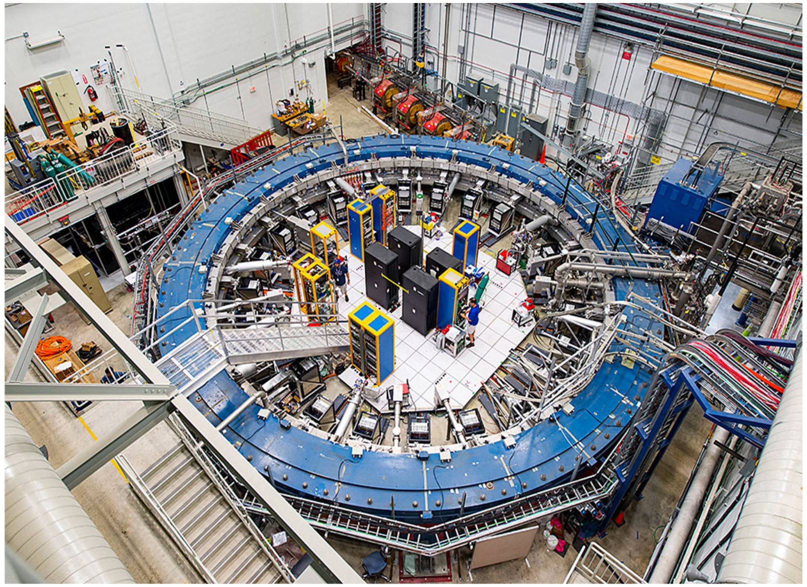
Muon g-2: Hadronic Contributions



Alex Keshavarzi
@AlexKeshavarzi

XXXIII International Workshop on High Energy Physics
“Hard Problems of Hadron Physics: Non-Perturbative QCD & Related Quests”

8th November 2021

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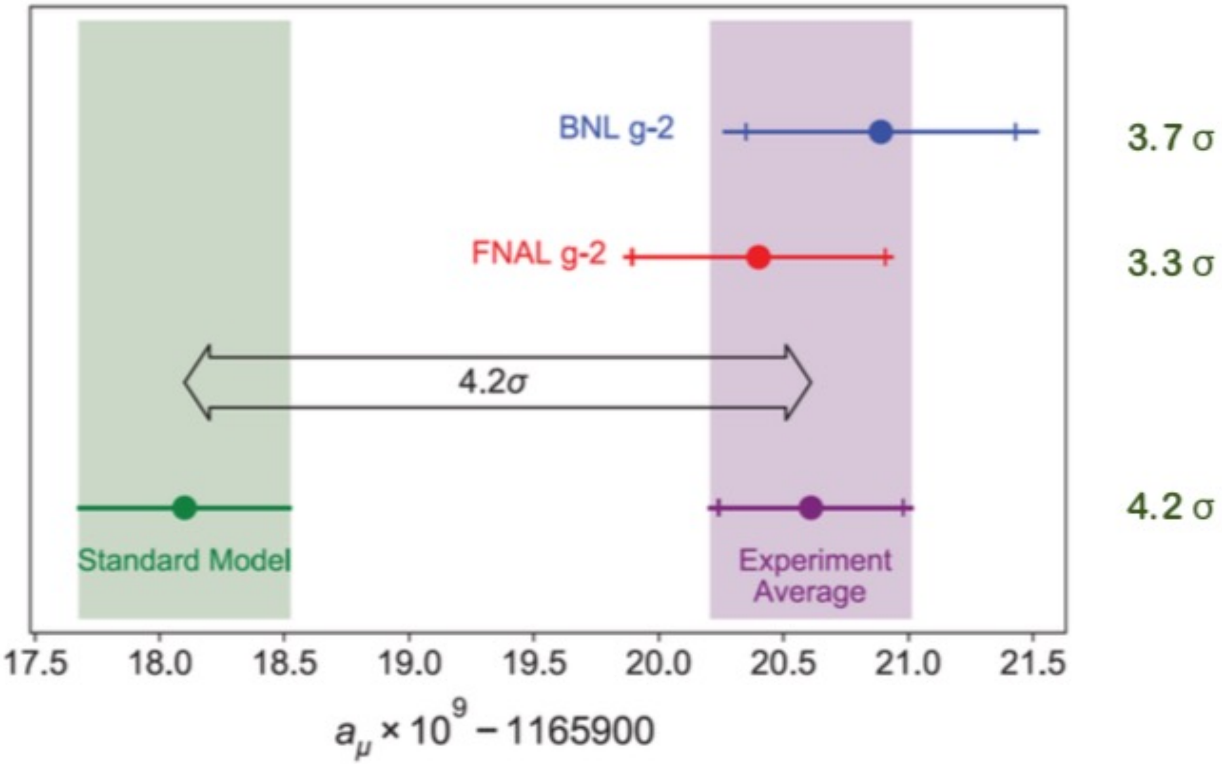
Muon g-2: FNAL confirms BNL



$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm] WA

Magnetic moments

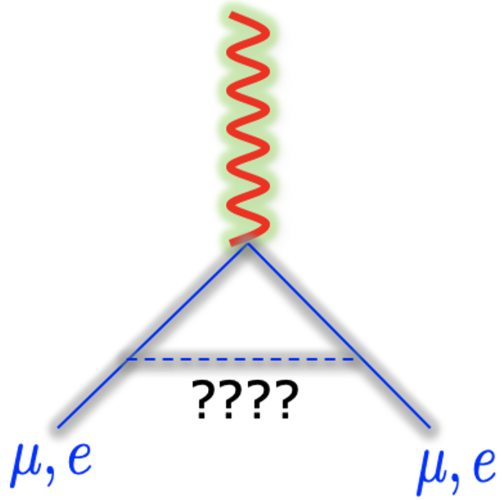
The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

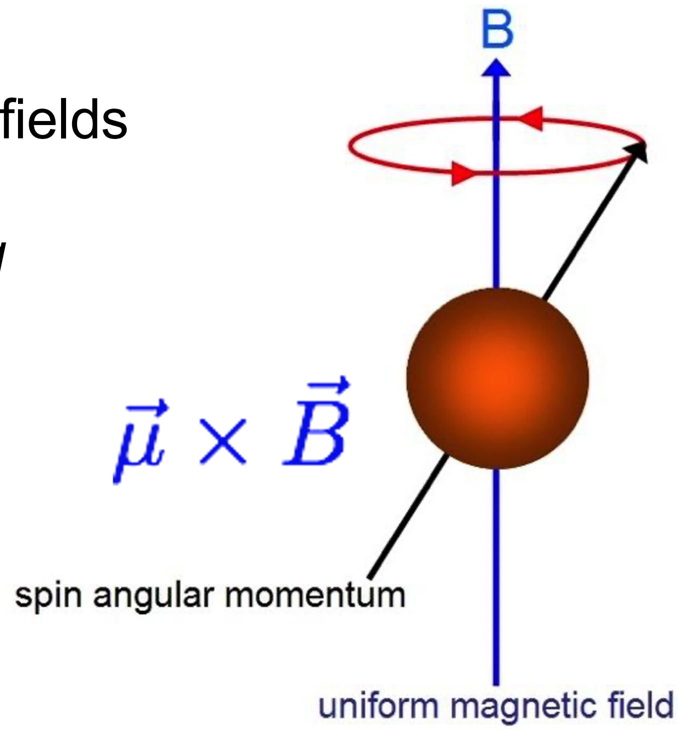
$$\vec{\mu} = g \frac{e}{2m_\mu} \vec{S}$$

Magnetic moment (spin) interacts with external B-fields

Makes spin precess at frequency determined by *g*

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





Muon g-2 Theory

arXiv.org > hep-ph > arXiv:2006.04822

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High Energy Physics – Phenomenology

[Submitted on 8 Jun 2020]

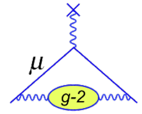
The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C. M. Carloni Calame, M. Cè, G. Colangelo, F. Curciarello, H. Czyż, I. Danilkin, M. Davier, C. T. H. Davies, M. Della Morte, S. I. Eidelman, A. X. El-Khadra, A. Gérardin, D. Giusti, M. Golterman, Steven Gottlieb, V. Gülpers, F. Hagelstein, M. Hayakawa, G. Herdoíza, D. W. Hertzog, A. Hoecker, M. Hoferichter, B.-L. Hoid, R. J. Hudspith, F. Ignatov, T. Izubuchi, F. Jegerlehner, L. Jin, A. Keshavarzi, T. Kinoshita, B. Kubis, A. Kupich, A. Kupść, L. Laub, C. Lehner, L. Lellouch, I. Logashenko, B. Malaescu, K. Maltman, M. K. Marinković, P. Masjuan, A. S. Meyer, H. B. Meyer, T. Mibe, K. Miura, S. E. Müller, M. Nio, D. Nomura, A. Nyffeler, V. Pascalutsa, M. Passera, E. Perez del Rio, S. Peris, A. Portelli, M. Procura, C. F. Redmer, B. L. Roberts, P. Sánchez-Puertas, S. Serednyakov, B. Shwartz, S. Simula, D. Stöckinger, H. Stöckinger-Kim, P. Stoffer, T. Teubner, R. Van de Water, M. Vanderhaeghen, G. Venanzoni, G. von Hippel, H. Wittig, Z. Zhang, M. N. Achasov, A. Bashir, N. Cardoso, B. Chakraborty, E.-H. Chao, J. Charles, A. Crivellin, O. Deineka, A. Denig, C. DeTar, C. A. Dominguez, A. E. Dorokhov, V. P. Druzhinin, G. Eichmann, M. Fael, C. S. Fischer, E. Gámiz, Z. Gelzer, J. R. Green, S. Guellati-Khelifa, D. Hatton, N. Hermansson-Truedsson et al. (32 additional authors not shown)

The Muon g-2 Theory Initiative

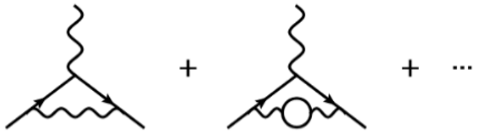
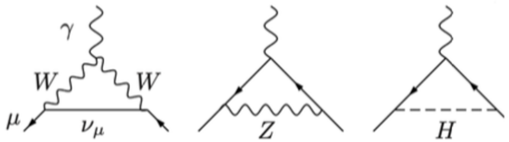
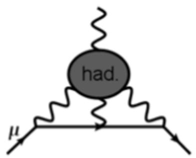
Muon g-2 in the SM

$\Delta a_\mu = 279(76) \times 10^{-11} \rightarrow 2.39(0.65)$ ppm



- a_μ arises due to quantum corrections / higher order interactions / loop contributions
- All SM particles contribute → Calculate and sum all sectors of the SM:

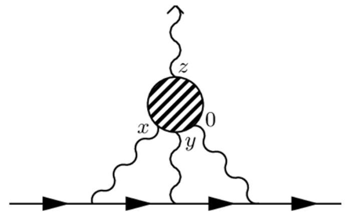
$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

			a_μ^{SM} portion	δa_μ^{SM} portion
QED		Perturbative (Known to five-loop)	$\sim$ 99.99%	~0.001%
EW		Perturbative (Known to two-loop)	$\sim$ 1 ppm	~0.2%
HVP		Non-perturbative (Data-driven & lattice)	$\sim$ 59 ppm	**~84%**
HLbL		Non-perturbative (Data-driven & lattice)	$\sim$ 1 ppm	**~16%**

Muon g-2 in the SM: HLbL

$$\Delta a_\mu = 279(76) \times 10^{-11} \rightarrow 2.39(0.65)\ \text{ppm}$$

- HLbL scattering - hadronic blob coupled to 3 off-shell/1 on-shell photon.
- Four point function - notoriously difficult to calculate.
- Previously only calculated from models with large systematics.

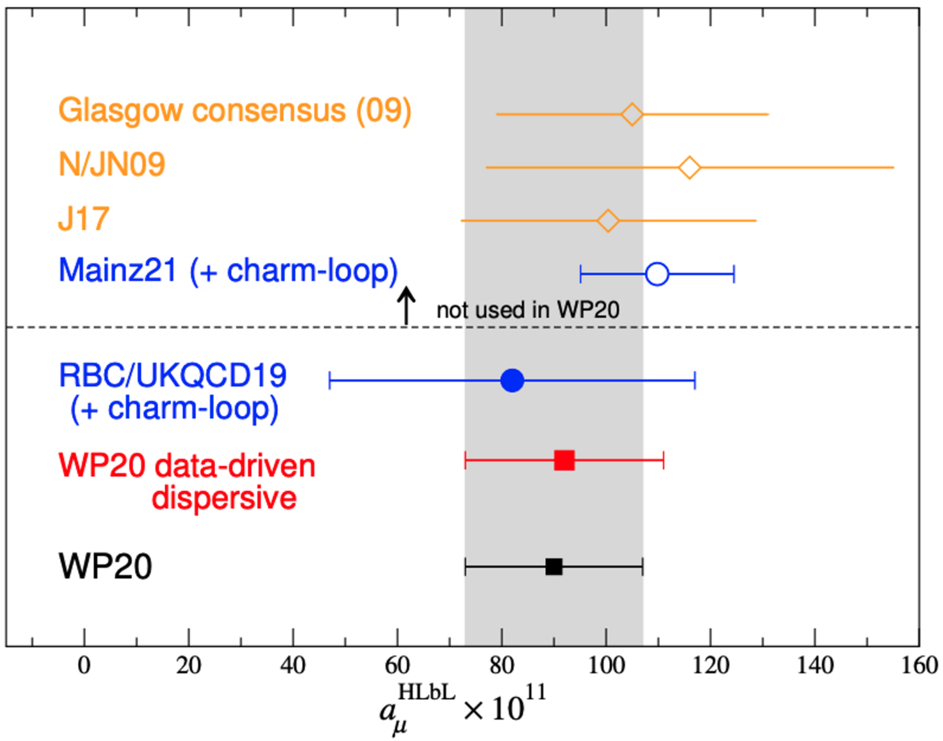


Data-driven (error ~ 0.2 ppm of a_μ^{SM})

- Model-independent dispersive evaluation, using data (e.g. π, η, η' TFFs) as input for hadronic insertions.

Lattice (error ~ 0.3 ppm of a_μ^{SM})

- Model-independent evaluation, computed on discretized Euclidean spacetime (lattice) in finite volume.



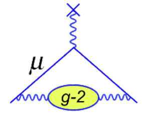
Recommended Muon g-2 TI result (before Mainz):

$$a_\mu^{\text{HLbL}} = 92(18) \times 10^{-11}$$

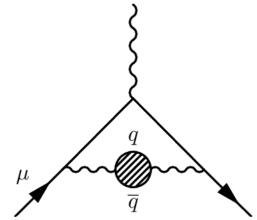
Improved, but still evolving. Still systematics dominated (goal < 10% uncertainty)

Muon g-2 in the SM: HVP

$$\Delta a_\mu = 279(76) \times 10^{-11} \rightarrow 2.39(0.65)\ \text{ppm}$$



- Hadronic Vacuum Polarisation - hadronic blob coupled to 2 photons.
- Two-point function - in principle, much easier than HLbL.
- Most precisely calculated from $e^+e^- \rightarrow$ hadrons cross section data.



Lattice (error ~ 1.6 ppm of a_μ^{SM})

- Uncertainties dominated by finite volume, discretisation and isospin breaking systematics.

Data-driven (error ~ 0.3 ppm of a_μ^{SM})

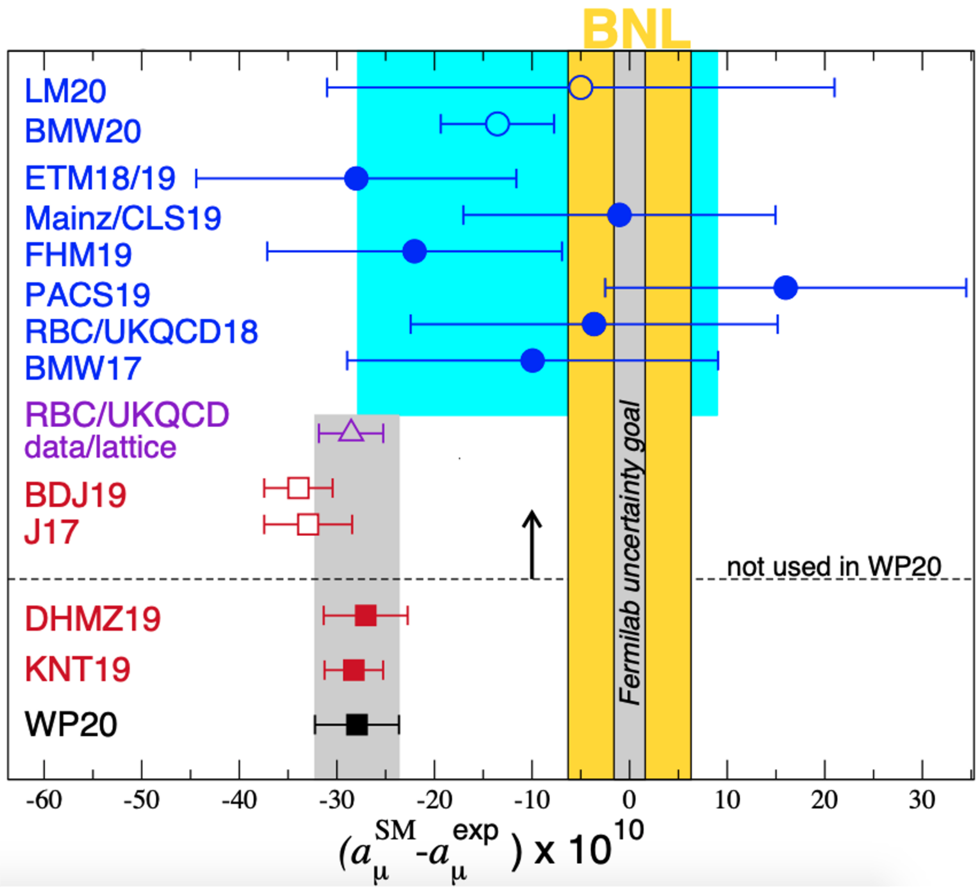
- Cross section data consistently combined and input into dispersion integral:

$$a_\mu^{\text{LO HVP}} = \frac{1}{4\pi^3} \int_{s_{th}}^{\infty} \mathrm{d}s\, K(s)\, \sigma_{\text{had}}(s)$$

- Several groups have achieved this.

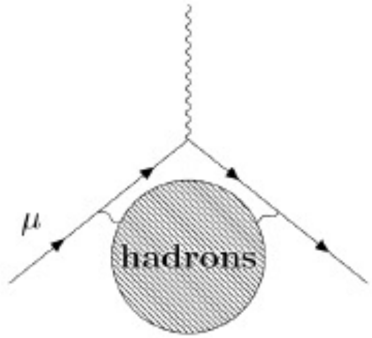
Recommended Muon g-2 TI value from data-driven result:

$$a_\mu^{\text{HVP}} = 6845(40) \times 10^{-11}$$

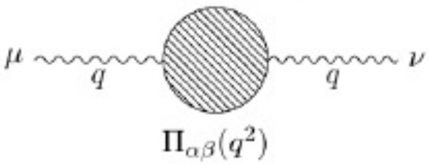


Dispersive HVP: theoretical setup

⇒ We want to calculate the leading order hadronic vacuum polarisation (HVP) contribution



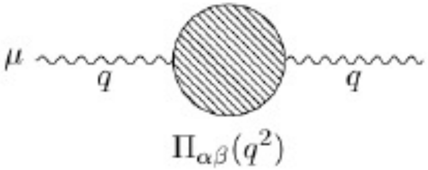
1) Feynman rules for HVP insertion to photon propagator:



$$= \frac{-ig^{\mu\alpha}}{(q^2 - i\varepsilon)}(-ie)i\Pi_{\alpha\beta}(q^2)(-ie)\frac{-ig^{\beta\nu}}{(q^2 - i\varepsilon)}$$

$\Pi_{\alpha\beta}(q^2)$

2) Employ analyticity:



$$= \frac{ie^2 g_{\mu\nu}}{(q^2 - i\varepsilon)^2}\frac{q^4}{\pi}\int_{s_{th}}^{\infty} \mathrm{d}s \frac{\mathrm{Im}\,\Pi(s)}{s(s - q^2 - i\varepsilon)}$$

$\Pi_{\alpha\beta}(q^2)$

3) Insert to vertex correction, solve for a_μ: $a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{\alpha}{\pi^2}\int_{s_{th}}^{\infty} \frac{\mathrm{d}s}{s}\mathrm{Im}\,\Pi_{\mathrm{had}}(s)K(s)$

4) Utilise optical theorem:

5) Arrive at equation for $a_\mu^{\mathrm{had,\,LO\,VP}}$:

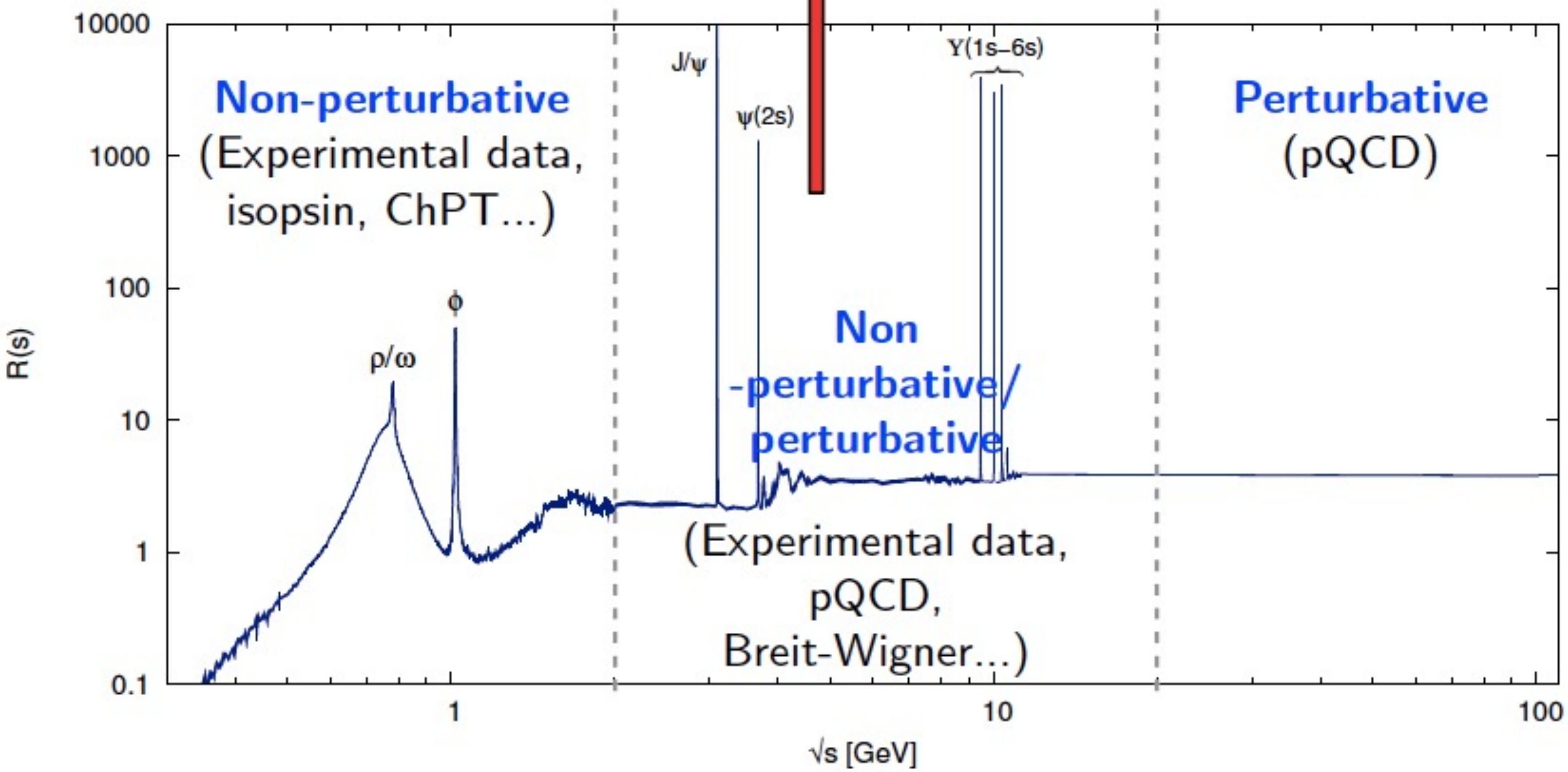
$$a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} \mathrm{d}s\, \sigma^0_{\mathrm{had},\gamma}(s)K(s)$$

$\sigma^0_{\mathrm{had},\gamma}$ = bare cross section, FSR included

⇒ Similar dispersion integrals for NLO and NNLO HVP

Building the hadronic R-ratio

$$a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{ds}{s}R(s)K(s), \text{ where } R(s) = \frac{\sigma^0_{\mathrm{had},\gamma}(s)}{4\pi\alpha^2/3s}$$

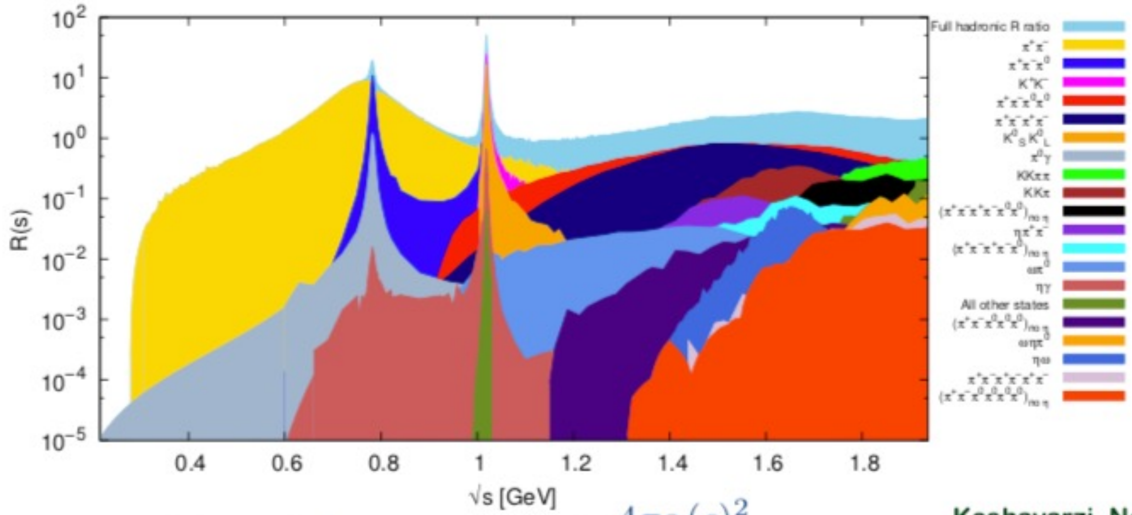


Dispersive HVP

Slide content by Aida El-Khadra.

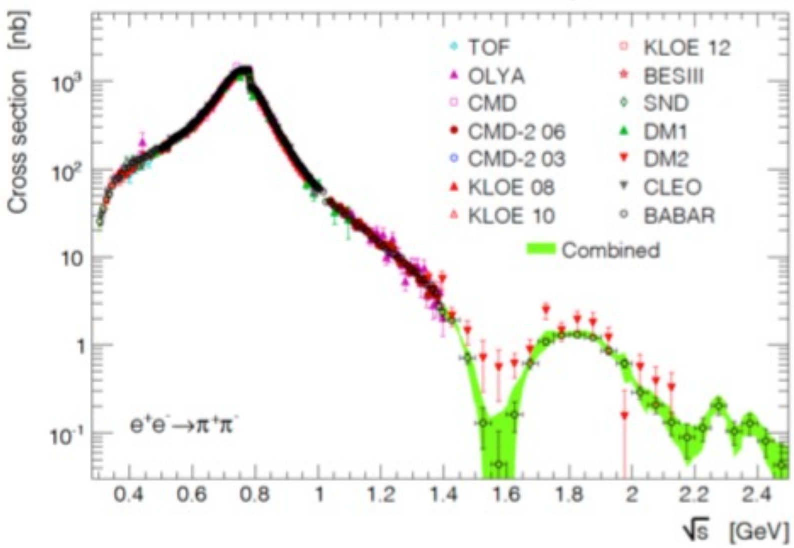
- Target: ~0.2% total error
- Dispersion relation + experimental data for $e^+e^- \to \mathrm{hadrons}$ (and τ data)
  - current uncertainty ~0.5%
  - can be improved with more precise experimental data
  - new experimental measurements expected/ongoing at BaBar, BES-III, Belle-II, CMD-3, SND, KEDR, KLOE,….
- Challenges:
  - below ~2 GeV: sum > 30 exclusive channels: 2π, 3π, 4π, 5π, 6π, $2K$, $2K\pi$, $2K2\pi$, $\eta\pi$,…. (use isospin relations for missing channels)
  - above ~1.8 GeV: inclusive, pQCD (away from flavor thresholds) + narrow resonances (J/ψ, Υ,..)
  - Combine data from different experiments/measurements: understanding correlations, sources of sys. error, tensions…
  - include FS radiative corrections

Low energy hadronic cross section



$$R(s) = \sigma(e^+e^- \to \text{hadrons}) / \frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner
PRD 2018



Davier, Hoecker, Malaescu, Zhang
EPJC 2020

Dispersive HVP from KNT

The muon $g-2$ and $\alpha(M_Z^2)$: a new data-based analysis

Alexander Keshavarzi[1], Daisuke Nomura[2,3] and Thomas Teubner[4]

[1] *Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom*
Email: a.i.keshavarzi@liverpool.ac.uk

[2] *KEK Theory Center, Tsukuba, Ibaraki 305-0801, Japan*
[3] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
Email: dnomura@post.kek.jp

[4] *Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom*
Email: thomas.teubner@liverpool.ac.uk

Abstract

This work presents a complete re-evaluation of the hadronic vacuum polarisation contributions to the anomalous magnetic moment of the muon, $a_\mu^{\rm had,\,VP}$ and the hadronic contributions to the effective QED coupling at the mass of the Z boson, $\Delta\alpha_{\rm had}(M_Z^2)$, from the combination of $e^+e^- \to$ hadrons cross section data. Focus has been placed on the development of a new data combination method, which fully incorporates all correlated statistical and systematic uncertainties in a bias free approach. All available $e^+e^- \to$ hadrons cross section data have been analysed and included, where the new data compilation has yielded the full hadronic R-ratio and its covariance matrix in the energy range $m_\pi \le \sqrt{s} \le 11.2$ GeV. Using these combined data and perturbative QCD above that range results in estimates of the hadronic vacuum polarisation contributions to $g-2$ of the muon of $a_\mu^{\rm had,\,LO\,VP} = (693.26 \pm 2.46) \times 10^{-10}$ and $a_\mu^{\rm had,\,NLO\,VP} = (-9.82 \pm 0.04) \times 10^{-10}$. The new estimate for the Standard Model prediction is found to be $a_\mu^{\rm SM} = (11\,659\,182.04 \pm 3.56) \times 10^{-10}$, which is 3.7σ below the current experimental measurement. The prediction for the five-flavour hadronic contribution to the QED coupling at the Z boson mass is $\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = (276.11 \pm 1.11) \times 10^{-4}$, resulting in $\alpha^{-1}(M_Z^2) = 128.946 \pm 0.015$. Detailed comparisons with results from similar related works are given.

← Major 2018 update to data combination methodology and data input.
Results for $a_\mu^{\text{had, VP}}$ and $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$.
Phys.Rev.D 97 (2018) 114025.

2019 data update and applications of data → compilation to other observables.
Results for a_e, a_μ, a_τ, $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$ and $\Delta\nu_{\rm Mu}^{\text{had, VP}}$.
Phys.Rev.D 101 (2020) 014029.

The $g-2$ of charged leptons, $\alpha(M_Z^2)$ and the hyperfine splitting of muonium

Alexander Keshavarzi[1,2], Daisuke Nomura[3] and Thomas Teubner[4]

[1] *Department of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, United Kingdom*
[2] *Department of Physics and Astronomy, The University of Mississippi, Mississippi 38677, U.S.*
Email: alexander.keshavarzi@manchester.ac.uk

[3] *KEK Theory Center, Tsukuba, Ibaraki 305-0801, Japan*
Email: dnomura@post.kek.jp

[4] *Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom*
Email: thomas.teubner@liverpool.ac.uk

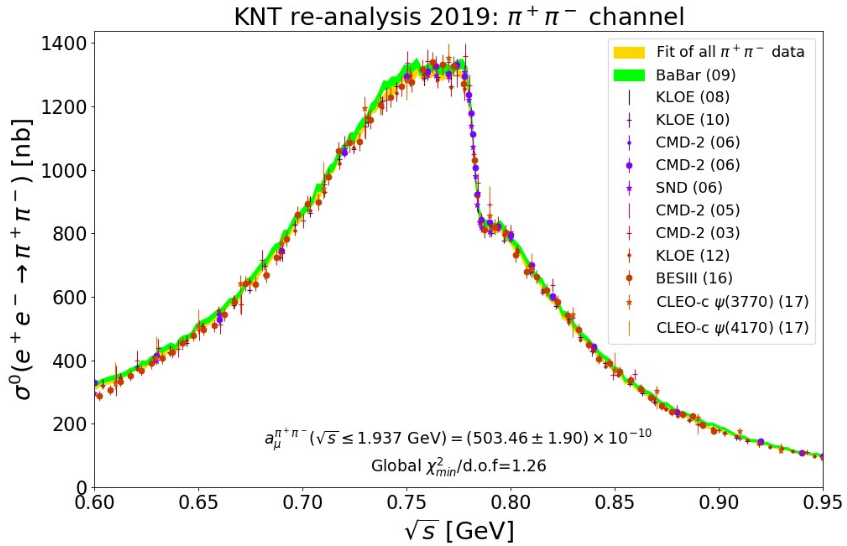
Abstract

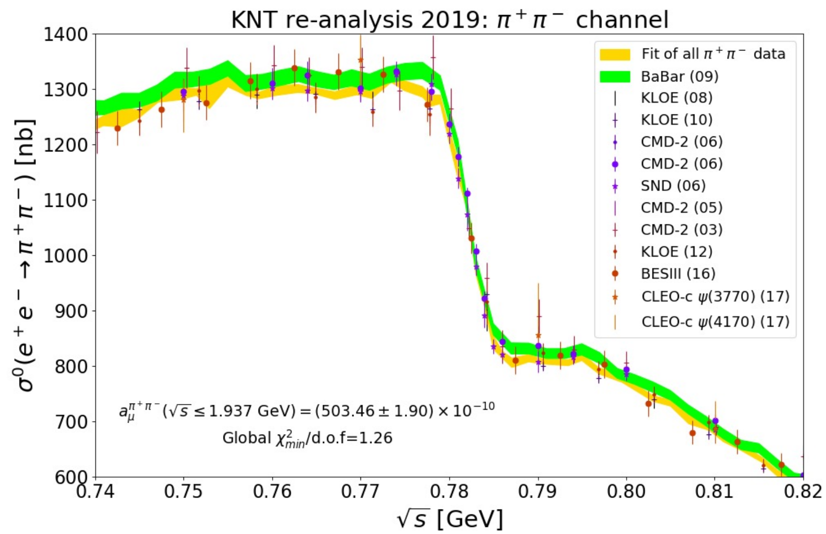
Following updates in the compilation of $e^+e^- \to$ hadrons data, this work presents re-evaluations of the hadronic vacuum polarisation contributions to the anomalous magnetic moment of the electron (a_e), muon (a_μ) and tau lepton (a_τ), to the ground-state hyperfine splitting of muonium and also updates the hadronic contributions to the running of the QED coupling at the mass scale of the Z boson, $\alpha(M_Z^2)$. Combining the results for the hadronic vacuum polarisation contributions with recent updates for the hadronic light-by-light corrections, the electromagnetic and the weak contributions, the deviation between the measured value of a_μ and its Standard Model prediction amounts to $\Delta a_\mu = (28.02 \pm 7.37) \times 10^{-10}$, corresponding to a muon $g-2$ discrepancy of 3.8σ.

The $\pi^+\pi^-$ channel *Phys.Rev.D* 101 (2020) 014029.

$\pi^+\pi^-$ accounts for over 70% of $a_\mu^{\text{had, LOVP}}$

→ Combines ~30 measurement totalling over 1000 data points





→ Correlated & experimentally corrected $\sigma^0_{\pi\pi(\gamma)}$ data entirely dominant

$$a_\mu^{\pi^+\pi^-}[0.305 \leq \sqrt{s} \leq 1.937 \text{ GeV}] = 503.46 \pm 1.14_{stat} \pm 1.52_{sys} \pm 0.05_{vp} \pm 0.14_{fsr}$$
$$= 503.46 \pm 1.91_{tot}$$

→ 14% local χ^2_{min}/d.o.f. error inflation due to tensions in clustered data

The $\pi^+\pi^-$ channel *Phys.Rev.D* 101 (2020) 014029.

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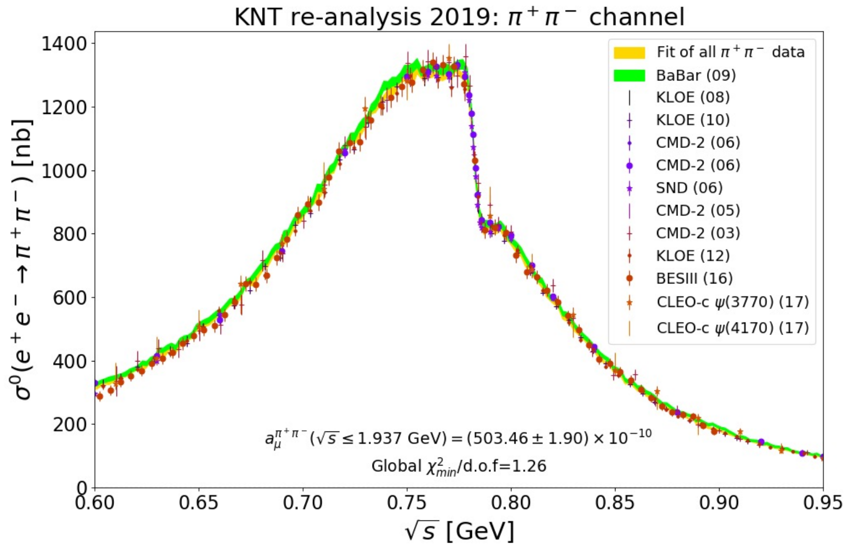

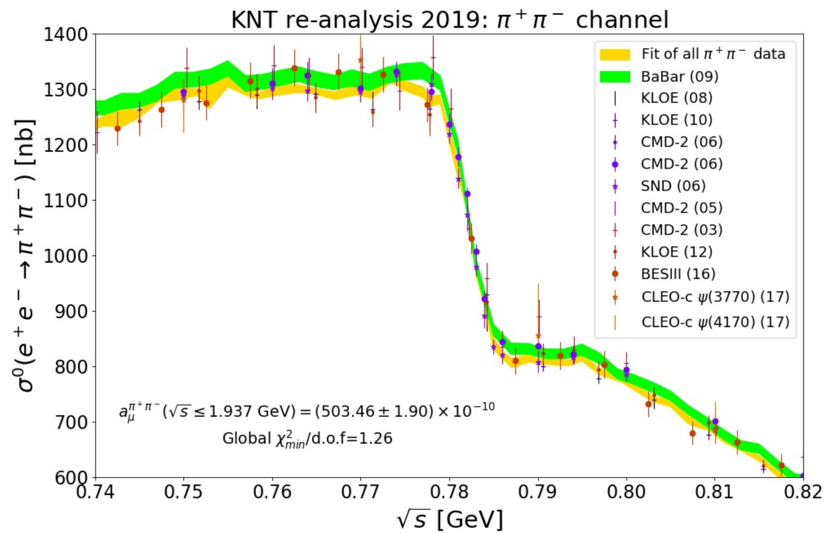

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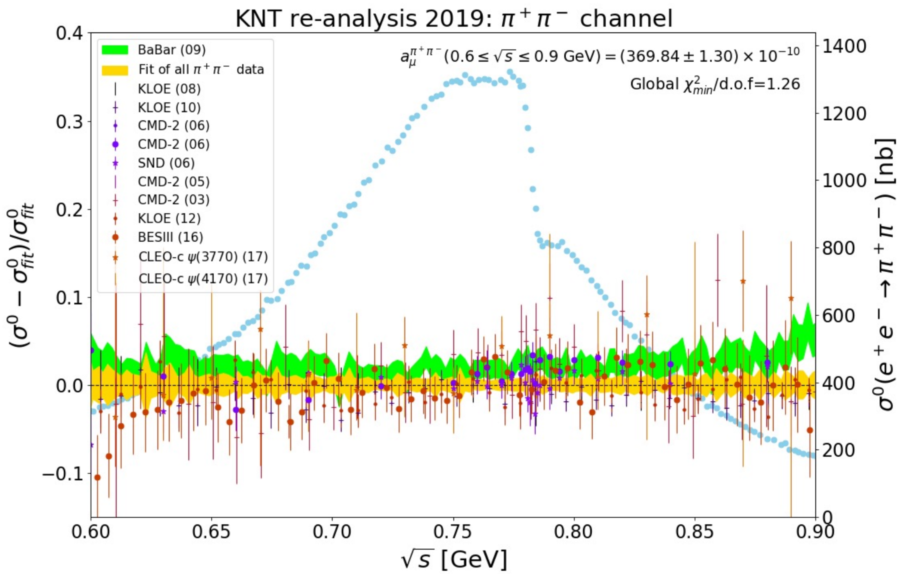
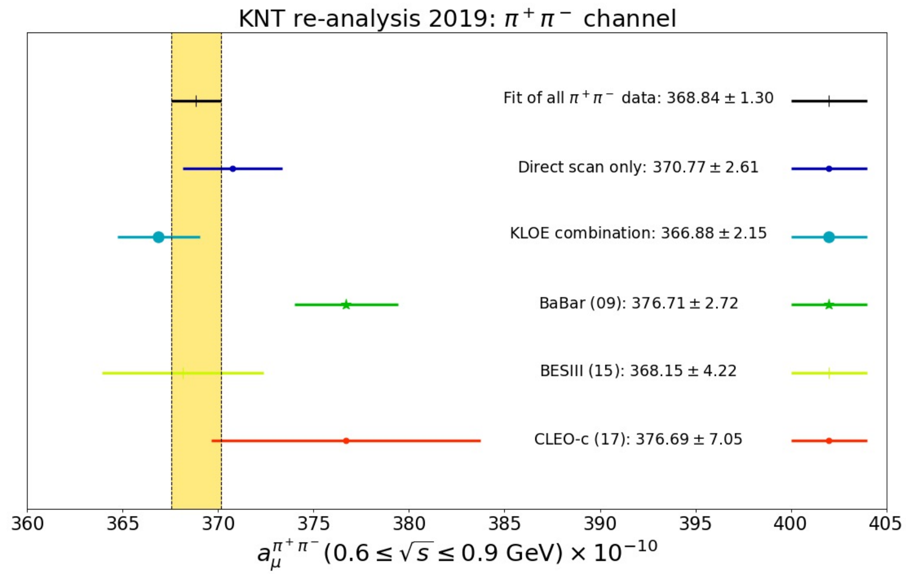
→ 14% local χ^2_{min}/d.o.f. error inflation due to tensions in clustered data

The $\pi^+\pi^-$ channel *Phys.Rev.D* 101 (2020) 014029.

Large difference between KNT vs. BaBar and KLOE vs. BaBar is still evident.





Compared to $a_\mu^{\pi^+\pi^-} = 503.5 \pm 1.9 \rightarrow a_\mu^{\pi^+\pi^-}$(BaBar data only) = 513.2 ± 3.8

Simple weighted average of all data → $a_\mu^{\pi^+\pi^-}$(weighted average) = 509.2 ± 2.9

(i.e. – no correlations in determination of mean value)

BaBar data dominate when no correlations are accounted for in the mean value.

- ➢ Highlights the importance of incorporating available correlated uncertainties in fit.

$a_\mu^{\text{had, LO VP}}$ from KNT *Phys.Rev.D* 101 (2020) 014029.

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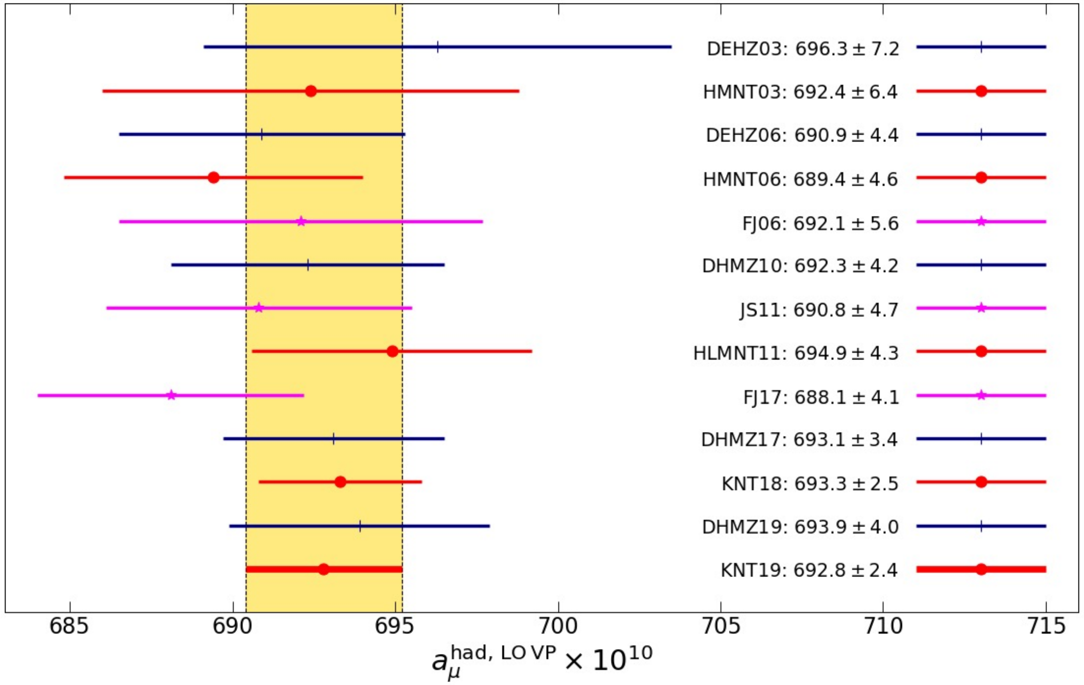
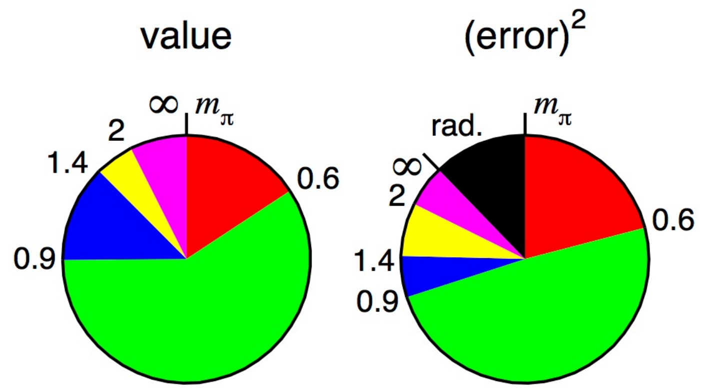
KNT18: $a_\mu^{\text{had, LOVP}} = 693.26 \pm 2.46_{tot}$

$$a_\mu^{\text{had, LOVP}} = 693.84 \pm 1.19_{stat} \pm 1.96_{sys} \pm 0.22_{vp} \pm 0.71_{fsr}$$
$$= 693.84 \pm 2.29_{exp} \pm 0.74_{rad}$$
$$= 692.78 \pm 2.42_{tot}$$



- Precision better than 0.4% (uncertainties include all available correlations and χ^2 inflation)



- Clear $\pi^+\pi^-$ dominance

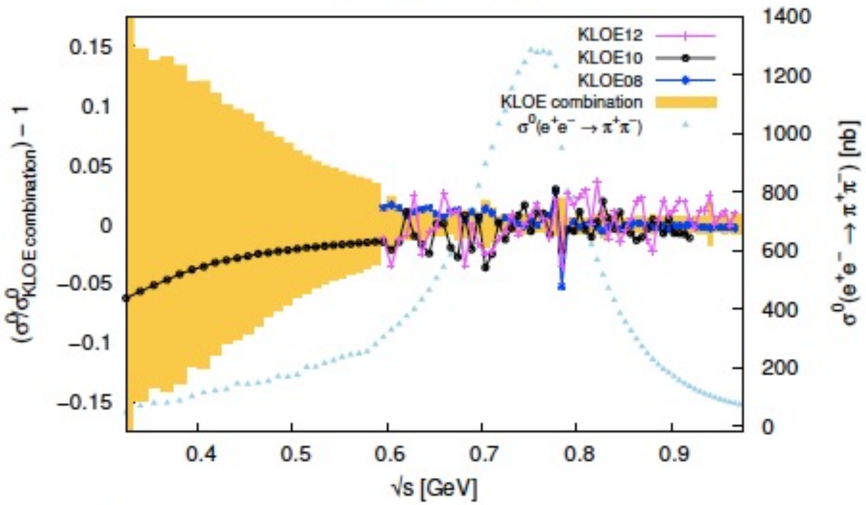
KNT vs. DHMZ: the use of correlations

Differences are dominated by the choices of how to use the correlations

$\Rightarrow$ Consider the combination of the KLOE $\pi^+\pi^-$ data sets:

KNT18

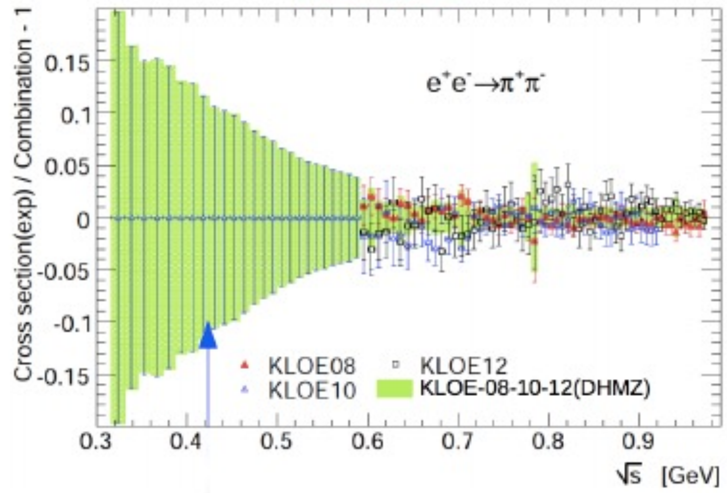
Use available uncertainty and correlation information to fully influence over entire energy range



$$a_\mu^{\pi^+\pi^-}(\sqrt{s} \leq 2.0\ \text{GeV}) = 503.74 \pm 1.96$$

DHMZ17

Only allow correlations to only influence the combination locally inside defined energy intervals



$$a_\mu^{\pi^+\pi^-}(\sqrt{s} \leq 2.0\ \text{GeV}) = 507.14 \pm 2.58$$

Take-home message: correlations are important and the choices of how to use them are not trivial

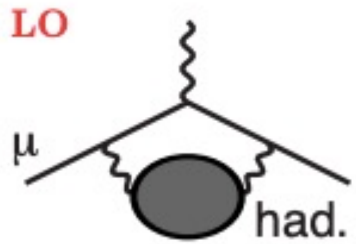
Data-driven HVP

Slide content by Aida El-Khadra.

First-time agreement between various groups…

Detailed comparisons by-channel and energy range between direct integration results:

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
$K_S K_L$	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
[3.7, ∞) GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\text{DV+QCD}}$	692.8(2.4)	1.2



+ evaluations using unitarity & analyticity constraints for $\pi\pi$ and $\pi\pi\pi$ channels
[CHS 2018, HHKS 2019]

Conservative merging to obtain a realistic assessment of the underlying uncertainties:
- account for differences in results from the same experimental inputs
- include correlations between systematic errors

$$\Rightarrow a_\mu^{\text{HVP,LO}} = 693.1\,(4.0) \times 10^{-10}$$

Lattice HVP

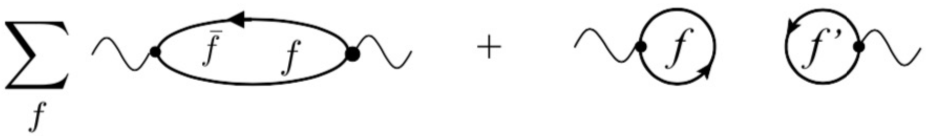
Slide content by Aida El-Khadra.

Calculate a_μ^{HVP} in Lattice QCD:

$$a_\mu^{\mathrm{HLO}} \equiv a_\mu^{\mathrm{HVP,LO}} = \sum_f a_{\mu,f}^{\mathrm{HVP,LO}} + a_{\mu,\mathrm{disc}}^{\mathrm{HVP,LO}}$$

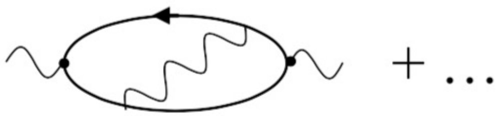
- Separate into connected for each quark flavor + disconnected contributions (gluon and sea-quark background not shown in diagrams)

  Note: almost always $m_u = m_d$



f= ud, s, c, b

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



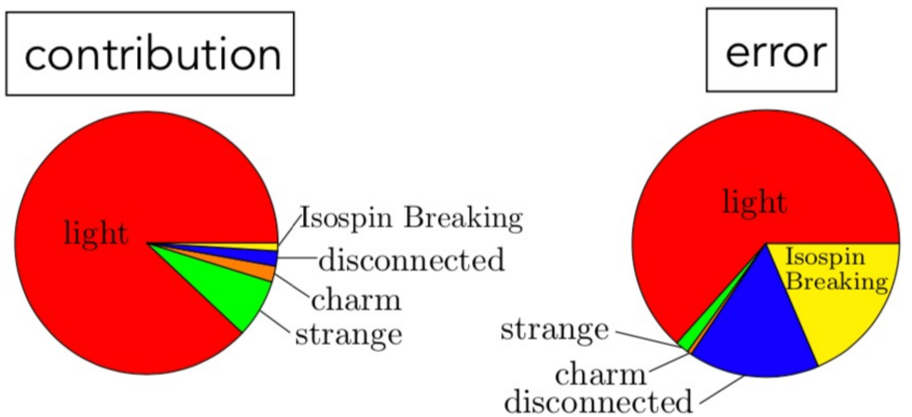
  - either perturbatively on isospin symmetric QCD background
  - or by using QCD + QED ensembles with $m_u \neq m_d$

Lattice HVP

Slide content by Aida El-Khadra.

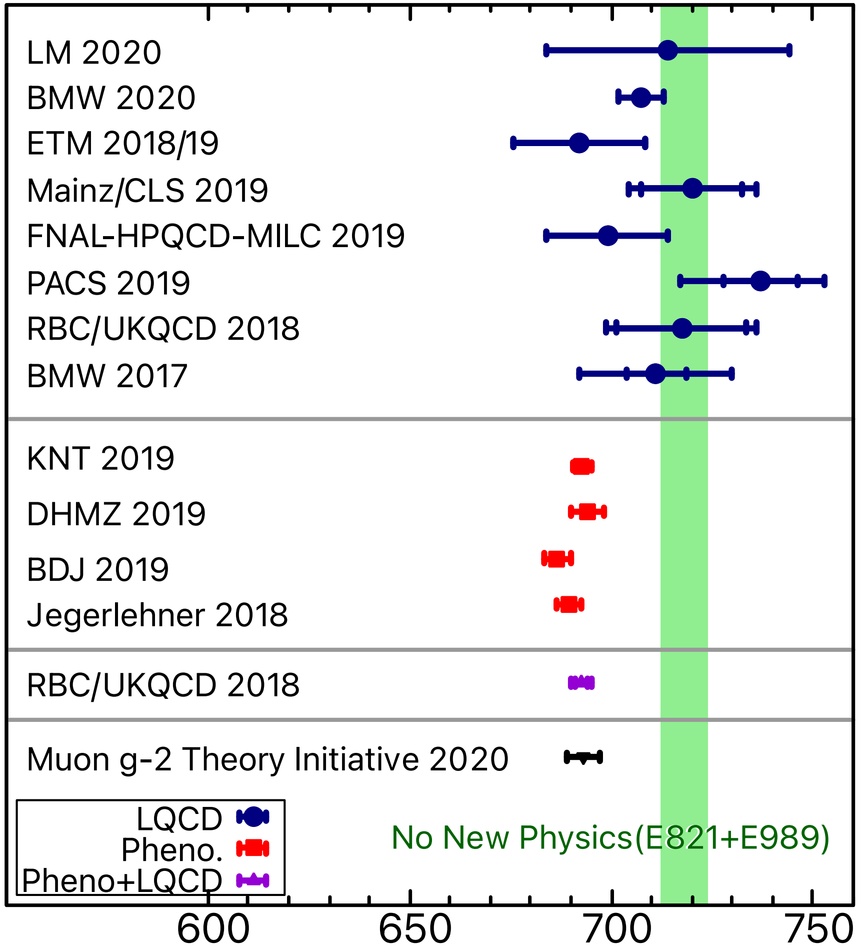
- Target: < 0.5% total error
- light-quark connected contribution, $a_{\mu,ud}^{\mathrm{HLO}}$:
  ~90% of total, with 1-3% error
- ``heavy" flavor contributions, $a_{\mu,s}^{\mathrm{HLO}}$, $a_{\mu,c}^{\mathrm{HLO}}$, $a_{\mu,b}^{\mathrm{HLO}}$:
  ~8%, 2%, 0.05% of total a_{μ}^{HLO}, can be calculated with sufficient precision
- disc. contribution:
  ~2% of total a_{μ}^{HLO}, contributes ~0.3-1% error to a_{μ}^{HLO}
- Isospinbreaking (QED + $m_u \neq m_d$) corrections:
  ~1% of total a_{μ}^{HLO}, contribute ~0.3-1% error

[V. Gülpers, adapted for WP from talk @ Lattice 2019, arXiv:2001.11898]



Lattice HVP

Slide content by Tom Blum.



HVP (BMW-20): $a_\mu = 707.5\ (5.5)$ x 10^{-10} (0.75%)

HVP (Lattice, WP): $a_\mu = 711.6\ (18.4)$ x 10^{-10} (2.6%)

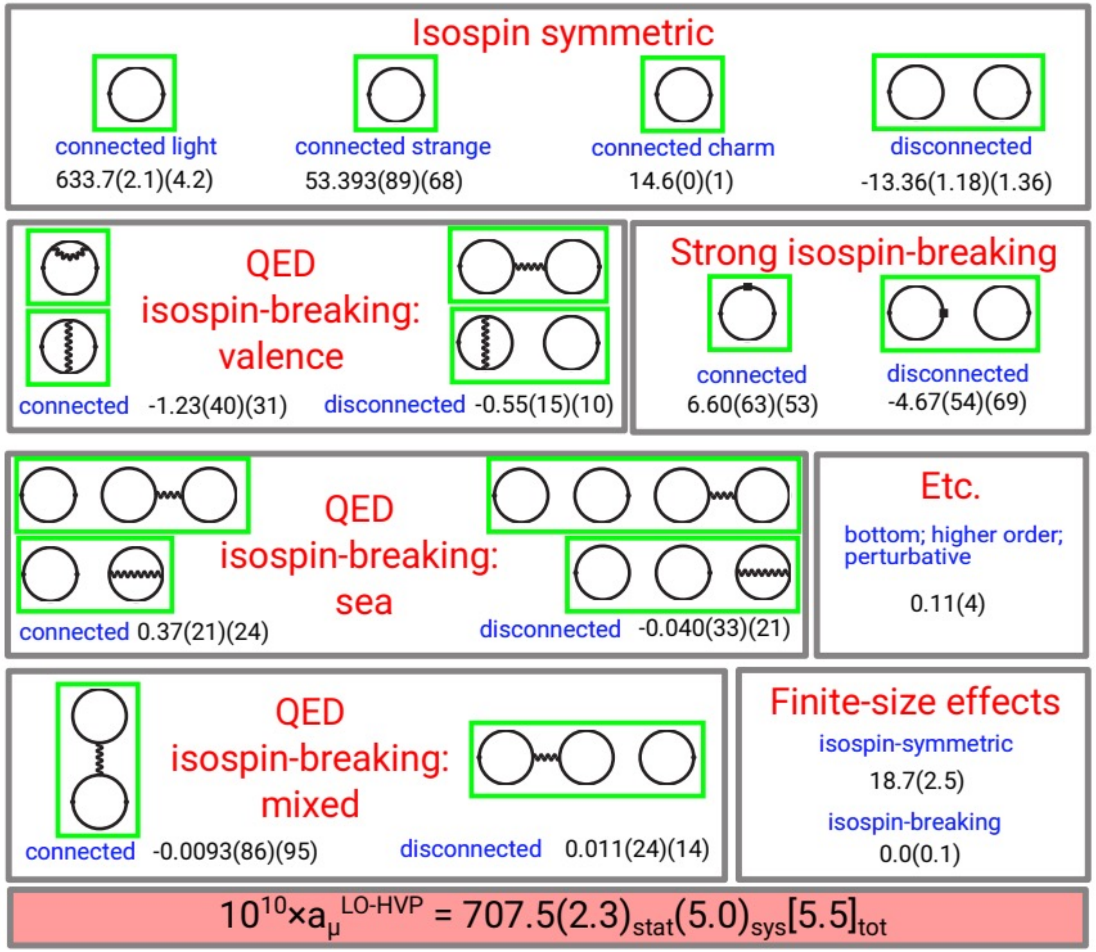
HVP (data driven): $a_\mu = 693.1\ (4.0)$ x 10^{-10} (0.58%)

Lattice, WP – data driven $\approx 18.5\ (18.8)$

BMW-20 – data driven $\approx 14.4\ (6.8)$

The BMW result

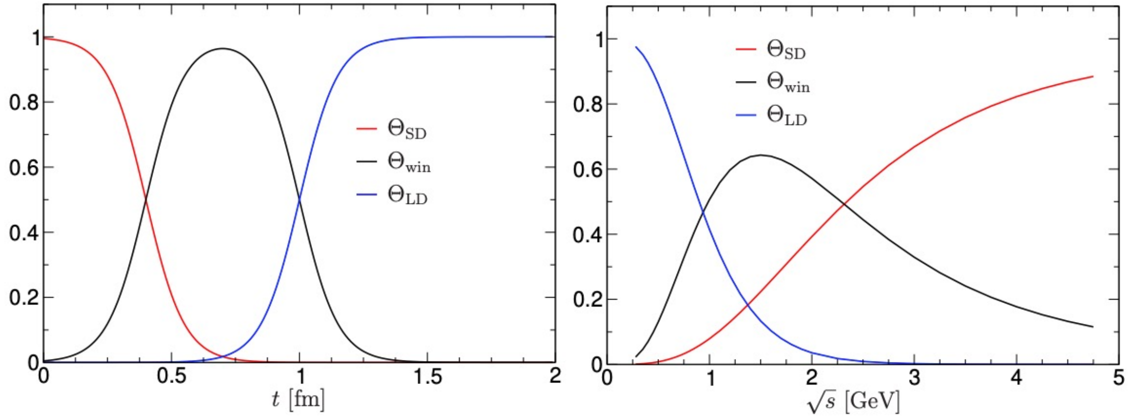
Borsanyi et al. Nature 2021



State-of-the-art lattice calculation of based on:

- current-current correlator, summed over all distances, integrated in time with appropriate kernel function
- using staggered fermions on an L ~ 6 fm lattice (L ~ 11fm used for finite volume corrections)
- at (and around) physical quark masses
- including isospin-breaking effects

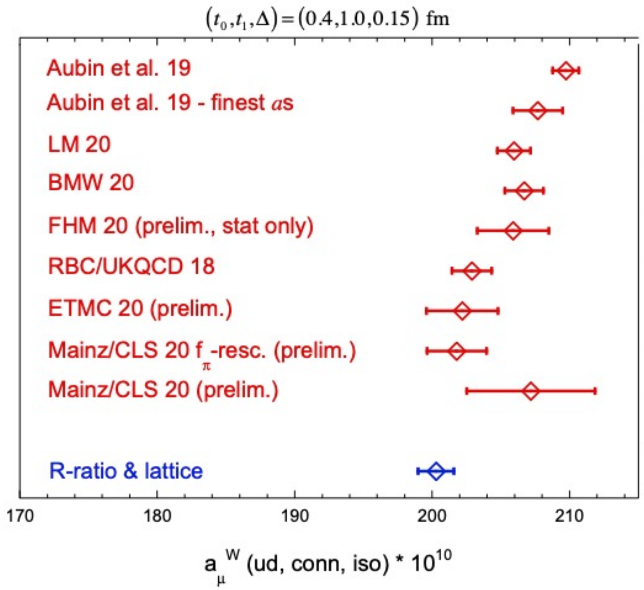
Comparing evaluations D. Giusti, talk at Lattice 2021

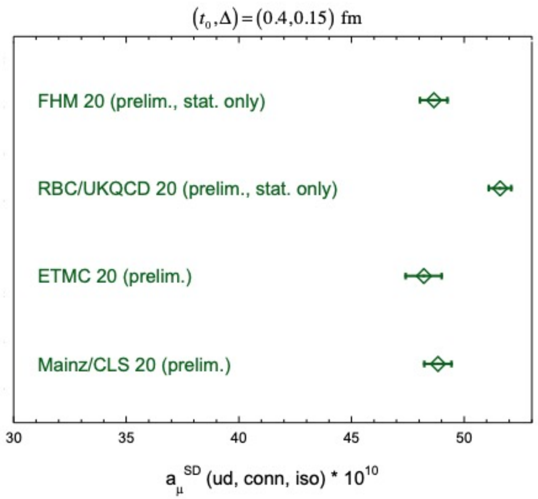


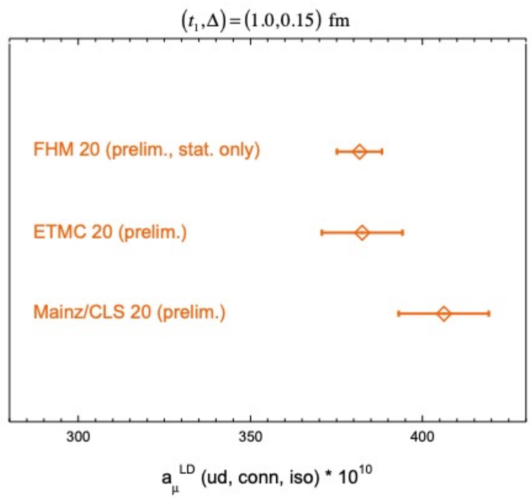
Weight functions for window quantities to compare lattice with lattice, and lattice with data

Comparing ud contributions:

f	$a_\mu^{SD}(f)\cdot 10^{10}$	$a_\mu^{W}(f)\cdot 10^{10}$	$a_\mu^{LD}(f)\cdot 10^{10}$
ud	48.2 (0.8)	202.2 (2.6)	382.5 (11.7)







Lattice HVP status

Slide content by Tom Blum.

To reach desired precision (2-5 per-mil):

- Strange, charm, (bottom) contributions in good shape.
  (will not resolve issues)
- FV corrections $(L > 6\ \mathrm{fm})$ reliable (NNLO χPT, LLGS, HP).
  Important to have a big box (BMW, PACS use L = 10 fm)
- Statistical precision top priority for DW, TM, Wilson (in progress).
  Improved bounding method, low-lying states for long distance tail.
- Physical masses
  (most groups already)
- More, more precise disconnected and IB calculations needed.
- Continuum limit and scale setting (per-mil) are crucial.

Looking to the future:

- Careful, step-by-step study of differences between various lattice calculations now underway, data driven comparison to follow.
- Continuum limit is main focus now, expect it will shift.
- Lattice needs to build consensus, c.f. data driven approach. Happening within Muon g-2 Theory Initiative.
- New results with errors comparable to BMW 2020 soon.

Conclusions

- Fermilab's Muon g-2 Experiment has confirmed BNL's result: the discrepancy between experiment and SM increases to 4.2σ.
- All SM contributions other than HVP, including HLbL, now fully cross checked and understood to be under control.
- Data-driven HVP dominates theory uncertainty with 0.6% error.
- The BMW lattice QCD result weakens the exp-SM discrepancy. It must be confirmed or refuted by cross checks and other lattice calculations.
- Improvements to come:
  - Updated HVP evaluation with new measurements of hadronic cross section data.
  - HVP comparisons for BMW result and between lattice groups/R-ratio as part of theory initiative.
  - HLbL uncertainty to reach ~10% .
  - New, full SM update from theory initiative before Fermilab's next result.