The muon g-2 in the SM

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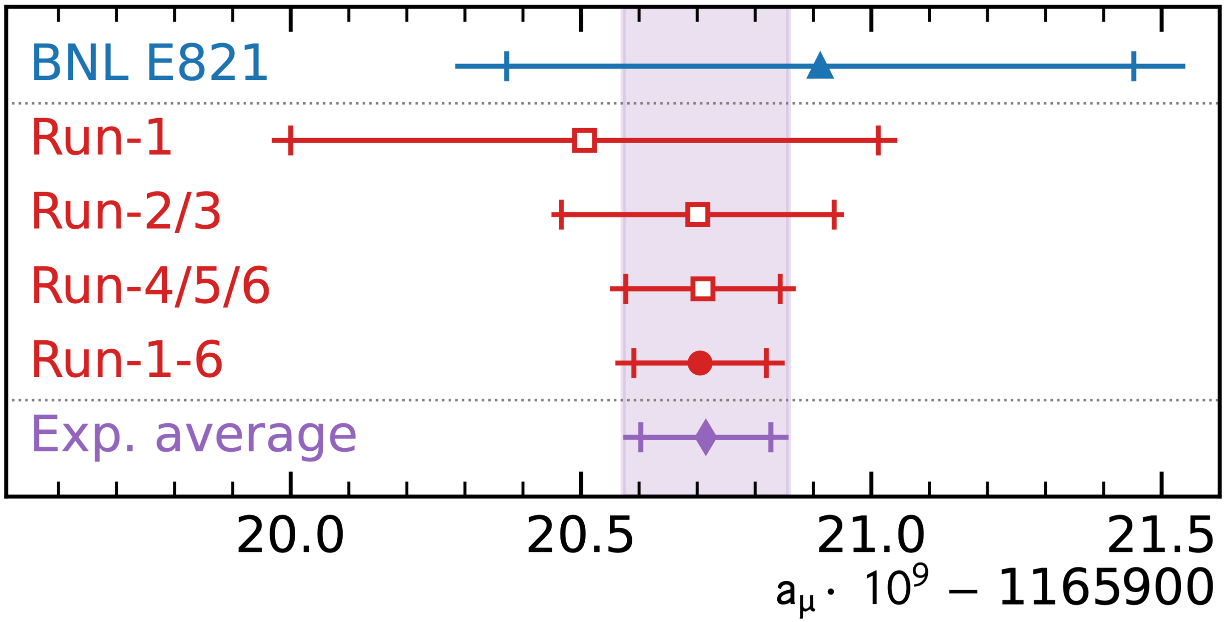
Muon g-2: FNAL confirms & improves BNL



a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [540ppb] BNL E821

a_μ^{EXP} = (116592070.5 ± 14.8) x 10^{-11} [127ppb] FNAL E989 (all runs)

a_μ^{EXP} = (116592071.5 ± 14.5) x 10^{-11} [124ppb] WA

- **FNAL reached fantastic final precision of 127ppb! See Siew Yan Ho's talk**
- **Muon g-2 proposal at J-PARC: See Gerco Onderwater's talk**

Muon g-2: the Standard Model prediction

WP25 = Updated White Paper of the Muon g-2 Theory Initiative:

arXiv:2505.21476

[WP20 = arXiv:2006.04822]

Muon g-2: the QED contribution

a_μ^{QED} = $(1/2)(\alpha/\pi)$ Schwinger 1948

+ $0.765857426\,(16)\,(\alpha/\pi)^2$

Sommerfield; Petermann; Suura&Wichmann ’57; Elend ’66; MP ’04

+ $24.05050988\,(28)\,(\alpha/\pi)^3$

Remiddi, Barbieri, Laporta … ; Czarnecki, Skrzypek ’99; MP ’04; Friot, Greynat & de Rafael ’05, Ananthanarayan, Friot, Ghosh 2020

+ $130.8780\,(60)\,(\alpha/\pi)^4$

Kinoshita & Lindquist ’81, … , Kinoshita & Nio ’04, ’05; Aoyama, Hayakawa,Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015; Steinhauser et al. 2013, 2015 & 2016 (all electron & τ loops, analytic); Laporta, PLB 2017 (mass independent term) COMPLETED[2]!

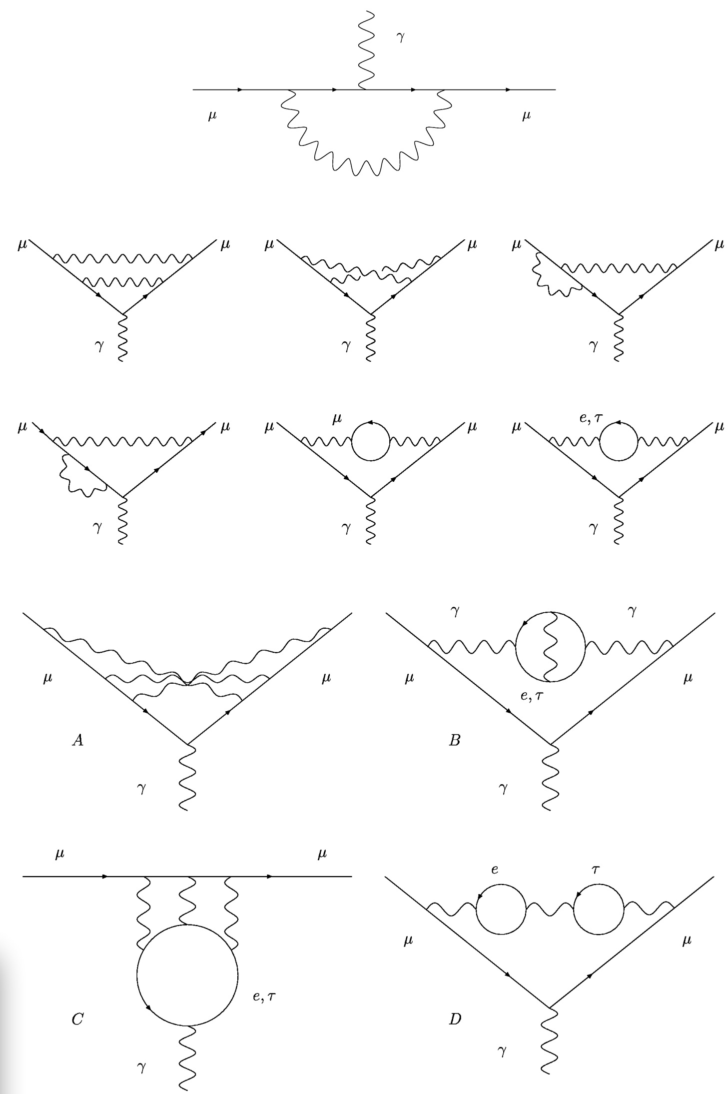
+ $750.15\,(86)\,(\alpha/\pi)^5$ COMPLETED!

Kinoshita et al. ‘90, … Aoyama, Hayakawa, Kinoshita, Nio 2012, 2015, 2017 & 2020. NB: Volkov 2404.00649 $A_1^{(10)}$ at variance with AHKN 2020, $\delta a_\mu \sim -0.6\times10^{-13}$. AHHN 2412.06473 result in agreement with Volkov.

Adding up, we get:

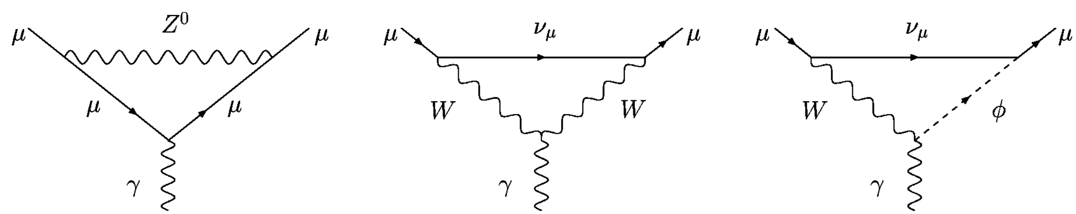
$a_\mu^{QED} = 116\,584\,718.8(2) \times 10^{-11}$ WP25 value

The error encompasses the difference 0.137×10^{-11} between the a_μ^{QED} values obtained using α(Cs) and α(Rb), and is comparable to the estimated error due to the missing 12th-order term: 0.1×10^{-11}.



The electroweak contribution

- **One-loop term:**



$$a_\mu^{\text{EW}}(\text{1-loop}) = \frac{5 G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1 + \frac{1}{5}\left(1 - 4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195 \times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda; Studenikin et al. ’80s

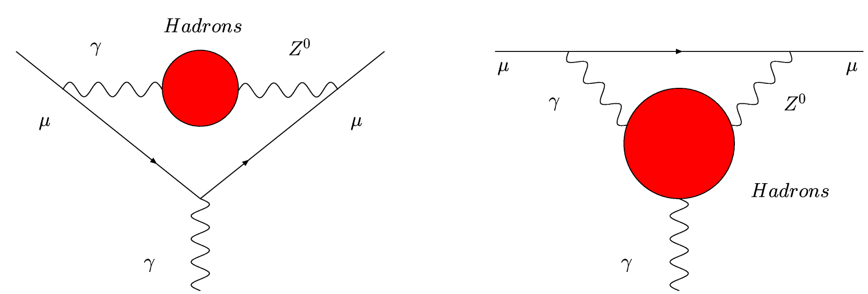
- **One-loop plus higher-order terms:**

$a_\mu^{EW} = 154.4\ (4) \times 10^{-11}$

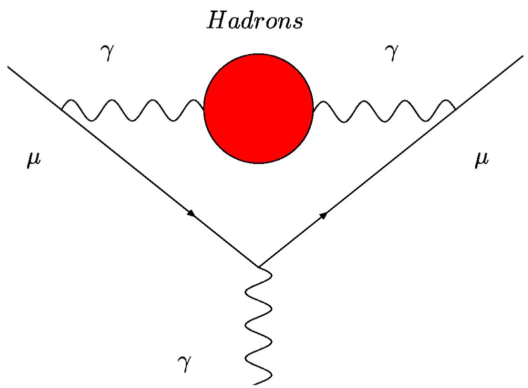
Hadronic loop uncertainties and 3-loop nonleading logs.

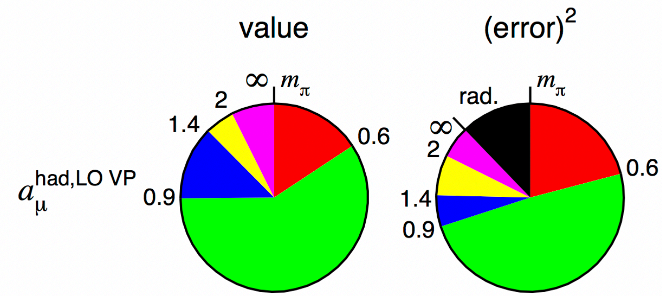
WP25 value

Kukhto et al. ’92; Czarnecki, Krause, Marciano ’95; Knecht, Peris, Perrottet, de Rafael ’02; Czarnecki, Marciano and Vainshtein ’02; Degrassi and Giudice ’98; Heinemeyer, Stockinger, Weiglein ’04; Gribouk and Czarnecki ’05; Vainshtein ’03; Gnendiger, Stockinger, Stockinger-Kim 2013; Ishikawa, Nakazawa, Yasui, 2019; Hoferichter, Lüdtke, Naterop, Procura, Stoffer 2025.



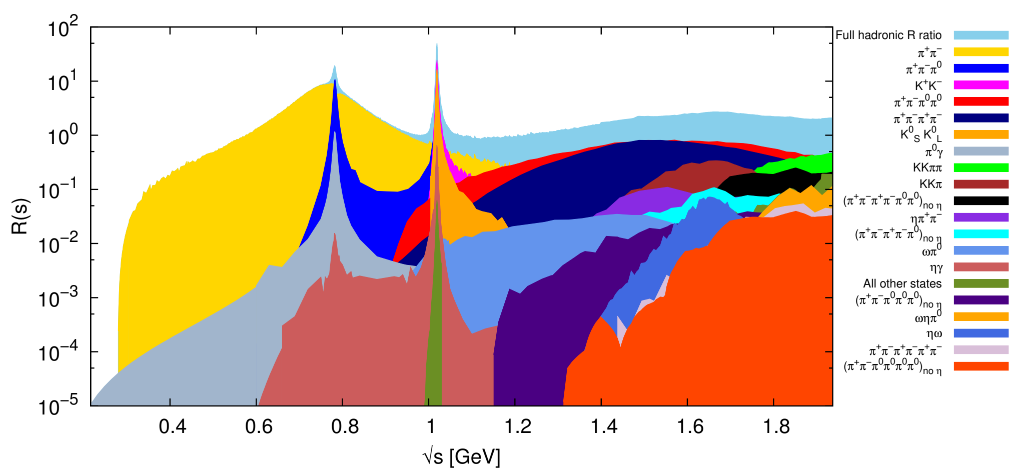
The hadronic LO contribution — dispersive approach





$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{\text{had}}^{(0)}(s)$$

$$K(s) = \int_0^1 dx \frac{x^2\,(1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

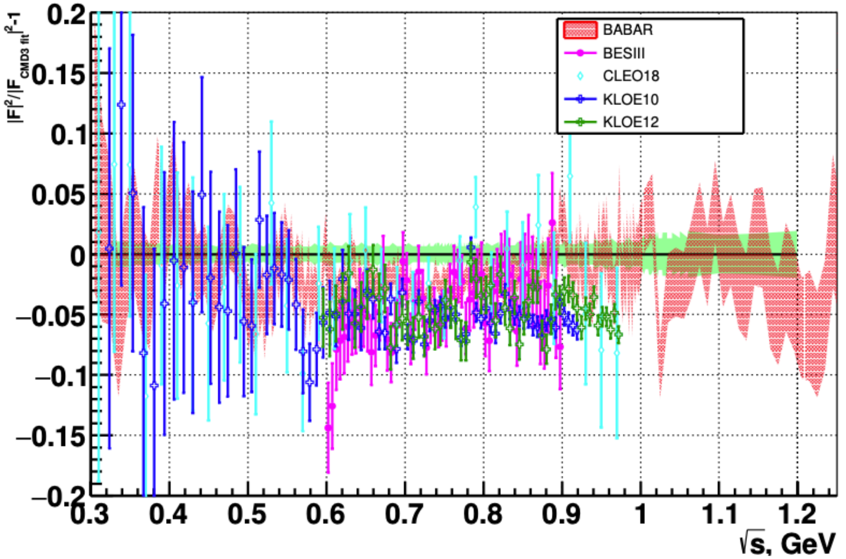


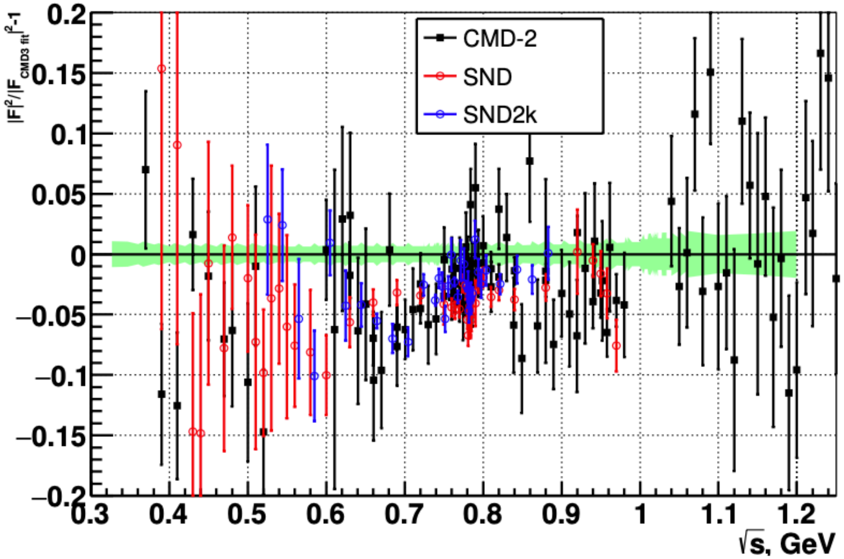
$$R(s) = \sigma(e^+e^- \to \text{hadrons}) / \frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner
PRD 2018

The CMD-3 σ($e^+e^- \to \pi^+\pi^-$) measurement

- **2023: CMD-3 released their σ($e^+e^- \to \pi^+\pi^-$) measurement from 0.32 to 1.2 GeV. It is larger than all previous measurements!**



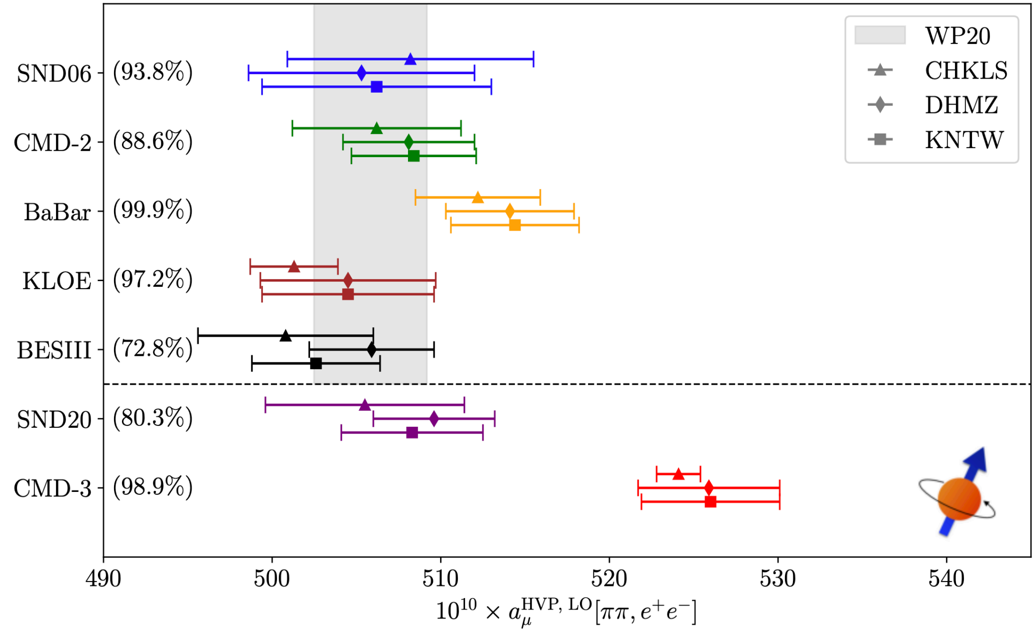


CMD-3 Collaboration, 2302.08834

$$a_\mu(\mathrm{exp}) - a_\mu^{\mathrm{SM}}(\text{CMD-3 } 2\pi) = 49\ (55) \times 10^{-11}$$

CMD-3 Collaboration, 2309.12910

The hadronic LO contribution — dispersive approach (2)



WP25

- **Due to significant spread of results, no new WP25 average for $\pi^+\pi^-$ channel.**
- **Radiative Corrections to $\sigma(s)$ are crucial and (still) under close scrutiny.**

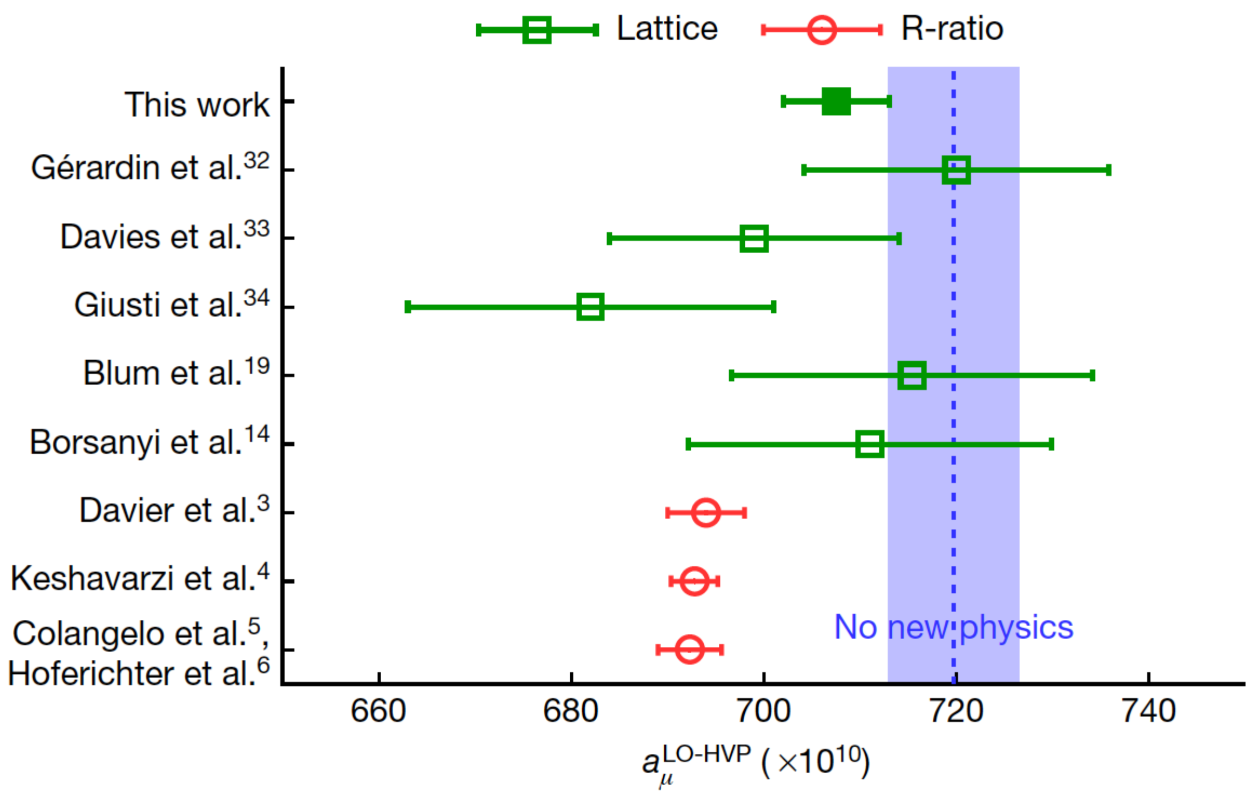
  RadioMonteCarLow Working Group: S. Actis et al, Eur. Phys. J. C66 (2010) 585
- **Ongoing review of MC tools relevant for low-energy hadronic cross sections including detailed comparisons of MC codes for $e^+e^- \to e^+e^-(\gamma)$, $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$ for scan & radiative-return experiments.**

  RadioMonteCarLow 2 Working Group: R. Aliberti et al, arXiv:2410.22882 [hep-ph]
- **New precision measurements of $e^+e^- \to \pi^+\pi^-(\gamma)$ are being prepared.**

- **In 2020 the BMW collaboration reached a 0.8% precision with a 2–2.5σ tension with the dispersive evaluations!**

$$a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst}\ [55]_{tot} \times 10^{-11}$$

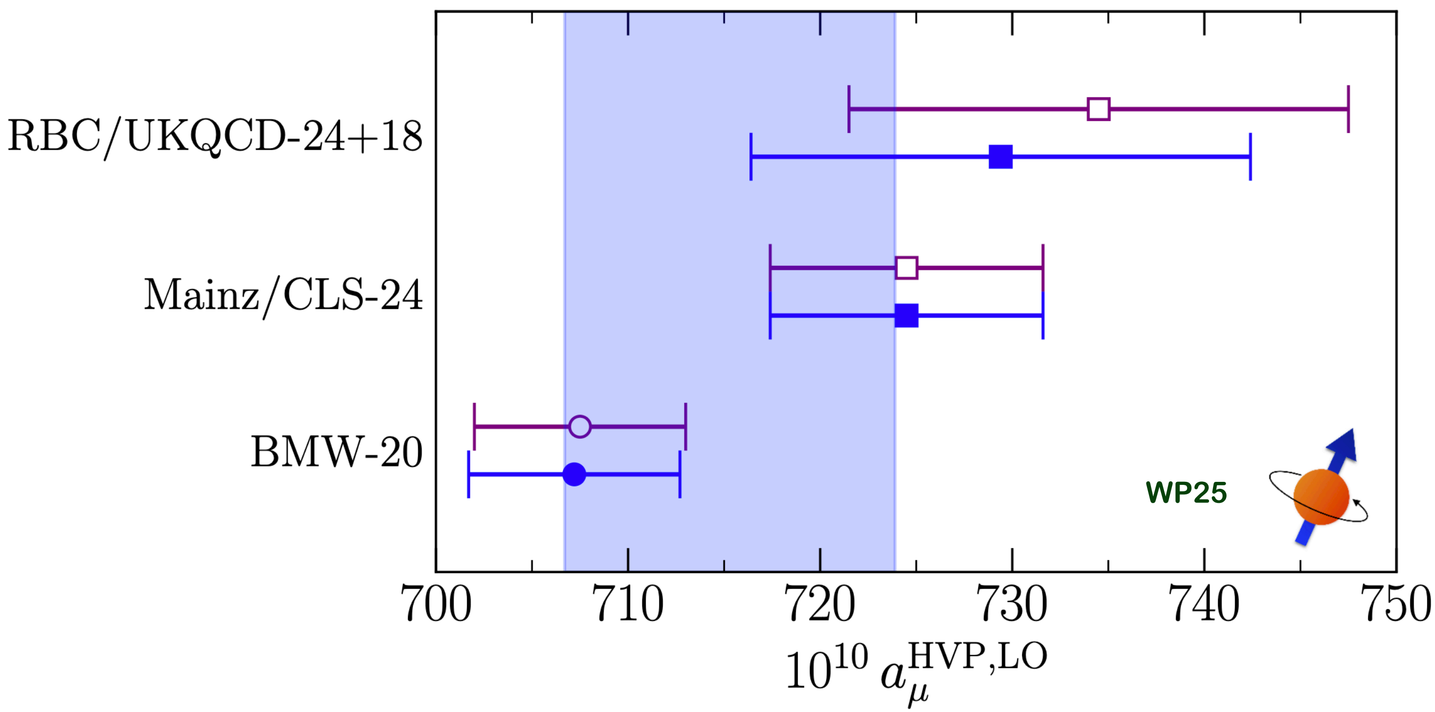
BMW 20



Borsanyi et al (BMW), Nature 2021

The hadronic LO contribution — lattice QCD (2)

- Since then, several results for the "window contributions" and two more full results:



$$a_\mu^{HLO} = 7132(61) \times 10^{-11}$$

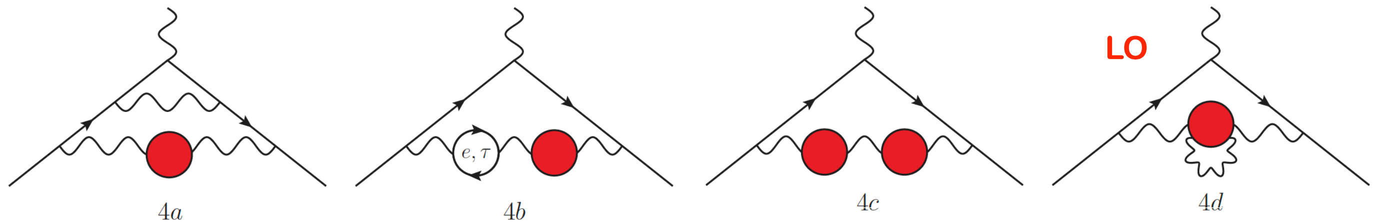
WP25

HVP NLO contributions to a_μ

- **NLO HVP contribution:**

$$a_\mu^{HVP}(NLO) = -\,99.6(1.3) \times 10^{-11}$$

Krause '96; Keshavarzi, Nomura, Teubner 2019;
Di Luzio, Keshavarzi, Masiero, Paradisi 2025; WP25



Normally incorporated in $a_\mu^{HVP}(LO)$.
MUonE will naturally include it!

- **The exact NLO space-like kernel is now known for lattice QCD & MUonE:**

$$a_\mu^{(4a)} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^1 \mathrm{d}x\, \kappa^{(4)}(x)\, \Delta\alpha_{\mathrm{h}}(t(x)), \qquad \kappa^{(4)}(x) = \frac{2-x}{x\,(x-1)}\, 2F^{(4)}(x-1)$$

$$F^{(4)}(u) = R_1(u) + R_2(u)\ln(-u) + R_3(u)\ln(1+u) + R_4(u)\ln(1-u) + \\ + R_5(u)\left[4\mathrm{Li}_2(u) + 2\mathrm{Li}_2(-u) + \ln(-u)\ln\left((1-u)^2(1+u)\right)\right]$$

$R_i(u)$ are known rational functions

Nesterenko 2112.05009. Balzani, Laporta, MP 2112.05704

- **The time-momentum representation of the NLO space-like kernel, used in lattice QCD determinations, has been computed recently.**

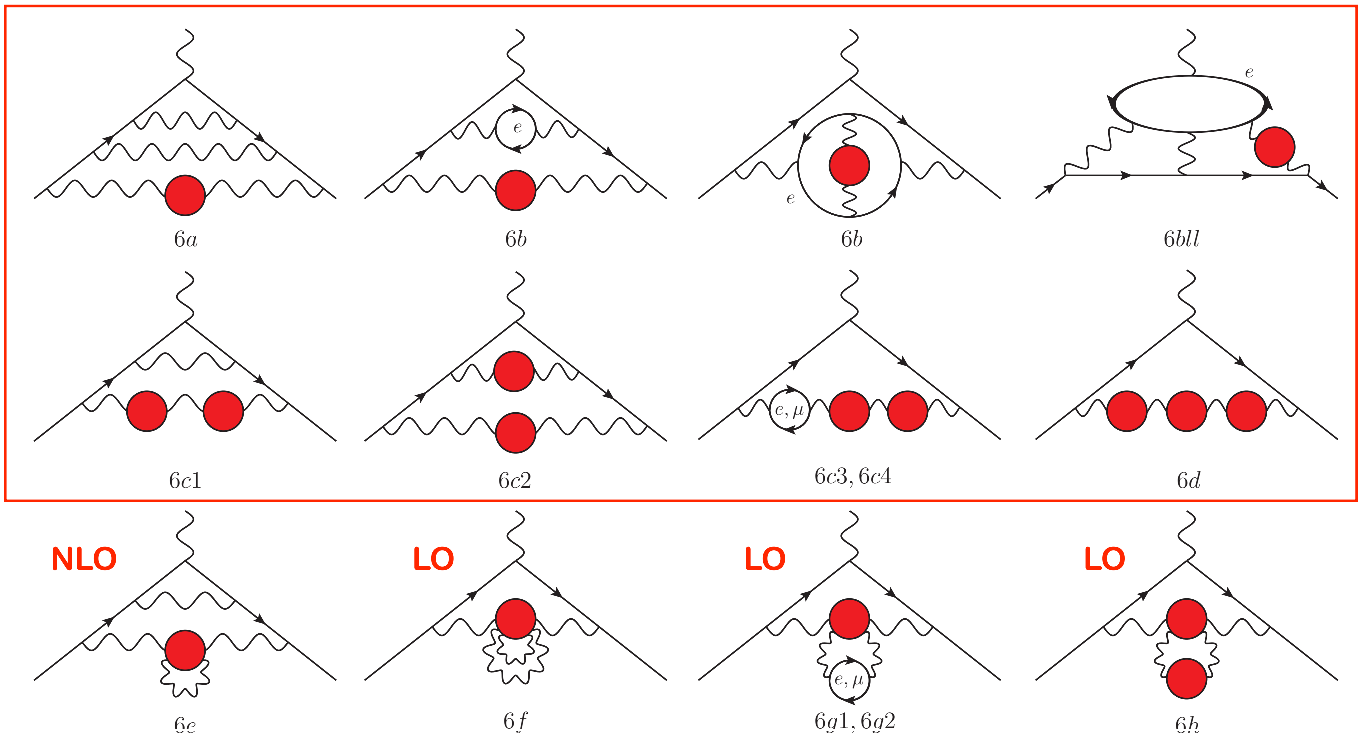
Balzani, Laporta, MP 2406.17940

HVP NNLO contributions to a_μ

- **NNLO HVP contribution:**

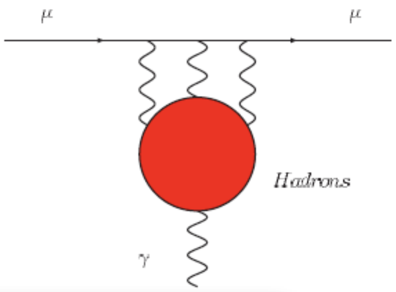
$a_\mu^{HVP}(NNLO) = 12.4\ (1) \times 10^{-11}$

Kurz, Liu, Marquard, Steinhauser 2014; WP25
Central value similar to present Fermilab's uncertainty



- **Also the NNLO space-like kernels are now known. They can be employed in lattice QCD calculations and at MUonE.**

Balzani, Laporta, MP, 2112.05704



- **Hadronic light-by-light at O(α^3)**
  - **This term had a very troubled life! But nowadays:**

$$a_\mu^{\text{HLbL}}\text{(LO)} = 112.6\ (9.6) \times 10^{-11}$$ WP25 (pheno+lattice)

  - **Significant improvements due to data-driven dispersive approach**

    Colangelo, Hoferichter, Kubis, Procura, Stoffer, 2014–17; Pauk, Vanderhaeghen 2014.

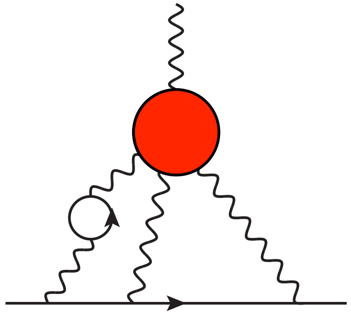
    and holographic QCD approach

    Cappiello, Cataà, D'Ambrosio 2011, …

  - **Great improvement of lattice results, in agreement with dispersive ones**

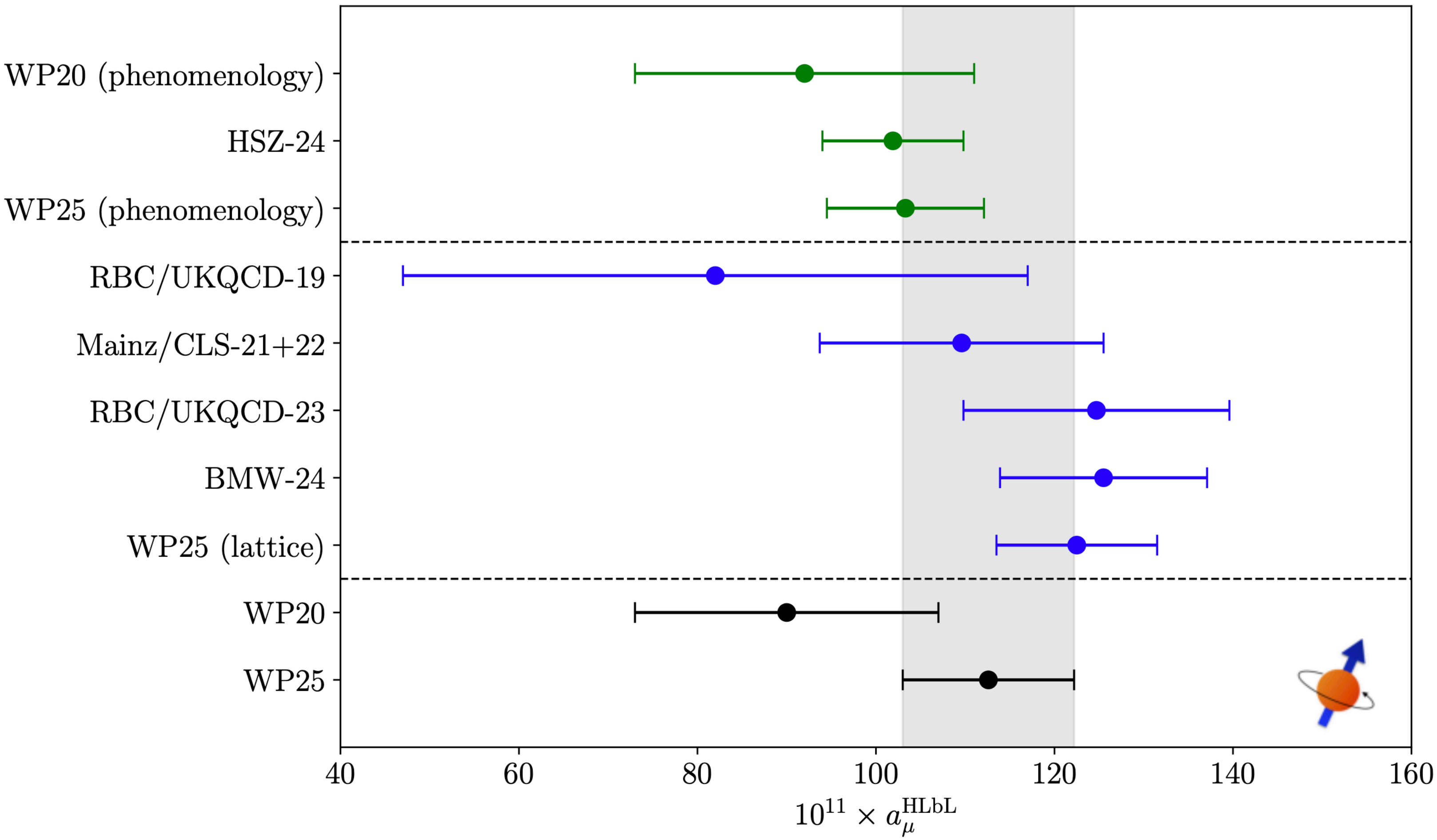
- **Hadronic light-by-light at O(α^4)**

$$a_\mu^{\text{HLbL}}\text{(NLO)} = 2.6\ (6) \times 10^{-11}$$



Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014; WP25

The hadronic LbL contribution (2)



WP25

Muon g-2: EXP vs SM

- Comparing the SM WP25 result with the measured muon g-2:

$$a_\mu^{EXP} = 116592071.5\ (14.5) \times 10^{-11}$$

EXP WA

$$a_\mu^{SM} = 116592033\ (62) \times 10^{-11}$$

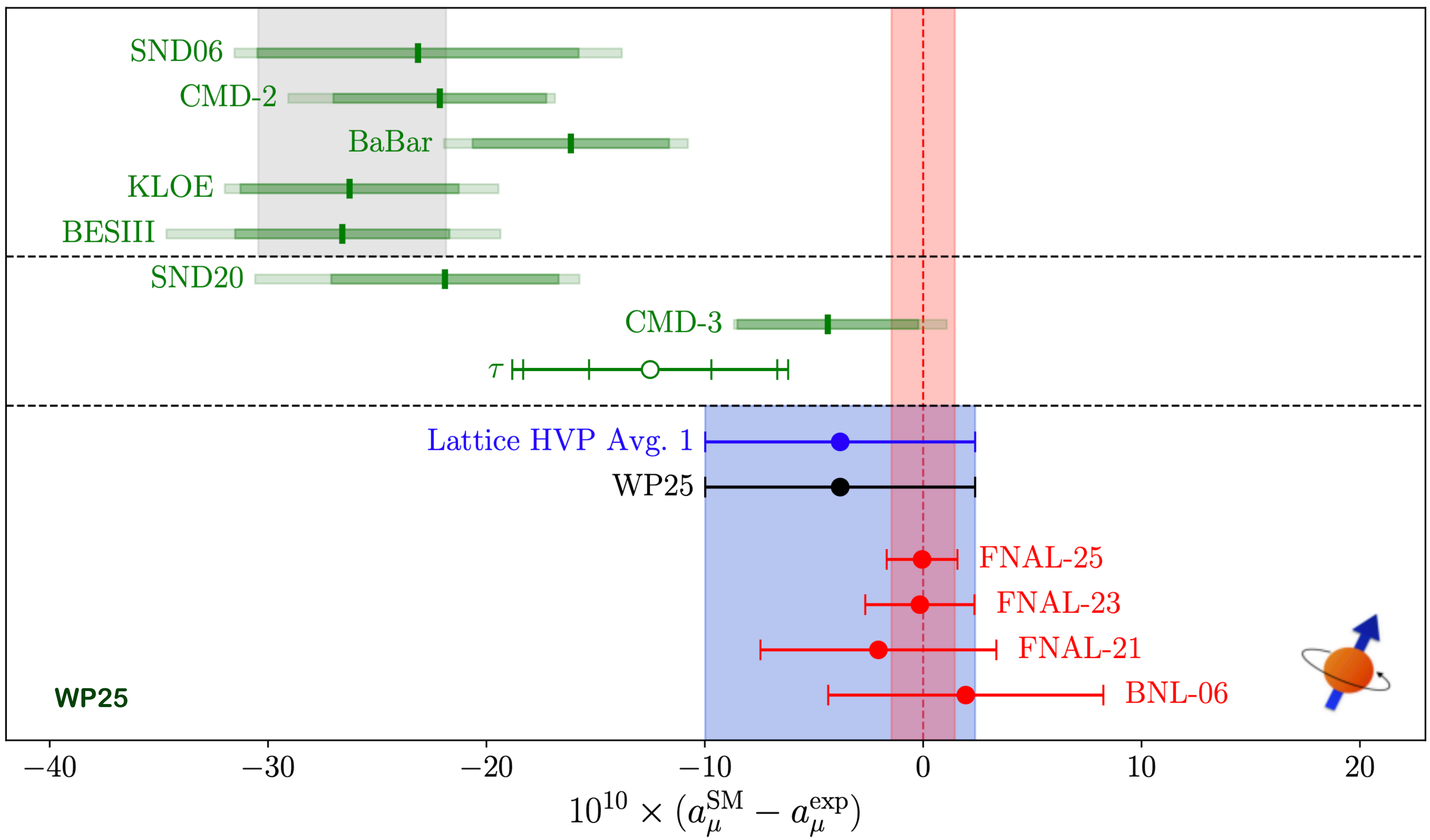
WP25

$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM} = 38\ (63) \times 10^{-11}$$

Perfect agreement!

If instead of the WP25 lattice QCD value of the HLO contribution we use the dispersive ones, we have a range of discrepancies.

Muon g-2: EXP vs SM (2)



WP25

Missed contributions in the hadronic cross section?

- **2008: could Δa_μ be due to missing contributions in the hadronic $\sigma(s)$?**
- **An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha_{had}^{(5)}(M_Z)$.**
- **Consider:**

$a_\mu^{HLO} \rightarrow$ $$a = \int_{4m_\pi^2}^{s_u} ds\, f(s)\,\sigma(s), \qquad f(s) = \frac{K(s)}{4\pi^3},\ s_u < M_Z^2,$$

$\Delta\alpha_{had}^{(5)} \rightarrow$ $$b = \int_{4m_\pi^2}^{s_u} ds\, g(s)\,\sigma(s), \qquad g(s) = \frac{M_Z^2}{(M_Z^2 - s)(4\alpha\pi^2)},$$

and the increase

$$\Delta\sigma(s) = \epsilon\sigma(s)$$

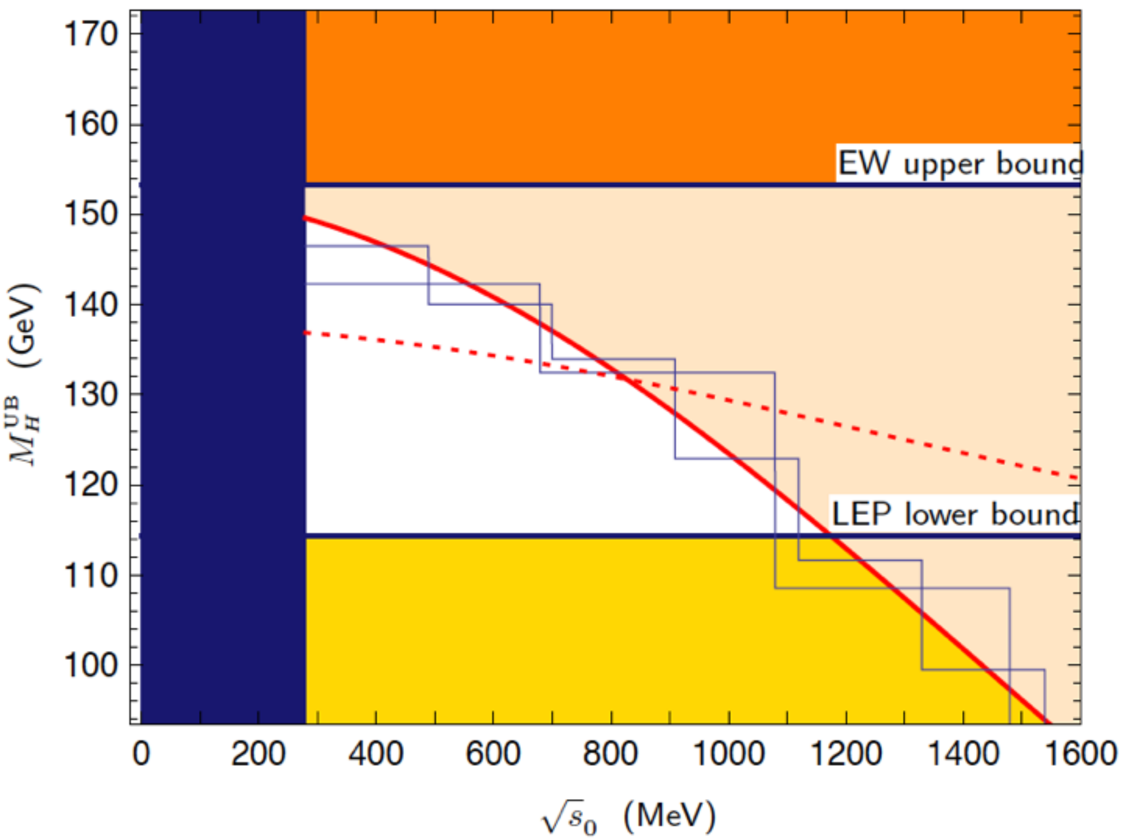
ε>0, in the range:

$$\sqrt{s} \in [\sqrt{s_0} - \delta/2, \sqrt{s_0} + \delta/2] \longrightarrow$$

Marciano, MP, Sirlin, PRD 2008

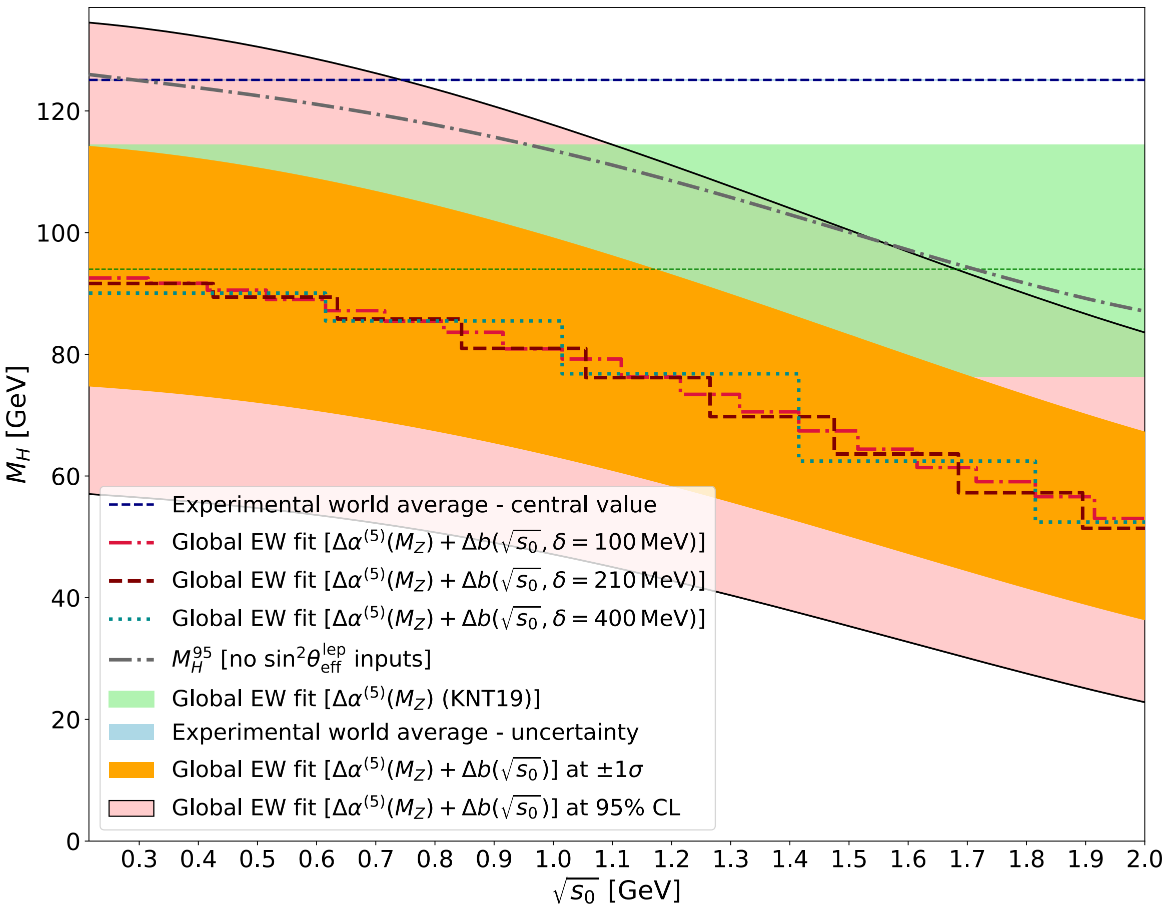
Muon g-2: connection with the SM Higgs mass (2008)

How much does the M_H upper bound from the EW fit change when we shift up $\sigma(s)$ by $\Delta\sigma(s)$ [and thus $\Delta\alpha_{had}^{(5)}(M_Z)$] to fix Δa_μ ?



Marciano, MP, Sirlin, PRD 2008

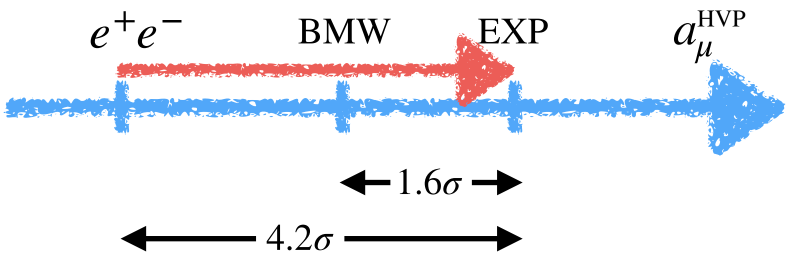
Muon g-2: connection with the SM Higgs mass (2020)



Shifts $\Delta\sigma(s)$ to fix Δa_μ are possible, but conflict with the EW fit if they occur above ~1 GeV

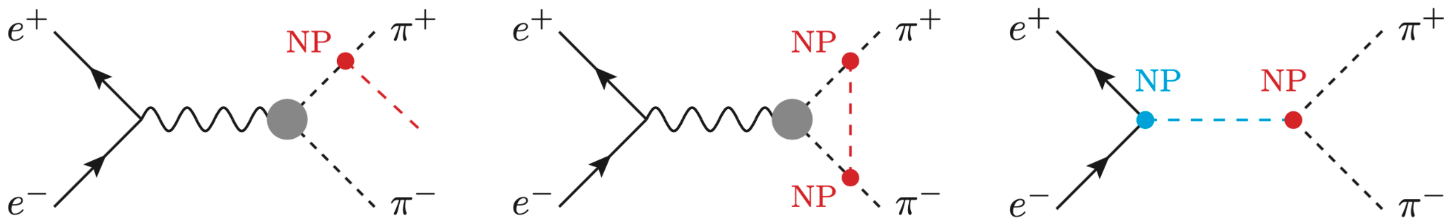
Keshavarzi, Marciano, MP, Sirlin, PRD 2020

Can NP solve the a_μ^{HLO} dispersive vs lattice puzzle?



- Can this puzzle be solved by NP in the hadronic cross section $\sigma_h(s)$?

  NP may couple only to hadrons (small effects) or both to hadrons & electrons:



If NP enters $\sigma_h(s)$ at tree-level, then σ_h in the HVP dispersive integral should be replaced by $\sigma_h - \Delta\sigma_h^{NP}$, with $\Delta\sigma_h^{NP} < 0$ needed to increase a_μ^{HVP}.

This sizeable negative NP interference with the SM is excluded by a number of experimental constraints.

Di Luzio, Masiero, Paradisi, MP, 2112.08312
Crivellin, Hoferichter, 2211.1251

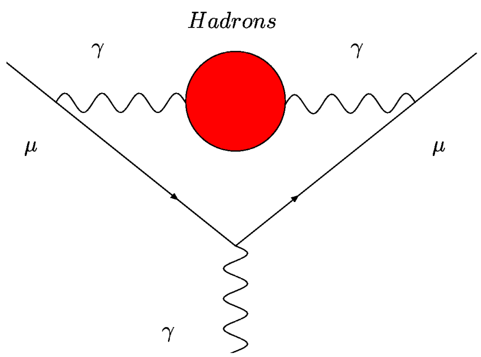
- NP in e^+e^- & $\mu^+\mu^-$ final states scatterings?

Darmé, Grilli di Cortona, Nardi, 2112.09139

The MUonE experiment

The spacelike method for a_μ^{HLO}

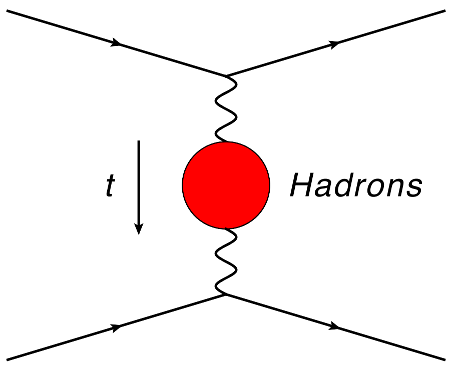
- **Leading hadronic contribution computed via the usual dispersive (timelike) formula:**



$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}_{\rm had}(s)$$

$$K(s) = \int_0^1 dx\, \frac{x^2\,(1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

- **Alternatively, simply exchanging the x and s integrations:**



$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{\rm had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

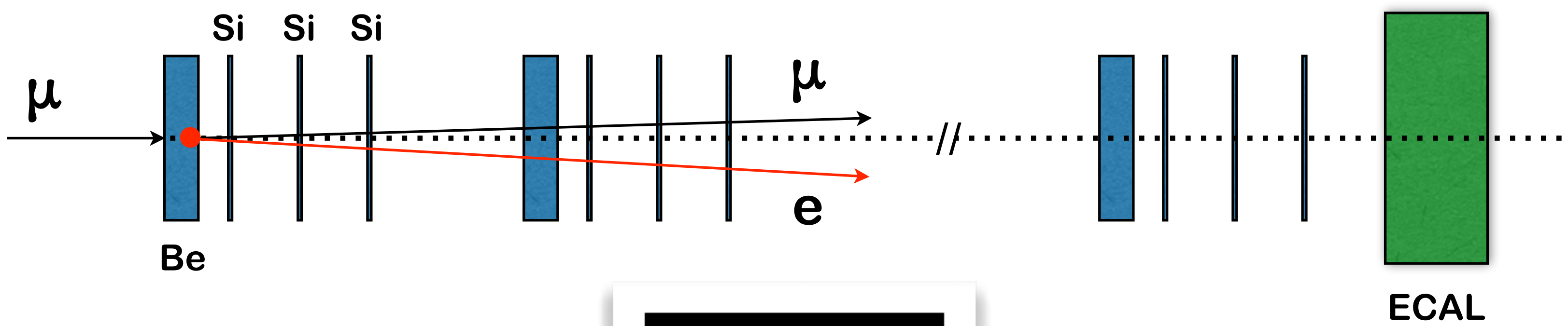
$\Delta\alpha_{had}$(t) is the hadronic contribution to the space-like running of α: proposal to measure a_μ^{HLO} via scattering data!

Carloni Calame, MP, Trentadue, Venanzoni, 2015

MUonE: Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can be measured via the **elastic scattering μ e → μ e**.

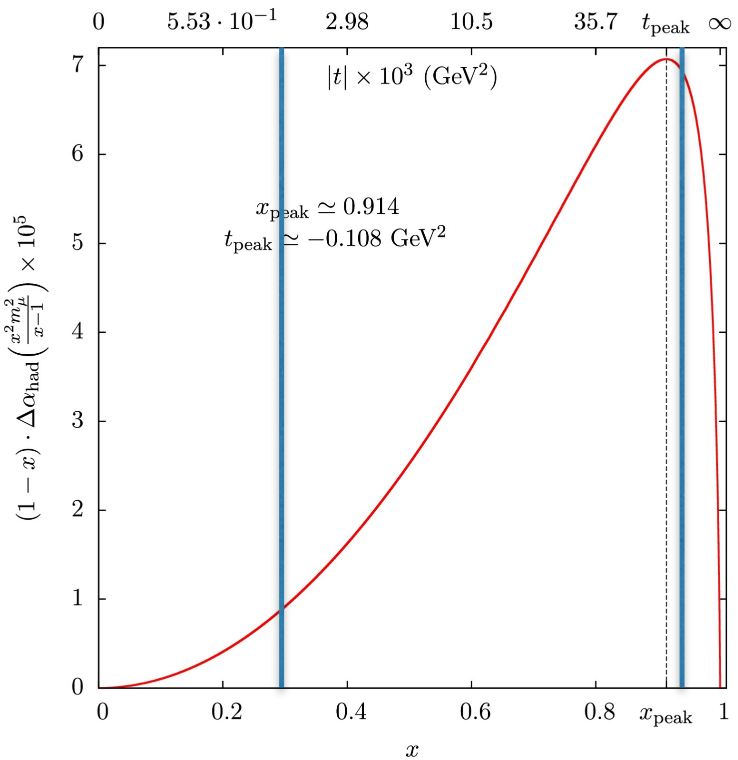
- We propose to scatter a 160 GeV muon beam, available at CERN's North Area, on a fixed electron target (Be or C). Modular apparatus: each station has one layer of Be/C (target) followed by several thin Silicon strip detectors.

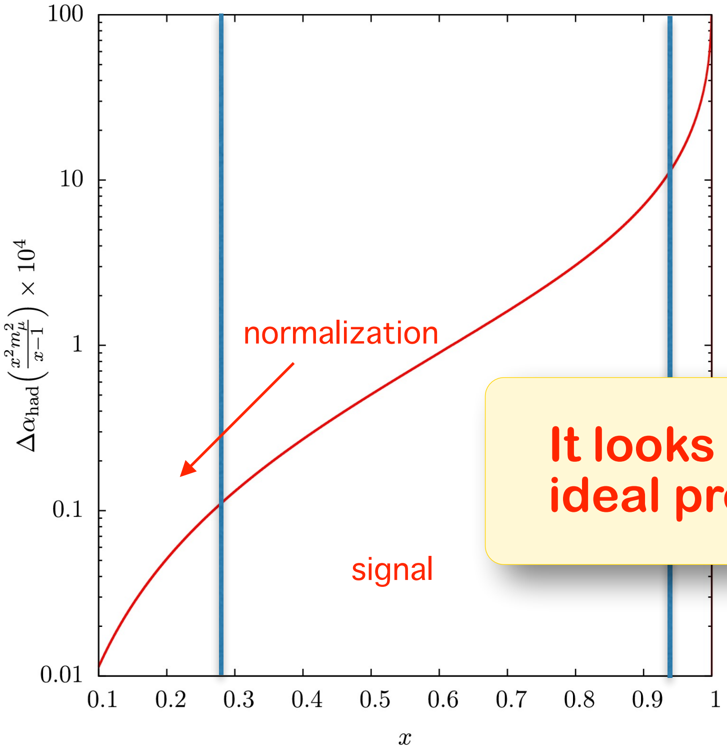


Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

- For a 150 GeV muon beam (√s~400 MeV), MUonE's scan region extends up to x=0.932, ie beyond the x=0.914 peak!





It looks like an ideal process!

MUonE — Status

- Statistics: With CERN's 160 GeV muon beam M2 (1.3×10^7 μ/s), incident on 40 15mm Be targets (total Be thickness: 60cm) and 3 years of data taking → $\mathcal{L}_{int} \sim 1.5 \times 10^7\ nb^{-1}$.

- With this $\mathcal{L}_{int}$ we estimate that measuring the shape of dσ/dt we can reach a statistical sensitivity of ~0.3% on a_μ^{HLO}, ie $\sim 20 \times 10^{-11}$.

- Systematic effects must be known at ≲ 10ppm!

- 2017, 2018, 2022: Test beams performed at CERN arXiv:1905.11677, 2102.11111

- 2023: Test run performed on M2 beam line.

- 2024: Phase 1 proposal approved by CERN SPSC. Small scale version of the final experiment, June-July running time in 2025 at the M2 beam line. 3 tracking stations, calorimeter, μ ID, and beam momentum spectrometer.

- 2025 goals: study signal and background under realistic conditions with a possible sensitivity to $\Delta\alpha_{had}(t)$. (Main) data taking at CERN just completed!

- Full experiment expected after CERN's LS3 (2027-2029).

The MUonE Collaboration

CERN

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)

Imperial College (London), Liverpool U.

INPP Krakow

Cornell U., Northwestern U., Virginia U., Regis U.

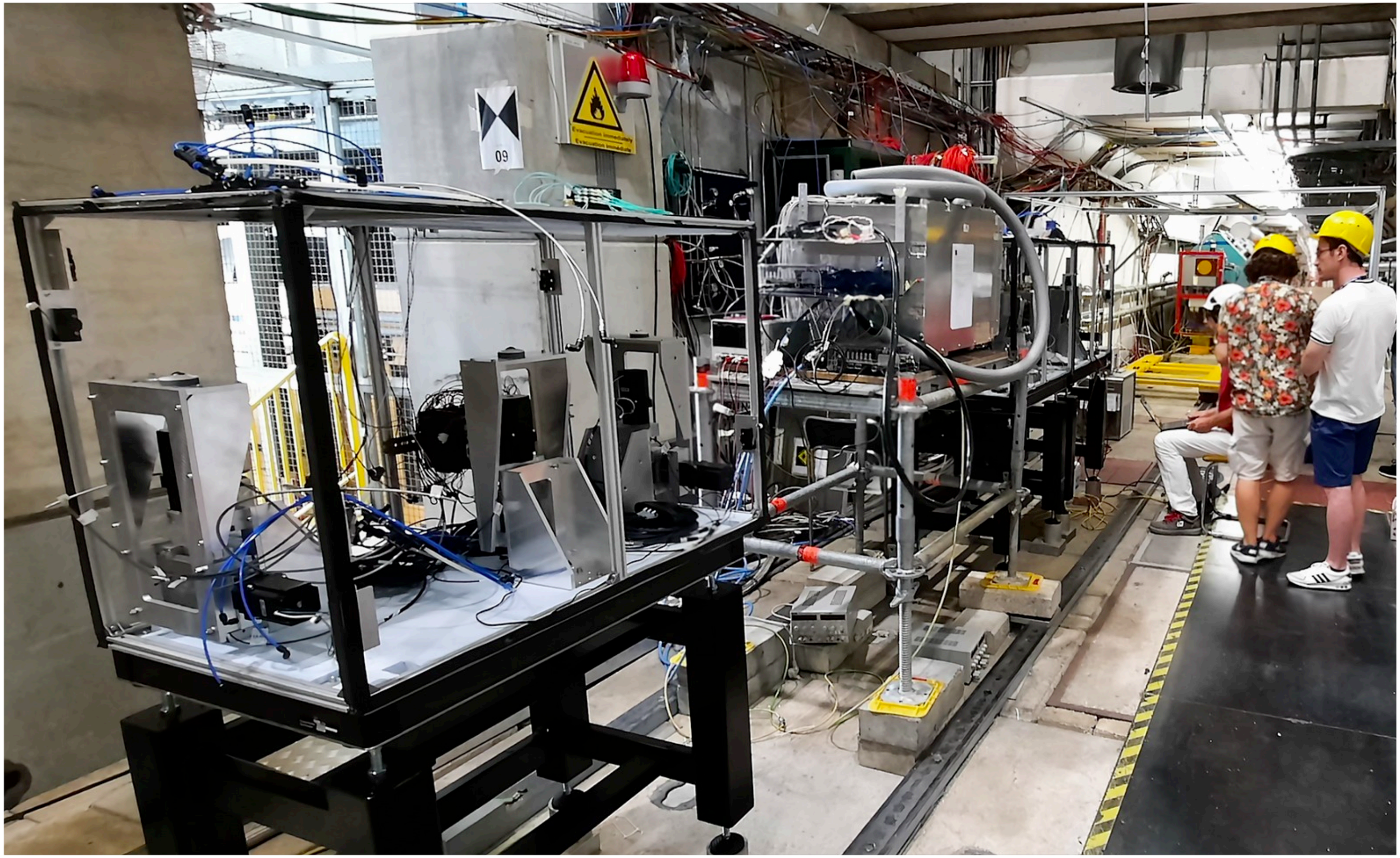
Peking U. (Beijing), Shanghai Jiao Tong U.

The MUonE Collaboration

Demokritos INPP (Athens)

PSI (Villigen), ETH Zürich

2023 Test Run at CERN on M2 beamline



R. N. Pilato, 7th Plenary Workshop of the Muon g-2 Theory Initiative, KEK, 12th September 2024

MUonE: theory papers

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, PLB 746 (2015) 325 [1504.02228 [hep-ph]]
P. Mastrolia, M. Passera, A. Primo, U. Schubert, JHEP 1711 (2017) 198 [1709.07435 [hep-ph]]
S. Di Vita, S. Laporta, P. Mastrolia, A. Primo, U. Schubert, JHEP 1809 (2018) 016 [1806.08241 [hep-ph]]
M. Alacevich et al, JHEP 02 (2019) 155 [1811.06743 [hep-ph]]
M. Fael, JHEP 1902 (2019) 027 [1808.08233 [hep-ph]]
M. Fael and M. Passera, PRL 122 (2019) 192001 [1901.03106 [hep-ph]]
P. Banerjee et al. [The MUonE TI], EPJC 80 (2020) 591 [2004.13663 [hep-ph]]
C. M. Carloni Calame et al, JHEP 11 (2020) 028 [2007.01586 [hep-ph]]
P. Banerjee, T. Engel, A. Signer, Y. Ulrich, SciPost Phys. 9 (2020) 027 [2007.01654 [hep-ph]]
R. Bonciani et al, PRL 128 (2022) 022002 [2106.13179 [hep-ph]]
E. Budassi et al, JHEP 11 (2021) 098 [2109.14606 [hep-ph]]
A.V. Nesterenko, JPG 49 (2022) 055001 [2112.05009 [hep-ph]]
E. Balzani, S. Laporta, M. Passera, PLB 834 (2022) 137462 [2112.05704 [hep-ph]]
M. Fael, F. Lange, K. Schönwald, M. Steinhauser, PRL128 (2022) 172003 [2202.05276 [hep-ph]]
M. Fael, F. Lange, K. Schönwald, M. Steinhauser, PRD 106 (2022) 034029 [2207.00027 [hep-ph]]
D. Greynat and E. de Rafael, JHEP 05 (2022) 084 [2202.10810 [hep-ph]]
E. Budassi, C.M. Carloni Calame, C.L. Del Pio, F. Piccinini, PLB 829 (2022) 137138 [2203.01639 [hep-ph]]
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MUonE — Theory workshops

Muon-electron scattering: Theory kickoff workshop

4-5 September 2017

Padova
Europe/Rome timezone

Overview
- Venue
- Timetable
- Logistic
- Map

Support

MUonE theory workshops:

Padova 2017
MITP Mainz 2018
Zurich 2019
MITP Mainz 2022
MITP Mainz 2024

Conclusions

- The measurement of the muon g–2 agrees with the SM prediction quoted by the new WP25 of the Muon g–2 Theory Initiative.
- However, puzzling tensions exist between dispersive and lattice QCD determinations of the leading hadronic contribution to a_μ.
- The MUonE experiment at CERN will measure directly the leading hadronic contribution to a_μ in a new, alternative, & independent way!