to Subir, the tireless and unorthodox hunter for **New Physics Beyond the Standard Models**

SubirFest2023, University of Oxford, 11-13 Sept. 2023

Light hidden BSM physics for the $(g\text{-}2)_{\mu}$ puzzle

Antonio Masiero

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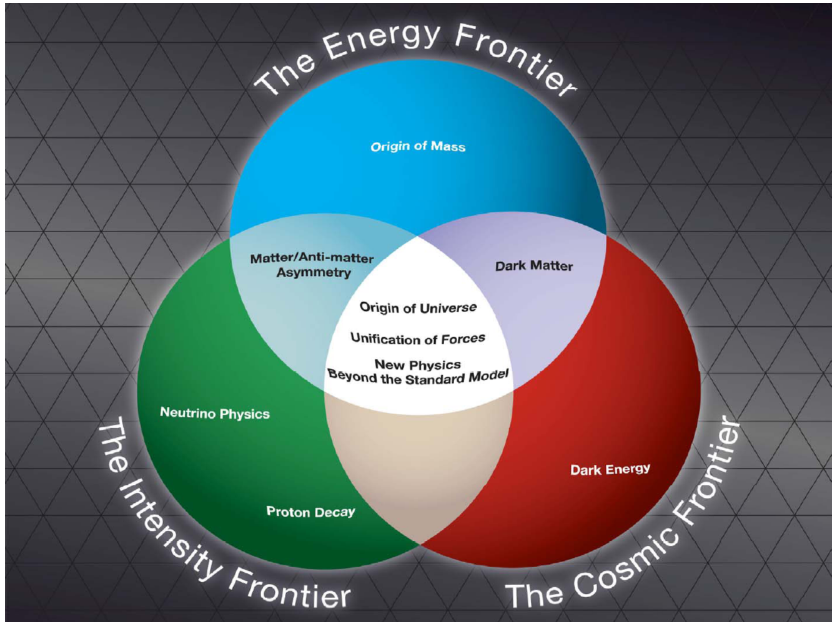
Based on works on the muon g-2 problem in collaboration with Luca Di Luzio, Bill Marciano, Paride Paradisi and Massimo Passera

On the "old" muon g-2 puzzle



During the long sequel of restless attempts of finding experimental evidences or at least hints of **NEW PHYSICS** beyond the SM along the **traditional High-Energy (HE) and High-Intensity (HI) paths**, several 3 or even 4 σ signals at variance w.r.t. the SM expectations **have shown up**, but they have also (rather sooner than later) **invariably faded away**.

A remarkable exception is represented by

the anomalous magnetic moment of the muon

which has been for **several years now** and **still** represents a **major observational evidence along the HI frontier of the possible presence of NEW PHYSICS**

$$\vec{\mu}_\ell = \frac{e}{2m}\vec{\ell}$$

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

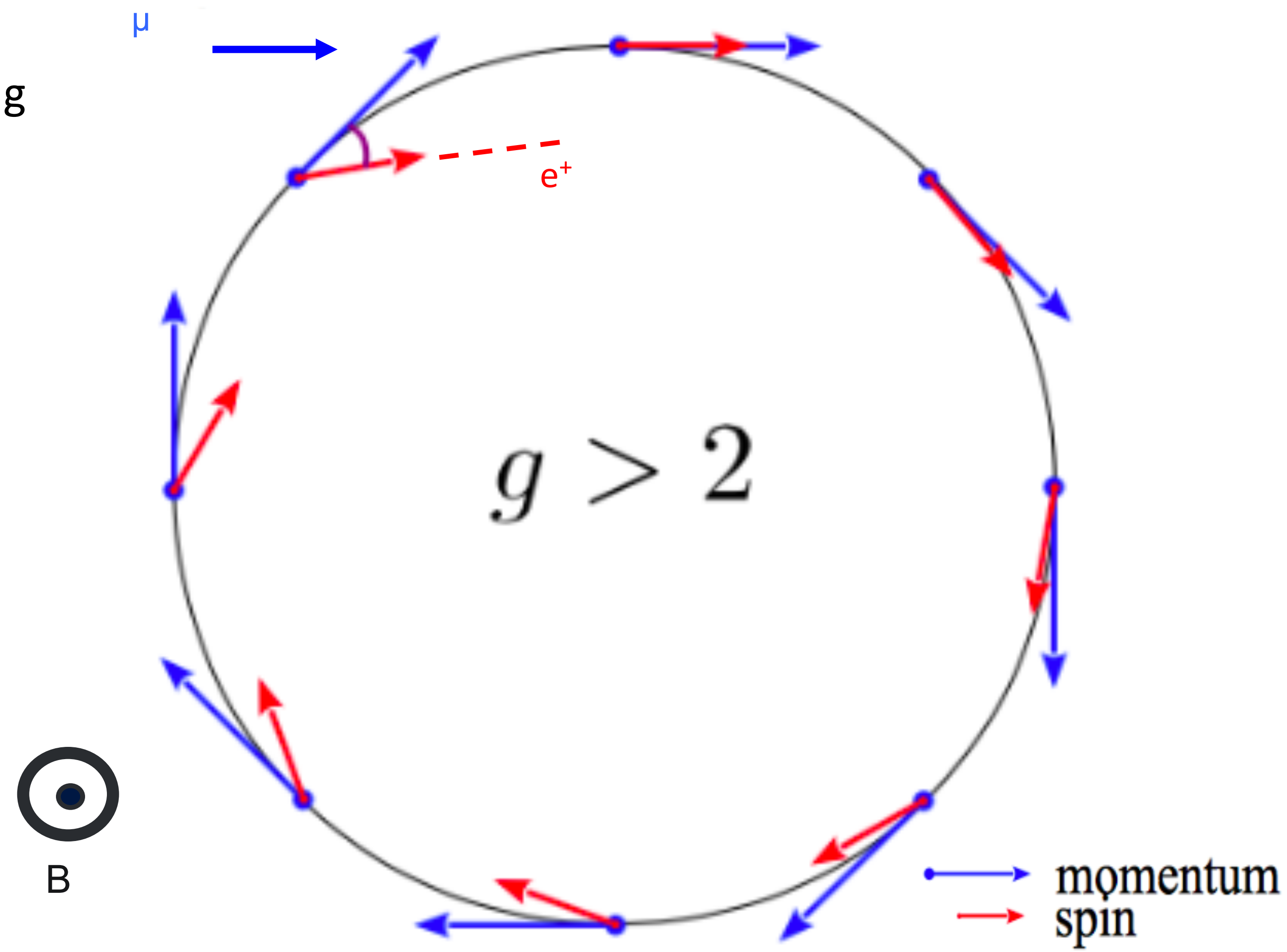
Put a beam of polarized muons into a storage ring

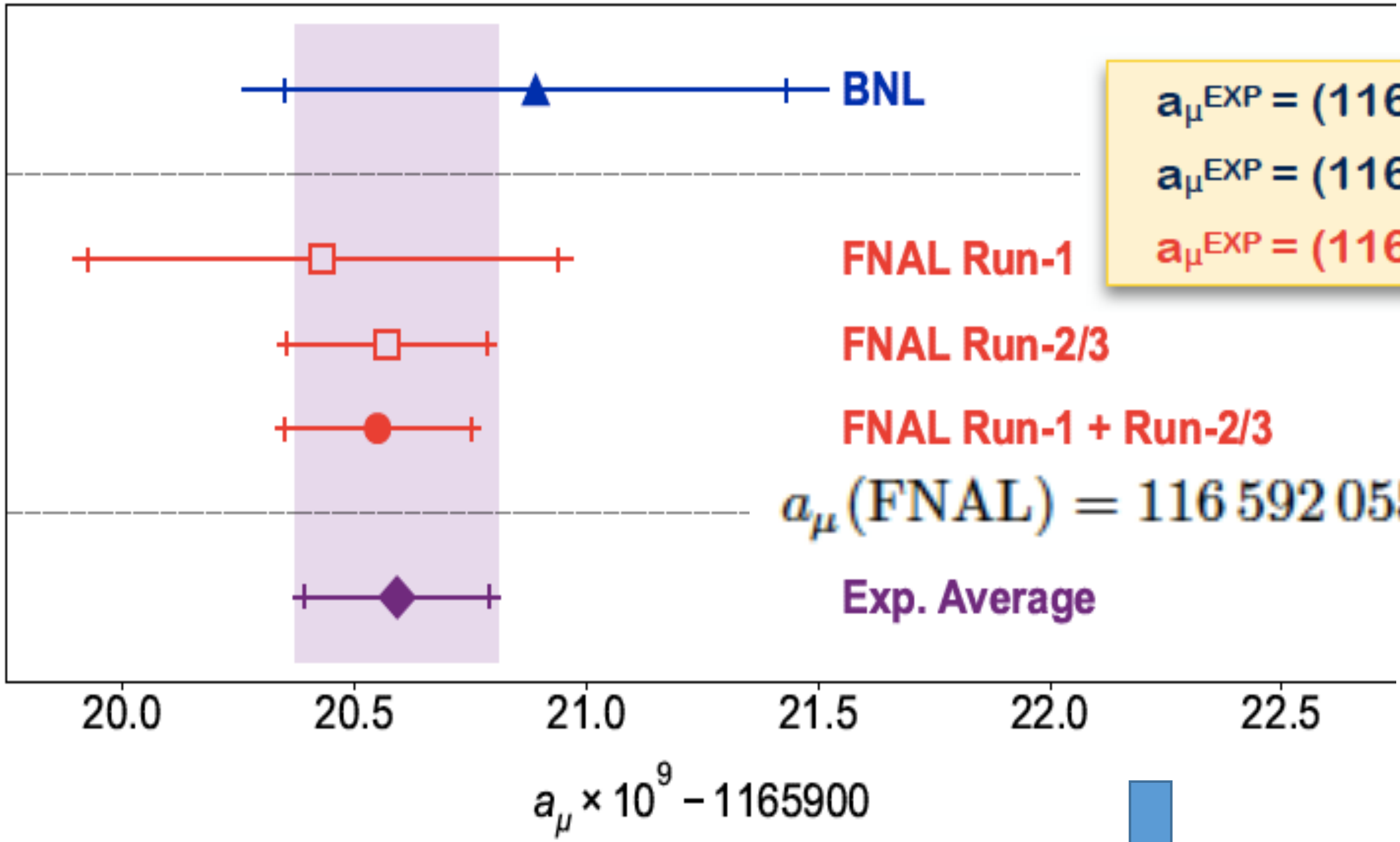
Both the muon spin and momentum precess

Because g is slightly greater than 2 the spin precesses faster than the momentum

$$a = (g-2)/2$$

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





$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [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

$$a_\mu(\mathrm{FNAL}) = 116\,592\,055(24) \times 10^{-11} \quad (0.20\,\mathrm{ppm}),$$

$$a_\mu(\mathrm{Exp}) = 116\,592\,059(22) \times 10^{-11} \quad (0.19\,\mathrm{ppm})$$

FNAL aims at 16×10^{-11}

FNAL E989 exp. New Result Aug 10, 2023: arXiv:2308.06230 [hep-ex]

Summary

- New result consistent with previous results
- Analyzing Runs 4+5+6
- Can still improve some systematics
- Should meet or exceed 140 ppb goal
- Final result mid-2025
- Looking forward to J-PARC g-2
- Await new theory estimate ...

D. Kawall (g-2 Muon Collaboration),
Sixth Plenary Workshop of the Muon g-2 Theory Initiative, Bern, Sept. 2023

g ≠ 2

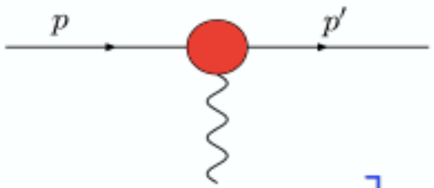
- **Kusch and Foley 1948:**

$$\left(\frac{g_e}{2}\right)^{\exp} \equiv 1 + a_e^{\exp} = 1.00119 \pm 0.00005$$

- **Schwinger 1948 (triumph of QED!):**

$$\left(\frac{g_e}{2}\right)^{\text{th}} \equiv 1 + a_e^{\text{th}} = 1.00116\ldots$$

- **We keep studying the lepton–γ vertex:**

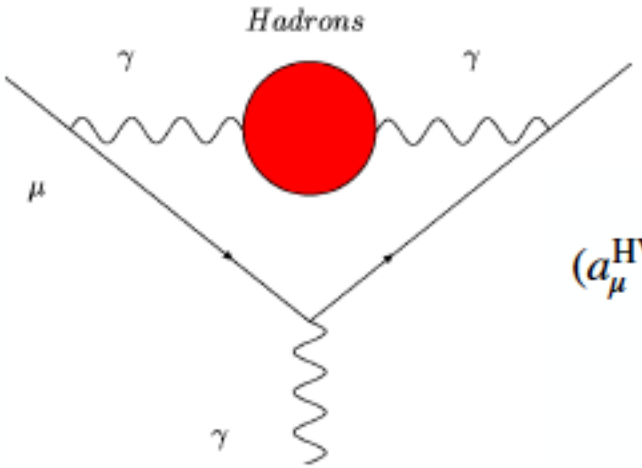


$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2(q^2) + \ldots\right]u(p)$$

$$F_1(0) = 1 \qquad F_2(0) = a_l$$

A pure "quantum correction" effect!

HVP: the major source of uncertainty in the muon g-2 SM computation



$\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

$$(a_\mu^{\rm HVP})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty}\frac{ds}{s}K(s)\,{\rm Im}\,\Pi_{\rm had}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty}ds\,K(s)\sigma_{\rm had}(s)$$

dispersion relations

optical theorem

kernel function

$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$

$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}K(s)\,R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$a_\mu^{\rm HLO} = 6895\,(33) \times 10^{-11}$	F. Jegerlehner, arXiv:1711.06089
$= 6939\,(40) \times 10^{-11}$	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
$= 6928\,(24) \times 10^{-11}$	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
$= 6931\,(40) \times 10^{-11}$ (0.6%)	WP20 value

WP20 = White Paper of the Muon g-2 Theory Initiative: arXiv:2006.04822

$$a_\mu^{\rm EXP} = 116592061(41) \times 10^{-11} \quad \text{[BNL + FNAL]}$$

$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-11} \quad \text{[WP20]}$$

With only RUN1 data

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = 251\,(59) \times 10^{-11} \qquad (4.2\sigma \text{ discrepancy!})$$

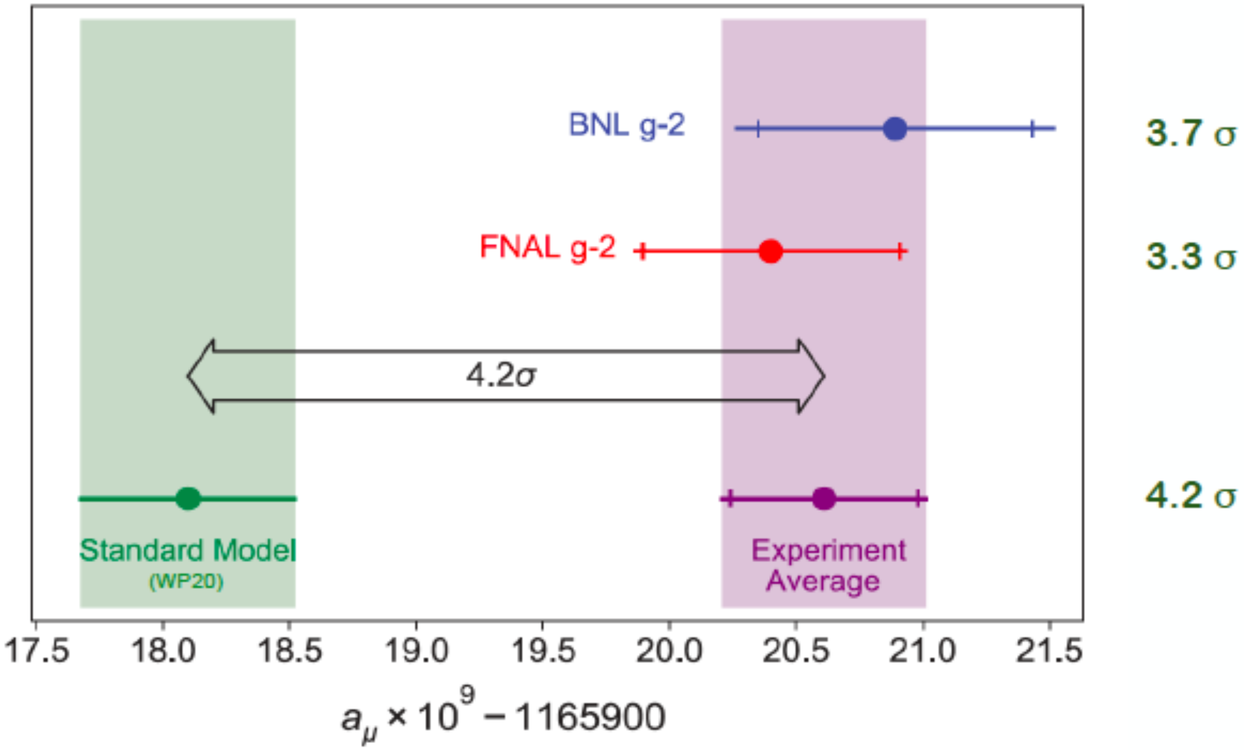
Now 5.1σ discrepancy

$$\underbrace{(0.1)_{\rm QED}\,,\quad (1)_{\rm EW}\,,\quad (18)_{\rm HLbL}\,,\quad (40)_{\rm HVP}\,,}_{(43)_{\rm TH}} \quad (41)_{\delta a_\mu^{\rm EXP}}\,.$$

Now **22**

- Hadronic uncertainties (HLbL & HVP) are very hard to improve.
- $\delta a_\mu^{\rm EXP} \approx 16 \times 10^{-11}$ by the E989 Muon $g-2$ exp. in a few years.

The OLD $(g\text{-}2)_\mu$ puzzle



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- FNAL aims at 16×10^{-11}. First 4 runs completed, 5th in progress.
- Muon g-2 proposal at J-PARC: Phase-1 with ~ BNL precision.

NEW PHYSICS for the muon g-2: at which scale?

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

- A weakly interacting NP at $\Lambda \approx v$ can naturally explain $\Delta a_\mu \approx 2 \times 10^{-9}$
- $\Lambda \approx v$ favoured by the *hierarchy problem* and by a WIMP DM candidate.

On the other hand, HE experiments (LEP, Tevatron, LHC) have NOT provided any clue for the presence of new (charged) particles at the ELW. scale

- NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.
- NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.

P. Paradisi, La Thuile 2021

The case of AXION-LIKE PARTICLES (ALPs)

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2} \frac{\partial^\nu a}{\Lambda} \bar{\mu} \gamma_\nu \gamma_5 \mu$$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi} \gamma_5 \psi$$

$$g_{a\gamma\gamma} \equiv \frac{2\sqrt{2}\,\alpha}{\Lambda} c_{a\gamma\gamma}$$

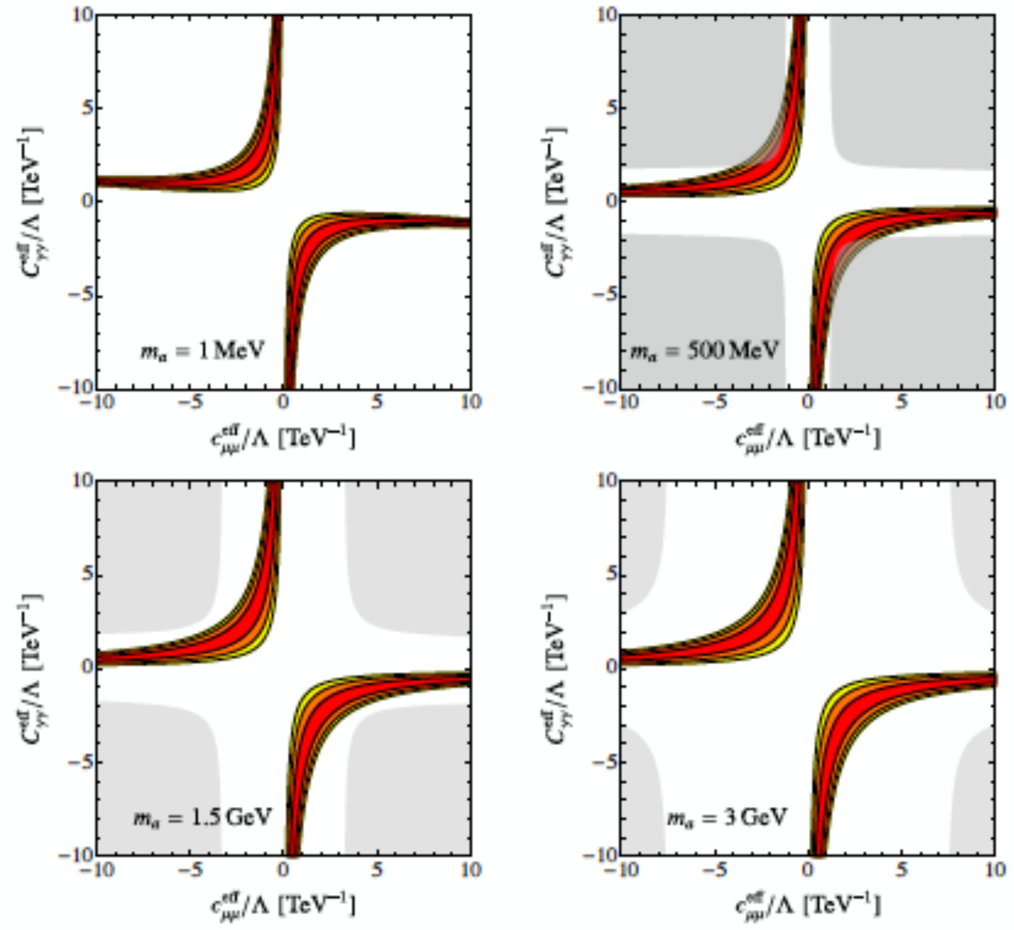
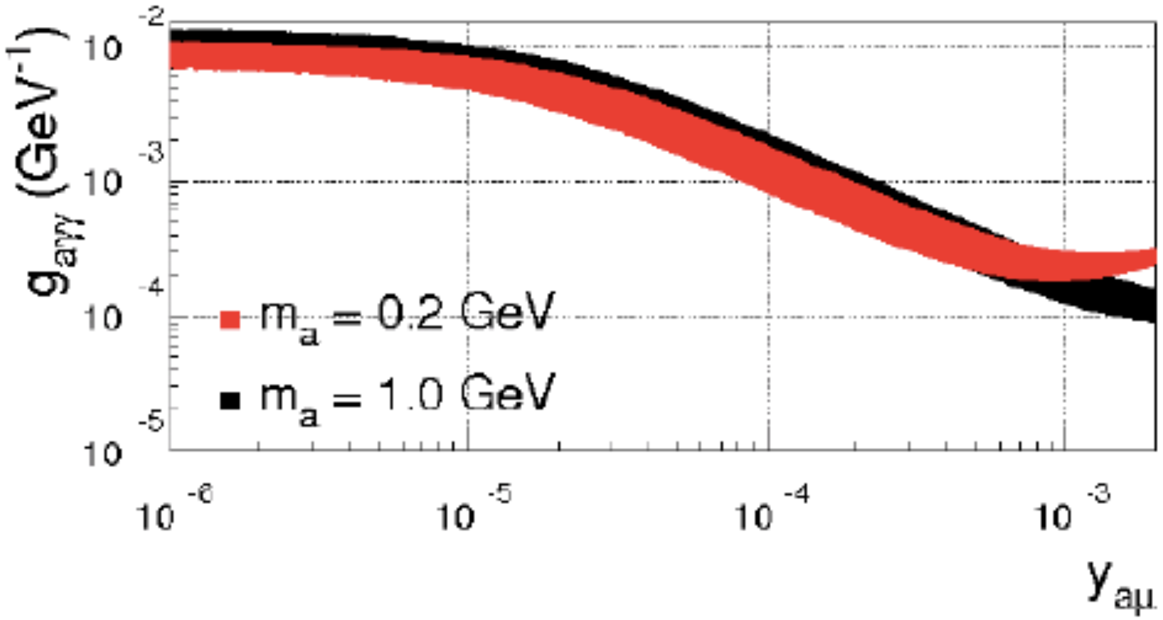


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]



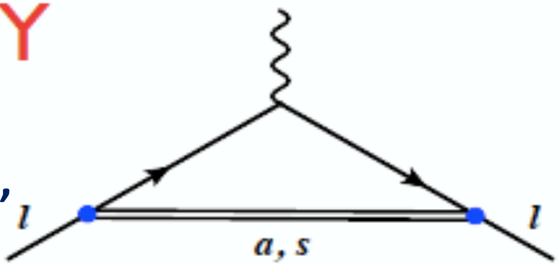
Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

Marciano, A.M., Paradisi, Passera '16

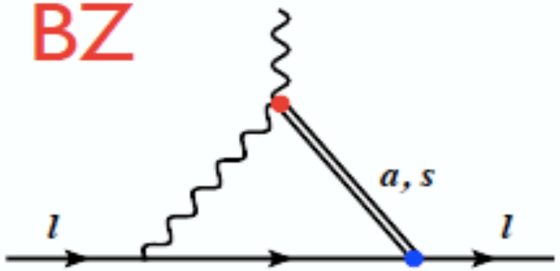
ALPs contributions to the muon g-2?

Marciano, AM, Paradisi, Passera '16; Bauer, Neubert, Thamm '17; Bauer, Neubert, Renner, Schnubel, Thamm '19; Cornella, Paradisi, Sumensari '19

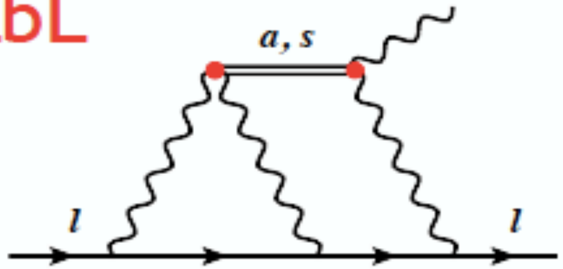
Y



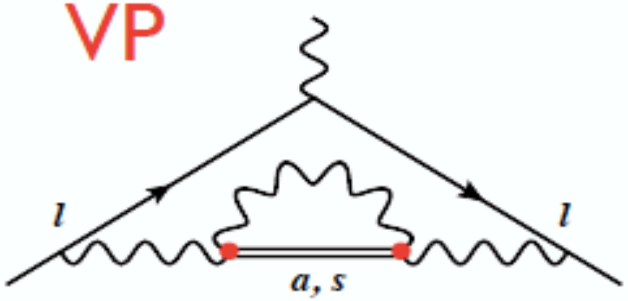
BZ



LbL



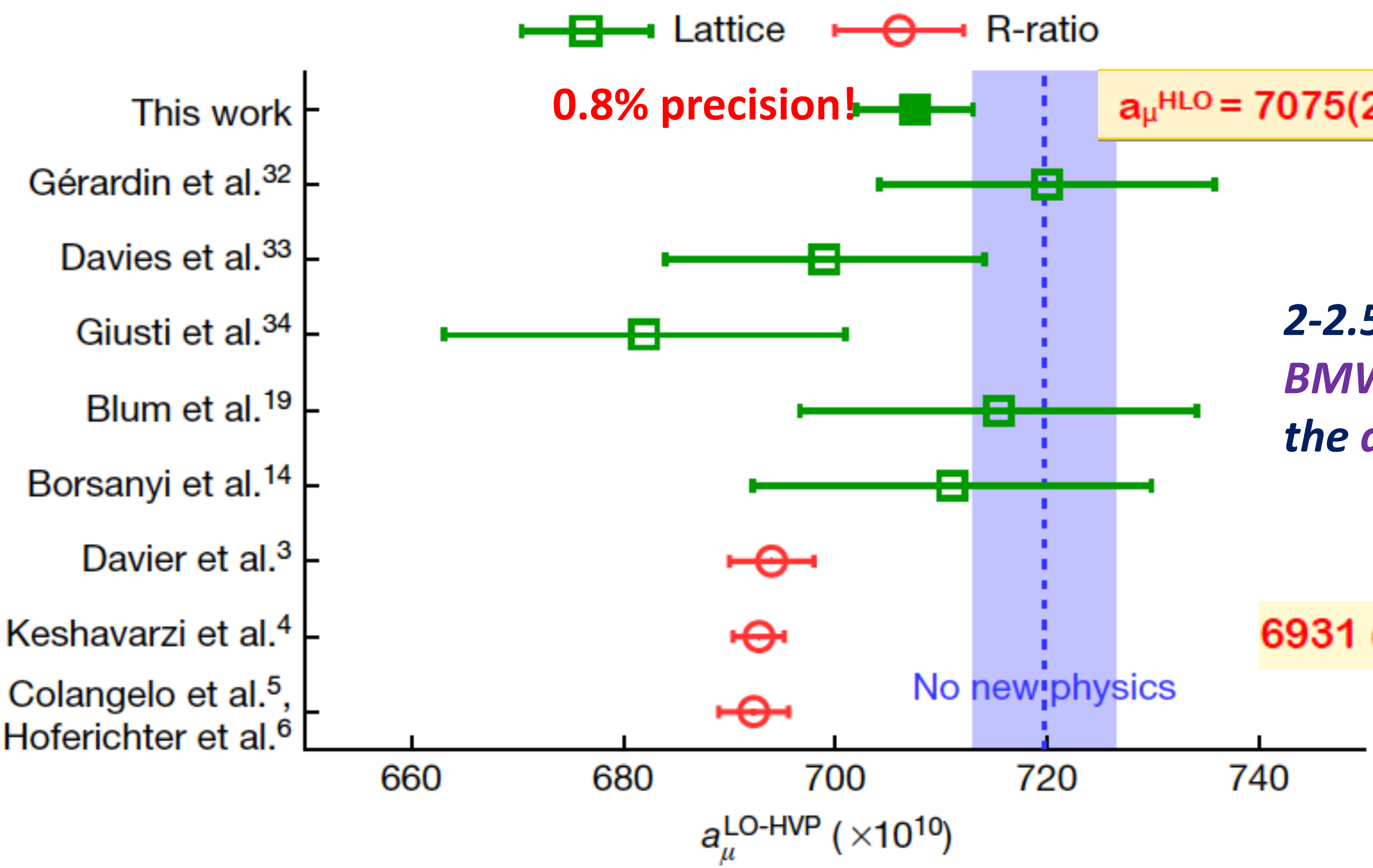
VP



- Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.
- They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \to e^+e^-$+ALP & $e^+e^- \to \gamma$+ALP searches.

BMWc20: S. Borsanyi et al. 2002.12347, published on Nature, April 7, 2021

first published lattice result with sub-percent precision!



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

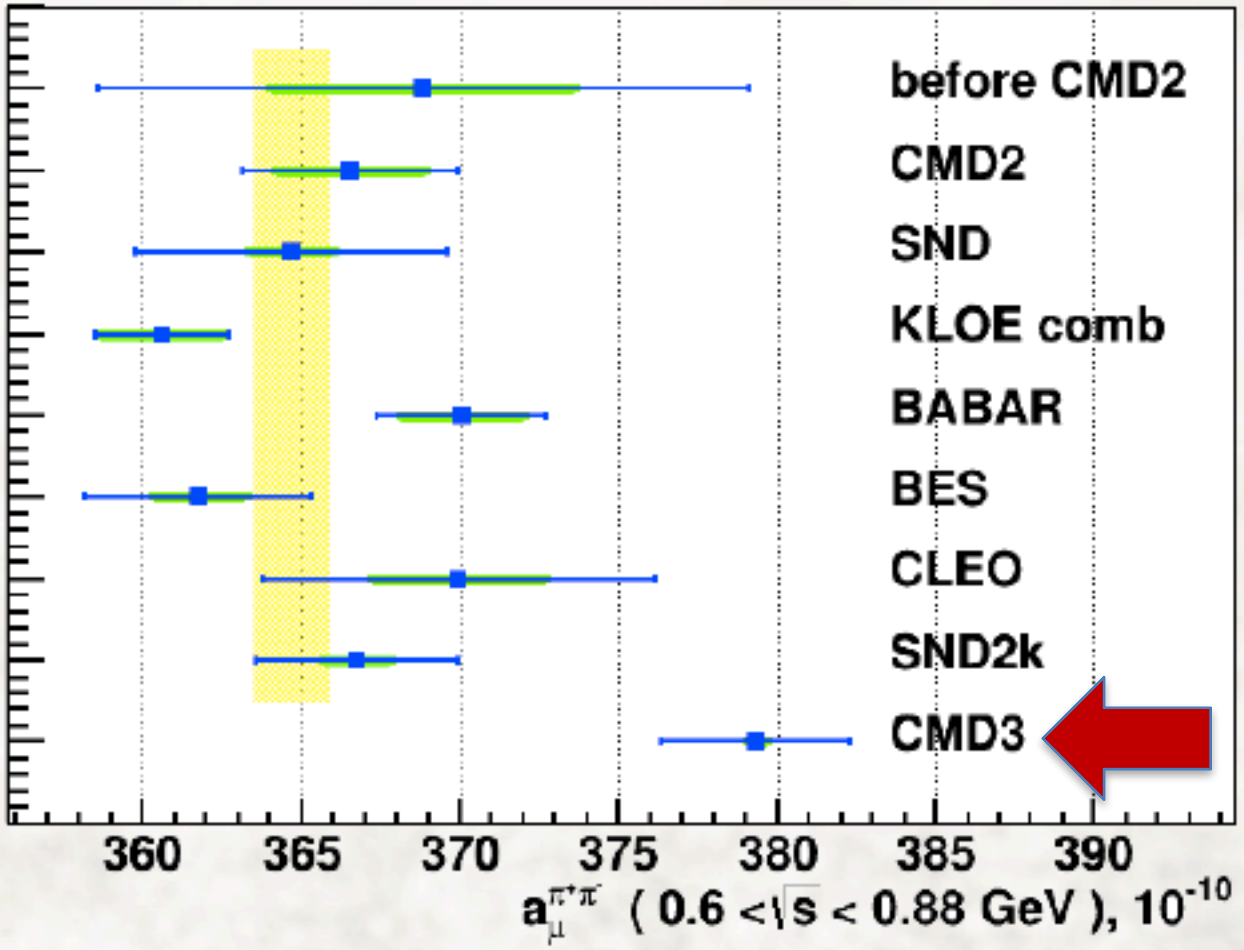
2-2.5σ tension between the BMWc lattice result and the dispersive evaluations

$6931\,(40) \times 10^{-11}$ (0.6%)

New result on R(s) from CMD3

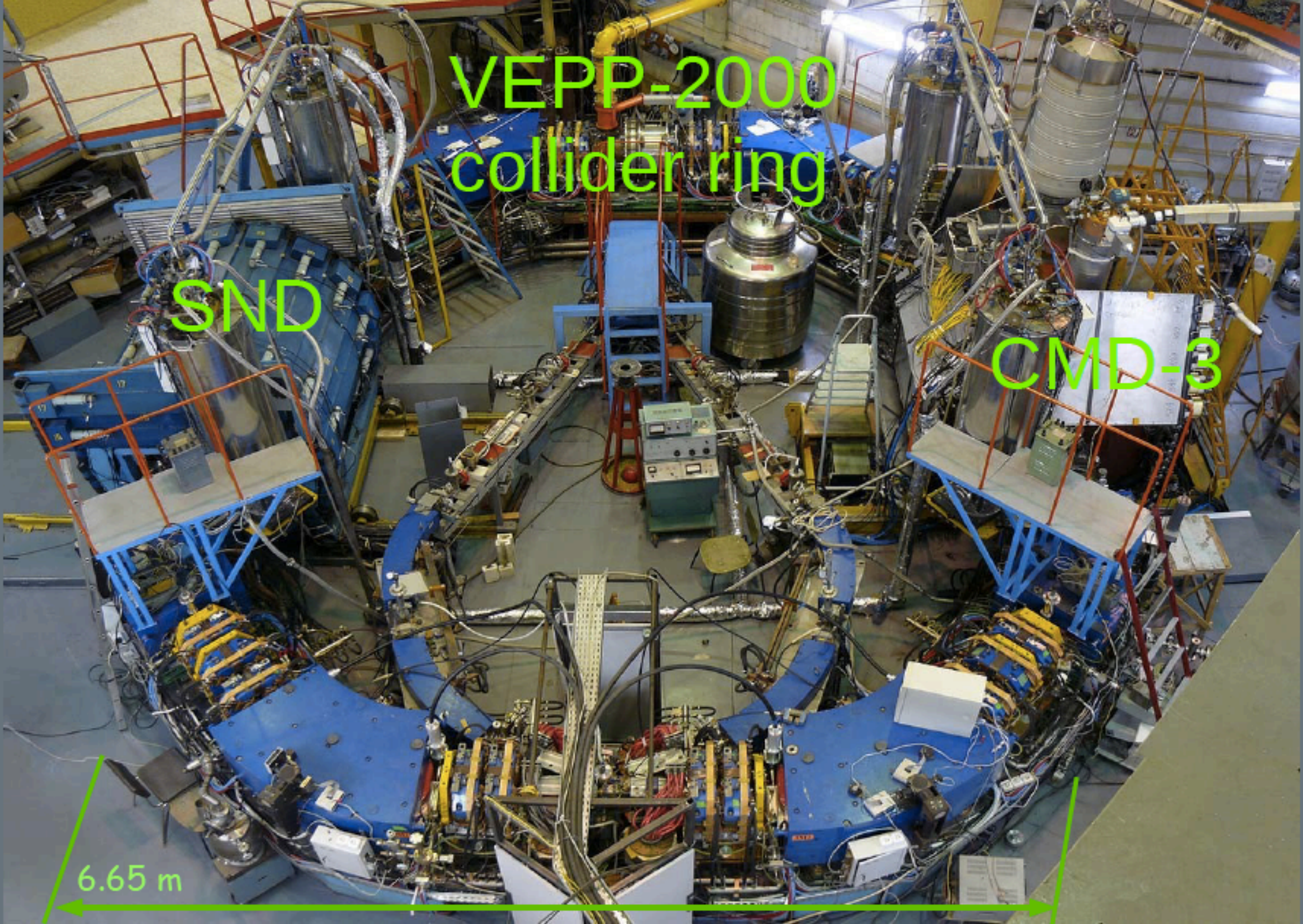
(VEPP – 2000 Novosibirsk)

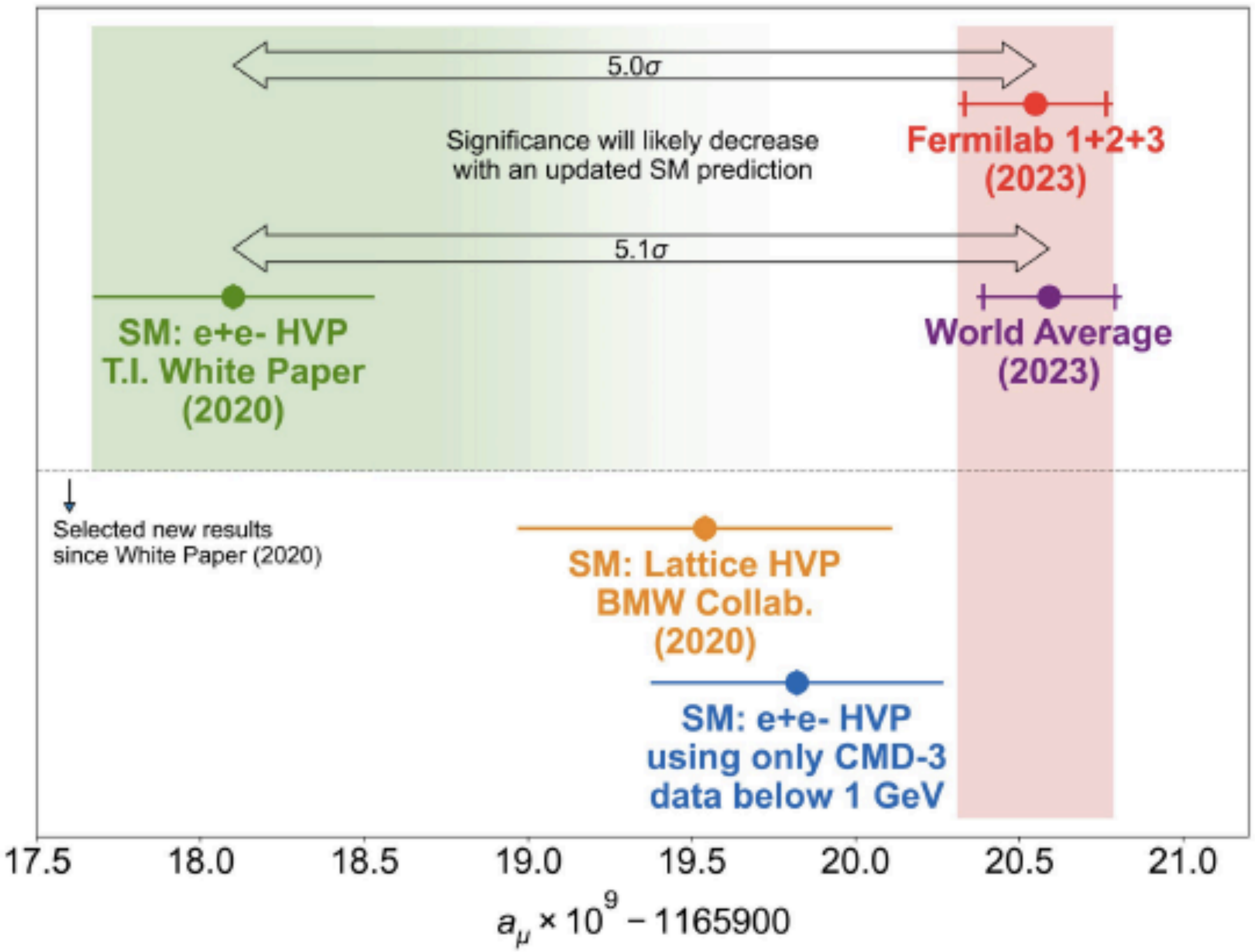
$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$



$0.6 < \sqrt{s} < 0.88$ GeV

	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0


VEPP-2000
collider ring
SND
CMD-3
6.65 m



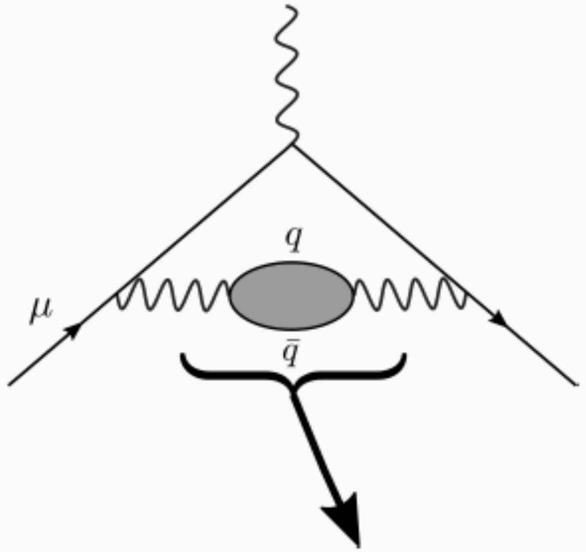
F. Ignatov (CMD-3 Coll.), 6th Plenary Workshop TI, Bern, Sept. 4 2023

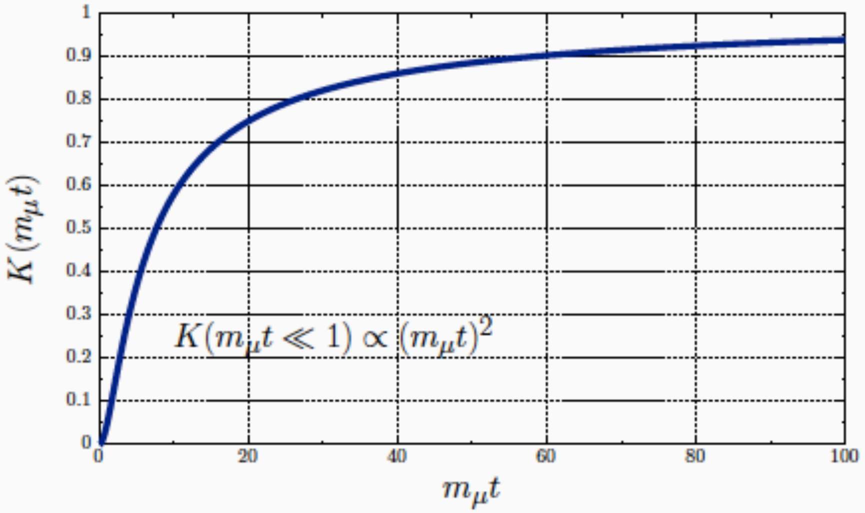
The CMD-3 is only one now over many other e+e- experiments (BaBar, KLOE, BES, CMD-2, SND, ...)

Unfortunately at the moment, we don't know the reasons of the disagreement between different experiments.

James Mott: https://indico.fnal.gov/event/60738/
Alex Keshavarzi: https://indico.fnal.gov/event/57249/contributions/271581/

LO-HVP from Lattice QCD





$$\Pi_{\mu\nu}(Q) = \int d^4x\, e^{iQ\cdot x} \langle J_\mu(x) J_\nu(0)\rangle = (\delta_{\mu\nu} Q^2 - Q_\mu Q_\nu)\, \Pi(Q^2)$$

$$\Downarrow$$

$$a_\mu^{\mathrm{LO-HVP}} = 4\alpha_{em}^2 \int_0^\infty dQ^2 \frac{1}{m_\mu^2} f\left(\frac{Q^2}{m_\mu^2}\right) \cdot (\Pi(Q^2) - \Pi(0)).$$

Time-Momentum representation (Bernecker & Meyer, 2011)

$$a_\mu^{\mathrm{LO-HVP}} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t), \quad V(t) \equiv \frac{1}{3} \sum_{i=1,2,3} \int d\vec{x}\, \langle J_i(\vec{x},t) J_i(0)\rangle$$

G.Gagliardi, Workshop of the Muon g-2 Theory Initiative, Edinburgh, Sept. 2022

Colangelo, El-Khadra, Hoferichter, Keshavarzi, Lehner, Stoffer, Teubner, arXiv:2205.12963v2 (2022)

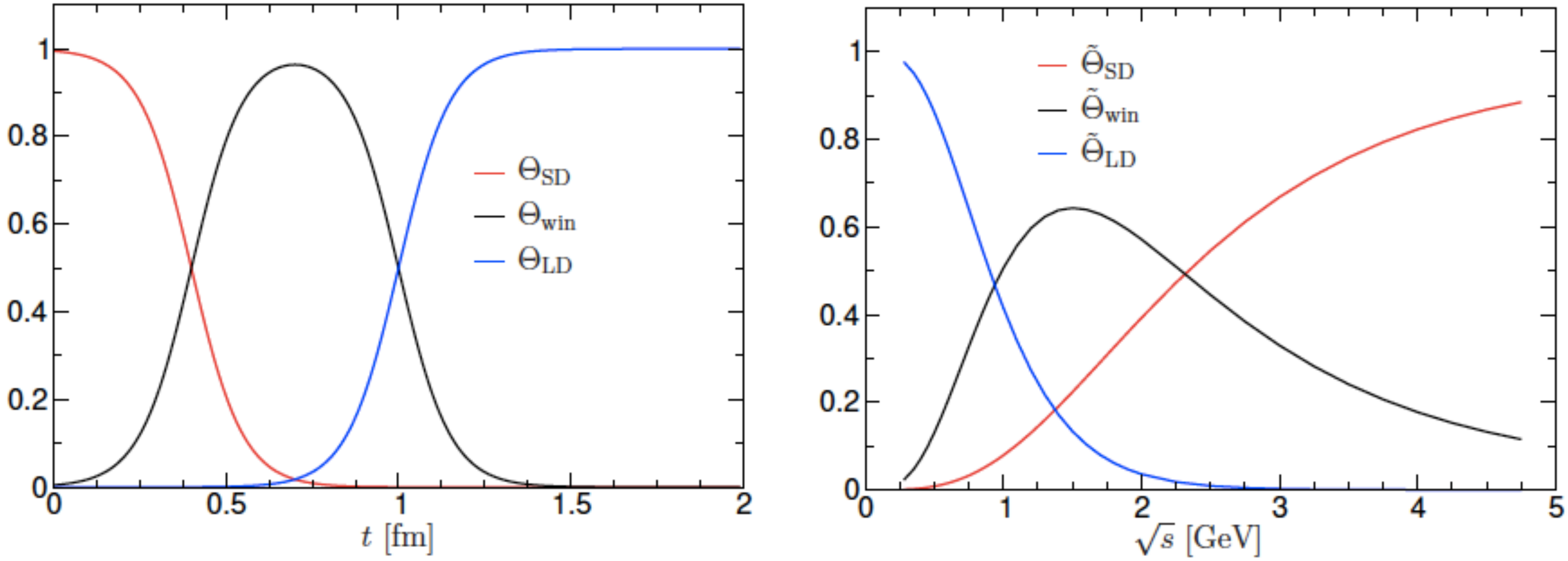
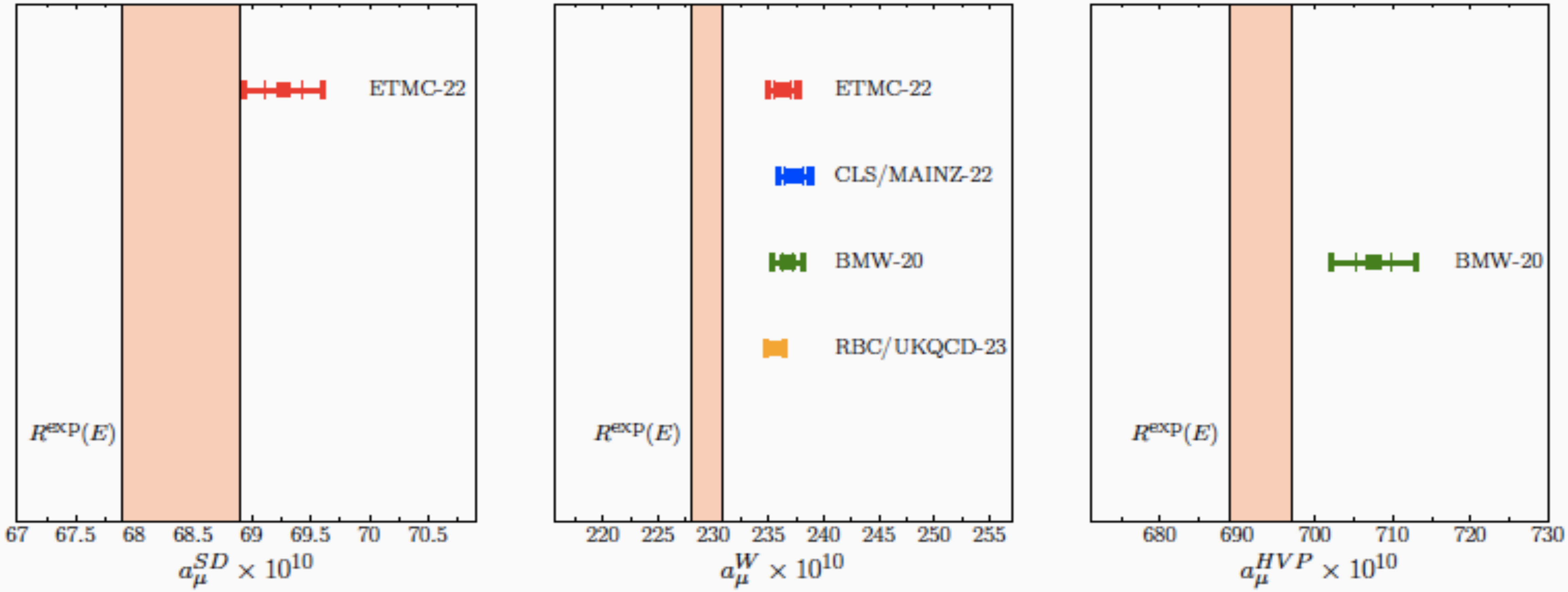


Figure 1: Short-distance, intermediate, and long-distance weight functions in Euclidean time (left), and their correspondence in center-of-mass energy (right).

The experimental ($R^{\text{exp}}(E)$-based) and the SM lattice QCD determination of the intermediate window are in significant tension [without CMD-3].

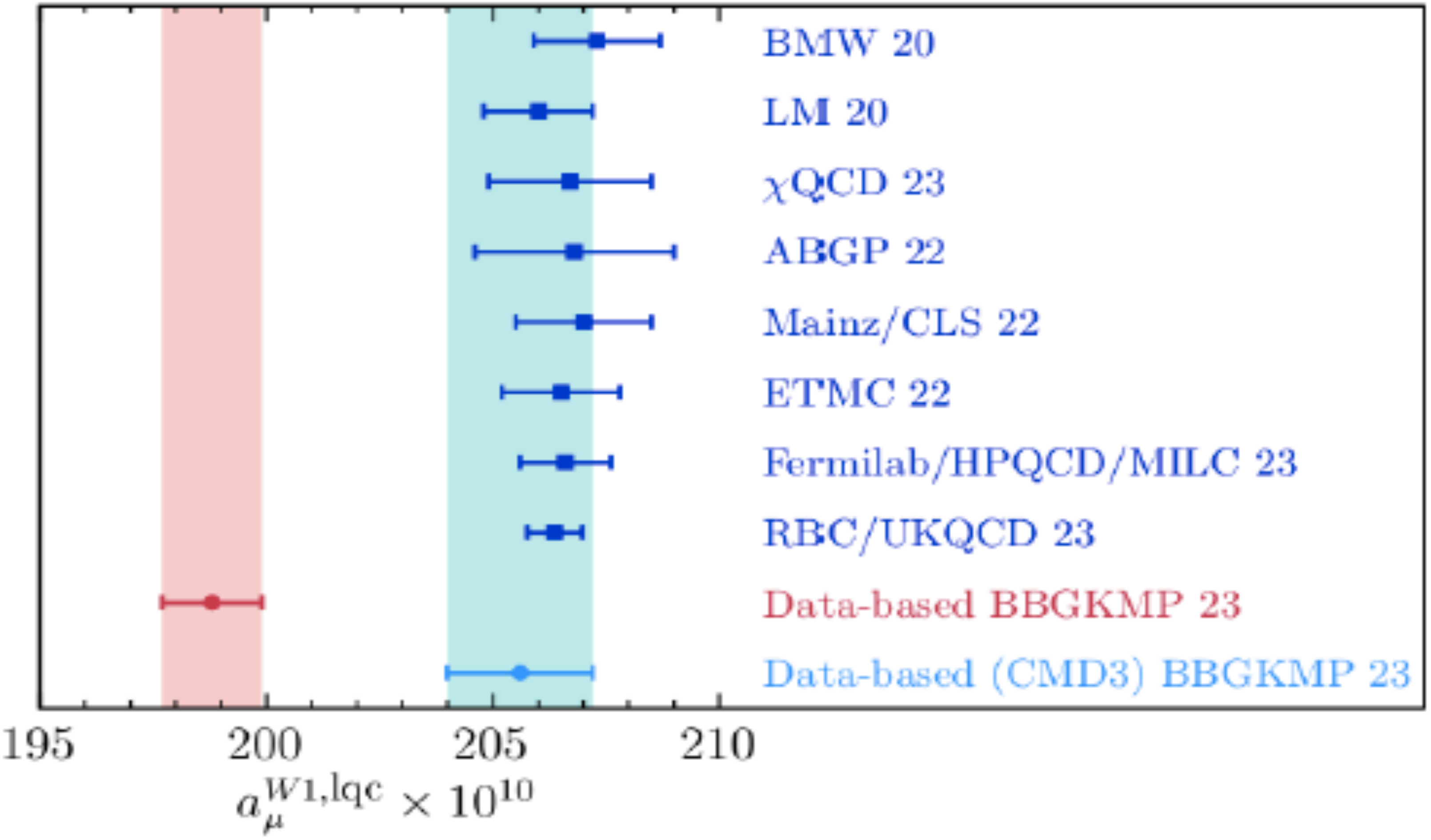


- Tension in a_μ^W is larger than 4σ (depending on how lattice results are combined).
- Substantial agreement for a_μ^{SD} suggests that the tension is localized at intermediate/low energies E.

G. Gagliardi, 6th Plenary Workshop TI, Bern, Sept. 4 2023

Potential impact of new CMD3 2pi data

Replace 2-pion data between 0.33 and 1.2 GeV by CMD3 data, keeping KNT19 data elsewhere (preliminary)



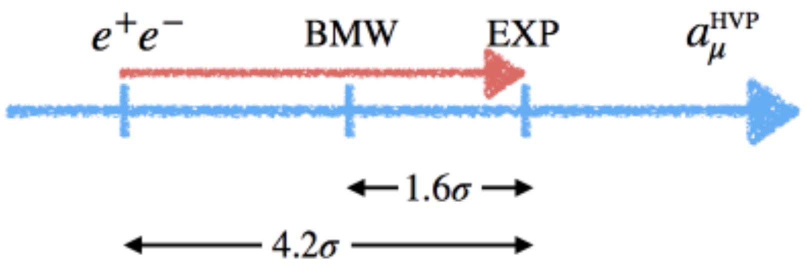
(M Golterman: Lattice 2023 talk)

New Physics to solve the new muon g-2 puzzle ?

Not including CMD3 → $(a_\mu^{\rm HVP})_{\rm EXP} = a_\mu^{\rm EXP} - a_\mu^{\rm SM,\,rest}$

$(a_\mu^{\rm HVP})^{\rm WP20}_{e^+e^-} = 6931(40) \times 10^{-11}$

$(a_\mu^{\rm HVP})_{\rm BMW} = 7075(55) \times 10^{-11}$



NP in $\sigma_{\rm had}(e^+e^- \to \text{hadrons})$ such that

1. $(a_\mu^{\rm HVP})^{\rm WP20}_{e^+e^-} \approx (a_\mu^{\rm HVP})_{\rm EXP}$
2. the approximate agreement between BMW and EXP is not spoiled
3. w/o a direct contribution $a_\mu^{\rm NP}$ (i.e. NP not in muons)

L. Di Luzio, A.M., P. Paradisi, M. Passera, PLB 2022 (arXiv 2112.08312)

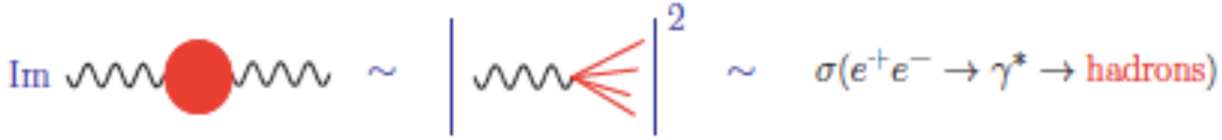
Can Δa_μ be due to a missing contribution in $\sigma_{\rm had}$?

[Marciano, Passera, Sirlin 2008 & 2010;
Keshavarzi, Marciano, Passera, Sirlin 2020.
See also Crivellin, Hoferichter, Manzari, Montull 2020;
Malaescu, Schott 2020;
Colangelo, Hoferichter, Stoffer 2020]

→ *a upward shift of* $\sigma_{\rm had}$ *induces an increase of* $\Delta\alpha^{(5)}_{\rm had}(M_Z)$

$$\alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha(M_Z) - \Delta\alpha^{(5)}_{\rm had}(M_Z) - \Delta\alpha_{\rm top}(M_Z)}$$

$$a_\mu^{\rm HLO} \simeq \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{s}, \qquad \Delta\alpha^{(5)}_{\rm had} = \frac{M_Z^2}{4\pi\alpha^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{M_Z^2 - s}$$

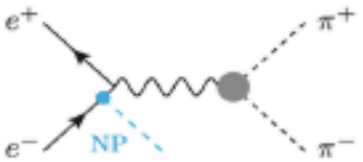


**Shifts $\Delta\sigma(s)$ to fix Δa_μ are possible,
but conflict with the EW fit if they occur above ~1 GeV**

Keshavarzi, Marciano, Passera, Sirlin, PRD 2020 (updated 2021)

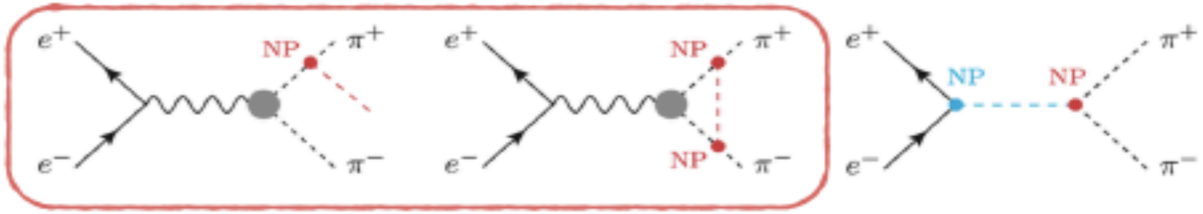
Light New Physics in σ_{had}

- Light new physics inducing a sub-GeV modification of σ_{had} is the only possibility



1. NP coupled only to electrons → severe bounds

[See however
Darmé, Grilli di Cortona, Nardi 2112.09139
NP in Bhabha scattering ? → backup slides]



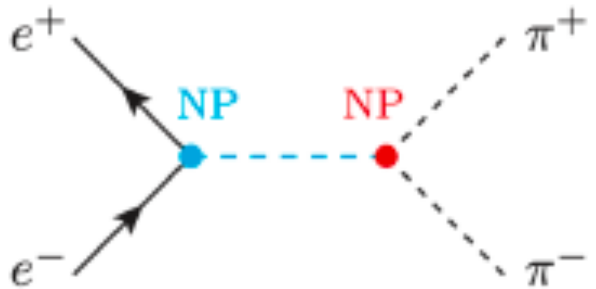
2. NP coupled only to hadrons

FSR effects due to NP should be included into $\sigma_{\text{had}}(s)$, not easy to be accounted for...
(depend on exp. cuts and mass of NP)

→ *however, we know that in the QED case*

$$(a_\mu^{\text{HVP}})^{\text{FSR}}_{e^+e^-} \approx 50 \times 10^{-11} \quad \longleftrightarrow \quad |(a_\mu^{\text{HVP}})_{\text{BMW}} - (a_\mu^{\text{HVP}})^{\text{WP20}}_{e^+e^-}| \approx 150 \times 10^{-11}$$

Light New Physics in σ_{had}



NP coupled both to hadrons and electrons

but **not** directly to the **muons** !

$\sim \quad \sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

$$(a_\mu^{\text{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{\mathrm{d}s}{s} K(s)\,\mathrm{Im}\,\Pi_{\text{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\text{had}}(s)$$

$$\sigma_{\text{had}} = \sigma_{\text{had}}^{\text{SM}} + \Delta\sigma_{\text{had}}^{\text{NP}}$$

$$\sigma_{\text{had}} - \Delta\sigma_{\text{had}}^{\text{NP}}$$

SUBTRACTION since NP does **NOT** contribute to the HVP at the LO, but it **DOES** contribute to the cross-section at the LO

a **POSITIVE** SHIFT on $(a_\mu^{\text{HVP}})_{e^+e^-}$ *requires* $\Delta\sigma_{\text{had}}^{\text{NP}} < 0$ *(negative interference)*

The unique scenario to obtain such a **SIZEABLE NEGATIVE interference**

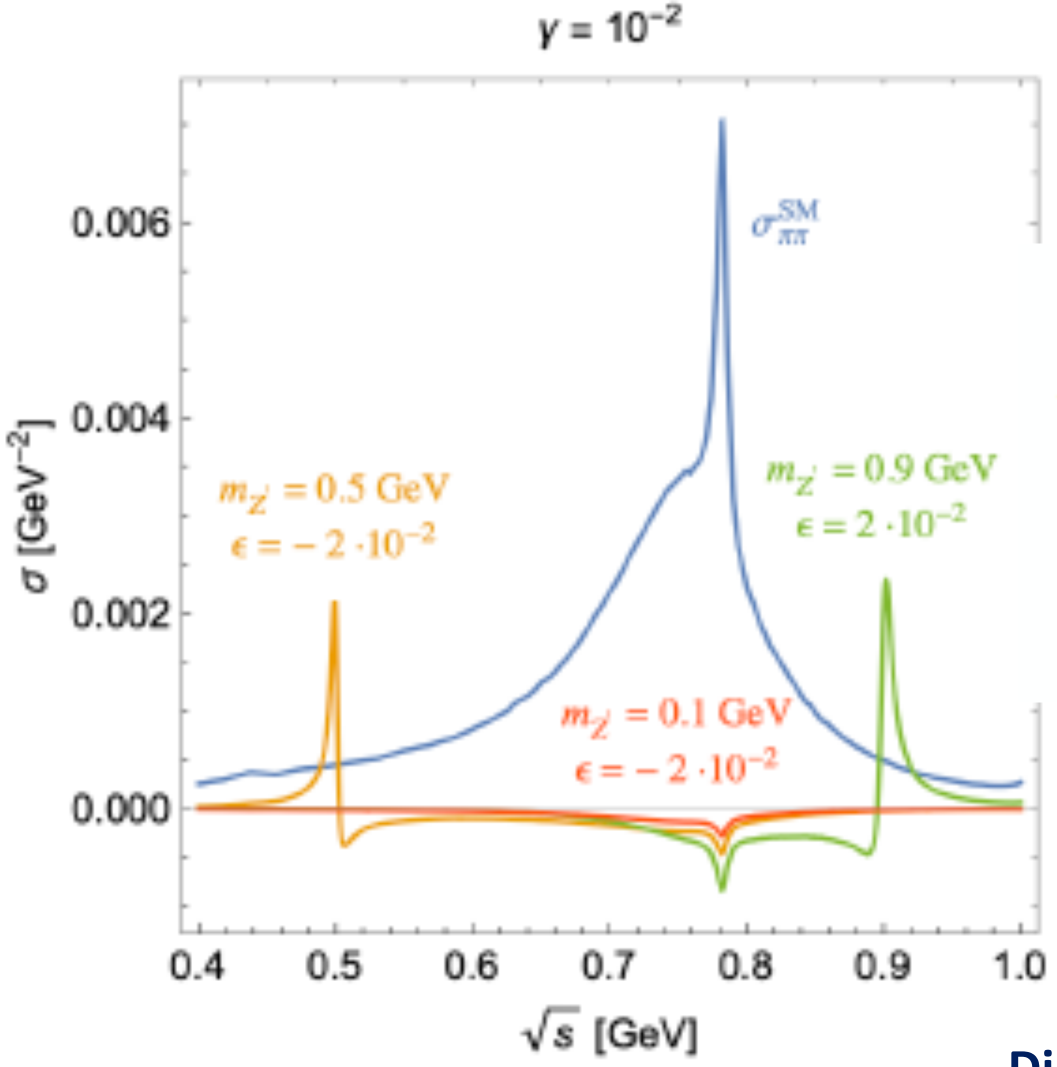
- **SIZEABLE** → **TREE-LEVEL** contribution to modify σ_{had} at $\sqrt{s}$ **< 1 GeV** (hence, **sub-GeV mediator** coupling to the hadronic and electron currents at tree-level)
- **NEGATIVE INTERF.** → NP particle couples via a **VECTOR** current to the u, d quarks (given the dominance of the $\pi^+\pi^-$ channel)

$$\mathcal{L}_{Z'} \supset (g_V^e\, \bar{e}\gamma^\mu e + g_V^q\, \bar{q}\gamma^\mu q) Z'_\mu \qquad q = u, d \qquad m_{Z'} \lesssim 1\ \mathrm{GeV}$$

→ *a light spin-1 mediator with vector couplings to first generation SM fermions*

$$\frac{\sigma_{\pi\pi}^{\mathrm{SM+NP}}}{\sigma_{\pi\pi}^{\mathrm{SM}}} = \left| 1 + \frac{g_V^e (g_V^u - g_V^d)}{e^2} \frac{s}{s - m_{Z'}^2 + i m_{Z'} \Gamma_{Z'}} \right|^2$$

Examples of benchmark values for $m_{Z'}$ and Z' couplings to electrons and up- and down-quarks suitable to solve the g-2 discrepancy



$$\Delta a_\mu = \frac{1}{4\pi^3}\int_{s_{\rm exp}}^{\infty} {\rm d}s\, K(s)(-\Delta\sigma_{\rm had}^{\rm NP}(s))$$

$\sqrt{s_{\rm exp}} \approx 0.3$ GeV for $\pi^+\pi^-$ channel

$$\Delta\sigma_{\rm had}^{\rm NP}(s) \approx \sigma_{\pi\pi}^{\rm SM}(s) \times \frac{2\epsilon s(s-m_{Z'}^2)+\epsilon^2 s^2}{(s-m_{Z'}^2)^2+m_{Z'}^4\gamma^2}$$

$$\epsilon \equiv g_V^e(g_V^u - g_V^d)/e^2$$

$$\gamma \equiv \Gamma_{Z'}/m_{Z'}$$

Di Luzio, A.M., Paradisi, Passera 2112. 08312

However, **severe constraints on the Z' couplings** to electrons and to hadrons

- for $m_{Z'} \lesssim 0.3$ GeV ($Z' \to e^+e^-$ is the main decay mode)

$e^+e^- \to \gamma Z'$ @ BaBar → $g_V^e \lesssim 2 \cdot 10^{-4}$

- for $m_{Z'} \gtrsim$ MeV

electron g-2 → $|g_V^e| \lesssim 10^{-2}\,(m_{Z'}/0.5\ \mathrm{GeV})$

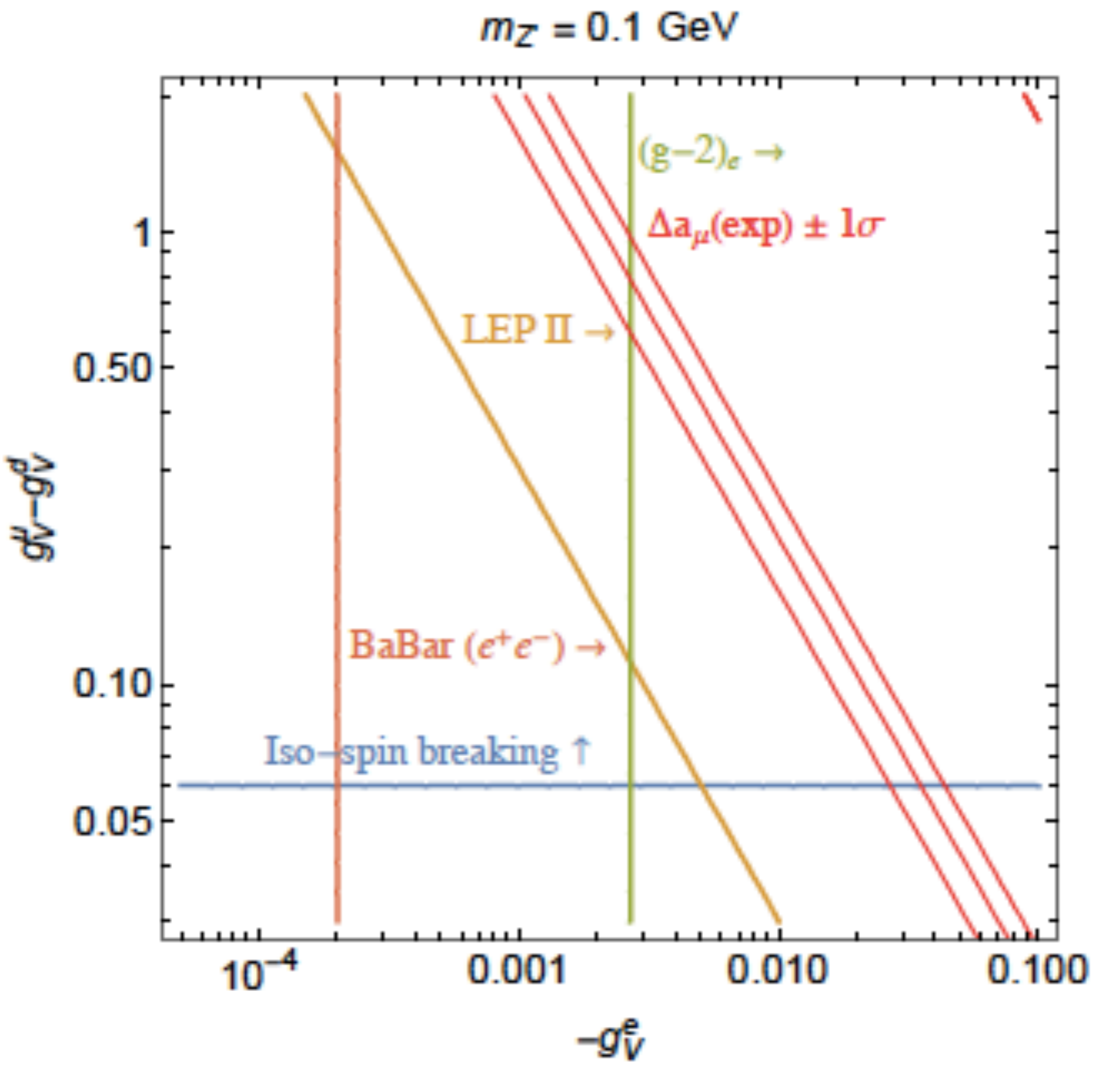
$e^+e^- \to q\bar{q}$ *has been measured with per-cent accuracy at LEP-II*

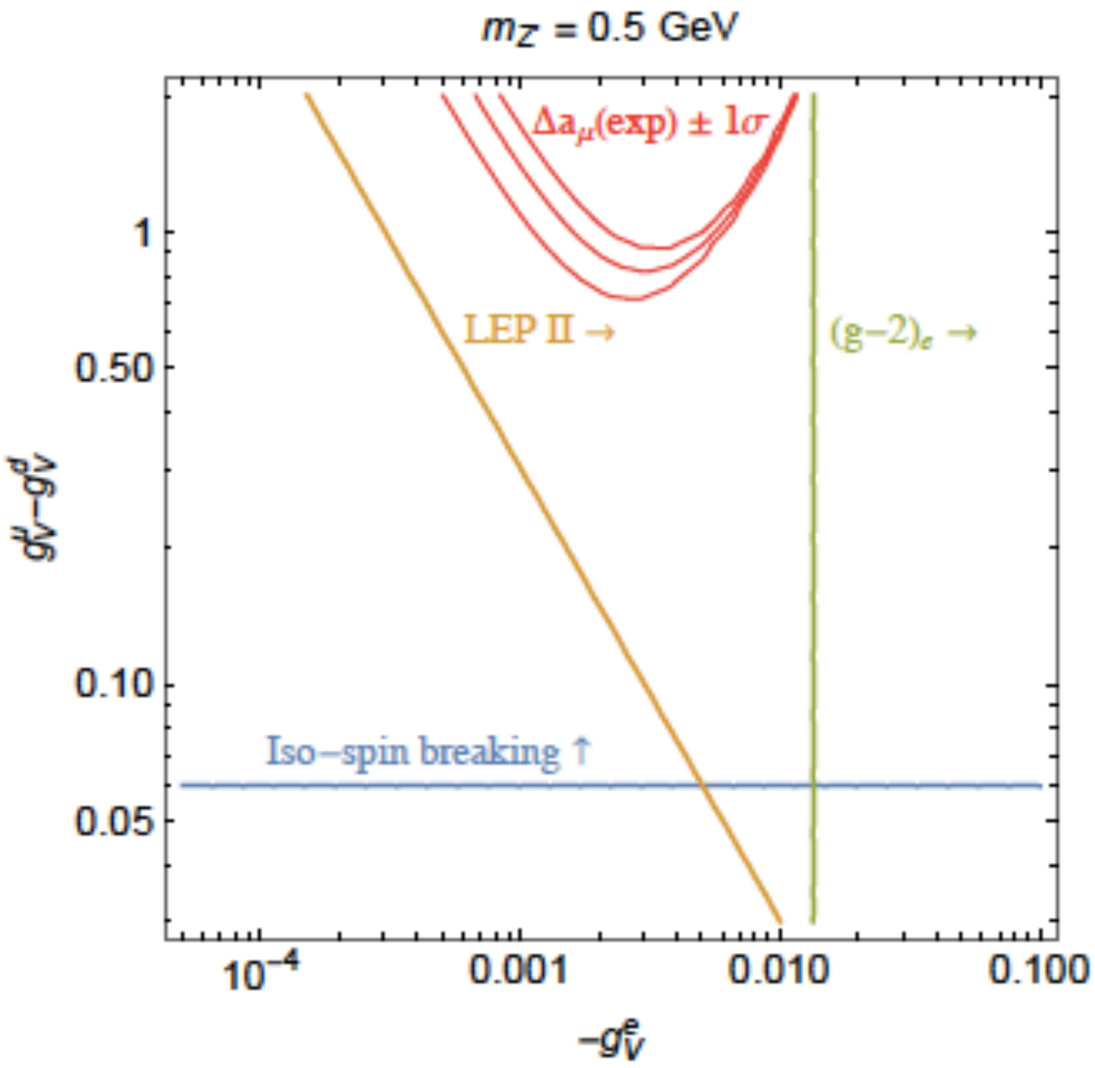
$$\frac{\sigma_{qq}^{\mathrm{SM+NP}}}{\sigma_{qq}^{\mathrm{SM}}} \approx 1 + 2\frac{g_V^e g_V^q}{e^2 Q_q} \quad \to \quad |g_V^e g_V^q| \lesssim 4.6 \cdot 10^{-4} |Q_q| \qquad (\epsilon \lesssim 3.3 \cdot 10^{-3})$$

Iso-spin breaking observables → $|g_V^u - g_V^d| \lesssim 0.06$

charged vs. neutral pion mass^2 difference $\Delta m^2 = m_{\pi^+}^2 - m_{\pi^0}^2$ **(rescaling the lattice QCD calculation of Frezzotti, Gagliardi, Lubicz, Martinelli, Sanfilippo and Simula 2112.01066)**

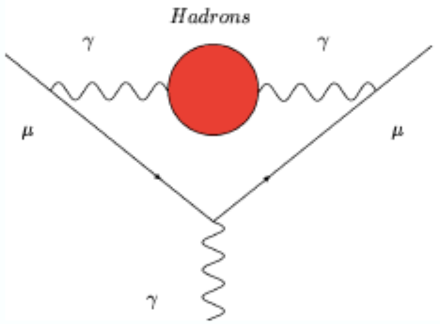
At least **TWO independent bounds prevent** to get a sizeable contribution to Δa_μ modifying σ_{had} via Z' exchange to **solve** the "**new**" μ g-2 puzzle





Spacelike proposal for a_μ

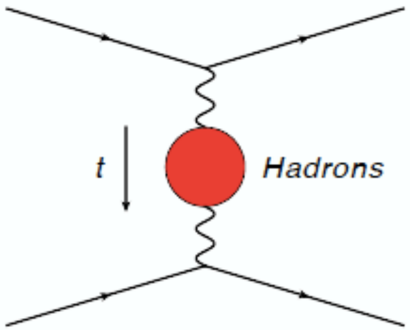
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the **timelike** formula:



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

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

- Alternatively, exchanging the x and s integrations in a_μ^{HLO}



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

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

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the **spacelike** region: **a_μ^{HLO} can be extracted from scattering data!**

Carloni Calame, MP, Trentadue, Venanzoni, 2015

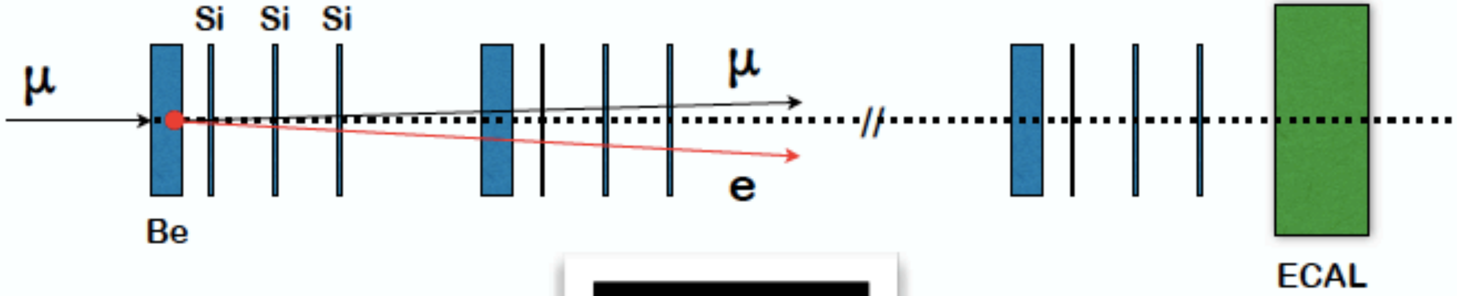
New Physics extracting $\Delta\alpha_{had}(t)$ at MUonE? Padova and Heidelberg 2020

→ **NO, NP cannot spoil the validity of such extraction**

MUonE: a new determination of $\Delta\alpha_{had}$

MUonE: Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can be measured via the **elastic scattering $\mu\, e \to \mu\, e$**.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each station has one layer of Beryllium (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

[Courtesy by M. Passera]

- Letter of Intent submitted to CERN SPSC in 2019: Test run approved for 2021 arXiv:2209.13084v1 [physics.atom-ph] 27 Sep 2022

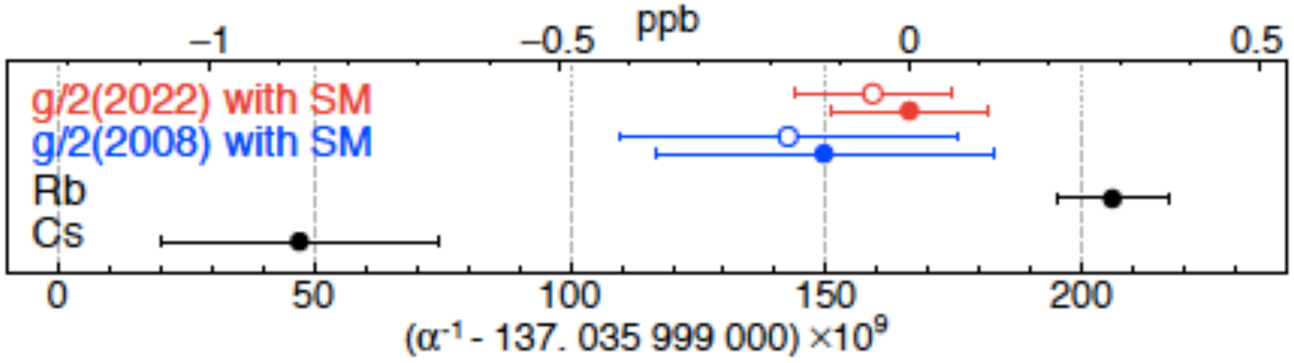
NEW Measurement of the Electron Magnetic Moment

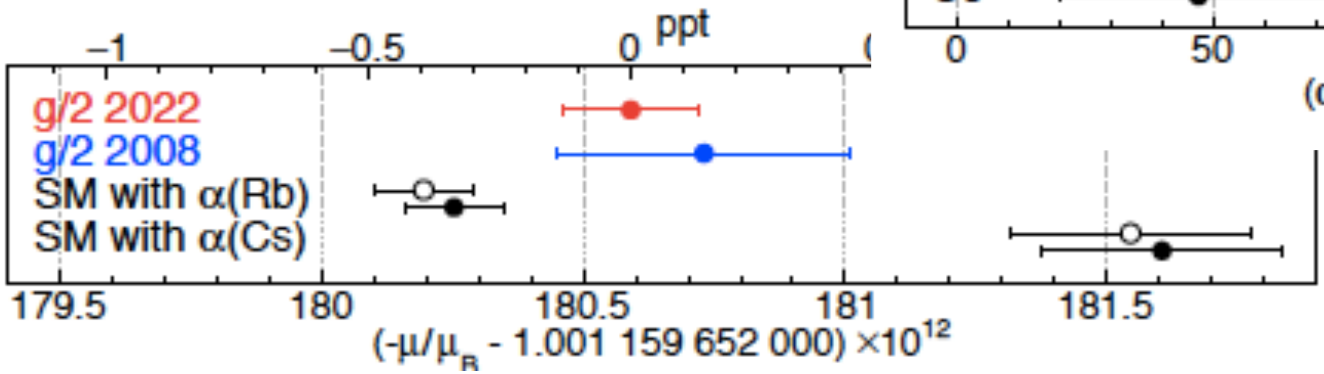
X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Center for Fundamental Physics, Northwestern University, Evanston, Illinois 60208, USA*

(Dated: September 28, 2022)

The electron magnetic moment in Bohr magnetons, $-\mu/\mu_B = 1.001\,159\,652\,180\,59\,(13)$ [0.13 ppt], is consistent with a 2008 measurement and is 2.2 times more precise. The most precisely measured property of an elementary particle agrees with the most precise prediction of the Standard Model (SM) to 1 part in 10^{12}, the most precise confrontation of all theory and experiment. The SM test will improve further when discrepant measurements of the fine structure constant α are resolved, since the prediction is a function of α. The magnetic moment measurement and SM theory together predict $\alpha^{-1} = 137.035\,999\,166\,(15)$ [0.11 ppb]





***Thanks**, Subir, for the many (always lively!) discussions with you on physics (and not only physics…) and for reminding me that **DOUBT** rather than **CERTAINTY** is our guiding principle*

to Subir, the tireless and unorthodox hunter for

New Physics

Beyond the Standard Models

BACK-UP SLIDES

LFV, $(g-2)_{lept}$ and $(EDM)_{lept}$ correlations in Effective Theories

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ vs. $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

- EDMs vs. $(g-2)_\mu$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-29} \left(\frac{\phi_e^{CPV}}{10^{-5}}\right) \; e\,\mathrm{cm}\,,$$

$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22} \, \phi_\mu^{CPV} \; e\,\mathrm{cm}\,,$$

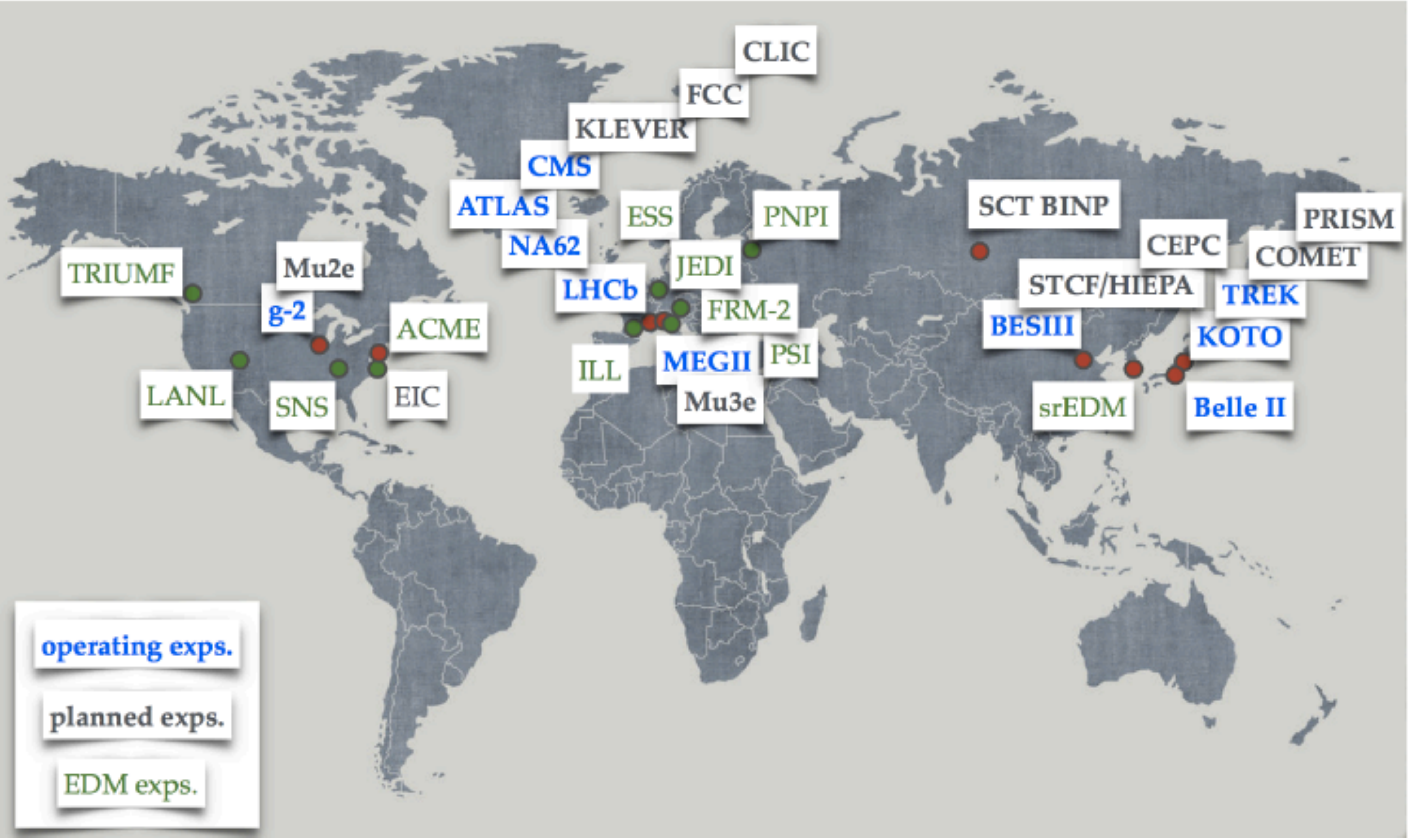
- Main messages:
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ requires a nearly flavor and CP conserving NP
  - Large effects in the muon EDM $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ are still allowed!

$$\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} \quad \Longleftrightarrow \quad \Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}$$

P. Paradisi, muEDM Workshop Pisa, 2022

Process	Present	Experiment	Future	Experiment
$\mu \to e\gamma$	4.2×10^{-13}	MEG	$\approx 6 \times 10^{-14}$	MEG II
$\mu \to 3e$	1.0×10^{-12}	SINDRUM	$\approx 10^{-16}$	Mu3e
μ^- Au $\to e^-$ Au	7.0×10^{-13}	SINDRUM II	?	
μ^- Ti $\to e^-$ Ti	4.3×10^{-12}	SINDRUM II	?	
μ^- Al $\to e^-$ Al	–		$\approx 10^{-16}$	COMET, MU2e
$\tau \to e\gamma$	3.3×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to \mu\gamma$	4.4×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to 3e$	2.7×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$\tau \to 3\mu$	2.1×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$d_e(\mathrm{e\ cm})$	1.1×10^{-29}	ACME	$\sim 3 \times 10^{-31}$	ACME III
$d_\mu(\mathrm{e\ cm})$	1.8×10^{-19}	Muon (g-2)	$\sim 10^{-22}$	PSI

Table: Present and future experimental sensitivities for relevant low-energy observables.


CLIC
FCC
KLEVER
CMS
ATLAS
NA62
ESS
PNPI
SCT BINP
PRISM
CEPC
COMET
TRIUMF
Mu2e
g-2
JEDI
LHCb
FRM-2
STCF/HIEPA
TREK
BESIII
ACME
KOTO
LANL
SNS
EIC
ILL
MEGII
PSI
Mu3e
srEDM
Belle II
operating exps.
planned exps.
EDM exps.

The ELECTRON magnetic moment

- **Status of Δa_e as of 2012**

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}} = -9.2\,(8.1) \times 10^{-13},$$

$$\delta a_e \times 10^{13}: \quad (0.6)_{\mathrm{QED4}}, \ (0.4)_{\mathrm{QED5}}, \ (0.2)_{\mathrm{HAD}}, \ (7.6)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\mathrm{EXP}}}.$$

  - The errors from QED4 and QED5 will be reduced soon to 0.1×10^{-13} [Kinoshita]
  - We expect a reduction of $\delta a_e^{\mathrm{EXP}}$ to a part in 10^{-13} (or better). [Gabrielse]
  - Work is also in progress for a significant reduction of $\delta\alpha$. [Nez]

- **Status of Δa_e as of 2018: 2.4σ discrepancy** [Parker et al., Science, '18]

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}}(\alpha_{\mathrm{Berkeley}}) = -8.8\,(3.6) \times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\mathrm{QED5}}, \ (0.1)_{\mathrm{HAD}}, \ (2.3)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\mathrm{EXP}}}.$$

- **Status of Δa_e as of 2020: 1.6σ discrepancy** [Morel et al., Nature, '20]

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}}(\alpha_{\mathrm{LKB2020}}) = 4.8\,(3.0) \times 10^{-13}$$

$$\delta a_e \times 10^{13}: \quad (0.1)_{\mathrm{QED5}}, \ (0.1)_{\mathrm{HAD}}, \ (0.9)_{\delta\alpha}, \ (2.8)_{\delta a_e^{\mathrm{EXP}}}.$$

[WP20, 2006.04822]

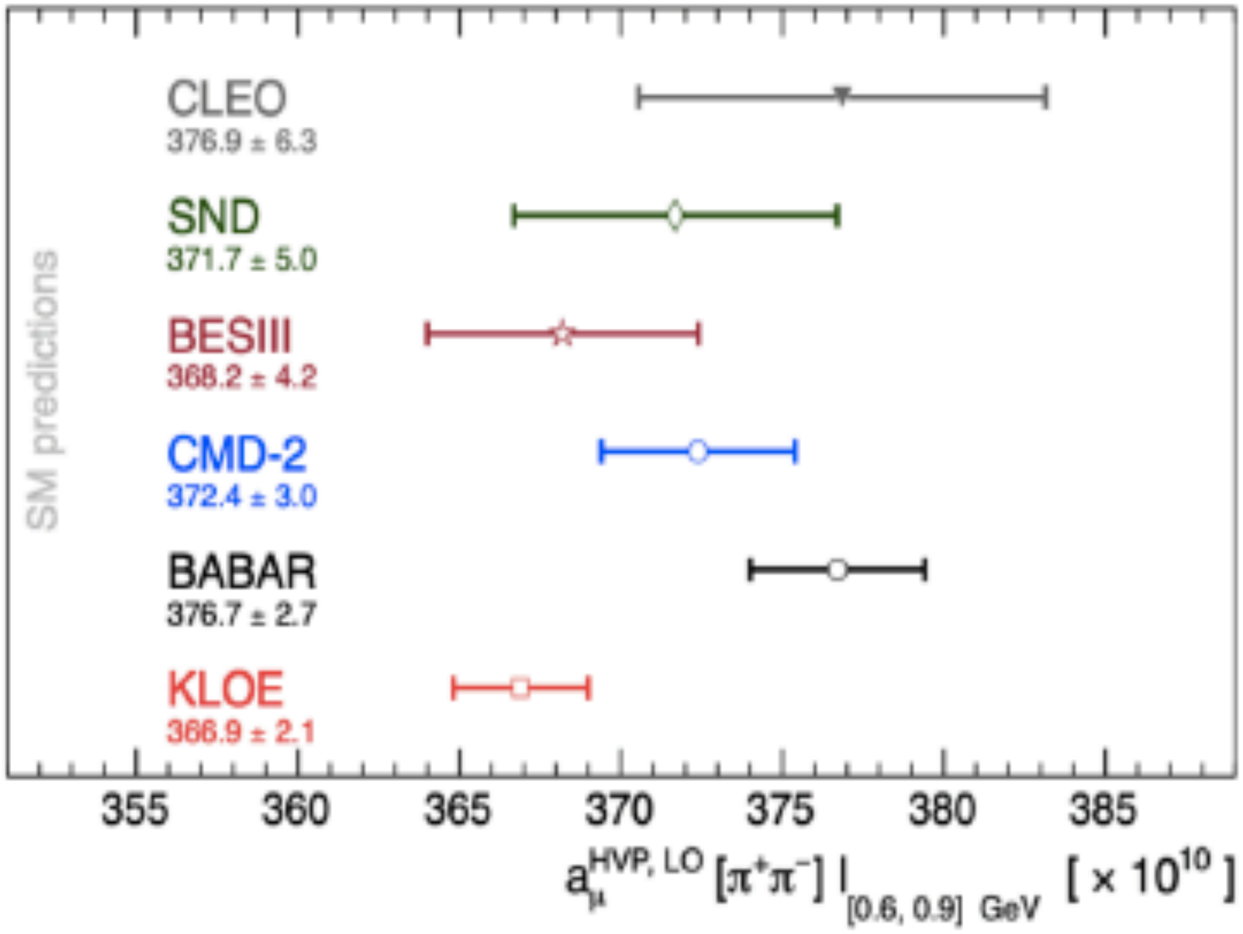


Figure 15: Comparison of results for $a_\mu^{\mathrm{HVP,\,LO}}[\pi\pi]$, evaluated between 0.6 GeV and 0.9 GeV for the various experiments.

NP in Bhabha scattering?

- What if the measurement of the KLOE luminosity is affected by NP ?

[Darmé, Grilli di Cortona, Nardi 2112.09139]

$$\mathcal{L}^{SM}_{e^+e^-} = \frac{N_{Bha}}{\sigma^{SM}_{eff}} \longrightarrow \mathcal{L}_{e^+e^-} = \mathcal{L}^{SM}_{e^+e^-} \frac{\sigma^{SM}_{eff}}{\sigma_{eff}}$$

$$\sigma_{eff} = \sigma^{SM}_{eff}(1+\delta_R)$$

$$\sigma_{had} \propto N_{had}/\mathcal{L}_{e^+e^-} \longrightarrow \sigma_{had} \to \sigma_{had}(1+\delta_R)$$

$$a_\mu^{LO,HVP} \to a_\mu^{LO,HVP}(1+\delta_R)$$

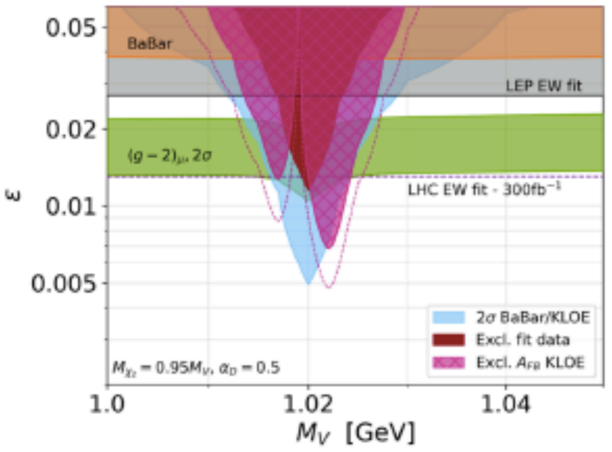
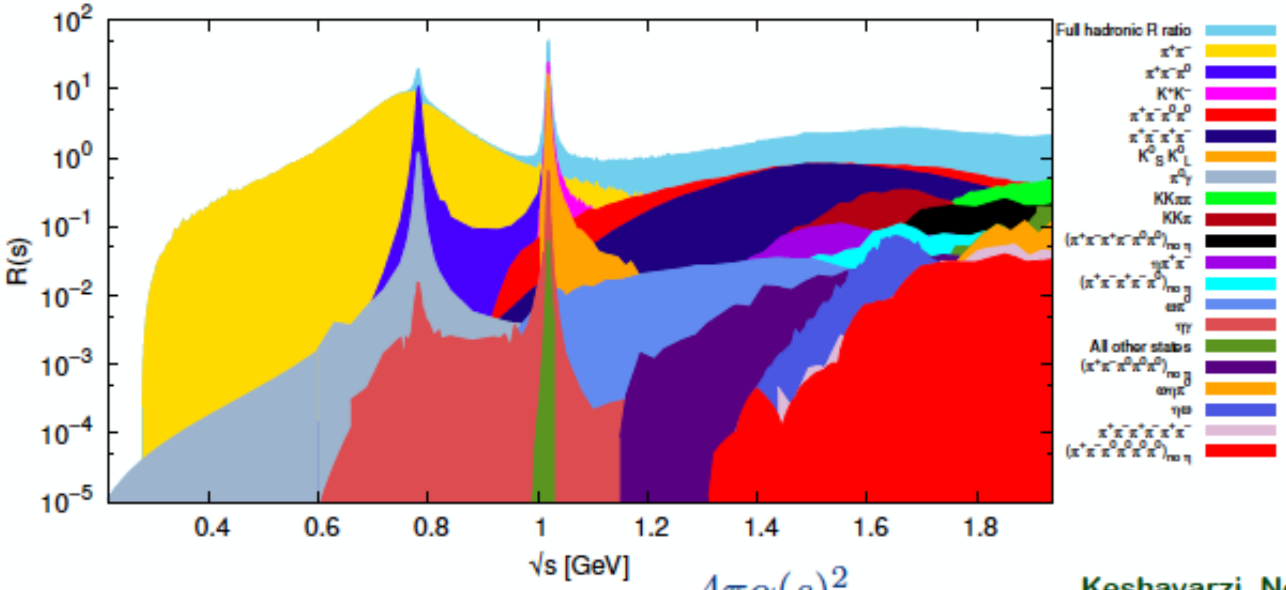


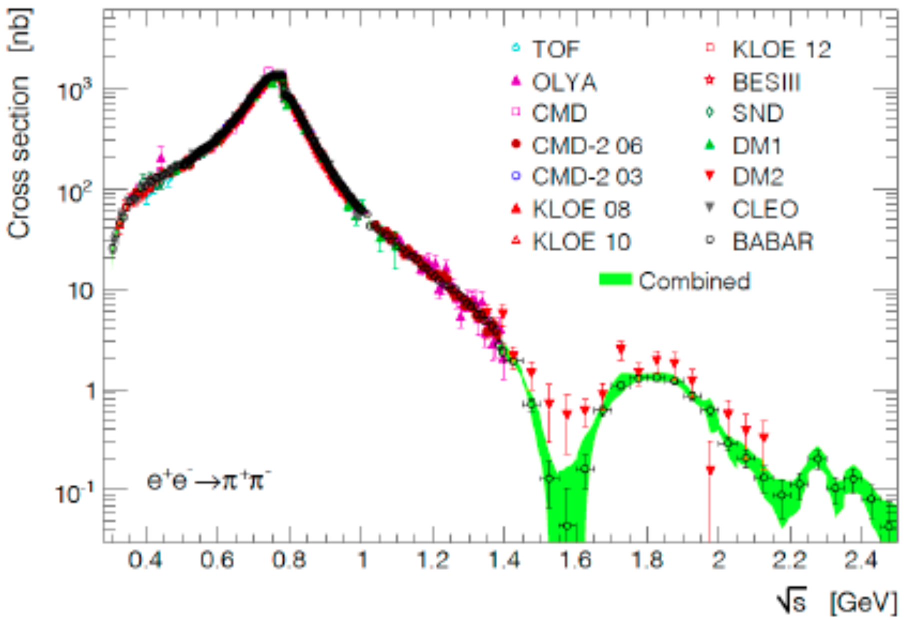
Figure 3. Parameter range compatible at 2σ with the experimental measurement of Δa_μ (green region) resulting from a redetermination of the KLOE luminosity, for $\alpha_D = 0.5$, $m_{\chi_2} = 0.95 m_V$ and $m_{\chi_1} = 25$ MeV. In the blue region the KLOE and BaBar results for σ_{had} are brought into agreement at 2σ. The red region corresponds to a shift of the KLOE measurement in tension with BaBar (and with the other experiments) at more than 2σ.

$e^+e^- \rightarrow \pi^+\pi^-$ dominance of the 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

$\Lambda \approx v$: SUSY and the muon $(g-2)$

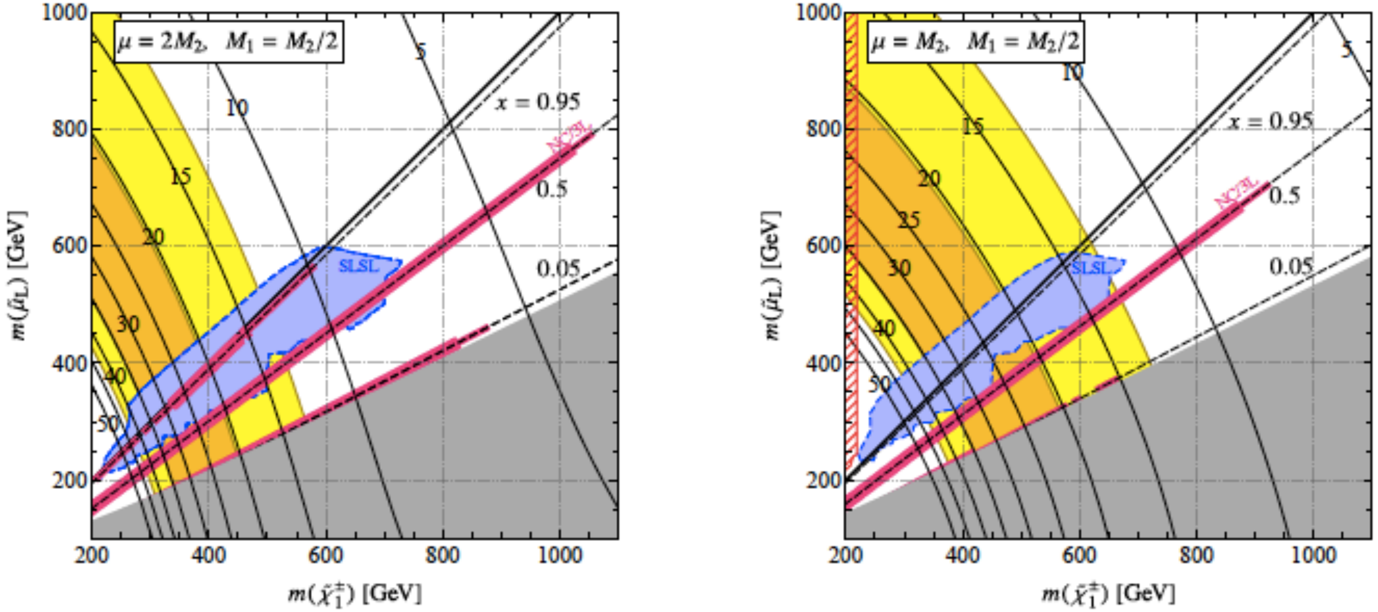
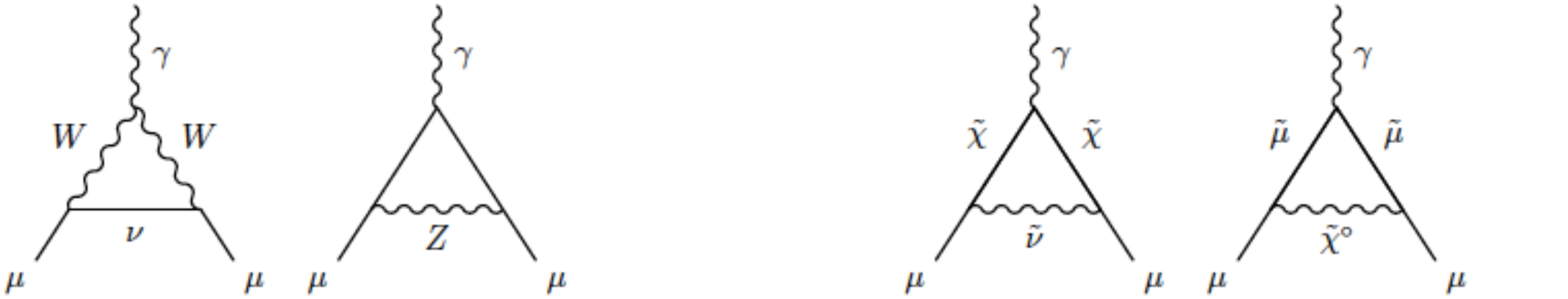


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].

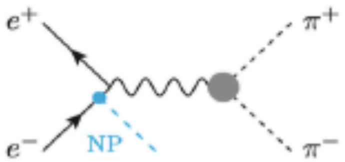


$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

$$a_\mu^{\rm SUSY} \approx \frac{g^2 m_\mu^2 \tan\beta}{32\pi^2 \tilde{m}^2} \underbrace{\approx 2 \times 10^{-9}}_{\tilde{m} = 500\,\mathrm{GeV}\ \&\ \tan\beta = 40}$$

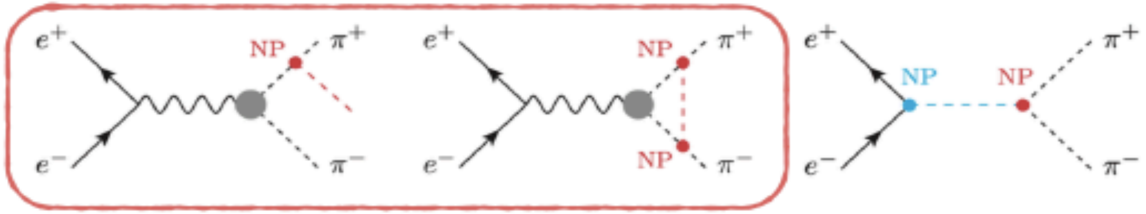
Light New Physics in $\sigma_{\mathbf{had}}$

- Light new physics inducing a sub-GeV modification of σ_{had} is the only possibility



1. NP coupled only to electrons → severe bounds

[See however
Darmé, Grilli di Cortona, Nardi 2112.09139
NP in Bhabha scattering ? → backup slides]



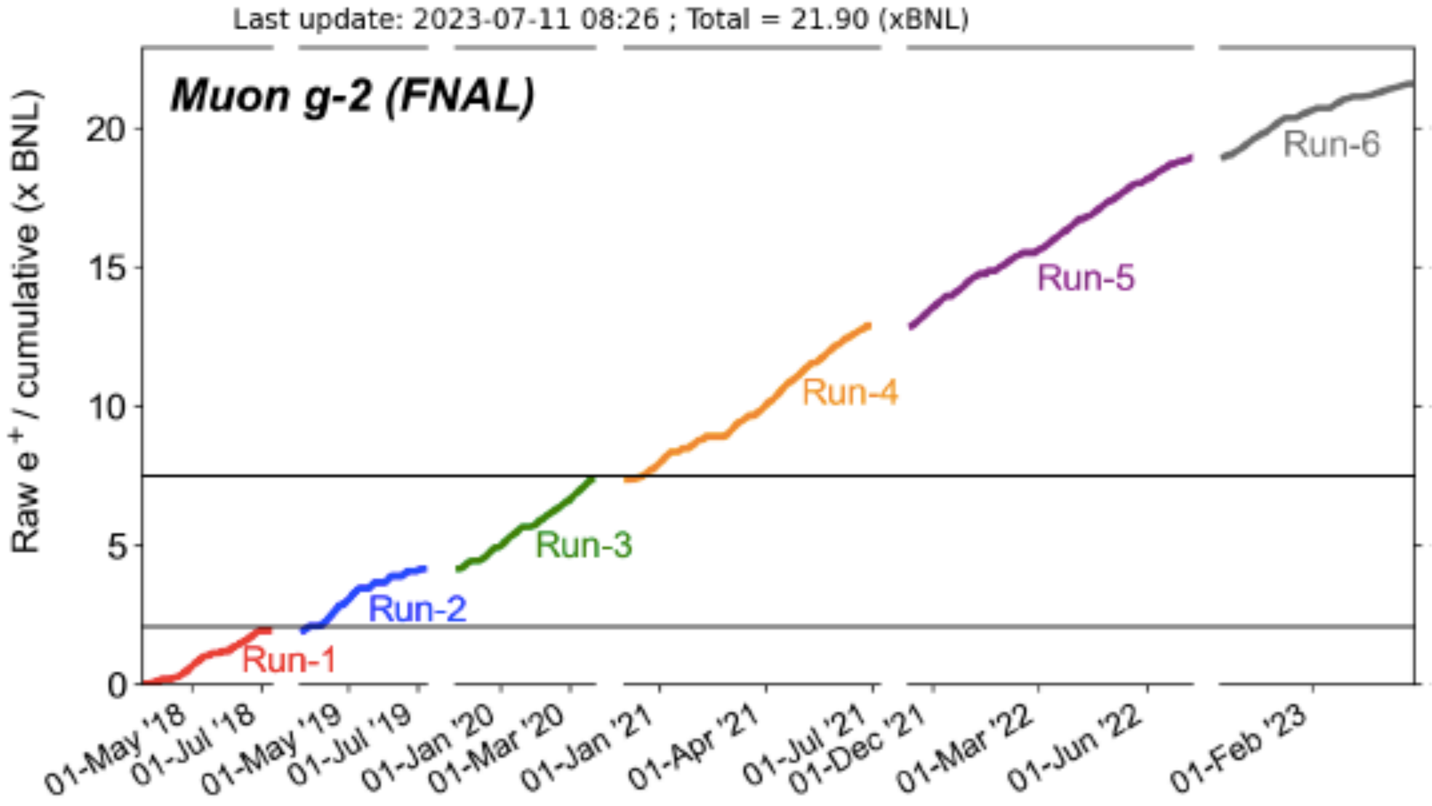
2. NP coupled only to hadrons

FSR effects due to NP should be included into $\sigma_{\mathrm{had}}(s)$, not easy to be accounted for…
(depend on exp. cuts and mass of NP)

→ *however, we know that in the QED case*

$$(a_\mu^{\mathrm{HVP}})^{\mathrm{FSR}}_{e^+e^-} \approx 50 \times 10^{-11} \quad \longleftrightarrow \quad |(a_\mu^{\mathrm{HVP}})_{\mathrm{BMW}} - (a_\mu^{\mathrm{HVP}})^{\mathrm{WP20}}_{e^+e^-}| \approx 150 \times 10^{-11}$$

- Run 1 (2018): $15 \times 10^9\, e^+$ analyzed
- Run 2 (2019) + Run 3 (2020): $71 \times 10^9\, e^+$ analyzed
- Run 1: $\pm$ 434 (stat) $\pm$ 157 (syst) $\pm$ 25 (ext param) (ppb)
- Run 2/3: $\pm$ 201 (stat) $\pm$ 68 (syst) $\pm$ 25 (ext param) (ppb)



"$g-2$ is not an experiment: it is a way of life."

[John Adams (Head of the Proton Synchrotron at CERN (1954-1961)]

This statement also applies to many theorists! [Nyffeler '16]

$$a_\mu^{\rm QED} = (1/2)\,(\alpha/\pi)$$ [Schwinger, 1948]

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

[Sommerfield; Petermann; Suura&Wichmann '57; Elend '66]

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

[Remiddi, Laporta, Barbieri...; Czarnecki, Skrzypek '99]

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

[Kinoshita et al. '81-'15; Steinhauser et al. '13-'16; Laporta '17]

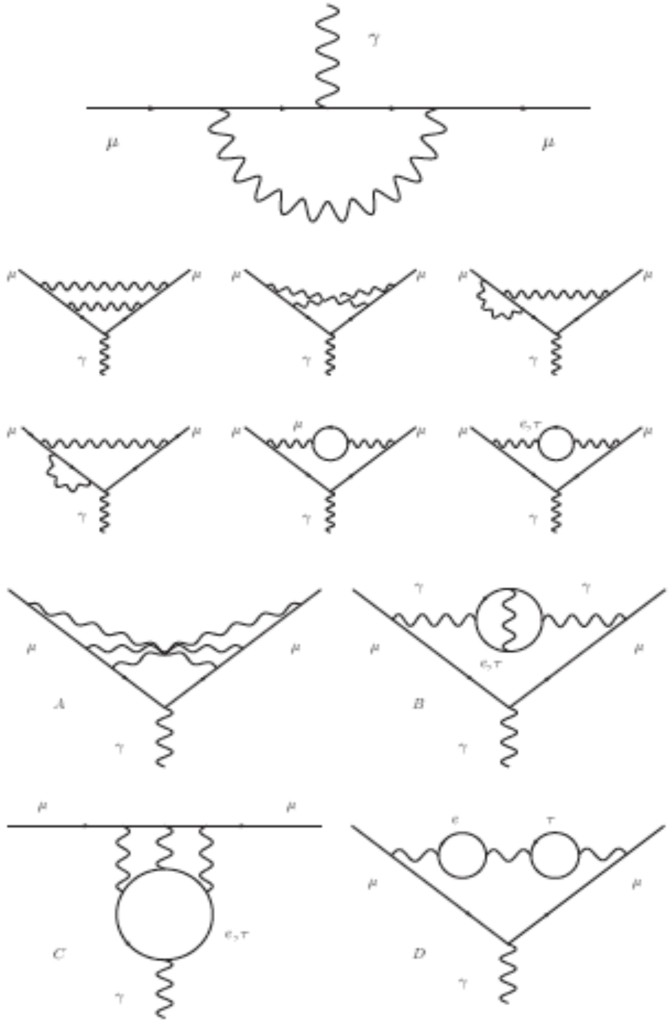
$$+\,750.86\,(88)\,(\alpha/\pi)^5$$ [Kinoshita et al. '90-'19]

$a_\mu^{\rm QED} = 116584718.931\,(19)(100)(23) \times 10^{-11}$

mainly from 4-loop coeff. unc. — 6-loop — from α(Cs)

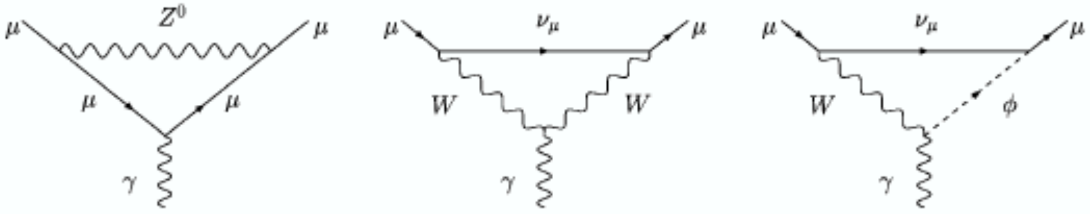
α = 1/137.035999046(27) [0.2ppb] Parker et al 2018 — WP20 value

[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]



EW contribution

- **One-loop term:**



$$a_\mu^{\text{EW}}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1 + \frac{1}{5}\left(1 - 4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M^2_{Z,W,H}}\right)\right] \approx 195\times10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

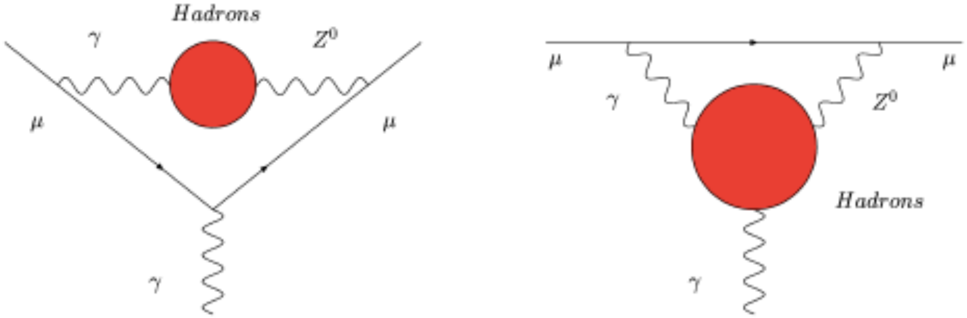
- **One-loop plus higher-order terms:**

$a_\mu^{EW} = 153.6\ (1.0) \times 10^{-11}$

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.

Hadronic loop uncertainties (and 3-loop nonleading logs).

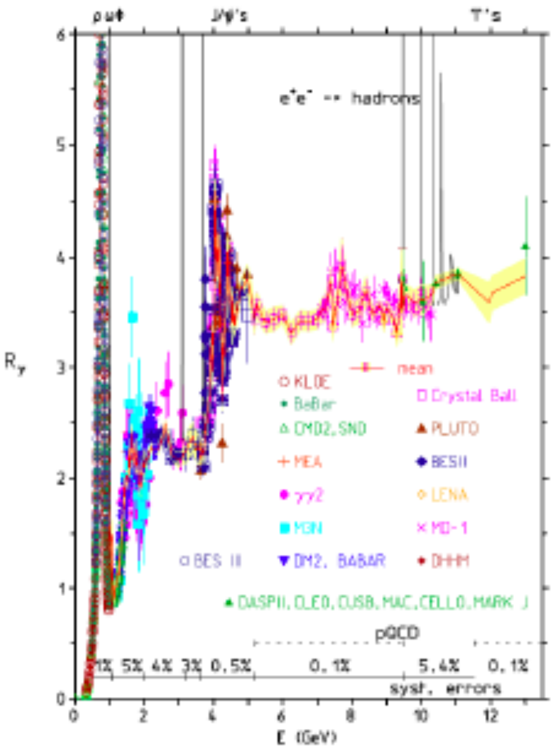
WP20 value



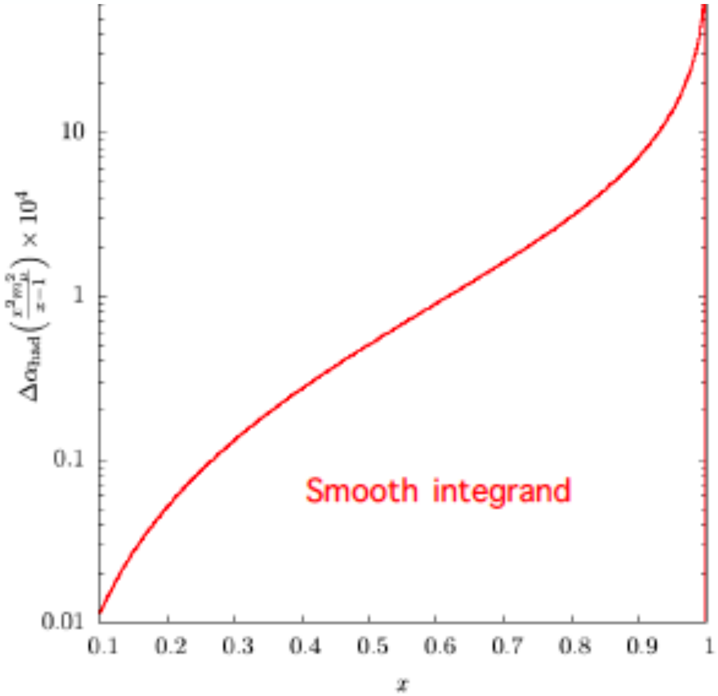
a_μ^{HLO} : timelike vs spacelike method

Timelike → **Spacelike**

$\Delta\alpha_{had}(t)$ can be measured via the elastic scattering $\mu\, e \to \mu\, e$.



F. Jegerlehner, arXiv:1511.04473



Carloni Calame, Passera, Trentadue, Venanzoni, PLB 2015

- ☑ Inclusive measurement
- ☑ Smooth integrand
- ☑ Direct interplay with lattice QCD