King's College London, Theoretical Particle Physics and Cosmology group (TPPC), Nov. 11, 2022

The "old" and the "new" muon g-2 puzzles

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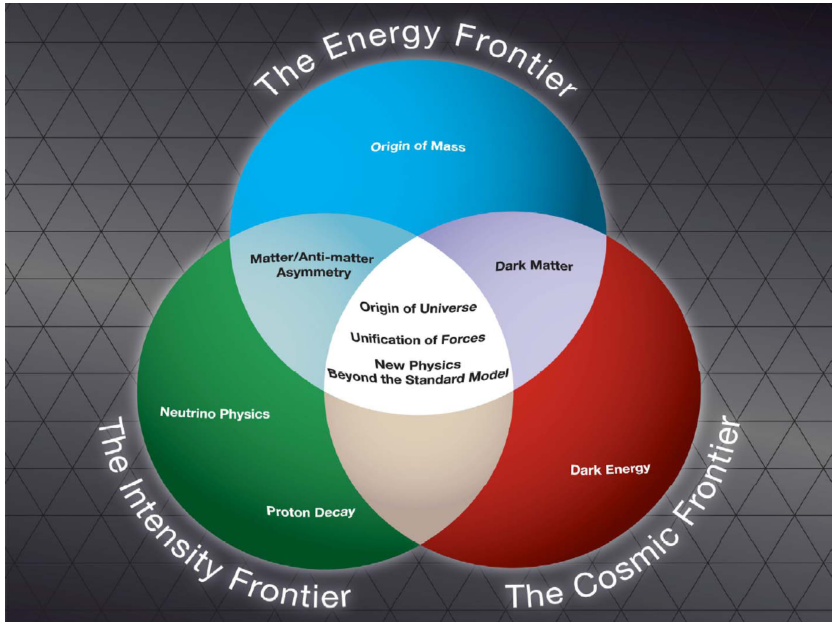
Based on works on the muon g-2 problem in collaboration with Luca Di Luzio, Bill Marciano, Paride Paradisi and Massimo Passera

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**

The other more recent hint of NEW PHYSICS along these two roads is again in the HI frontier, namely the possible violation of lepton flavour universality in some B-meson semileptonic decays.

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

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

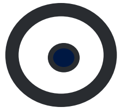
Put a beam of polarized muons into a storage ring

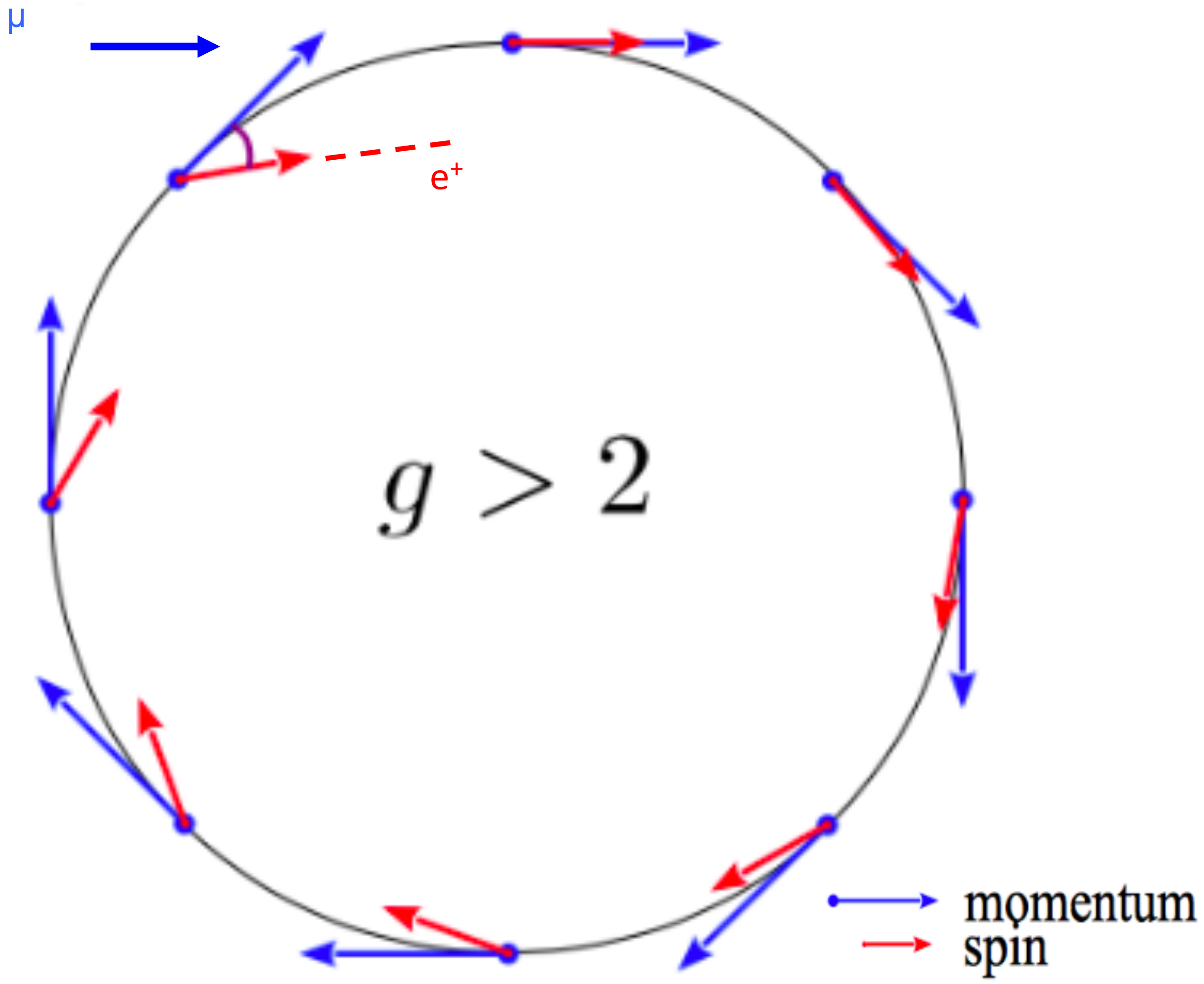
Both the muon spin and momentum precess

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

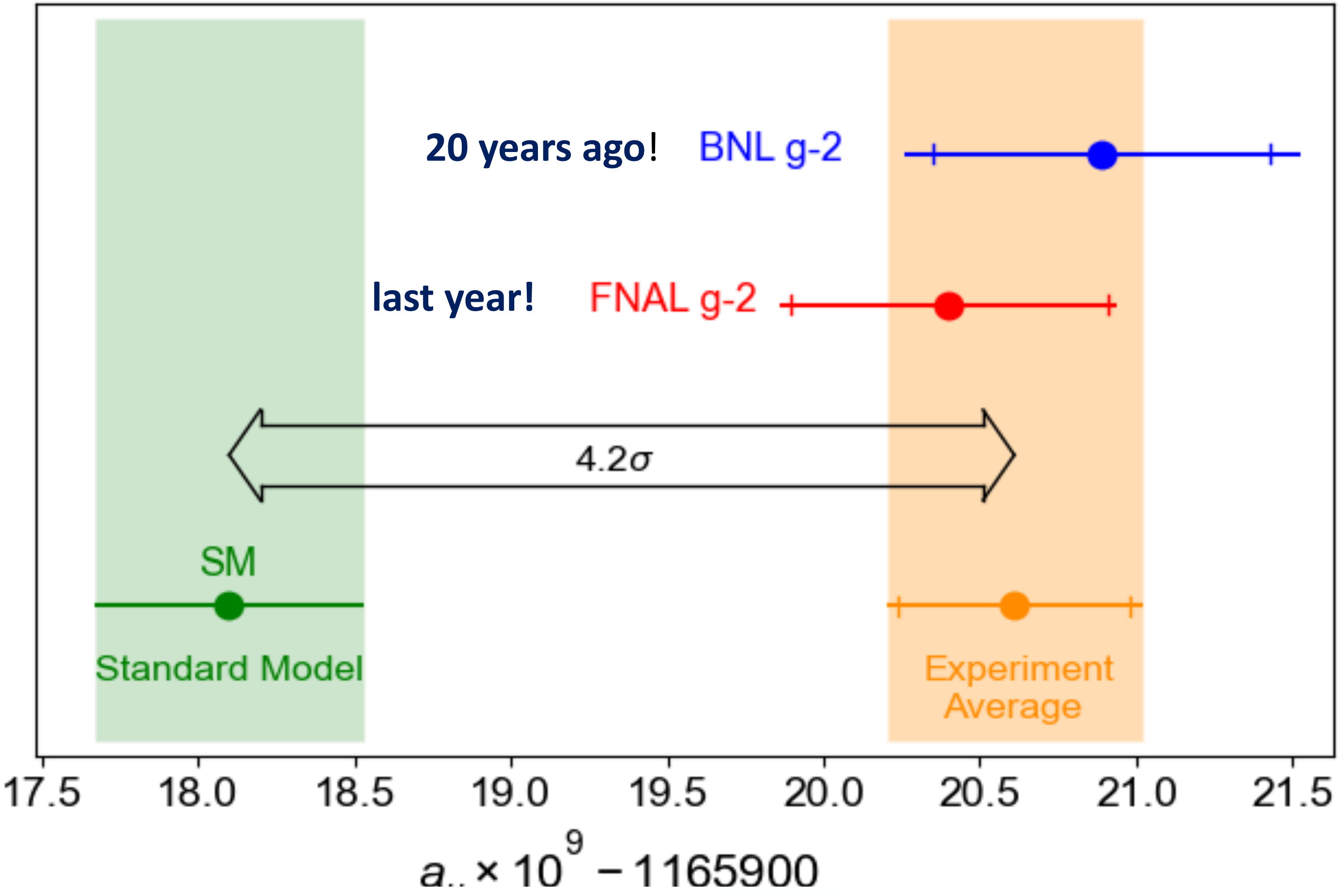
a = (g-2)/2

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





The EXP. situation



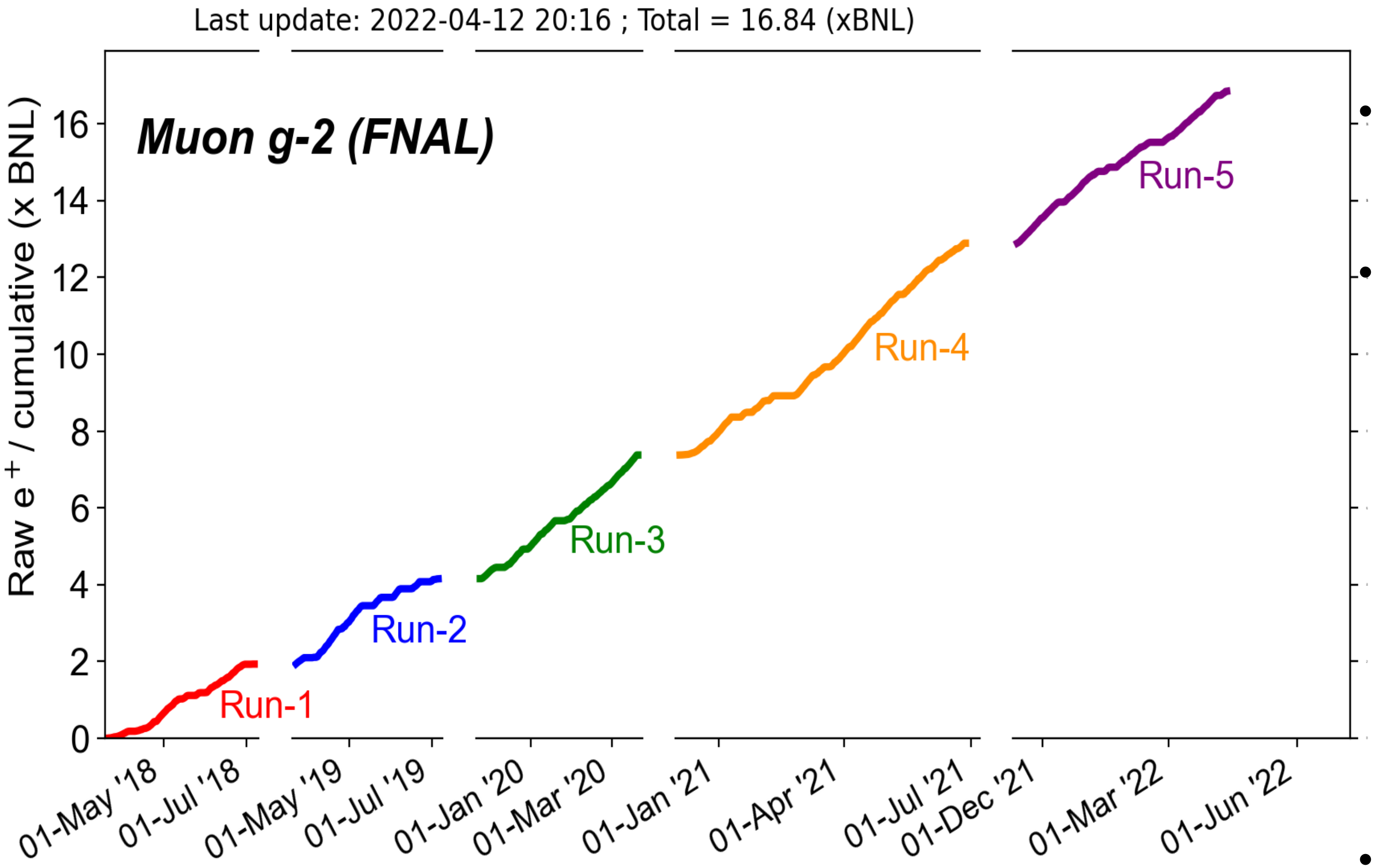
$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

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

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

FNAL aims at 16×10^{-11}

The EXP. prospects



- Run-1 result confirmed the BNL result with only 6% of our total statistics so far
- Run-2/3 result expected to be published early next year
  - ~ 2x improvement on the statistical error
  - Reduction in the systematic errors, closing in on the TDR goal
  - **Would be helpful to have a recommendation for what theory prediction(s) to compare to in the paper**
- There's still more data to analyse with runs 4 and 5 and we'll add more with run 6

g ≠ 2

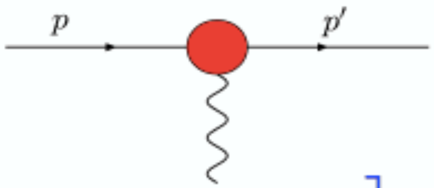
- **Kusch and Foley 1948:**

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

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

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

- **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!

"$g-2$ 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]

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

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

[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]

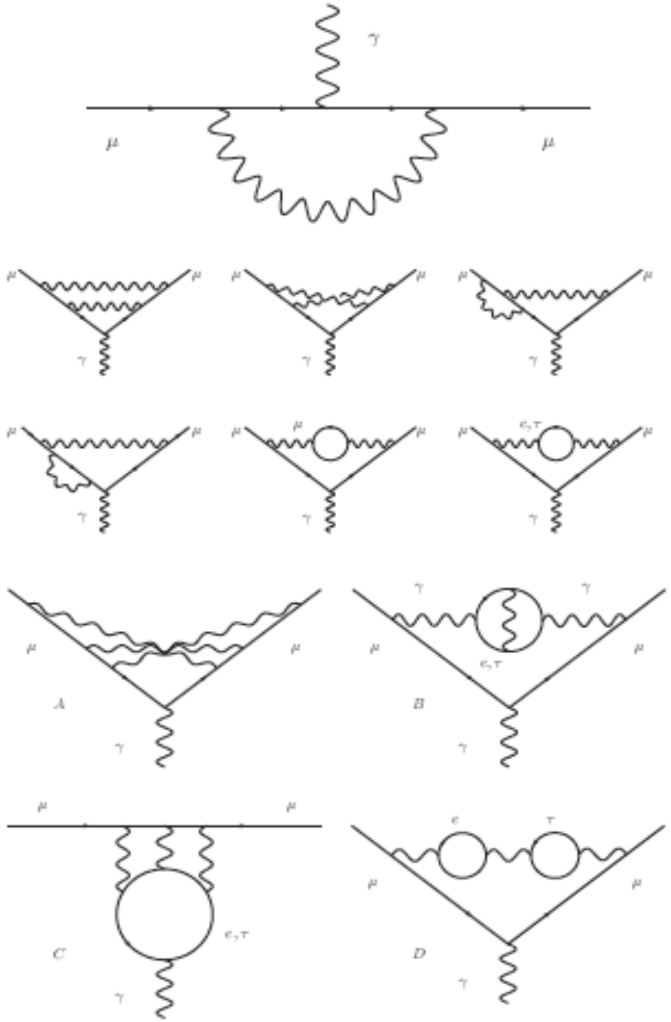
$$+\,750.86\,(88)\,(\alpha/\pi)^5 \text{ [Kinoshita et al. '90-'19]}$$

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

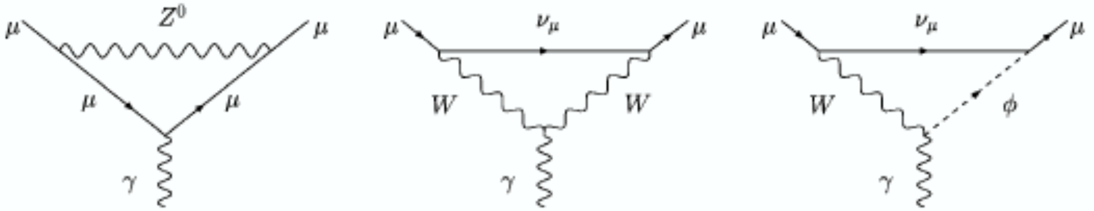
mainly from 4-loop coeff. unc. — 6-loop — from α(Cs)

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

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



- **One-loop term:**



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

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

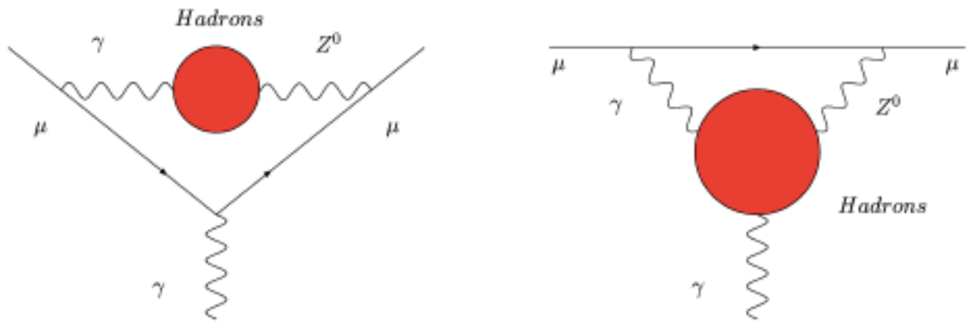
- **One-loop plus higher-order terms:**

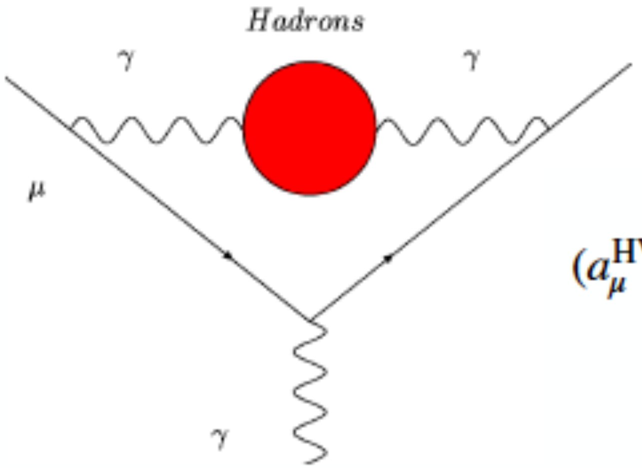
$a_\mu^{\text{EW}} = 153.6\ (1.0) \times 10^{-11}$

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





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

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

dispersion relations

optical theorem

kernel function

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

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

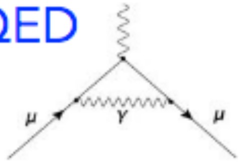
a_μ^{HLO} = 6895 (33) x 10^{-11}	F. Jegerlehner, arXiv:1711.06089
= 6939 (40) x 10^{-11}	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
= 6928 (24) x 10^{-11}	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
= 6931 (40) x 10^{-11} (0.6%)	WP20 value

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

The 4 classes of SM contributions: uncertainty largely dominated by the hadronic contributions in Vacuum Polarization (HVP) and Light-by-Light (HLbL)

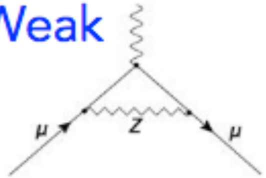
$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$$

QED



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

Weak

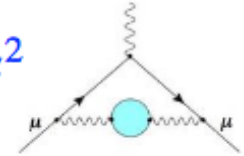


$+\ldots$ $153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

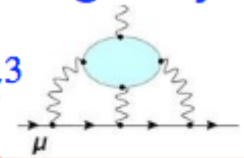
α^2



$+\ldots$ $6845\,(40) \times 10^{-11}$ [0.6%] 0.37 ppm

…Light-by-Light (HLbL)

α^3



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

Numbers from Theory Initiative Whitepaper

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

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

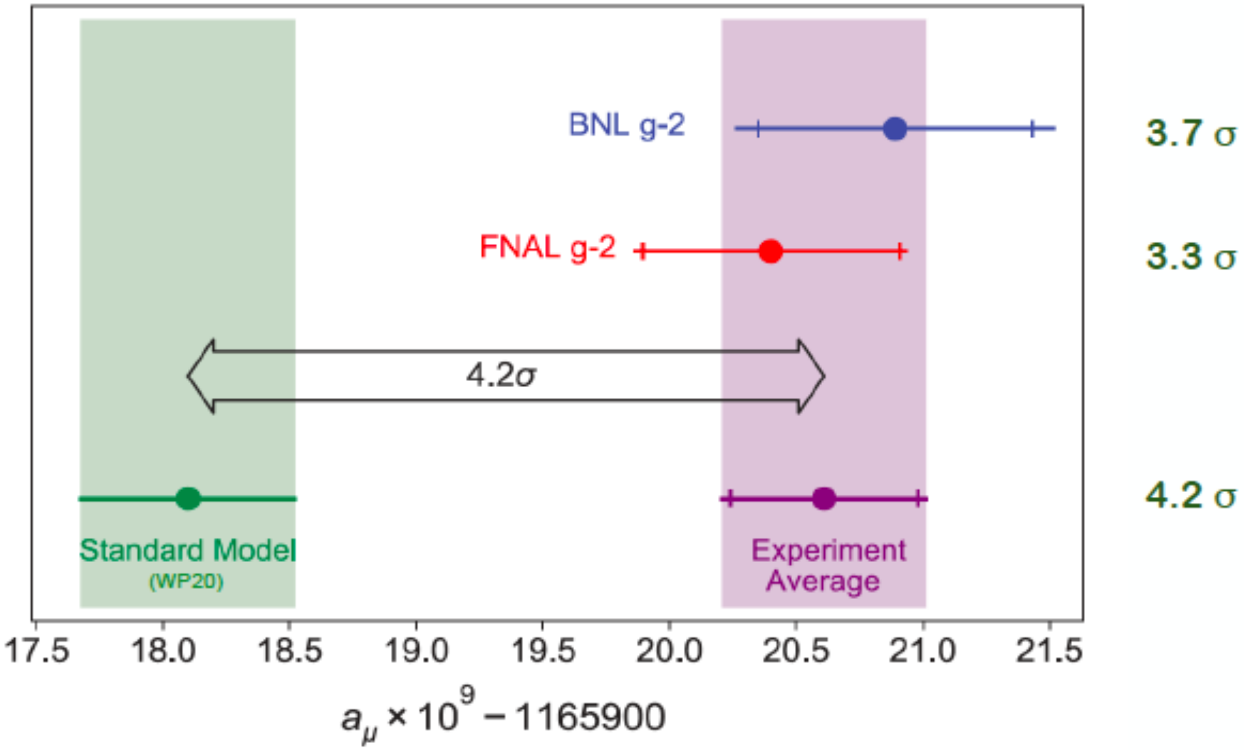
$$\boldsymbol{\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} \equiv a_\mu^{\mathrm{NP}} = 251\,(59) \times 10^{-11}} \qquad \textbf{(4.2}\boldsymbol{\sigma}\textbf{ discrepancy!)}$$

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

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

Muon g-2: FNAL confirms BNL

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



a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [0.54ppm] BNL E821

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a_μ^{EXP} = (116592061 ± 41) x 10^{-11} [0.35ppm] WA

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

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

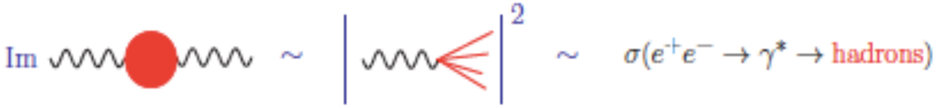
$a_\mu^{SM} = 116591810\ (43) \times 10^{-11}$ WP20 $a^{\rm HLO}_{\mu,e^+e^-} = 6931(40) \times 10^{-11}$

$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM} = 251\ (59) \times 10^{-11}$ 4.2 σ

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

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

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



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

Shifts below ~1 GeV conflict with the quoted exp. precision of σ(s)

Crivellin, Hoferichter, Manzari, Montuli;
de Rafael; Malaescu, Schott;
Colangelo, Hoferichter, Stoffer

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

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

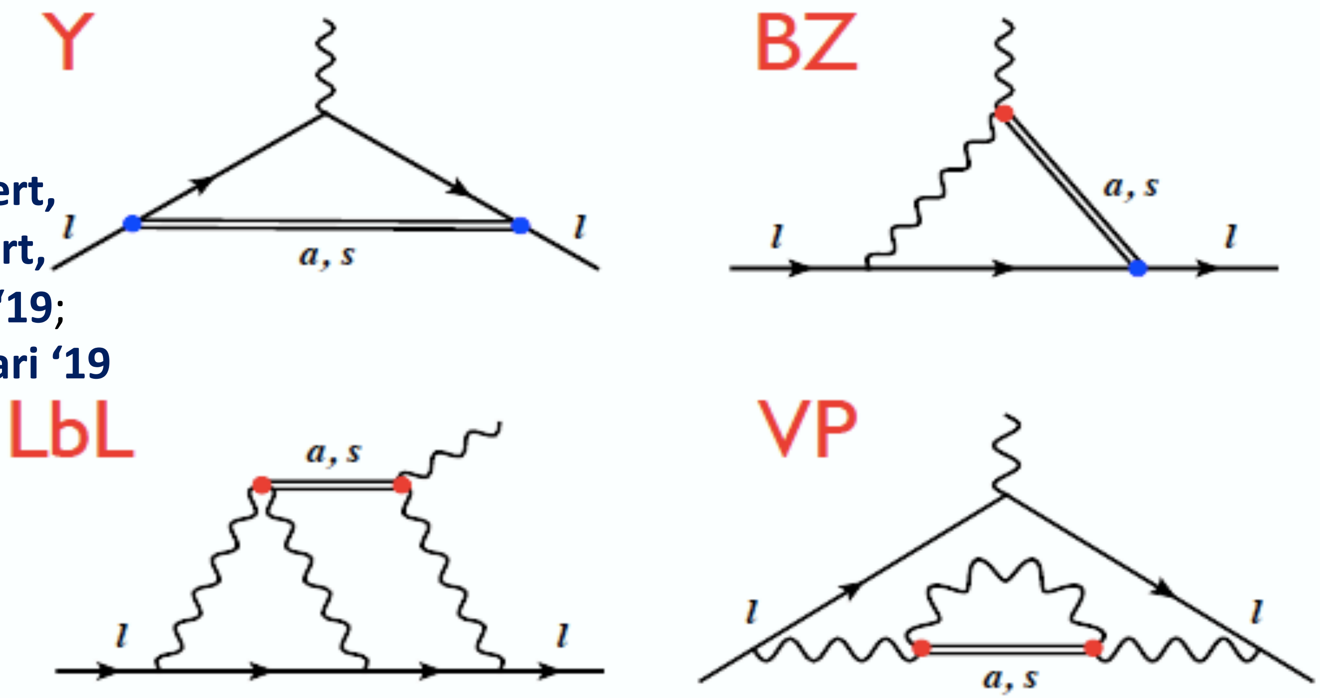
- NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.
- NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.

P. Paradisi, La Thuile 2021

The case of AXION-LIKE PARTICLES (ALPs)

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



- 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.

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

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

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

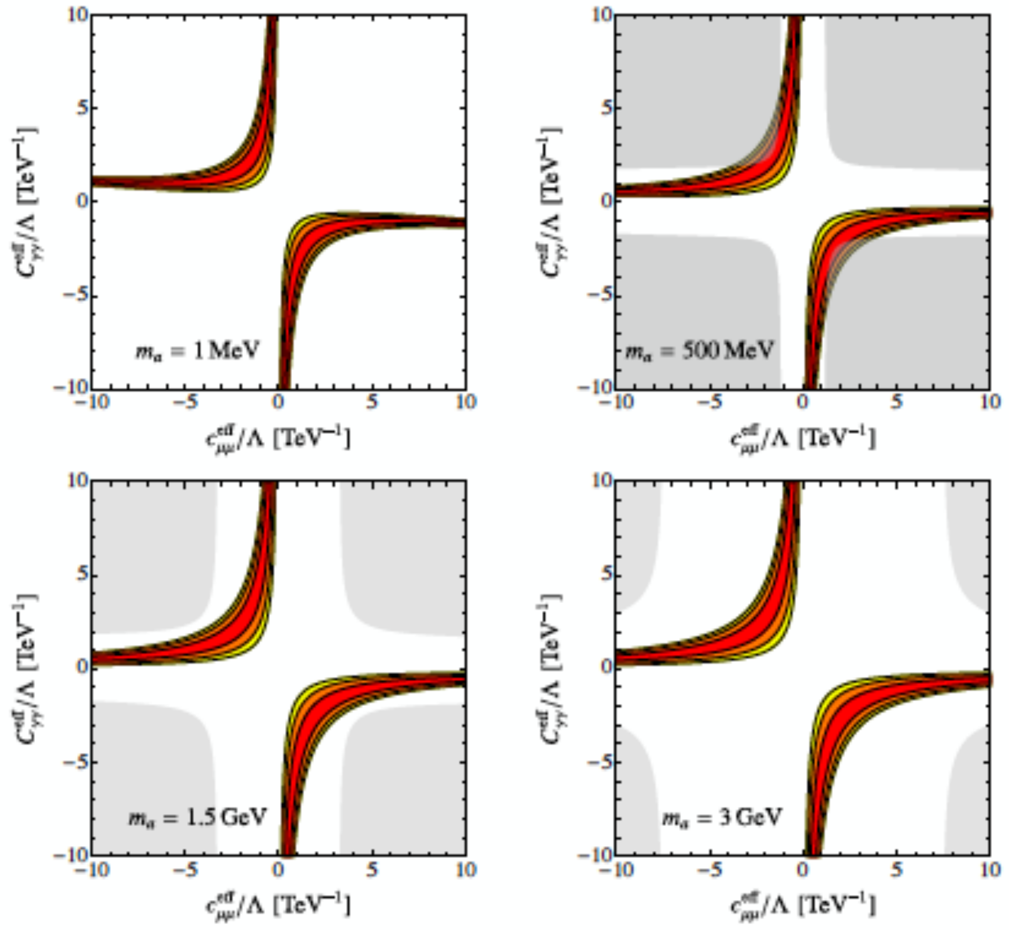
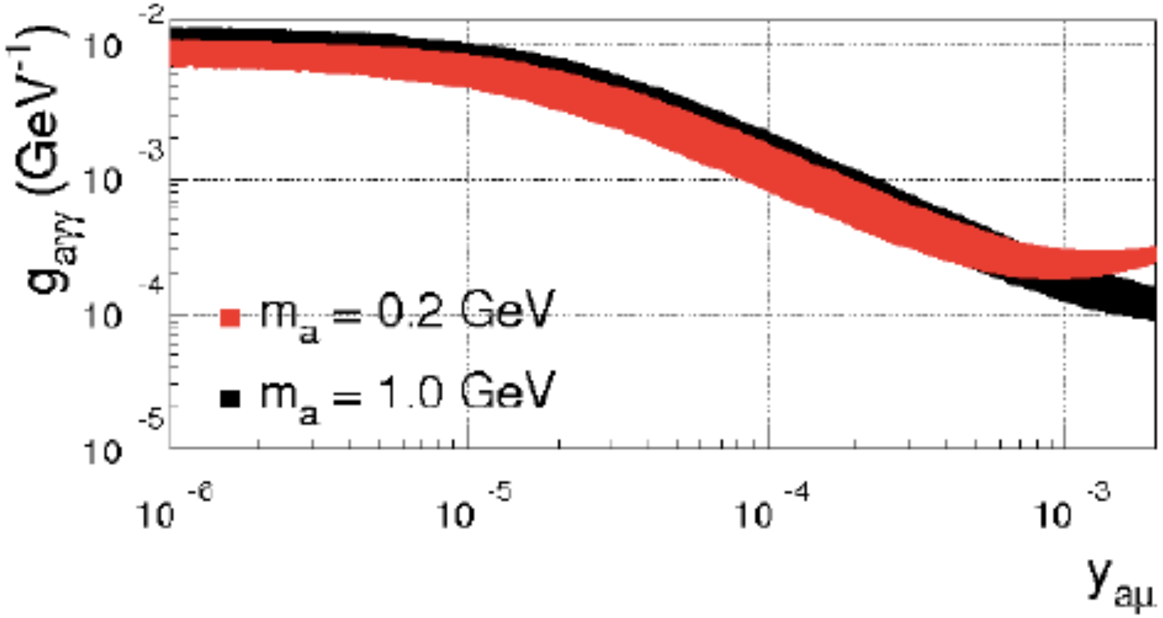


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

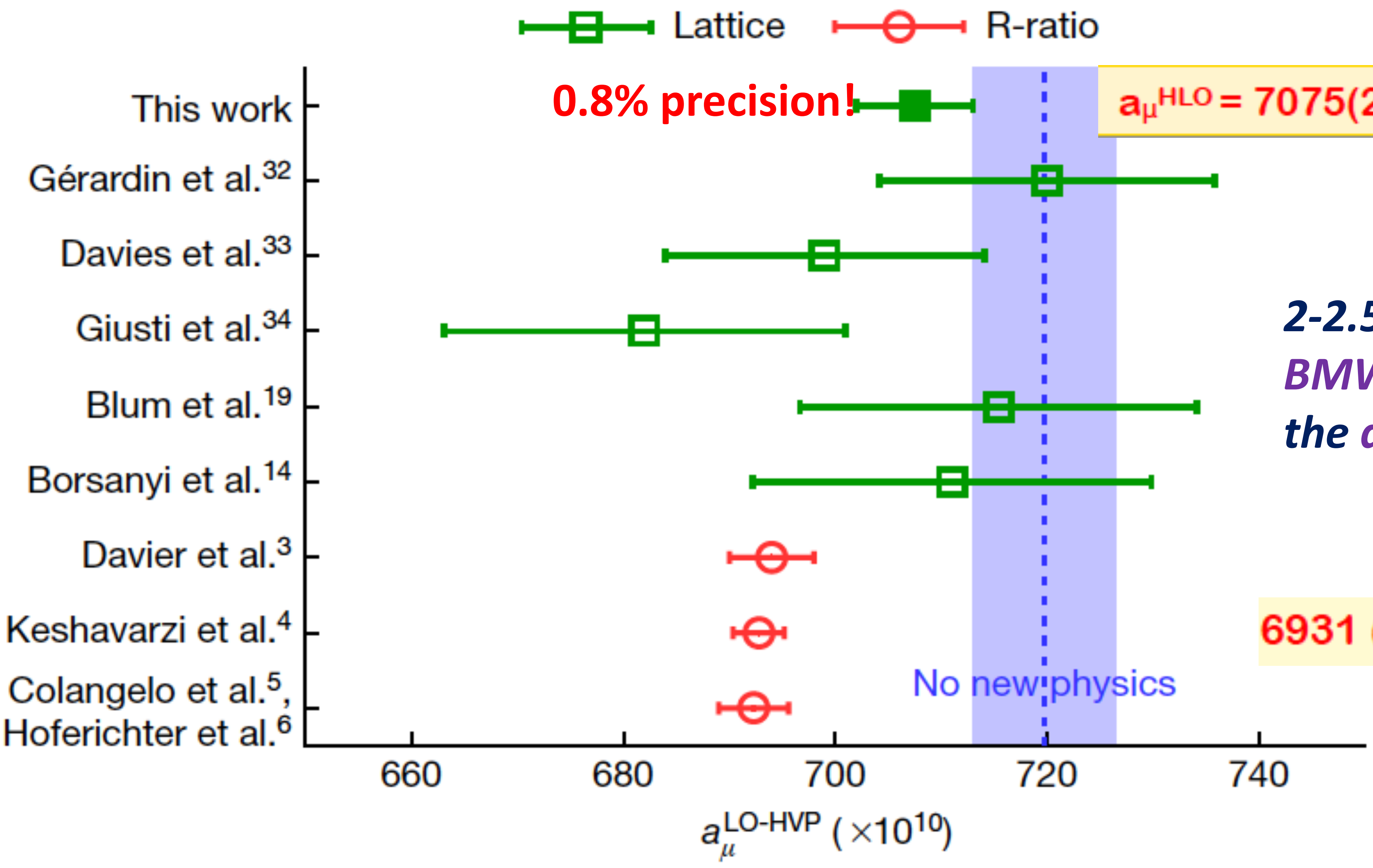


Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

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

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

first published lattice result with sub-percent precision!



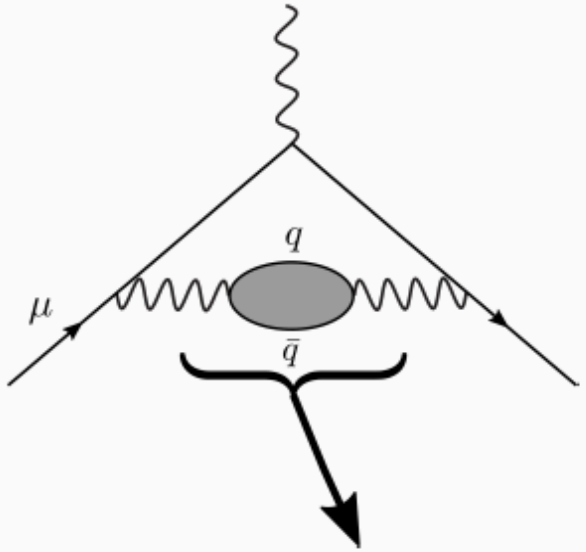
0.8% precision!

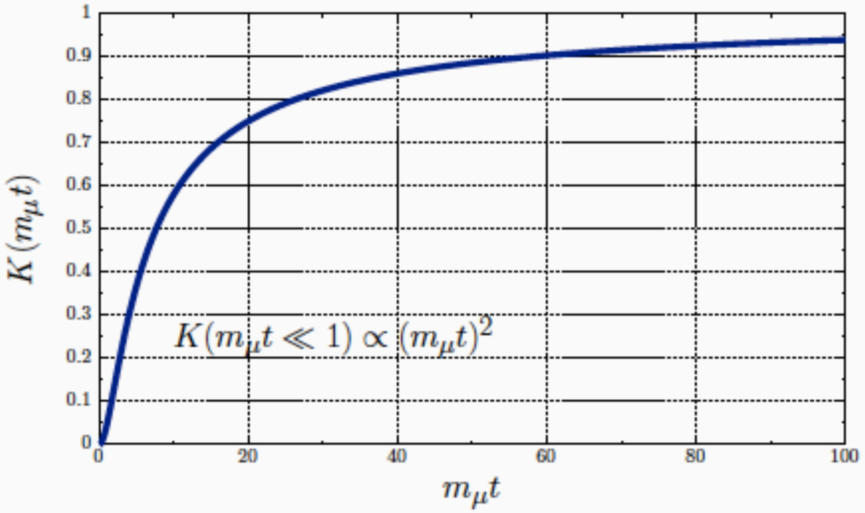
$a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst}$ $[55]_{tot} \times 10^{-11}$

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

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

LO-HVP from Lattice QCD





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

$$\Downarrow$$

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

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)

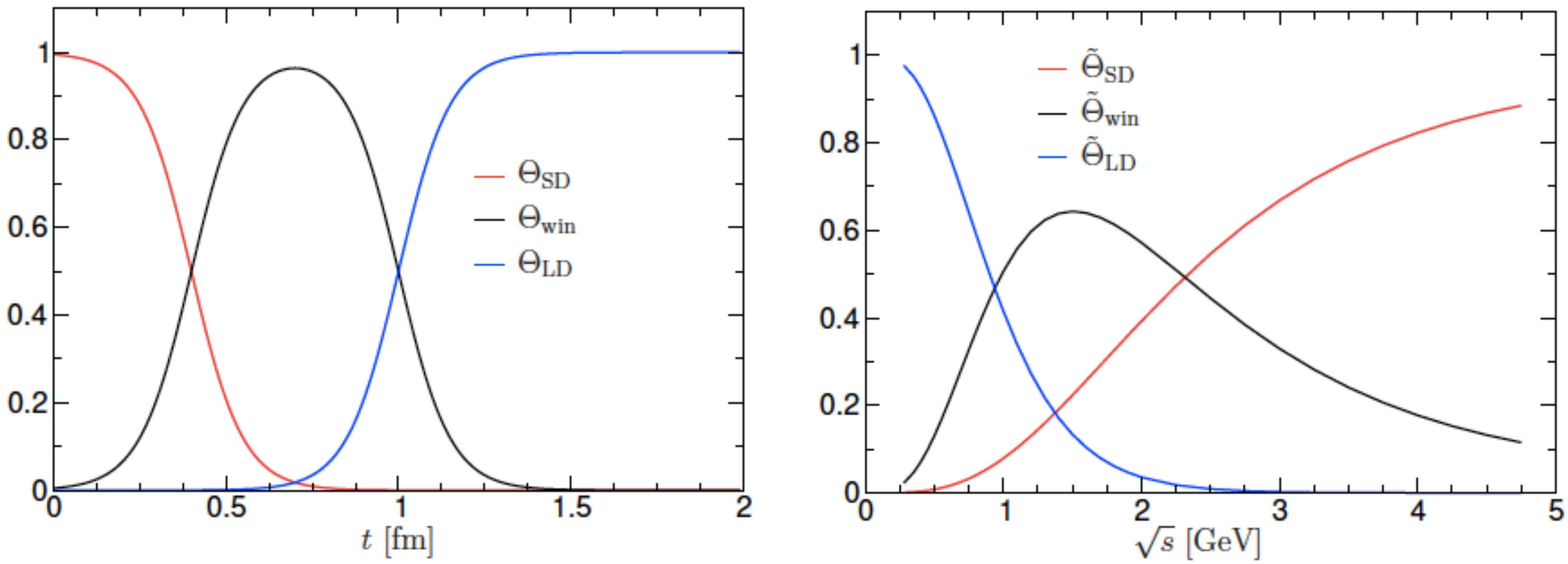
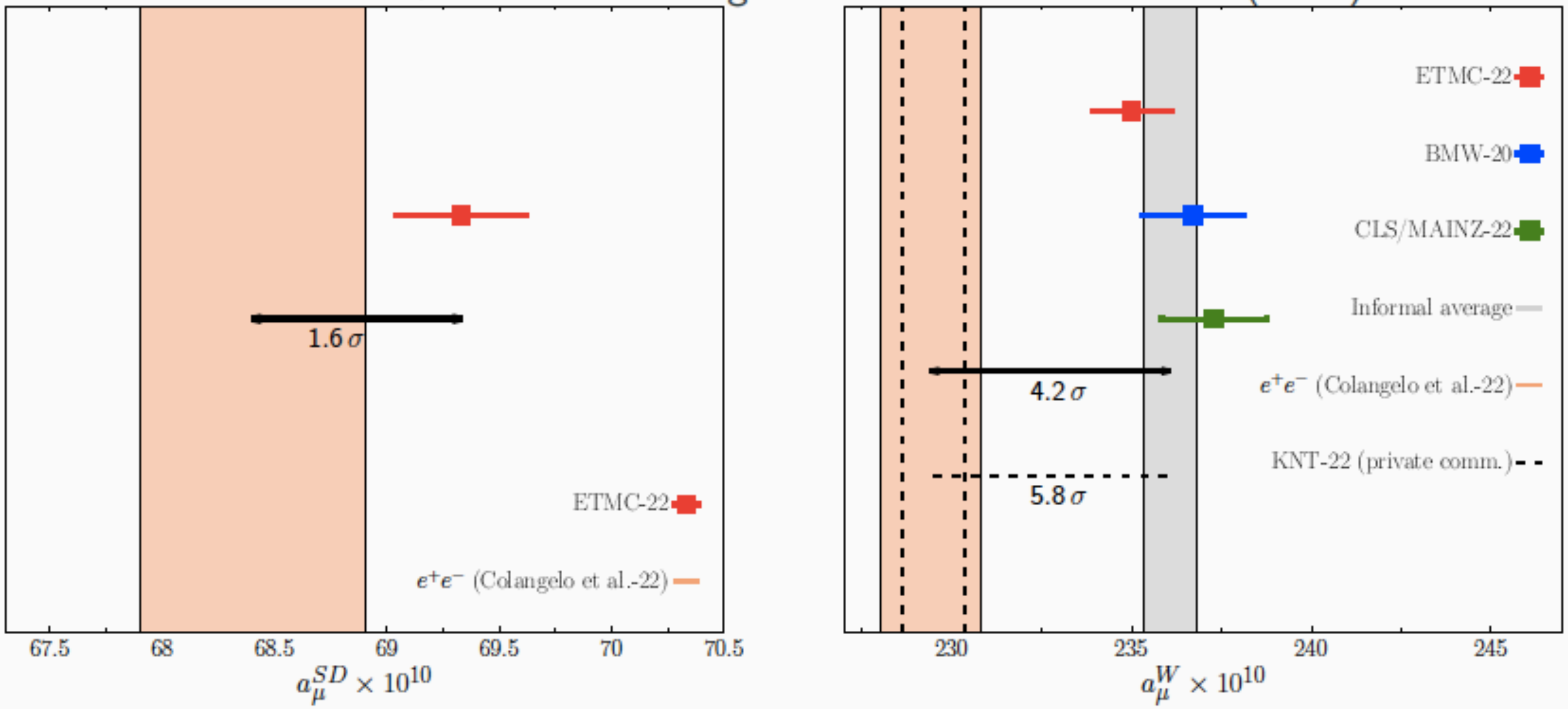


Figure 1: Short-distance, intermediate, and long-distance weight functions in Euclidean time (left), and their correspondence in center-of-mass energy (right).

G. Gagliardi, Edinburgh 2022, on behalf of the ETM Collaboration

Comparison with $e^+e^- \to$ hadrons results

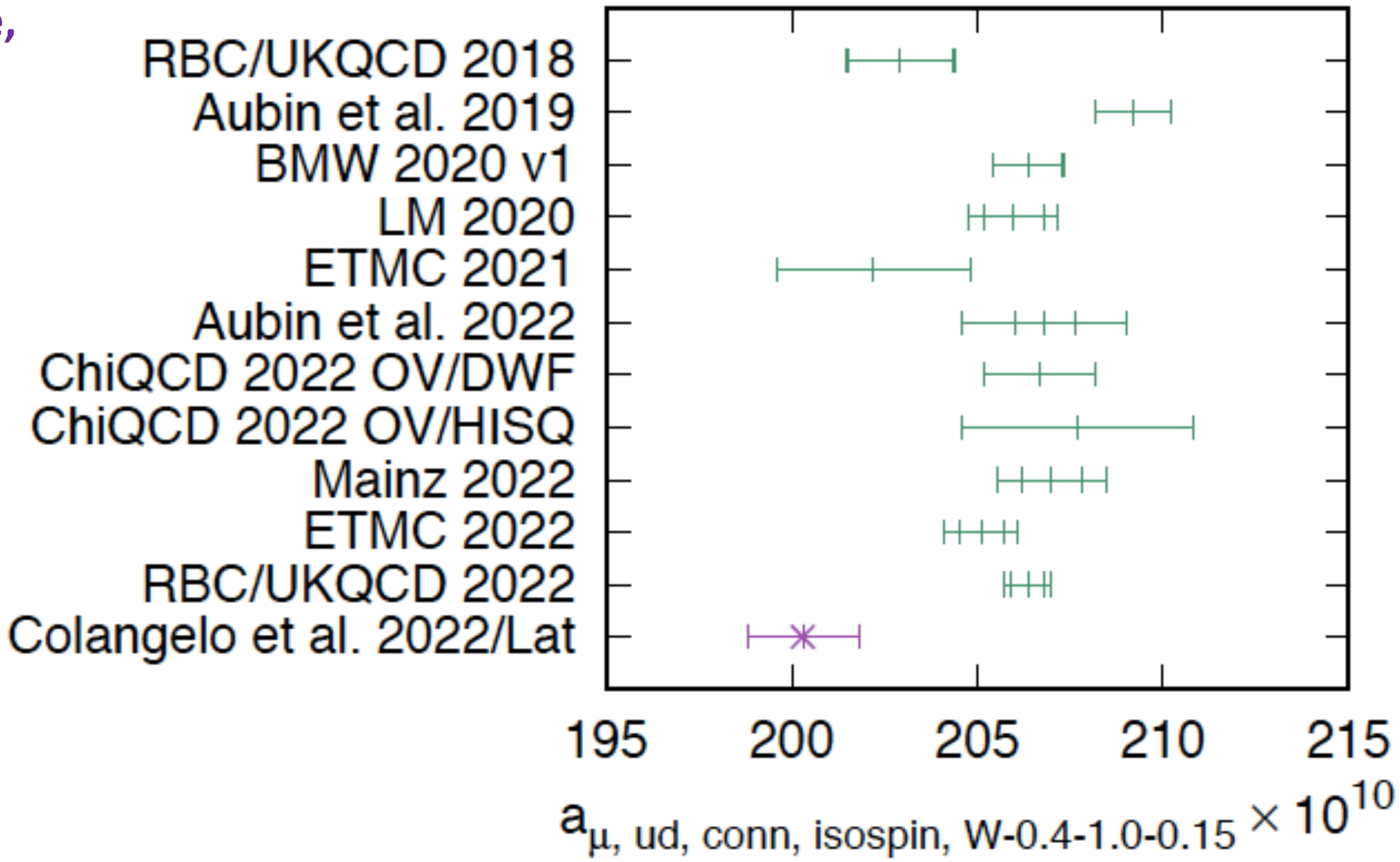
$e^+e^- \to$ hadrons from Colangelo et al. arXiv:2205.12963 (2022).



- Tension in a_μ^W rises to 4.2σ if we combine ETMC '22, BMW '20 and CLS/Mainz '22 (informal average $\to$ next WP).
- Deviation of $e^+e^- \to$ hadrons data w.r.t. the SM in the low and (possibly) intermediate energy regions, but not in the high energy region.

The RBC/UKQCD22 result in context

C. Lehner, Workshop of the Muon g-2 Theory Initiative, Edinburgh, Sept. 2022



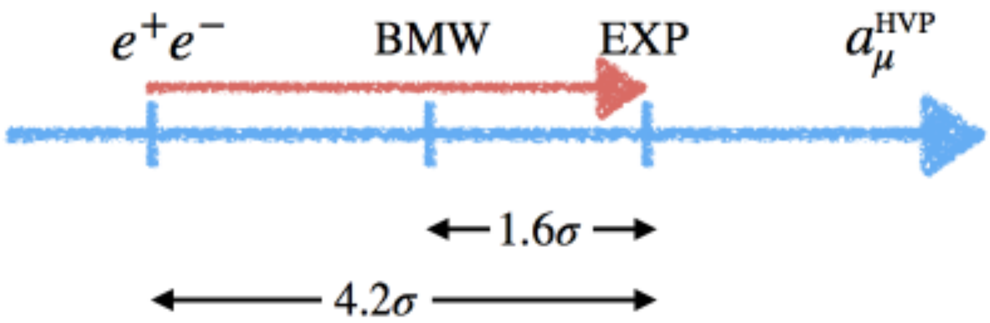
- 3.9σ tension of RBC/UKQCD22 with Colangelo et al. 22/Lattice

The NEW g-2 puzzle

$$(a_\mu^{\mathrm{HVP}})_{\mathrm{EXP}} = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM,\,rest}}$$

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

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



If the new lattice results * – i.e., **BMWc** & (only for the (SD) + W windows, but not for the relevant LD window) **Mainz 2022+ETMC 2022 + RBC/UKQCD 2022** are correct (and will be confirmed also for the LD window!), then:

i) The “old” g-2 discrepancy would be basically gone, but

ii) A new significant discrepancy between the $e^+ e^-$ data- driven and lattice QCD evaluations of a_μ^{HVP} becomes quite significant

*** The lattice FNAL/QCDMILC collaboration is going to unblind its data soon**

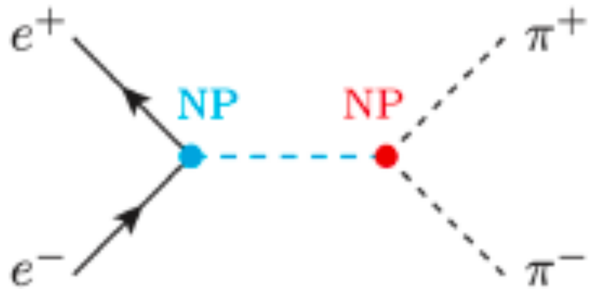
New Physics to solve the new muon g-2 puzzle ?

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

1. $(a_\mu^{\rm HVP})_{e^+e^-}^{\rm WP20} \approx (a_\mu^{\rm HVP})_{\rm EXP}$
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)

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



NP coupled both to hadrons and electrons
but **not** directly to the **muons** !

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

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

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

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

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

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

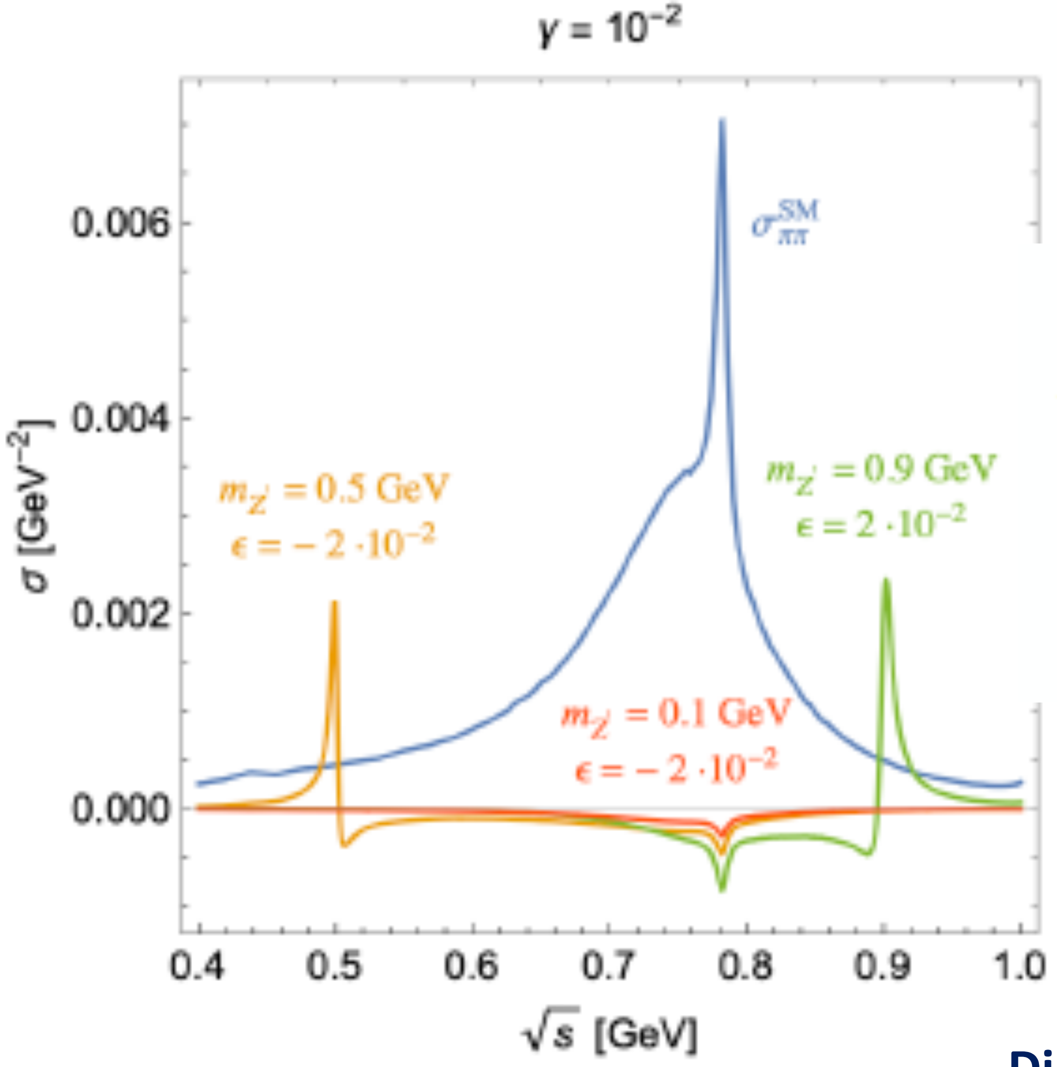
$$\mathcal{L}_{Z'} \supset (g_V^e\,\bar{e}\gamma^\mu e + g_V^q\,\bar{q}\gamma^\mu q)Z'_\mu \qquad q = u, d \qquad m_{Z'} \lesssim 1\ \text{GeV}$$

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

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

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

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



$\sqrt{s_{\rm exp}} \approx 0.3$ 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*

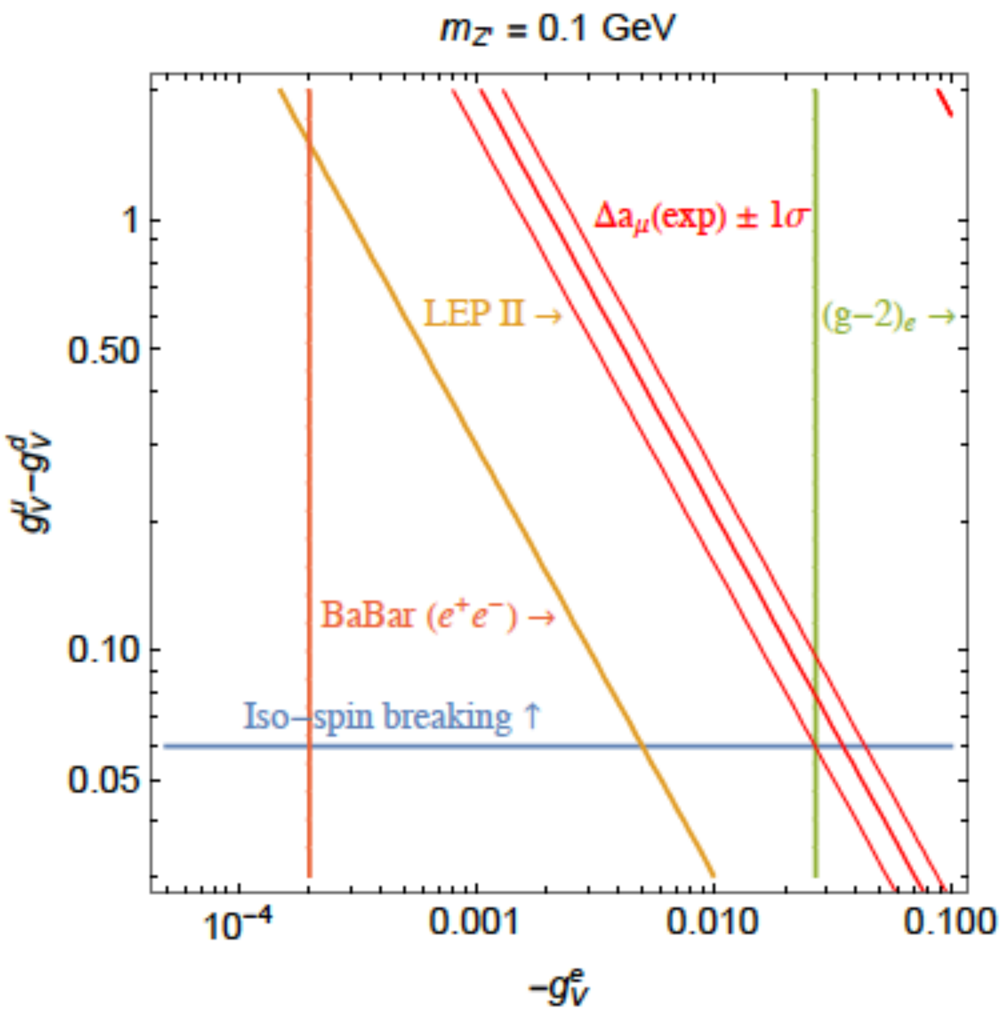
$$\frac{\sigma_{qq}^{\mathrm{SM+NP}}}{\sigma_{qq}^{\mathrm{SM}}} \approx 1 + 2\frac{g_V^e g_V^q}{e^2 Q_q} \quad \rightarrow \quad |g_V^e g_V^q| \lesssim 4.6 \cdot 10^{-4} |Q_q| \qquad (\epsilon \lesssim 3.3 \cdot 10^{-3})$$

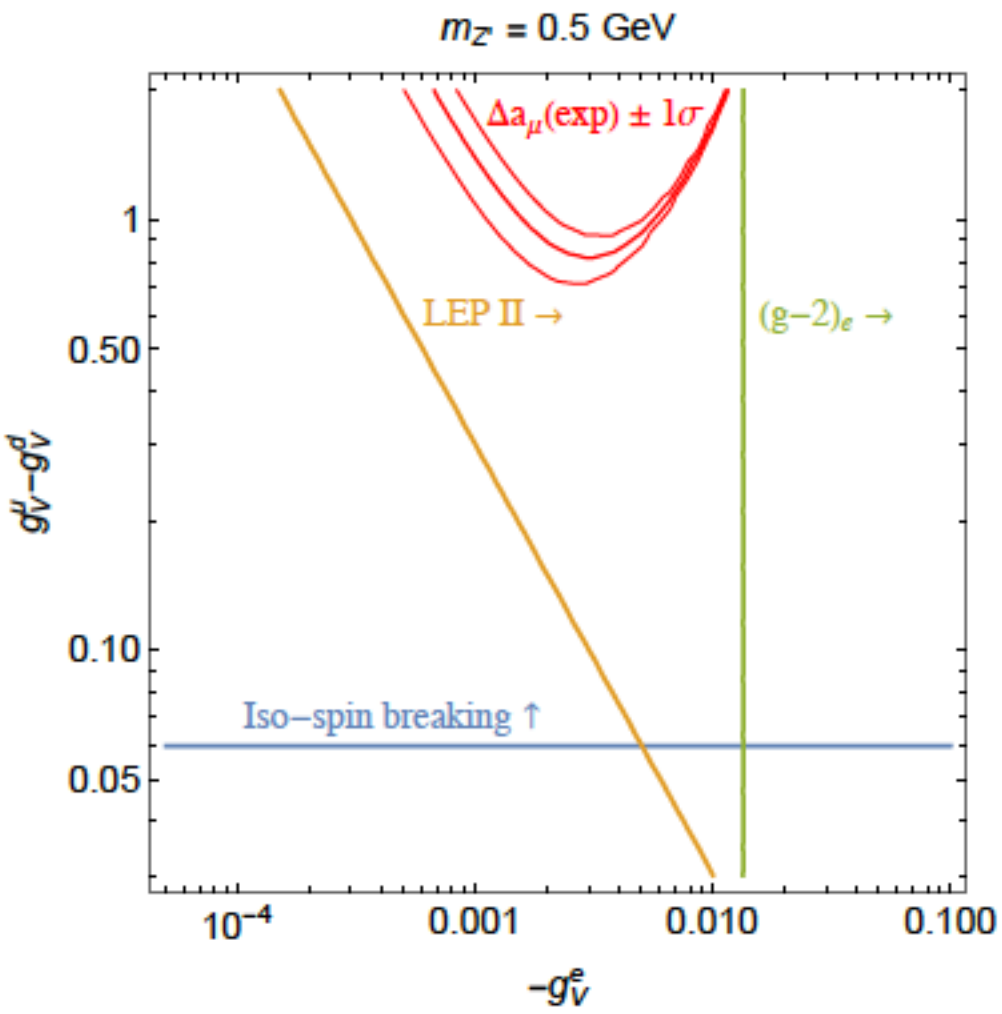
Iso-spin breaking observables → $|g_V^u - g_V^d| \lesssim 0.06$

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)

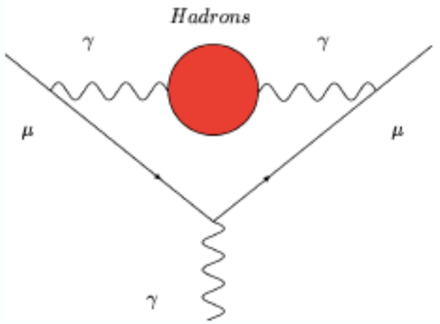
At least TWO independent bounds prevent to get a sizeable contribution to Δa_μ modifying σ_{had} via Z' exchange to solve the "new" μ g-2 puzzle





Spacelike proposal for a_μ

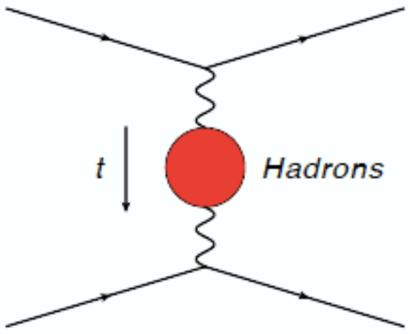
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the timelike formula:



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

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

- 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

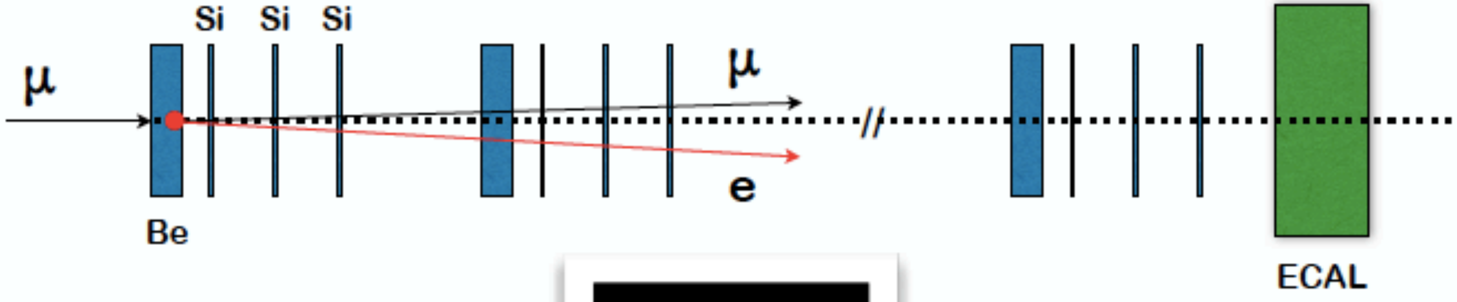
New Physics extracting $\Delta\alpha_{had}(t)$ at MUonE? Padova and Heidelberg 2020

→ **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

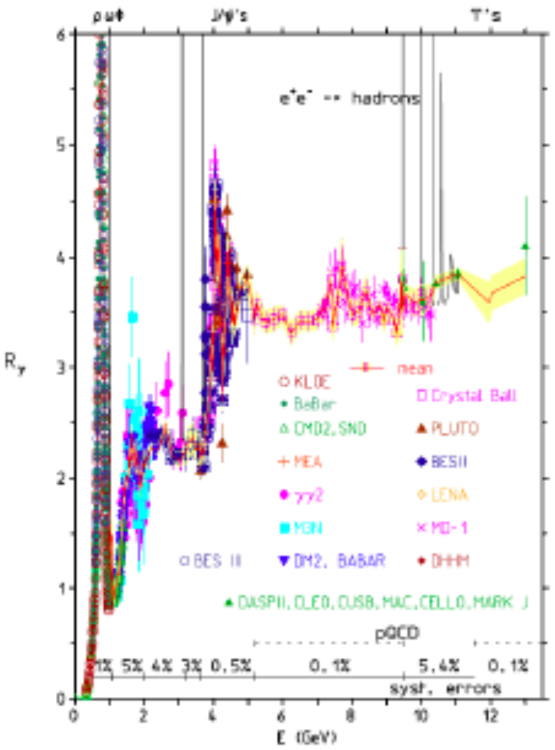
[Courtesy by M. Passera]

- Letter of Intent submitted to CERN SPSC in 2019: Test run approved for 2021

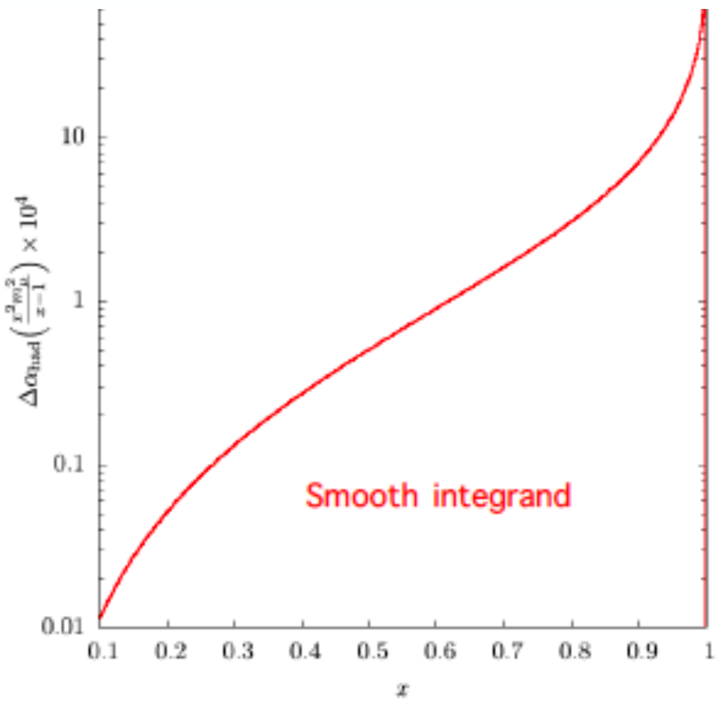
a_μ^{HLO} : timelike vs spacelike method

Timelike → Spacelike

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



F. Jegerlehner, arXiv:1511.04473



Carloni Calame, Passera, Trentadue, Venanzoni, PLB 2015

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

The ELECTRON magnetic moment

- **Status of Δa_e as of 2012**

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

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

  - The errors from QED4 and QED5 will be reduced soon to 0.1×10^{-13} [Kinoshita]
  - We expect a reduction of $\delta a_e^{\rm EXP}$ 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]

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

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

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

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

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

arXiv:2209.13084v1 [physics.atom-ph] 27 Sep 2022

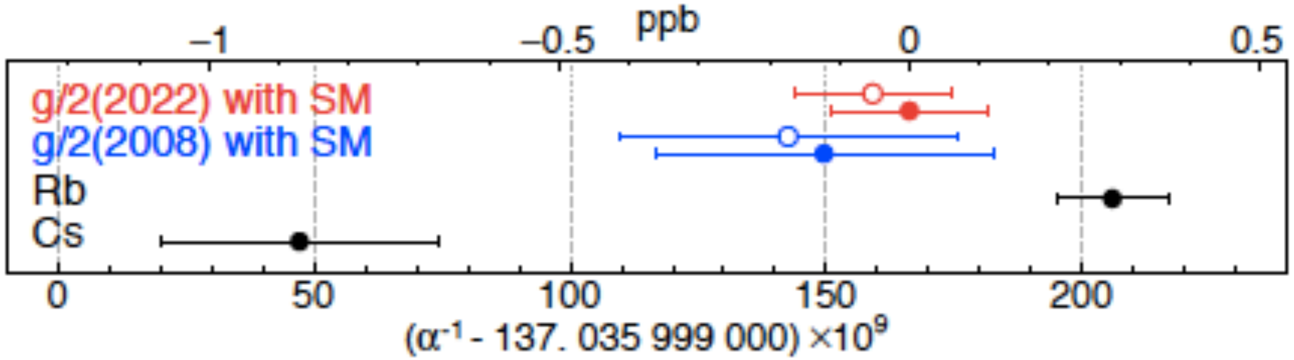
NEW Measurement of the Electron Magnetic Moment

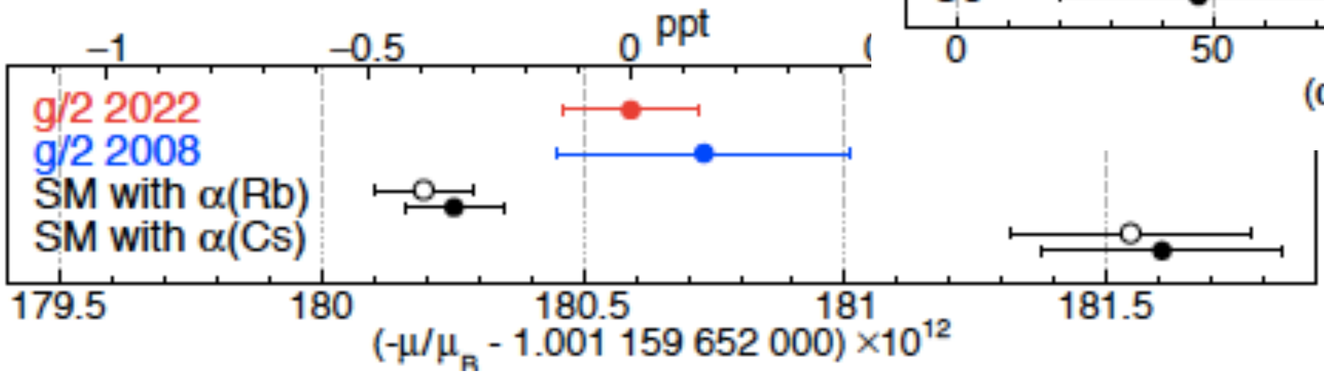
X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

[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]





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. $(g-2)_\mu$

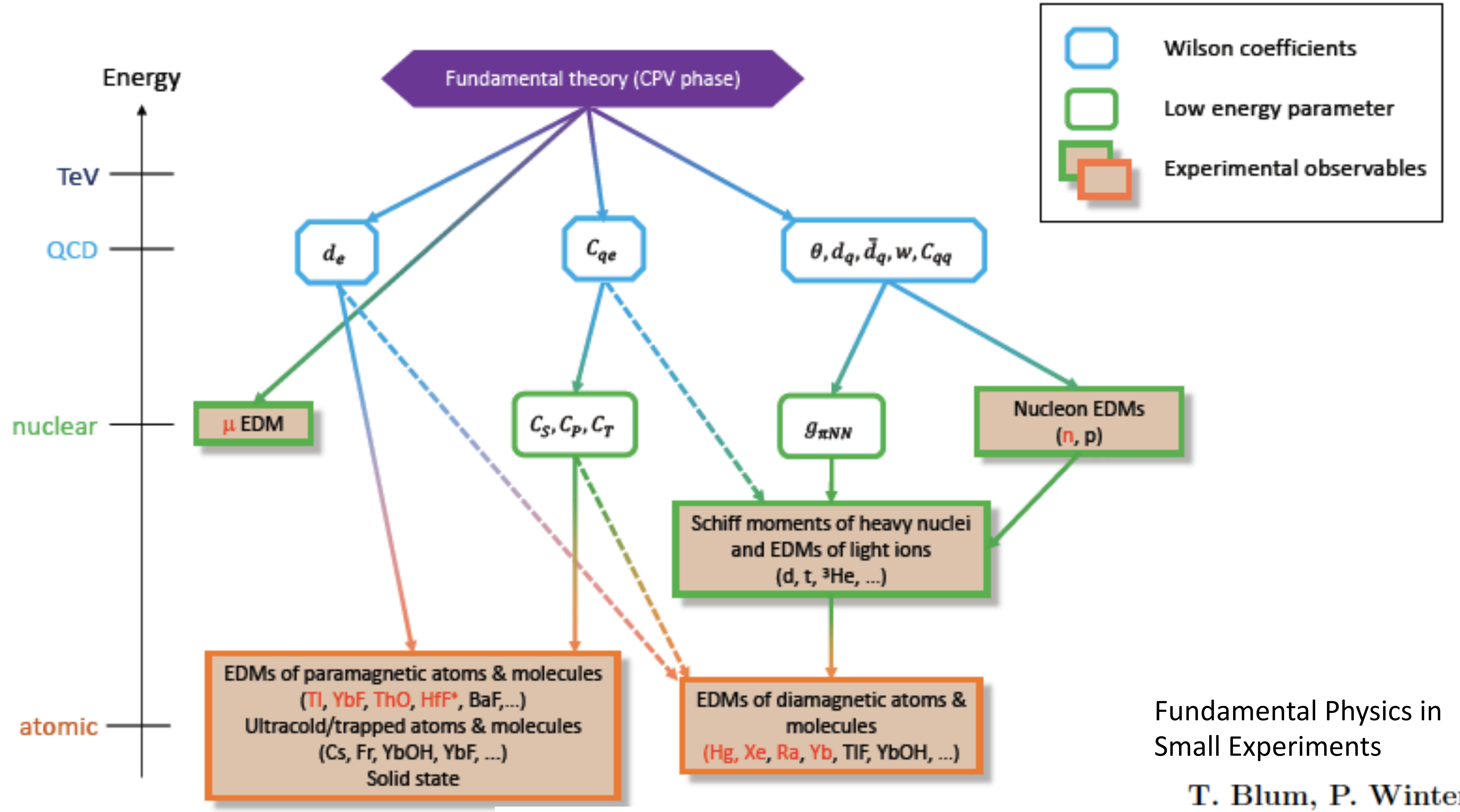
$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-29} \left(\frac{\phi_e^{CPV}}{10^{-5}}\right) \; e\,\mathrm{cm}\,,$$

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

- 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



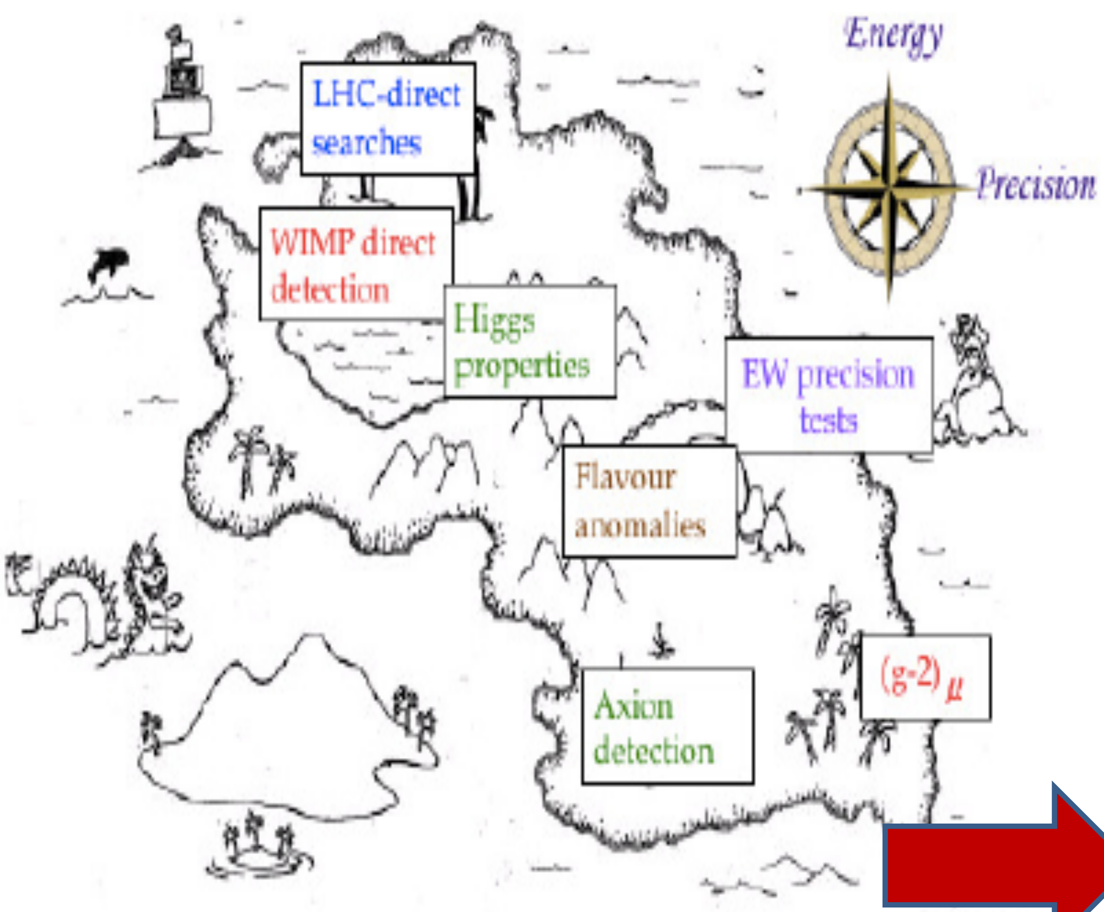
Fundamental Physics in Small Experiments

T. Blum, P. Winter

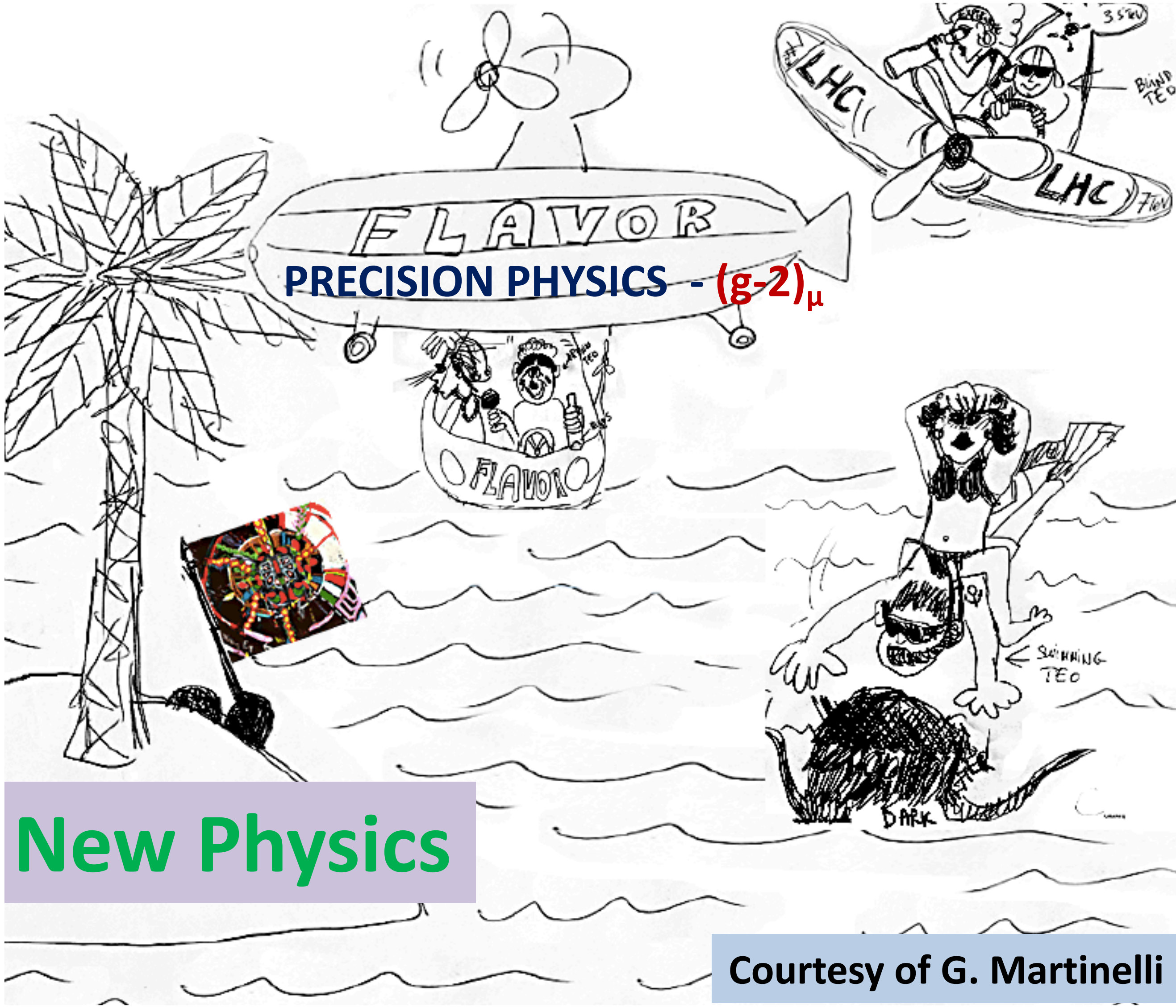
T. Bhattacharya, T.Y. Chen, V. Cirigliano, D. DeMille, A. Geraci, N.R. Hutzler, T.M. Ito, D. Kaplan, O. Kim, R. Lehnert, W.M. Morse, Y.K. Semertzidis

Community Planning Exercise: Snowmass 2021

TERRA INCOGNITA



[Casas @ Moriond 2017]



PRECISION PHYSICS - $(g\text{-}2)_\mu$

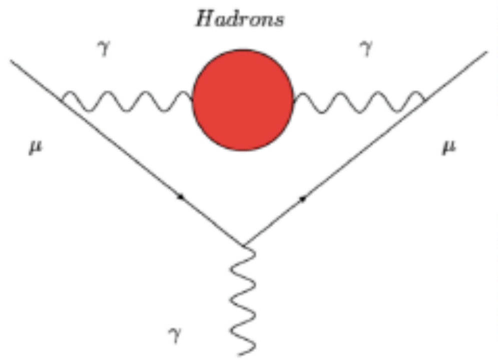
New Physics

Courtesy of G. Martinelli

BACK-UP SLIDES

A closer look at $\sigma_{\rm had}$

- dominated by $e^+e^- \to \pi^+\pi^-$ channel (70% of the full hadronic)



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

- what is $\sigma_{\rm had}(s)$?

  - Includes Final State Radiation (FSR)

  - Initial State Radiation (ISR) and FSR/ISR interference are subtracted

  - Vacuum polarization also subtracted (by rescaling exp. cross-section by $|\alpha/\alpha(s)|^2$)

  → part of higher-order HVP

[WP20, 2006.04822]

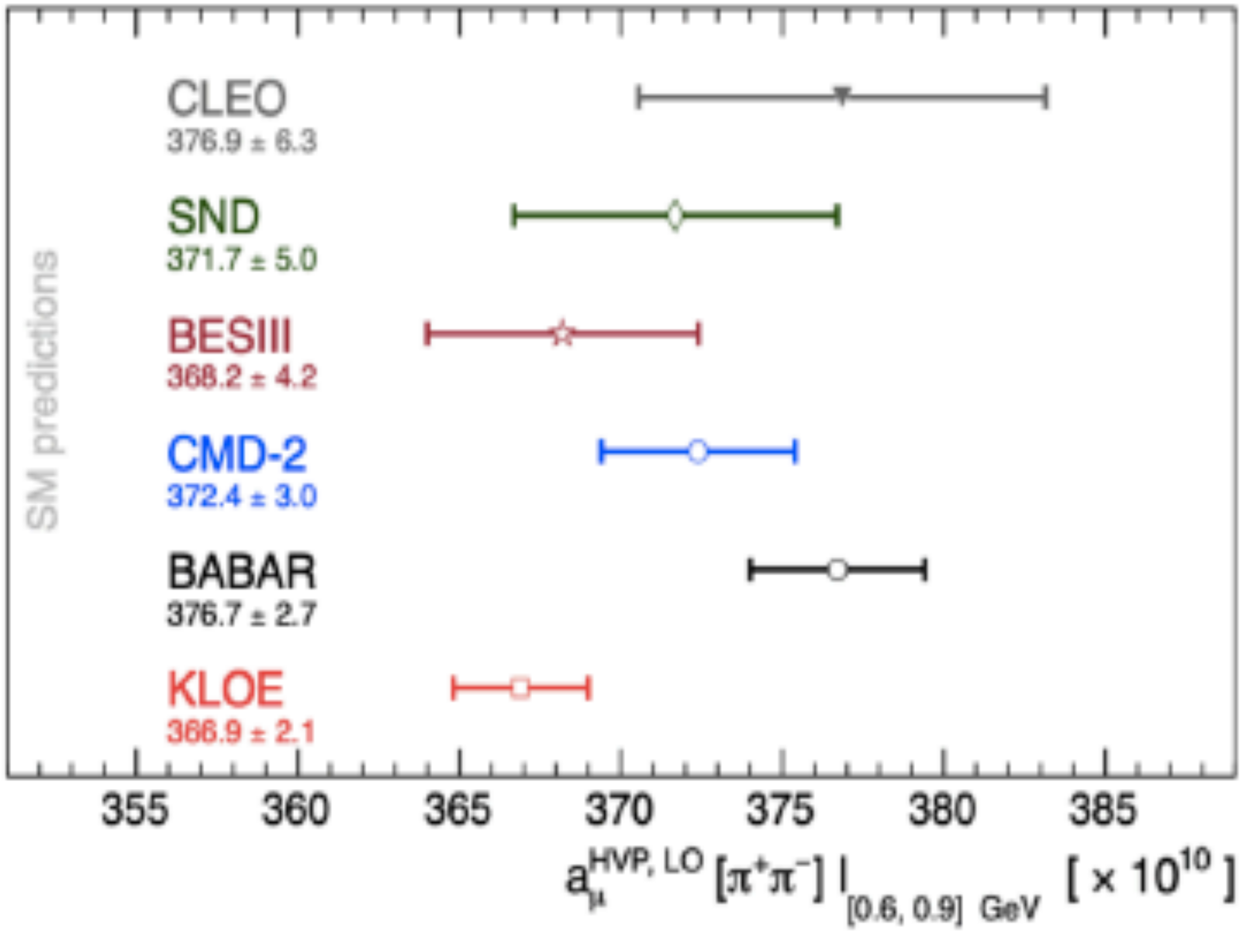


Figure 15: Comparison of results for $a_\mu^{\mathrm{HVP,\,LO}}[\pi\pi]$, evaluated between 0.6 GeV and 0.9 GeV for the various experiments.

NP in Bhabha scattering?

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

[Darmé, Grilli di Cortona, Nardi 2112.09139]

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

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

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

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

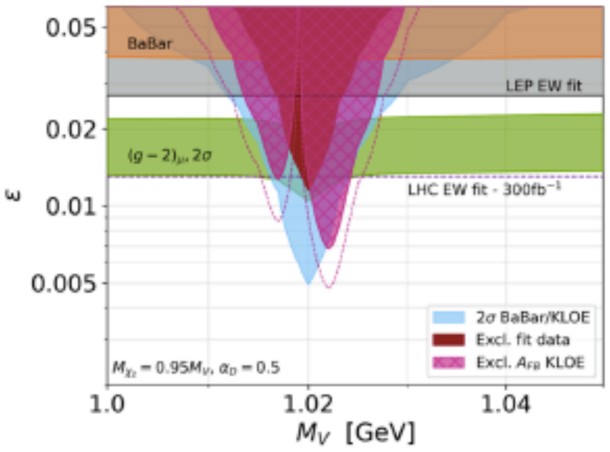
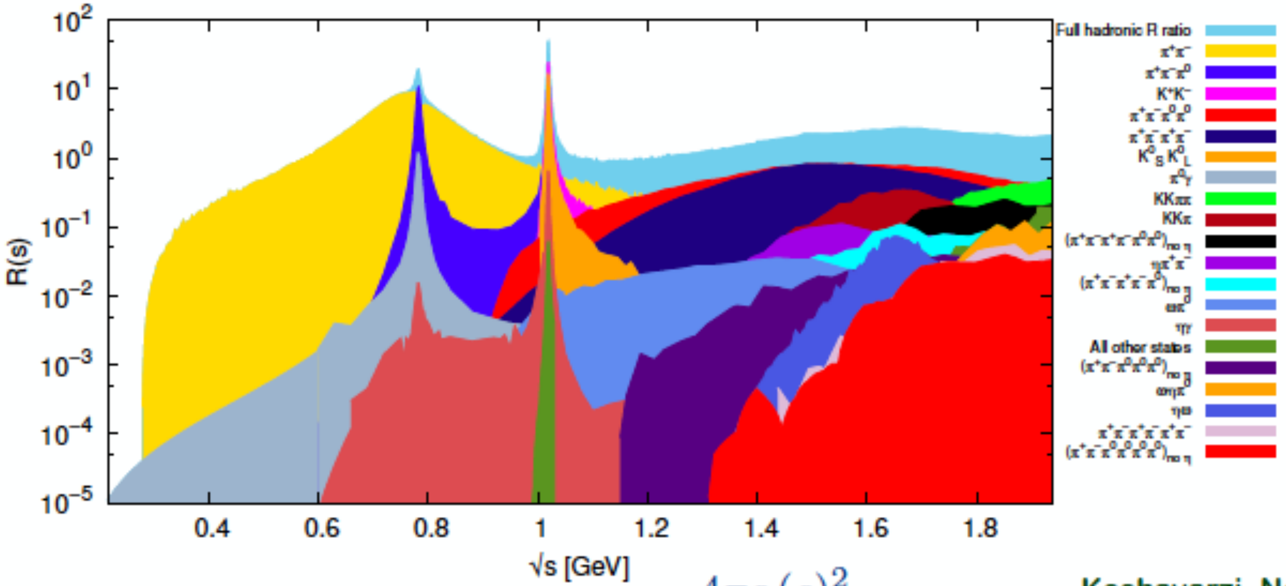


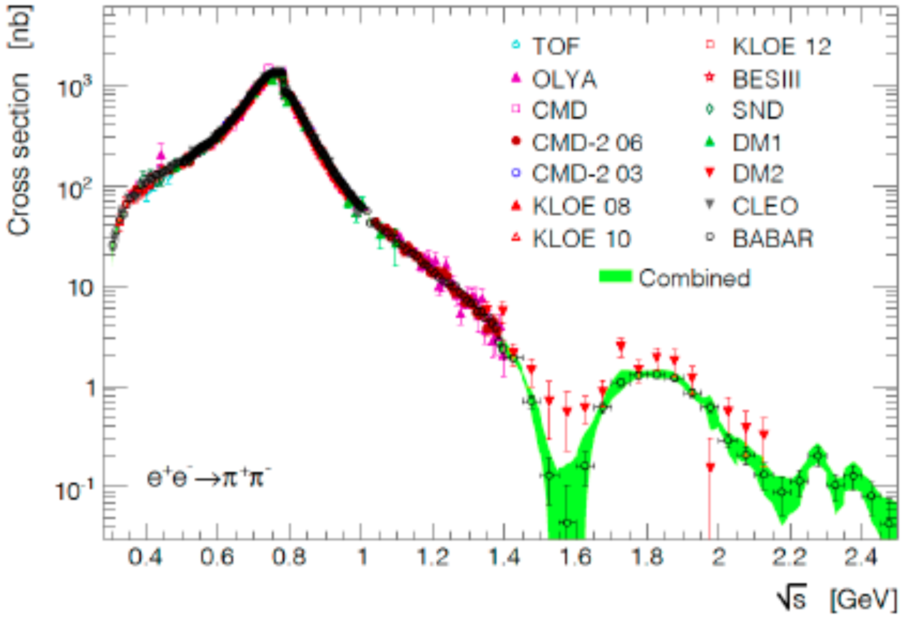
Figure 3. Parameter range compatible at 2σ with the experimental measurement of Δa_μ (green region) resulting from a redetermination of the KLOE luminosity, for $\alpha_D = 0.5$, $m_{\chi_2} = 0.95 m_V$ and $m_{\chi_1} = 25$ MeV. In the blue region the KLOE and BaBar results for $\sigma_{\rm had}$ are 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.

$e^+e^- \to \pi^+\pi^-$ 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 $(g-2)$

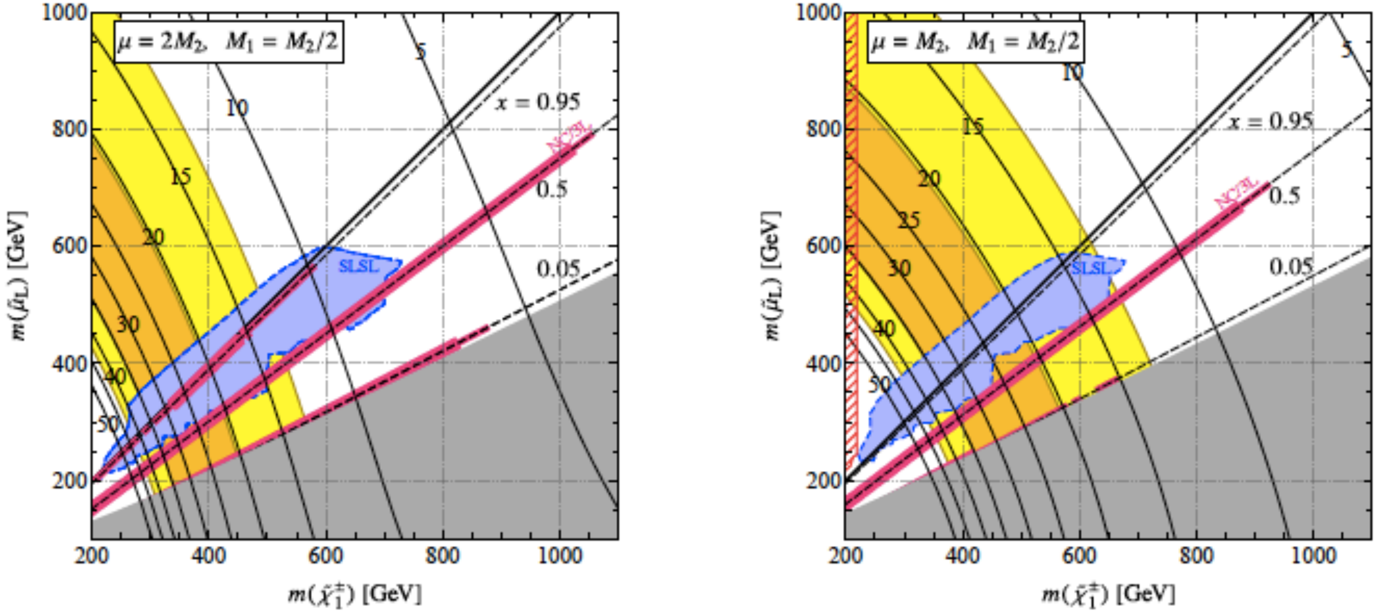
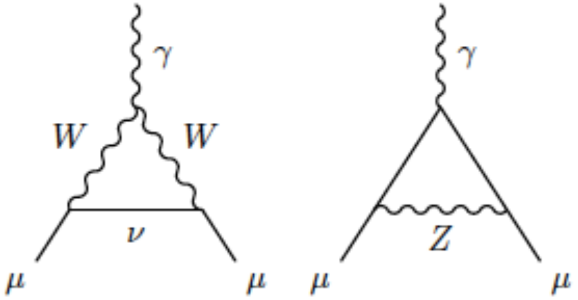
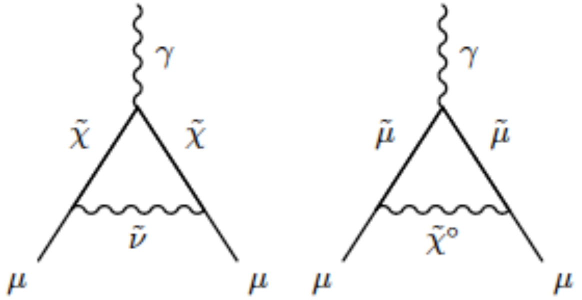


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].





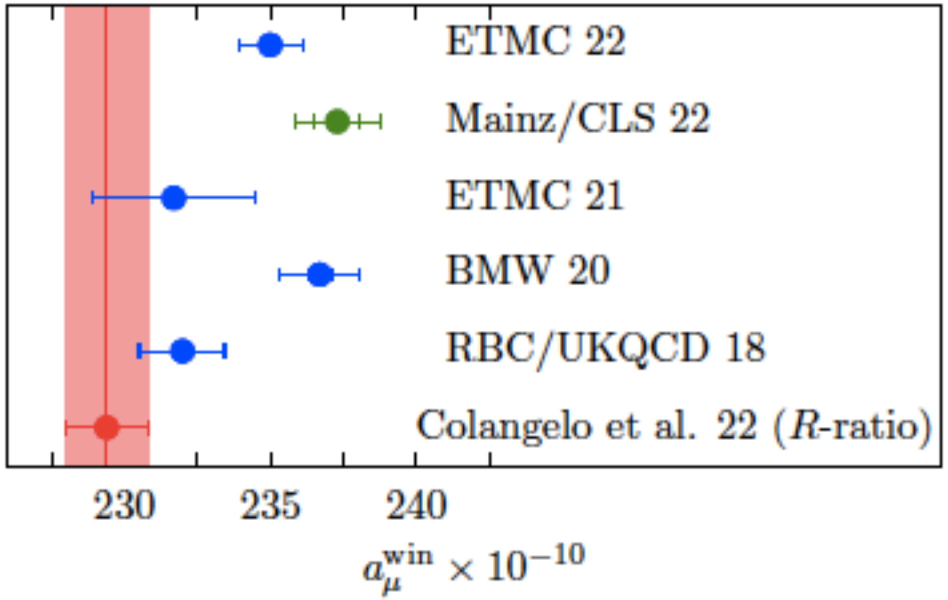
$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

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

Comparison with results for a_μ^{win}

- Isospin-breaking correction $+(0.70 \pm 0.47) \times 10^{-10}$ included:

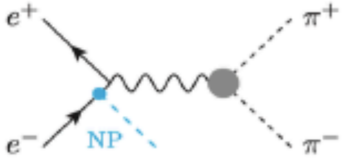
$$a_\mu^{\mathrm{win}} = (237.30 \pm 0.79_{\mathrm{stat}} \pm 1.13_{\mathrm{syst}} \pm 0.05_{\mathrm{Q}} \pm 0.47_{\mathrm{IB}}) \times 10^{-10}$$



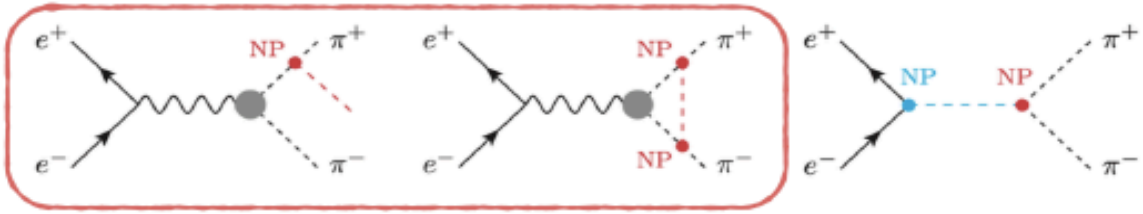
- 3.9σ tension with data-driven estimate in [2205.12963, Colangelo et al.].
- Genuine difference between lattice and data-driven results?

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]



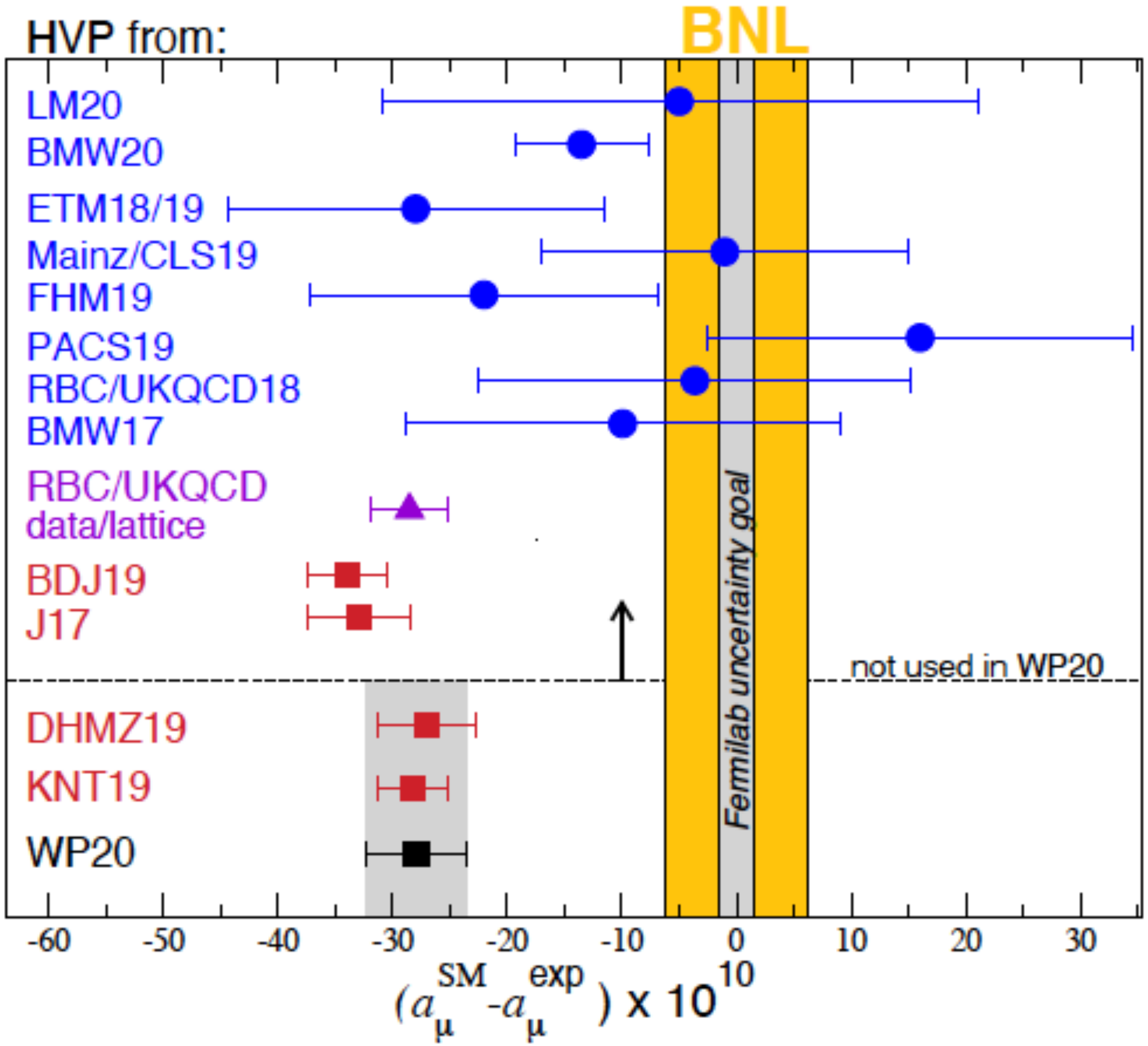
2. NP coupled only to hadrons

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*

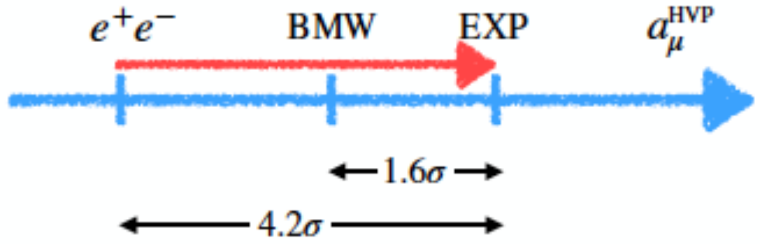
$$(a_\mu^{\text{HVP}})^{\text{FSR}}_{e^+e^-} \approx 50 \times 10^{-11} \quad \longleftrightarrow \quad |(a_\mu^{\text{HVP}})_{\text{BMW}} - (a_\mu^{\text{HVP}})^{\text{WP20}}_{e^+e^-}| \approx 150 \times 10^{-11}$$

HADRONIC VACUUM POLARIZATION CONTRIBUTION



Ab-initio lattice calculations

Dispersive relations,
$e^+e^- \to$ hadrons exps.



some conclusive thoughts:

- attempt **to solve the "new" muon g-2 puzzle introducing NP which modifies σ (e^+e^- → hadrons), but without affecting a_μ^{HVP}** :
  a) NP → light (<1 GeV) vector **Z'** coupling only to electrons and hadrons;
  b) the **experimental constraints** on the size of such couplings **prevent** the Z' exchange to provide the needed enhancement of the hadronic σ to suitably address the new g-2 puzzle

- **Two** directions to be vigorously pursued:
  i) perform **new** independent **lattice QCD** computations of the HVP contribution to a_μ to assess the validity of the **BMWc result** ;
  ii) identifies **new** experimental ways to probe a_μ^{HVP} (the **MUonE** exp. can (hopefully reasonably) soon provide an **independent determination** of the leading hadronic contributions to a_μ alternative to both the dispersive and lattice methods)