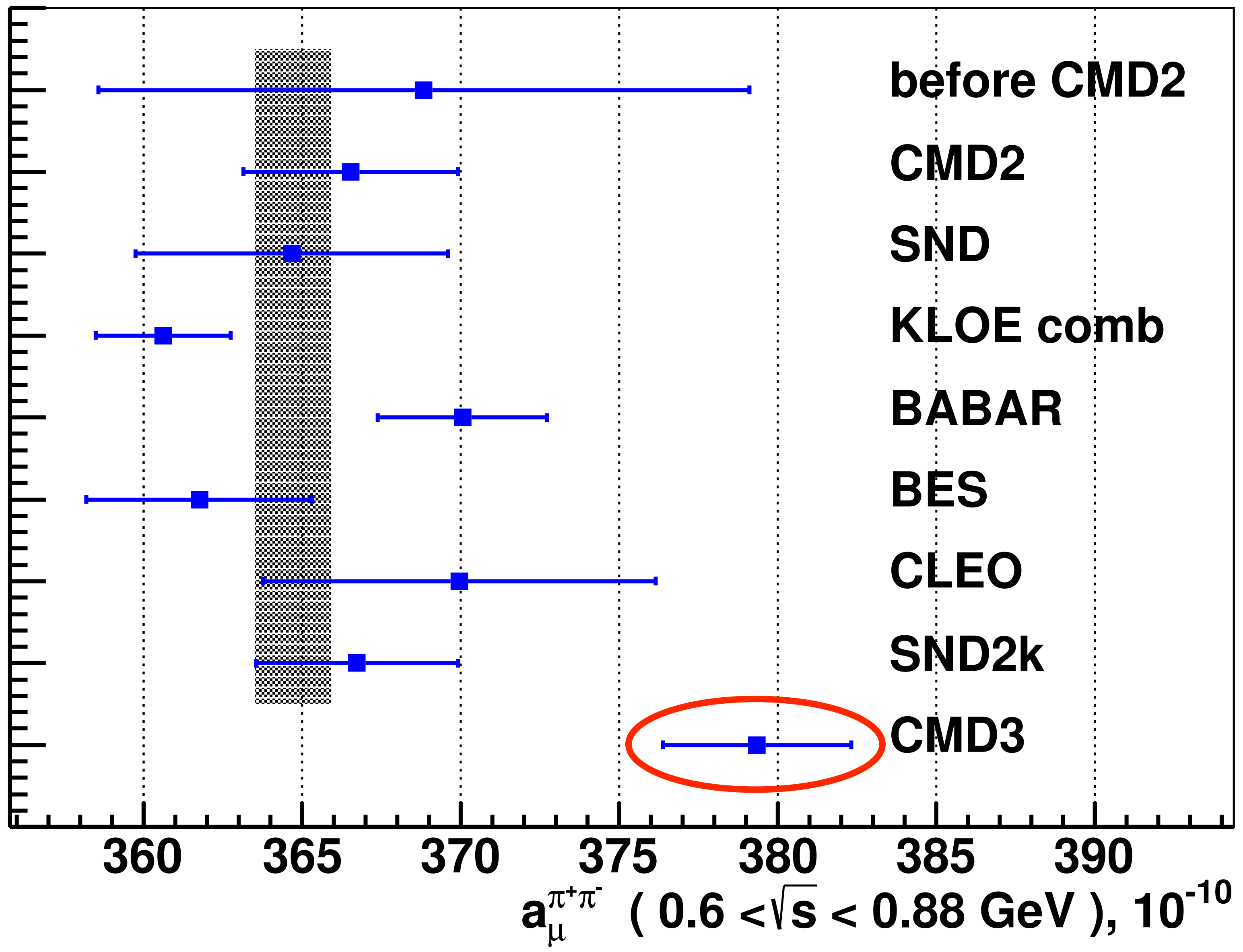
HVP: data-driven

T. Teubner @ Zurich workshop

New results for $\sigma_{\mathrm{had}}(s)$:

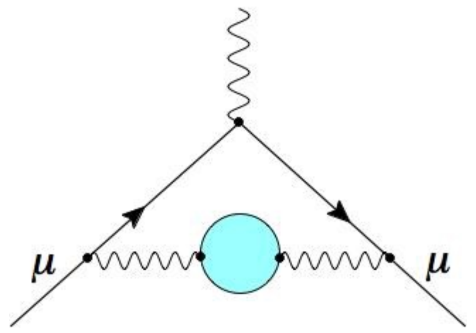
- **pi+pi-pi0**, BESIII (2019), arXiv:1912.11208
- **pi+pi-** [covariance matrix erratum], BESIII (2020), Phys.Lett.B 812 (2021)
- **K+K-pi0**, SND (2020), Eur.Phys.J.C 80 (2020) 12, 1139
- **etapi0gamma** (res. only), SND (2020), Eur.Phys.J.C 80 (2020) 11, 1008
- **pi+pi-**, SND (2020), JHEP 01 (2021) 113
- **etaomega** → pi0gamma, SND (2020), Eur.Phys.J.C 80 (2020) 11, 1008
- **pi+pi-pi0**, SND (2020), Eur.Phys.J.C 80 (2020) 10, 993
- **pi+pi-pi0**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112003
- **pi+pi-2pi0omega**, BaBar (2021), Phys. Rev. D 103, 092001
- **etaetagamma**, SND (2021), Eur.Phys.J.C 82 (2022) 2, 168
- **etaomega**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112004
- **pi+pi-pi0eta**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112004
- **omegaetapi0**, BaBar (2021), Phys. Rev. D 103, 092001
- **pi+pi-4pi0**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112004
- **pi+pi-pi0pi0eta**, BaBar (2021), Phys.Rev.D 103 (2021) 9, 092001
- **pi+pi-3pi0eta**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112004
- **2pi+2pi-3pi0**, BaBar (2021), Phys. Rev. D 103, 092001
- **omega3pi0**, BaBar (2021), Phys.Rev.D 104 (2021) 11, 112004
- **pi+pi-pi+pi-eta**, BaBar (2021), Phys. Rev. D 103, 092001
- **inclusive**, BESIII (2021), Phys.Rev.Lett. 128 (2022) 6, 062004
- …

New: from CMD-3 [F. Ignatov et al, arXiv:2302.08834]



A new puzzle!

- discrepancies between experiments now $\gtrsim (3-5)\,\sigma$ need to be understood/resolved
- (virtual) scientific seminar + discussion panel on CMD-3 measurement March 27 (8:00 –11:00 am US CDT) Discussions are continuing….
- 6th Muon g-2 Theory Initiative workshop (4-8 Sep 2023, Bern)



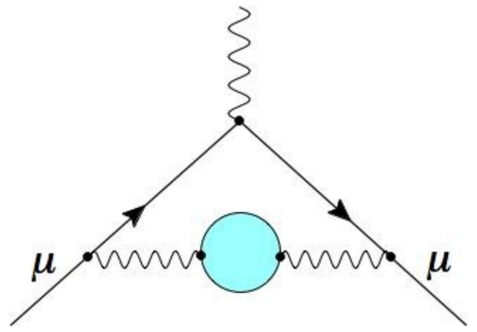
HVP: data-driven

Ongoing work on experimental inputs:

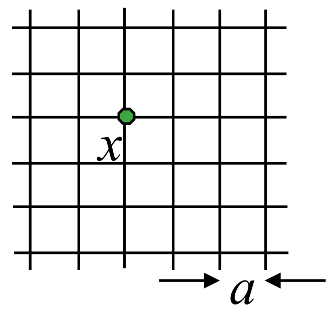
- BaBar: new analysis of large data set in $\pi\pi$ channel, also $\pi\pi\pi$, other channels
- KLOE: new analysis of large data set in $\pi\pi$ channel, other channels
- SND: new results for $\pi\pi$ channel, other channels in progress
- BESIII: new results in 2021 for $\pi\pi$ channel, continued analysis also for $\pi\pi\pi$, other channels
- Belle II: arXiv:2207.06307 (Snowmass WP)
  Better ultimate statistics than BaBar or KLOE; similar or better systematics for low-energy cross sections

Ongoing work on theoretical aspects:

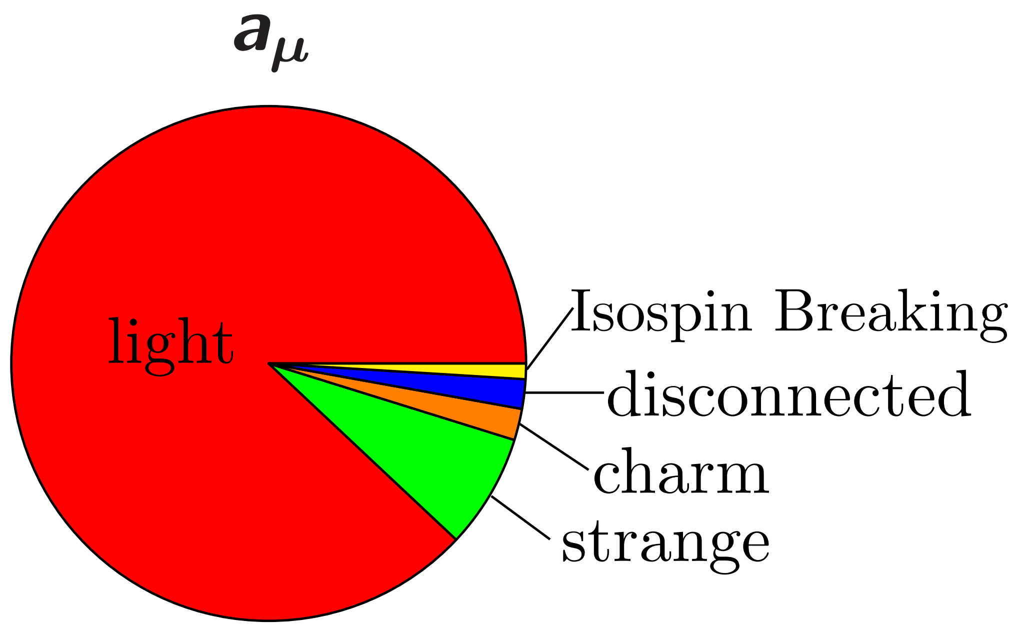
- better treatment of structure dependent radiative corrections (NLO) in $\pi\pi$ and $\pi\pi\pi$ channels
  so far: FsQED (scalar QED + pion form factor)
  tests of radiative corrections using exp. measurement of charge asymmetry [Ignatov + Lee, arXiv:2204.12235]
  new dispersive treatment [Colangelo at al, arXiv2207.03495]
- Developing NNLO Monte Carlo generators (STRONG 2020 workshop https://agenda.infn.it/event/28089/)
- including τ decay data: requires nonperturbative evaluation of IB correction [M. Bruno et al, arXiv:1811.00508]



Lattice HVP: Introduction



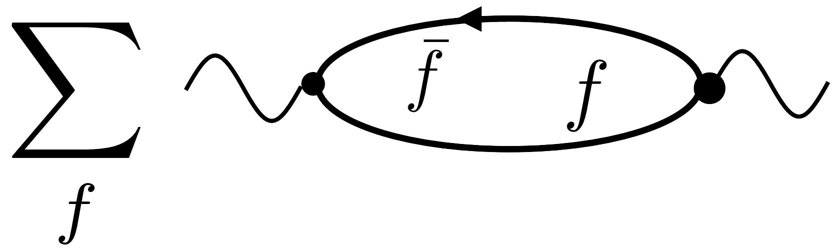
Calculate a_μ^{HVP} in Lattice QCD: $$a_\mu^{\mathrm{HVP,LO}} = \sum_f a_{\mu,f}^{\mathrm{HVP,LO}} + a_{\mu,\mathrm{disc}}^{\mathrm{HVP,LO}}$$



- Separate into connected for each quark flavor + disconnected contributions (gluon and sea-quark background not shown in diagrams)

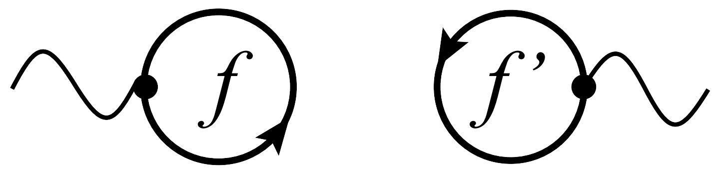
  Note: almost always $m_u = m_d$

$f = ud, s, c, b$



- light-quark connected contribution: $a_\mu^{\mathrm{HVP,LO}}(ud)$ ~90% of total
- s,c,b-quark contributions $a_\mu^{\mathrm{HVP,LO}}(s,c,b)$ ~8%, 2%, 0.05% of total

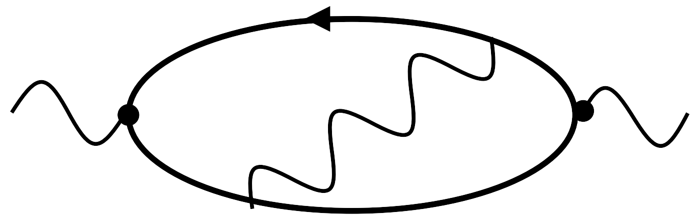
$+$



- disconnected contribution: $a_{\mu,\mathrm{disc}}^{\mathrm{HVP,LO}}$ ~2% of total

- need to add QED and strong isospin breaking ($\sim m_u - m_d$) corrections:

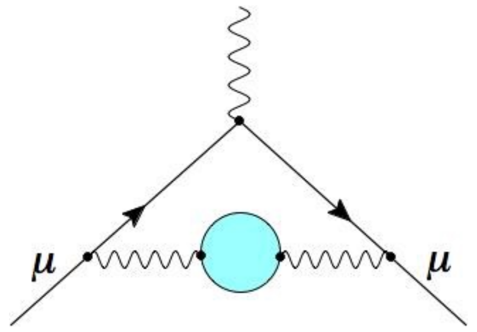
$+$



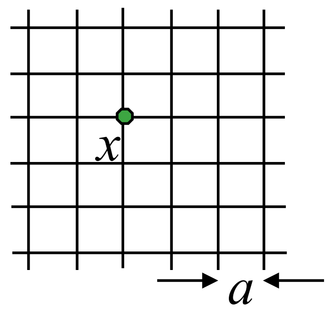
$+ \ldots$

- Isospinbreaking (QED + $m_u \neq m_d$) corrections: $\delta a_\mu^{\mathrm{HVP,LO}}$ ~1% of total

$$a_\mu^{\mathrm{HVP,LO}} = a_\mu^{\mathrm{HVP,LO}}(ud) + a_\mu^{\mathrm{HVP,LO}}(s) + a_\mu^{\mathrm{HVP,LO}}(c) + a_{\mu,\mathrm{disc}}^{\mathrm{HVP,LO}} + \delta a_\mu^{\mathrm{HVP,LO}}$$



Lattice HVP: results



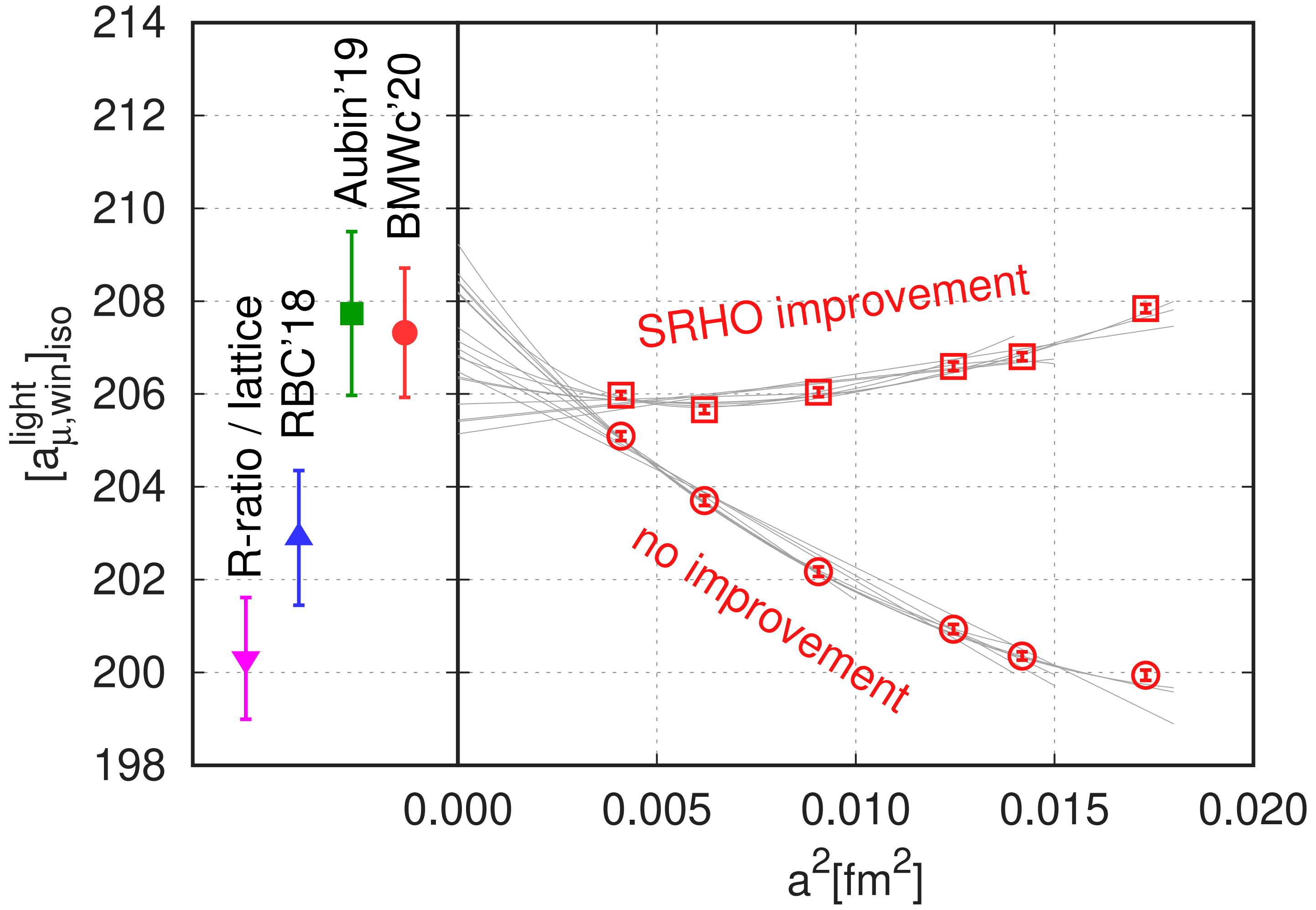
$$a_\mu^{\mathrm{HVP,LO}} = 4\,\alpha^2 \int_0^\infty dt\, C(t)\, \tilde{w}(t)$$

In 2020 WP:

- Lattice HVP average at $2.6\,\%$ total uncertainty: $a_\mu^{\mathrm{HVP,LO}} = 711.6\,(18.4) \times 10^{10}$
- BMW 20 [Sz. Borsanyi et al, arXiv:2002.12347, 2021 Nature] first LQCD calculation with sub-percent ($0.8\,\%$) error in tension with data-driven HVP (2.1σ)
- Further tensions for intermediate window:

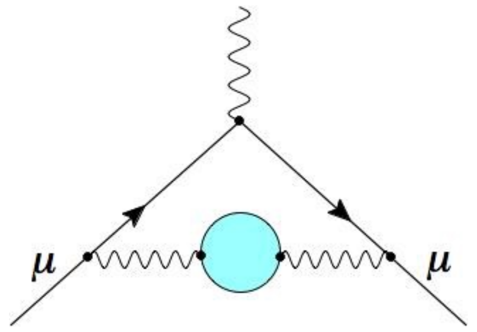
  -3.7σ tension with data-driven evaluation

  -2.2σ tension with RBC/UKQCD18

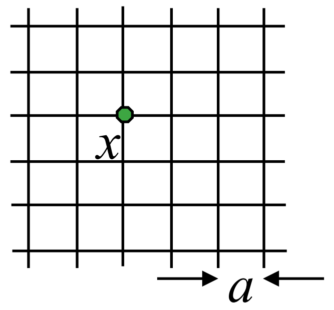


Staggered fermions:

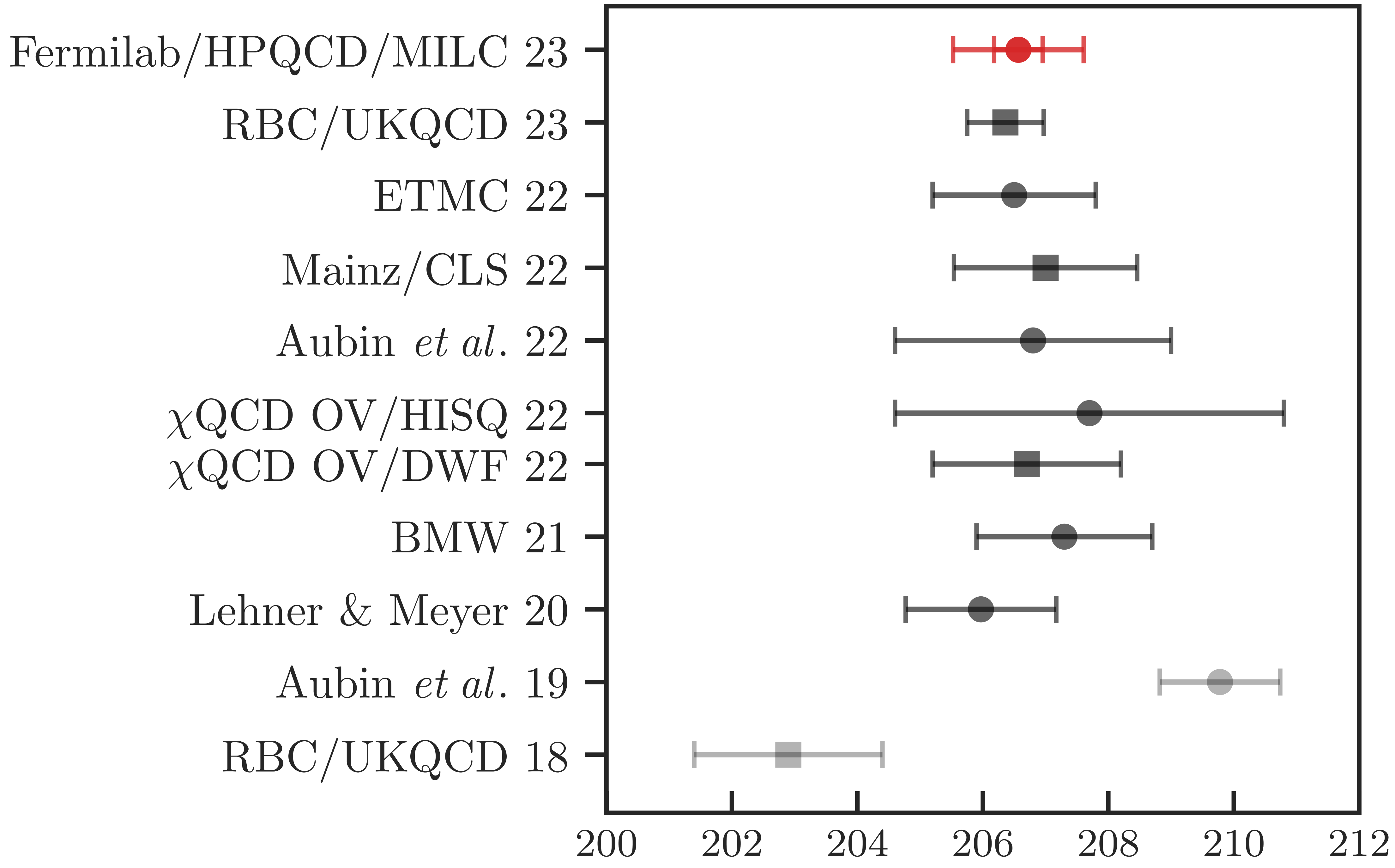
- taste-breaking effects (which yield taste splittings) are significant (sometimes dominant) source of discretization errors
- possible to use EFT schemes (ChPT, Chiral Model, MLLGS) to correct for taste-splitting effects before taking continuum extrapolation: continuum limit should not be affected



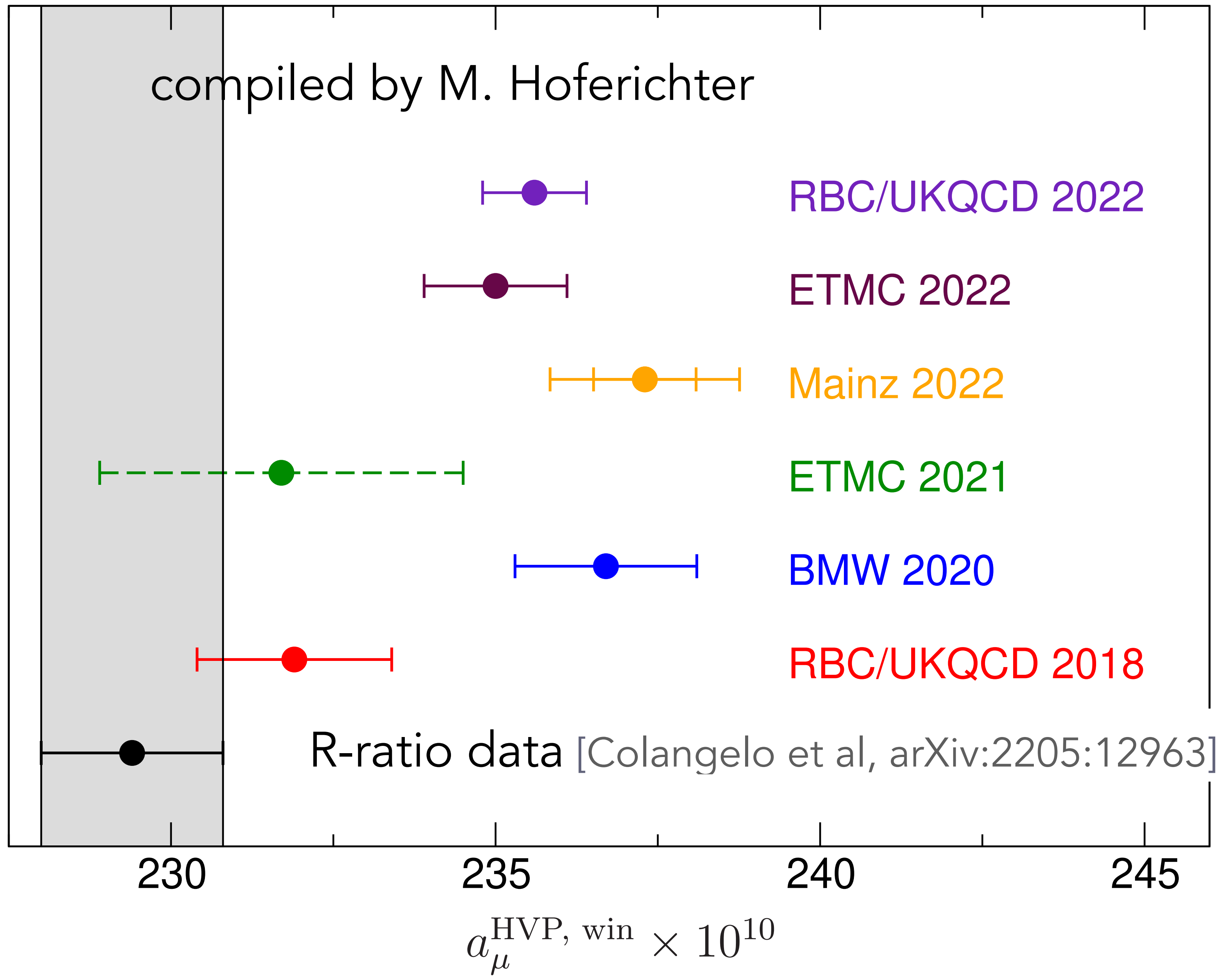
Lattice HVP: results



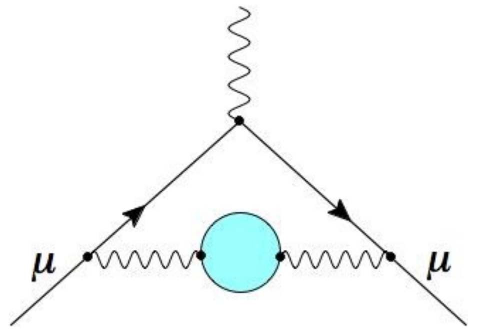
- new results in 2022/2023 for intermediate window, a_μ^W from six different lattice groups.
- blind analyses: Fermilab/HPQCD/MILC + RBC/UKQCD
- lattice-only comparison of light-quark connected contribution to intermediate window:



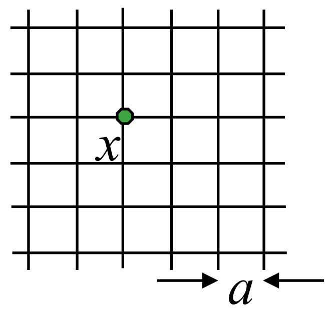
- LQCD results including all contributions



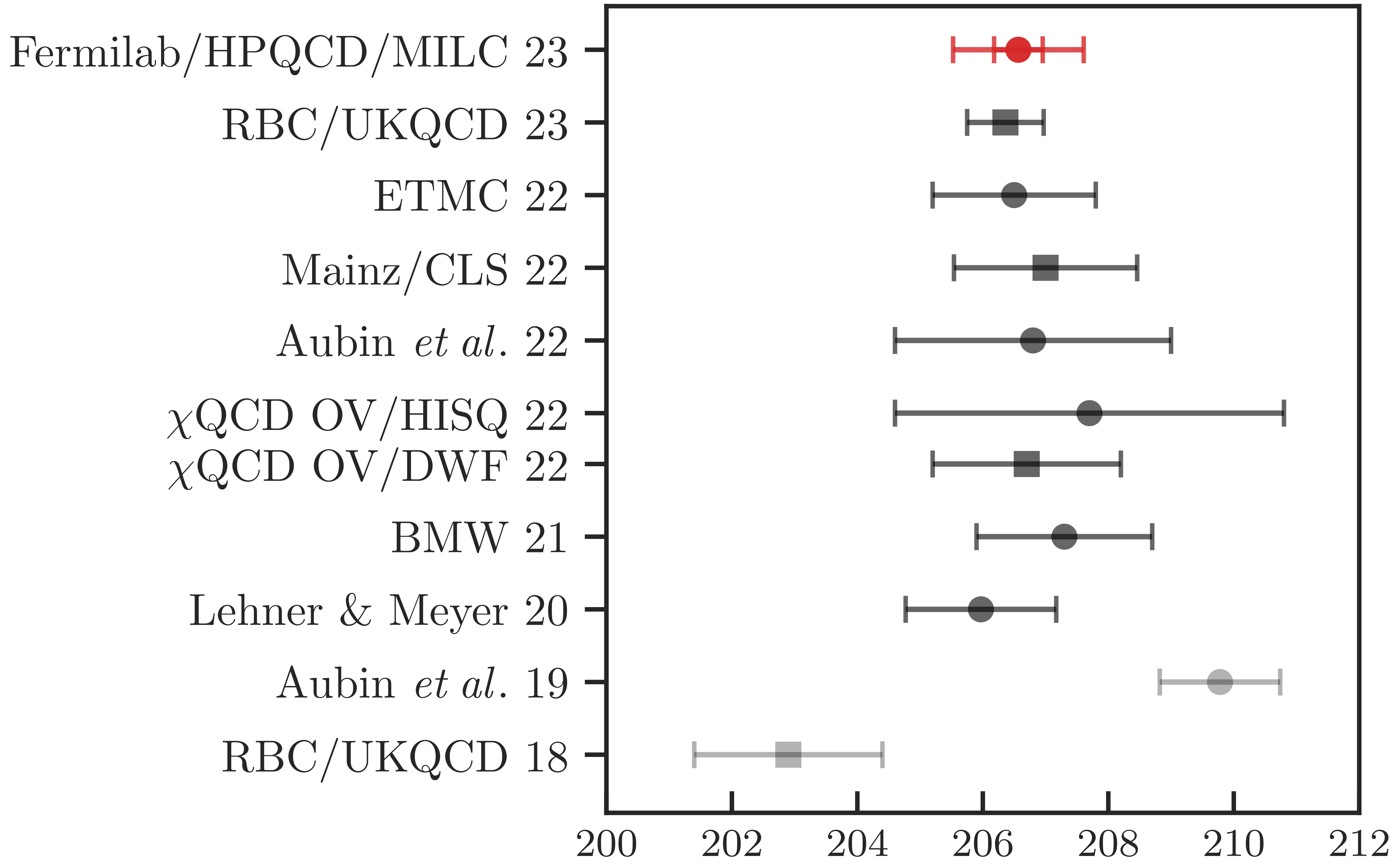
$\sim (3.5 - 4)\sigma$ tensions between LQCD and (pre-2023) data-driven evaluations



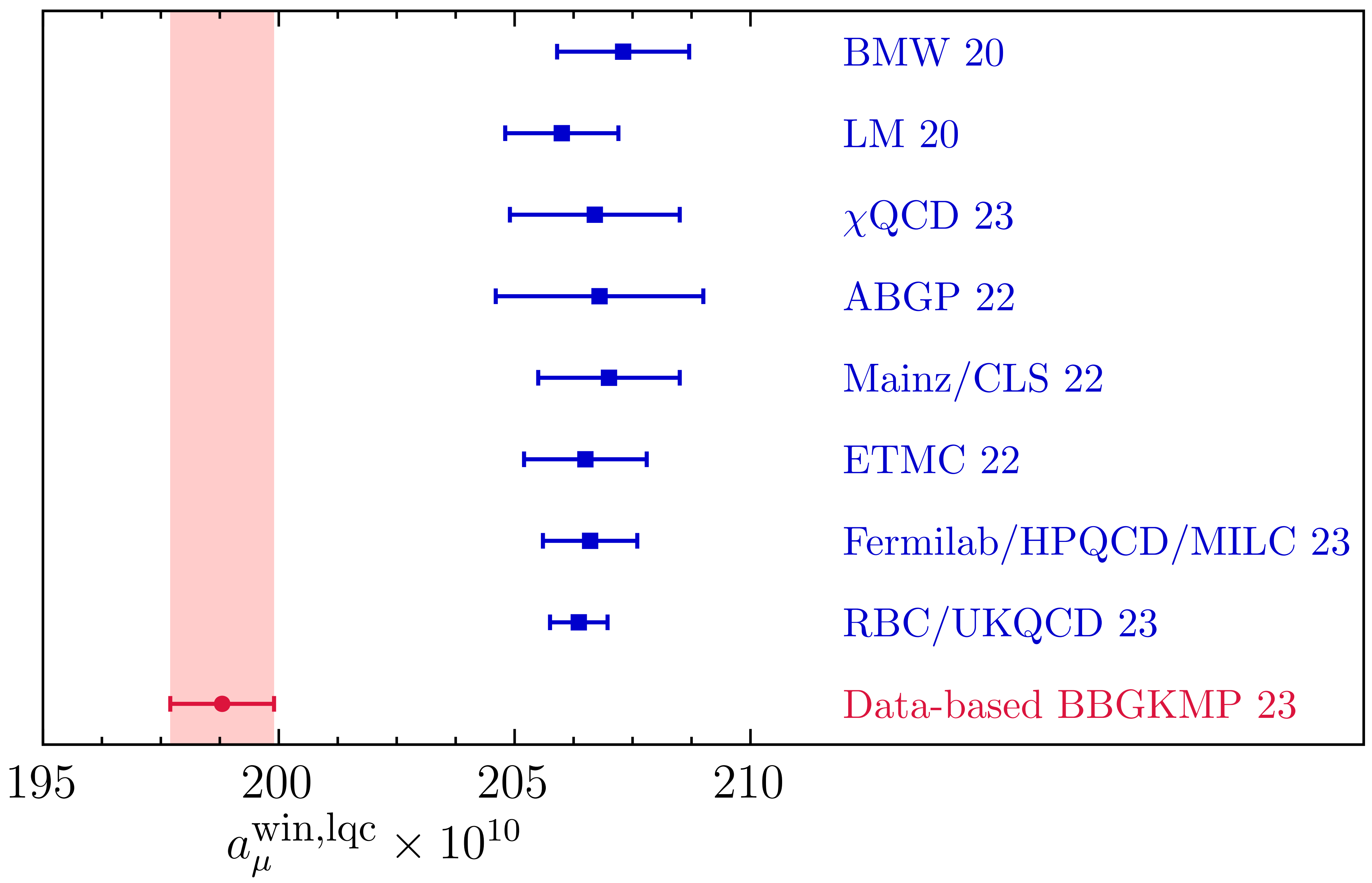
Lattice HVP: results



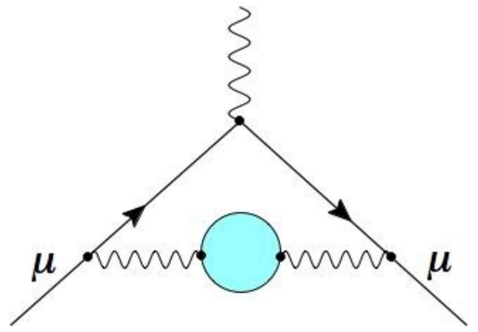
- new results in 2022/2023 for intermediate window, a_μ^W from six different lattice groups.
- blind analyses: Fermilab/HPQCD/MILC + RBC/UKQCD
- lattice-only comparison of light-quark connected contribution to intermediate window:



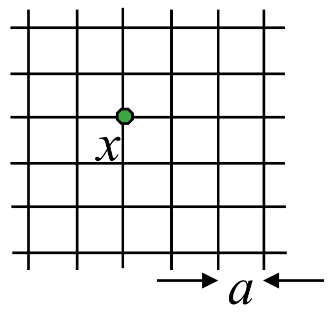
- dispersive evaluation of light-quark connected contribution [benno, et al, arXiv:2306.



➠ primary source of tension



Lattice HVP: outlook



Ongoing work:

Evaluations of short-distance windows [ETMC, RBC/UKQCD]

Proposals for computing more windows:

- Use linear combinations of finer windows to locate the tension (if it persists) in $\sqrt{s}$
  [Colangelo et al, arXiv:12963]
- Use larger windows, excluding the long-distance region $t \gtrsim 2\,\mathrm{fm}$ to maximize the significance of any tension [Davies at at, arXiv:2207.04765]

For total HVP:

- independent lattice results at sub-percent precision: coming soon!
- Including $\pi\pi$ states for refined long-distance computation
  (Mainz, RBC/UKQCD, FNAL/MILC)
- include smaller lattice spacings to test continuum extrapolations (needs adequate computational resources)

g-2 sessions @ Lattice 2023 conference

Summary

- ☆ consistent results from independent, precise LQCD calculations for light-quark connected contribution to **intermediate window** a_μ^{W} (~ 1/3 of $a_\mu^{\mathrm{HVP,LO}}$) ➠ $3-4\,\sigma$ tension with data-driven results?
- ☆ still need independent LQCD results for long-distance contribution, total HVP: coming soon
  ➠ develop method average for lattice HVP results, **assess tensions (if any)** with data-driven average
- ☆ Programs and plans in place to improve by 2025:
  - data-driven HVP: **if differences are resolved/understood,** $\sim 0.3\,\%$
    new measurements from BaBar, KLOE, SND, Belle II,…. will shed light on current discrepancies (blind analyses are paramount!)
    improved treatment of structure dependent radiative corrections (NLO) in $\pi\pi$ and $\pi\pi\pi$ channels
  - lattice HVP: **if no tensions** between independent lattice results, $\sim 0.5\,\%$
  - dispersive HLbL and lattice HLbL: no puzzles, steady progress, $\sim 10\,\%$
- ☆ **IF tensions/differences between data-driven HVP and lattice HVP are resolved,** SM prediction will likely match precision goal of the Fermilab experiment.
- ☆ IF NOT, will need detailed comparisons, explore connections between HVP, $\sigma(e^+e^-)$, $\Delta\alpha$, global EW fits.

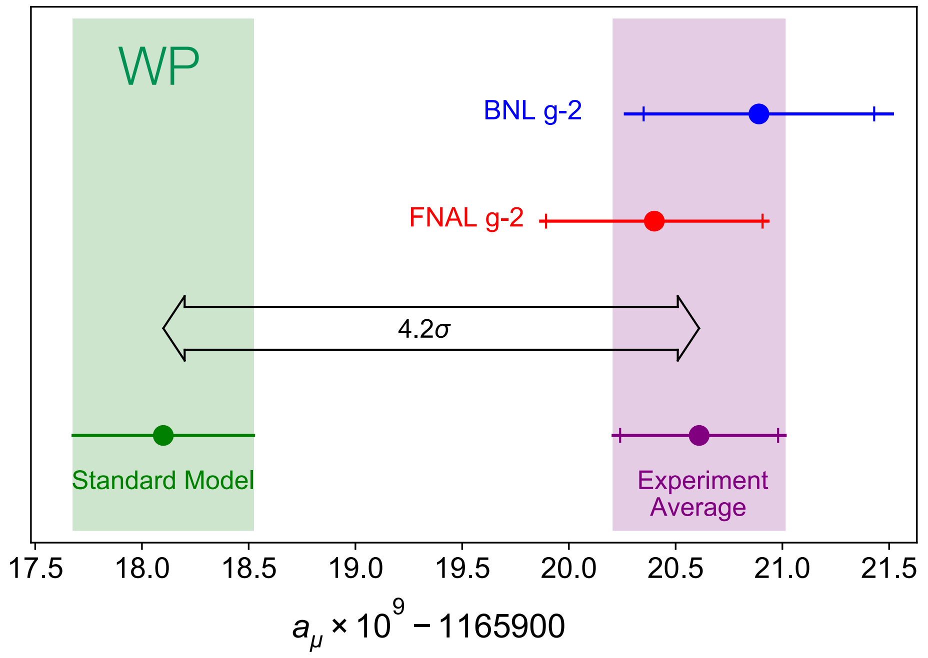
- ☆ BSM implications ➠ appendix

➠ **continued coordination by Theory Initiative: workshops, WPs, …**

Near-term Timeline


Physics Reports

The anomalous magnetic moment of the muon in the Standard Model



Theory Initiative:

- ☆ ongoing activities: develop method average for Lattice HVP
- ☆ CMD-3 seminar (virtual): **27 March 2023** at 8:00am US CDT
- ☆ WP update with all available results ~ early 2024

★ TI workshops:

Jun 2021 @ KEK (virtual)	Sep 2022 @ Higgscentre
Sep 2023 @ Bern	Summer 2024 @ KEK

Outlook

- Experimental program beyond 2025:
  - J-PARC: Muon g-2/EDM
  - Fermilab: future muon campus experiments?
  - Belle II, BESIII, Novosibirsk,…
  - Chiral Belle (?)
- Data-driven/dispersive program beyond 2025:
  - development of NNLO MC generators
  - for HLbL, improved experimental/lattice inputs together with further development of dispersive approach
- MUonE will provide a space-like measurement of HVP
- Lattice QCD beyond 2025:
  - access to future computational resources (coming Exascale) will enable improvements of all errors (statistical and systematic)
  - concurrent development of better methods and algorithms (gauge-field sampling, noise reduction) will accelerate progress
  - beyond g-2: a rich program relevant for all areas of HEP

CENTRE FOR THEORETICAL PHYSICS Higgs

UK LFT

KEK

INSTITUTE for NUCLEAR THEORY

NVIDIA

THE UNIVERSITY of EDINBURGH

STORJ

Fermilab

I ILLINOIS

NEC

Atos

U.S. DEPARTMENT OF ENERGY | Office of Science

UNIVERSITY of WASHINGTON

RIKEN BNL Research Center

Cảm ơn!

epcc

URA UNIVERSITIES RESEARCH ASSOCIATION

STRONG 2020

Fermi Research Alliance LLC

HIM HELMHOLTZ Helmholtz-Institut Mainz

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRiSMA

Ip3

UCONN DEPARTMENT OF PHYSICS

JOHANNES GUTENBERG UNIVERSITÄT MAINZ