General Seminar Miniworkshop Congiunto INFN LNF - INFN Roma: First results from the Muon g-2 Experiment at Fermilab, 15 Apr. 2021

Theoretical implications of the leptonic g-2 measurements

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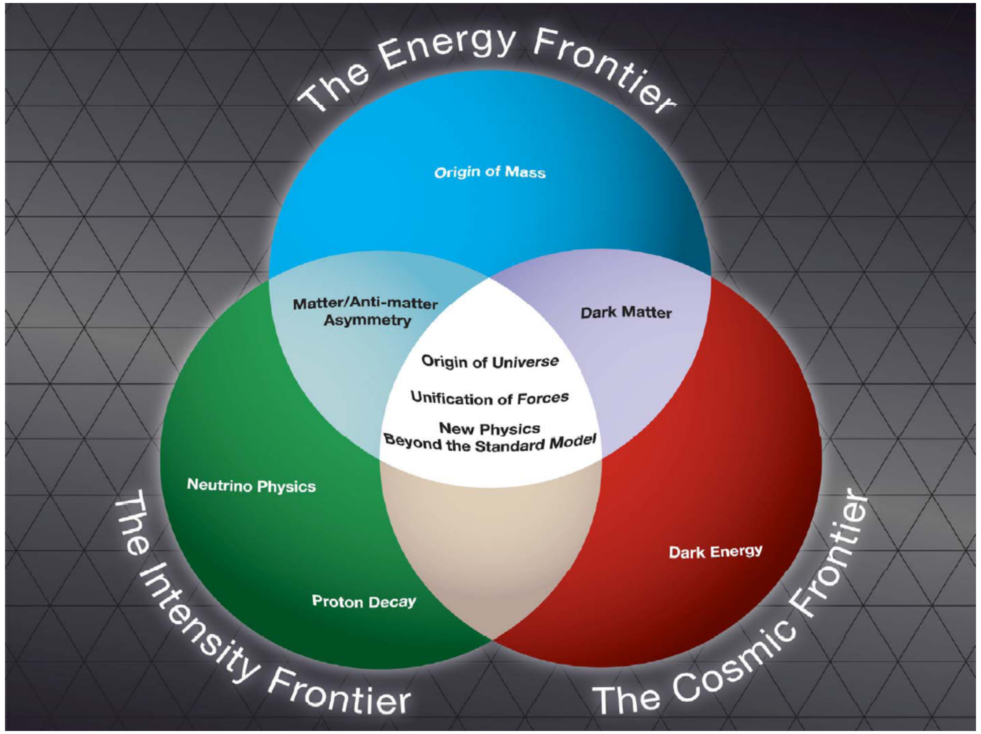
INFN and Univ. of Padova



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.

What the SM does not account for…

neutrino masses
dark matter
baryogenesis
inflation

OBSERVATIONAL REASONS
of **New Physics**:
all of them along
the **ASTROPARTICLE frontier**

$M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
$E_{VACUUM} (DE) / M_{HIGGS} \sim 10^{-14}$
$\Theta_{CPV\ in\ STRONG\ INTERAC.} < 10^{-9}$

THEORETICAL REASONS:
the unbearable **fine-tuning** of fundamental parameters

+ other "aesthetic" puzzles
the **flavour "problem"**, the barely **missed true unification** of fundamental interactions, the inclusion of **gravity** in a QM consistent framework, …

- Uhlenbeck and Goudsmit in 1925 proposed for electrons

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$
$$g = 2 \quad \text{(not 1!)}$$

- Dirac 1928:

$$(i\partial_\mu - eA_\mu)\,\gamma^\mu\psi = m\psi$$

- A Pauli term in Dirac's eq would give a deviation…

$$a\frac{e}{2m}\sigma_{\mu\nu}F^{\mu\nu}\psi \quad \rightarrow \quad g = 2(1+a)$$

…but there was no need for it! g=2 stood for ~20 yrs.

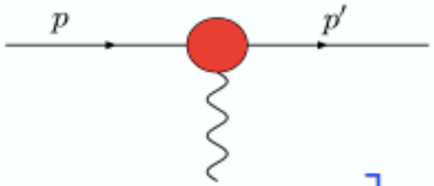
- **Kusch and Foley 1948:**

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

- **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:**



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

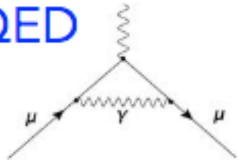
$$F_1(0) = 1 \qquad F_2(0) = a_l$$

A pure "quantum correction" effect!

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

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

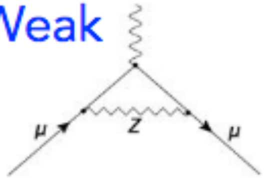
QED



+…

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

Weak



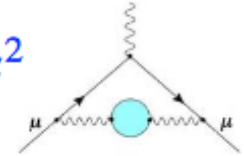
+…

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

Hadronic…

…Vacuum Polarization (HVP)

α^2

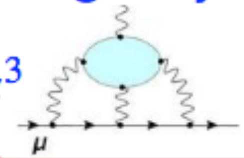


+…

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

…Light-by-Light (HLbL)

α^3



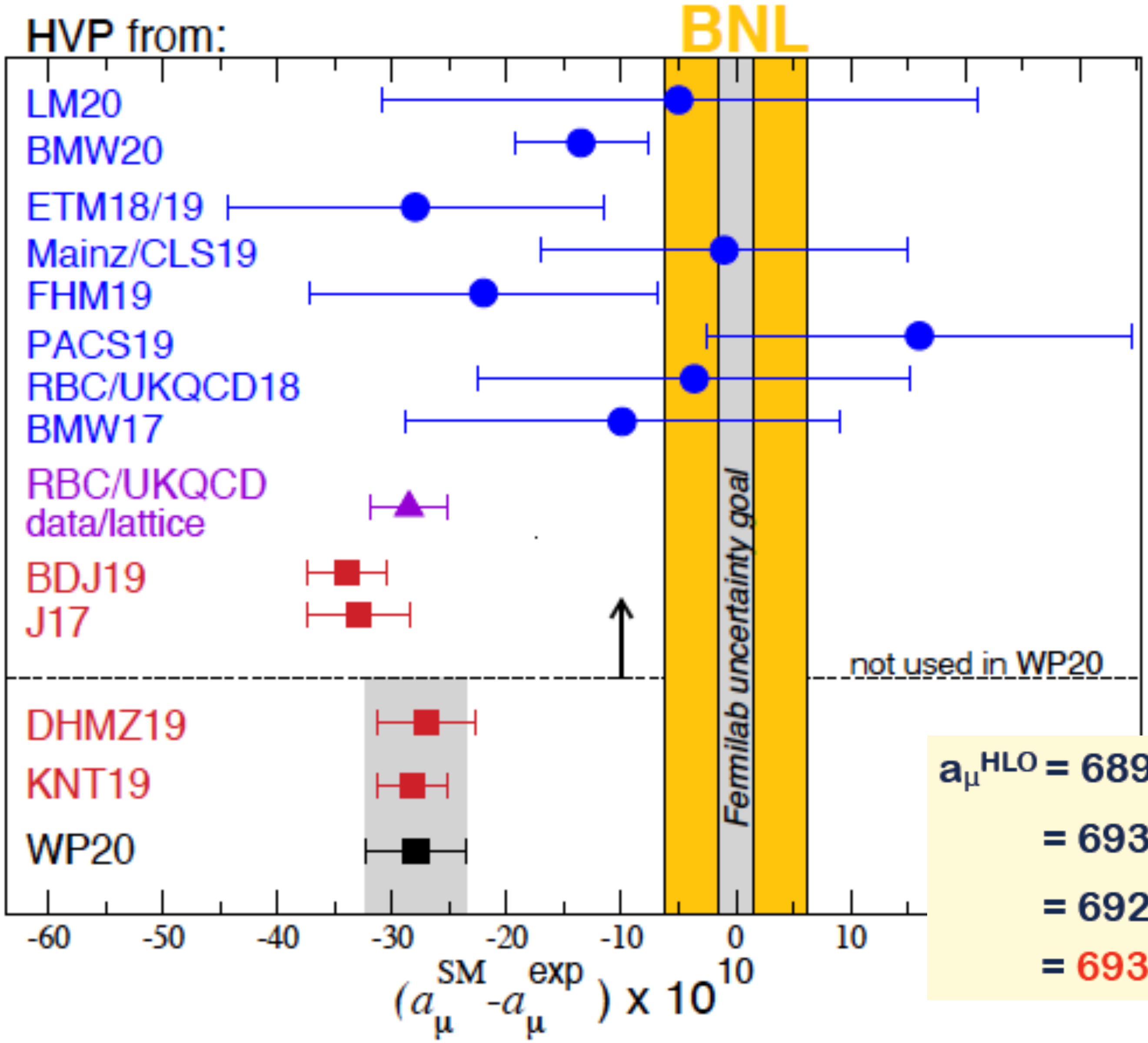
+…

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

Numbers from Theory Initiative Whitepaper

HADRONIC VACUUM POLARIZATION CONTRIBUTION

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



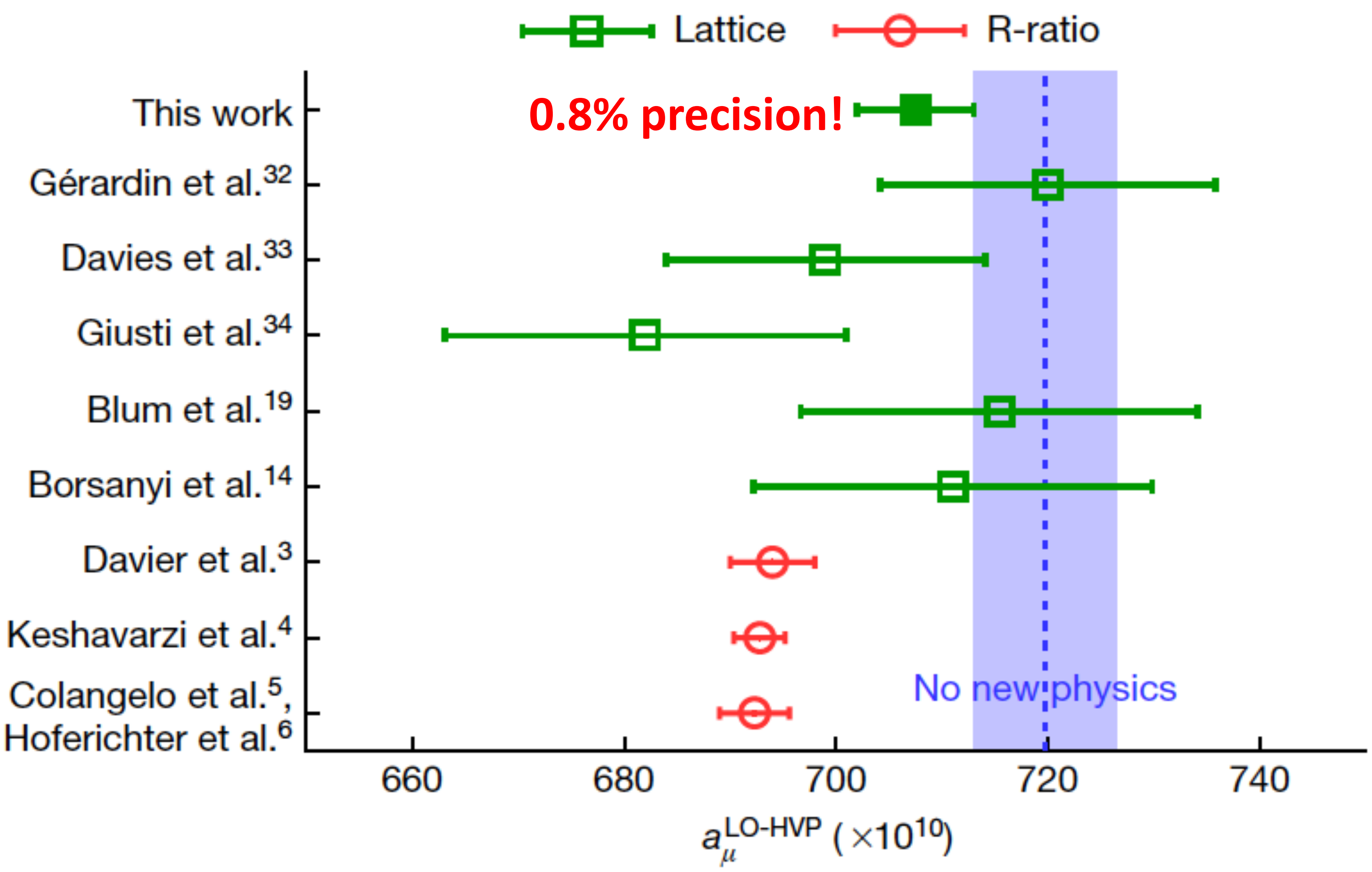
Ab-initio lattice calculations

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

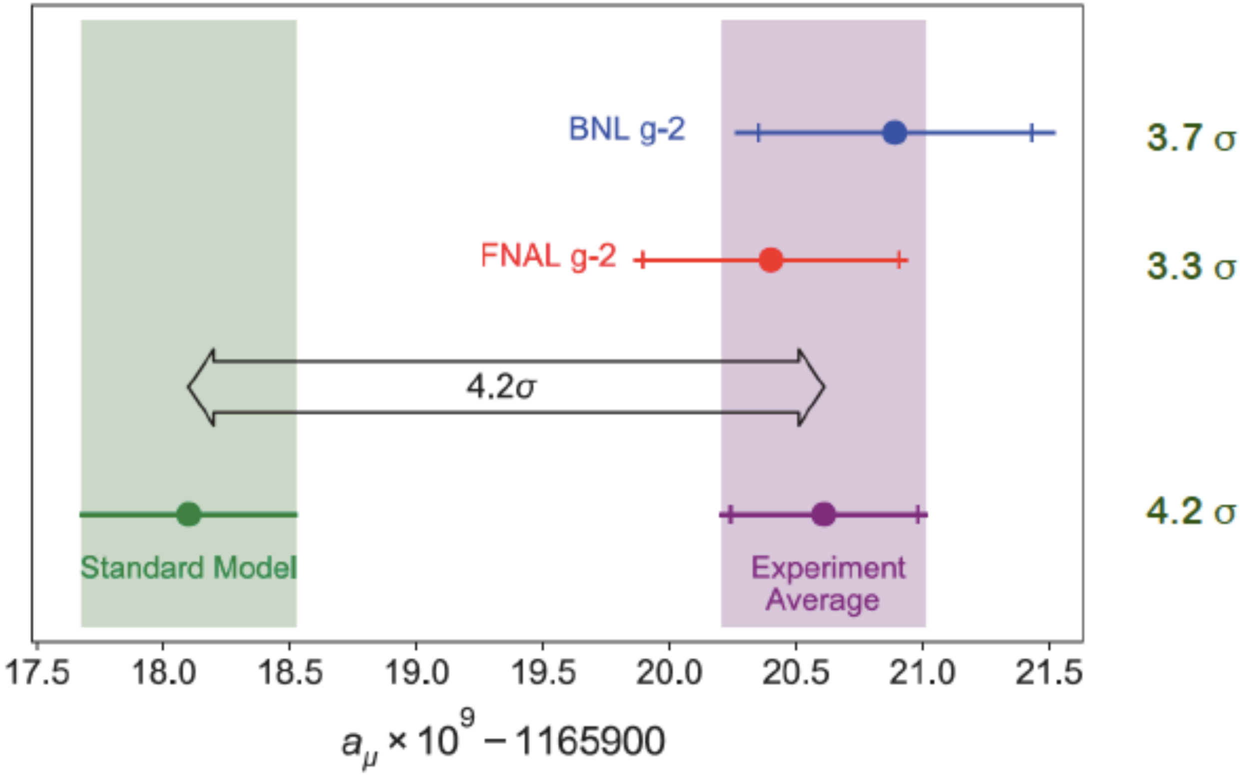
$a_\mu^{HLO} = 6895\ (33) \times 10^{-11}$	F. Jegerlehner, arXiv:1711.06089
$= 6939\ (40) \times 10^{-11}$	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
$= 6928\ (24) \times 10^{-11}$	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
$= 6931\ (40) \times 10^{-11}$ (0.6%)	Muon g-2 TI WP: arXiv:2006.04822

BMW20: S. Borsanyi et al. 2002.12347, published on Nature, April 7, 2021

first published lattice result with sub-percent precision!



Muon g-2: FNAL confirms BNL



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

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

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

- FNAL aims at 16×10^{-11}. First 3 runs completed, 4th in progress.
- Muon g-2 proposal at J-PARC: Phase-1 with ~ BNL precision.

Comparing the SM prediction with the measured muon g-2 value:

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

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

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

Is Δa_μ due to new physics beyond the SM?

Could Δa_μ (using DRs for a_μ^{SM}) be due to some **missing contributions** in the hadronic cross section?

Yes, possible to increase the hadronic cross section to account for Δa_μ , BUT:

- If such increase occurs because of new (so far missed) contributions **ABOVE ~ 1 GeV** → **conflict with the EW precision fit** arises

  Marciano, Passera, Sirlin 2008 & 2010;
  Keshavarzi, Marciano, Passera, Sirlin 2020

- If such increase occurs **BELOW ~1 GeV** → entails a **conflict with the precision of the measured hadronic cross section**

(KMPS 2020, updated 2021)

$a_\mu \Longleftrightarrow \Delta\alpha$: recent related literature

M. Passera, talk at the IAS, Apr. 13, 2021

- Crivellin, Hoferichter, Manzari and Montull, “Hadronic vacuum polarization: $(g\text{-}2)_\mu$ versus global electroweak fits,” arXiv:2003.04886.

- Eduardo de Rafael, “On Constraints Between $\Delta\alpha_{had}(M_Z^2)$ and $(g_\mu\text{-}2)_{HVP}$,’’ arXiv:2006.13880.

- Malaescu and Schott, “Impact of correlations between a_μ and α_{QED} on the EW fit,” arXiv:2008.08107.

- Colangelo, Hoferichter and Stoffer, “Constraints on the two-pion contribution to hadronic vacuum polarization,” arXiv:2010.07943.

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

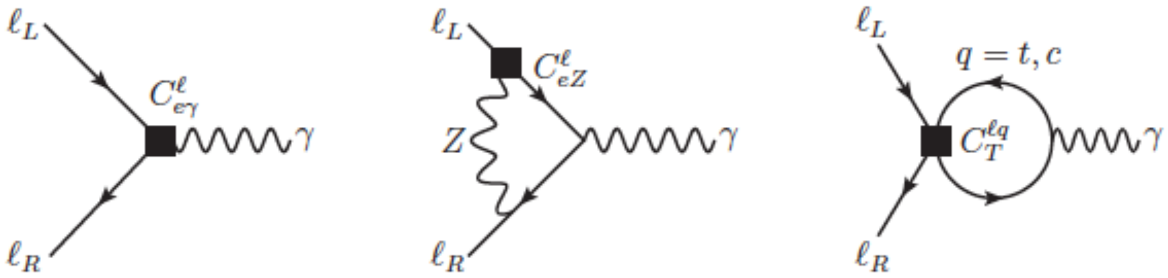
$$\mathcal{L}_{\rm EFT}(\Lambda \gg v) = \frac{C^\ell_{e\gamma}}{\Lambda^2}\,(\bar\ell_L \sigma^{\mu\nu} e_R) H F_{\mu\nu} + h.c. \quad \Longrightarrow \quad \Delta a_\mu = \frac{4 m_\mu v}{e\Lambda^2} C^\mu_{e\gamma}$$

- **What is the NP scale Λ probed by $\Delta a_\mu \equiv a_\mu^{\rm NP} = (2.79 \pm 0.76) \times 10^{-9}$?**

The muon g-2 in the Standard Model EFT [Buttazzo and P.P., '20]

- **SMEFT Lagrangian relevant for Δa_ℓ**

$$\mathcal{L} = \sum_{V=B,W} \frac{C^\ell_{eV}}{\Lambda^2} (\bar{\ell}_L \sigma^{\mu\nu} e_R) H V_{\mu\nu} + \sum_{q=c,t} \frac{C^{\ell q}_T}{\Lambda^2} (\bar{\ell}_L \sigma_{\mu\nu} e_R)(\overline{Q}_L \sigma^{\mu\nu} q_R) + h.c.$$



$$\Delta a_\ell \simeq \frac{4 m_\ell v}{e\Lambda^2} \left(C^\ell_{e\gamma} - \frac{3\alpha}{2\pi} \frac{c_W^2 - s_W^2}{s_W c_W} C^\ell_{eZ} \log\frac{\Lambda}{m_Z} \right) - \sum_{q=c,t} \frac{4 m_\ell m_q}{\pi^2} \frac{C^{\ell q}_T}{\Lambda^2} \log\frac{\Lambda}{m_q},$$

$$\frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda}\right)^2 |C^\mu_{e\gamma}| \qquad \frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{50\,\mathrm{TeV}}{\Lambda}\right)^2 |C^\mu_{eZ}|$$

$$\frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{100\,\mathrm{TeV}}{\Lambda}\right)^2 |C^{\mu t}_T| \qquad \frac{|\Delta a_\mu|}{3\times 10^{-9}} \approx \left(\frac{10\,\mathrm{TeV}}{\Lambda}\right)^2 |C^{\mu c}_T|$$

- **Strongly coupled NP:** $C^\mu_{e\gamma}, C^{\mu t}_T \sim g^2_{\rm NP}/16\pi^2 \lesssim 1$ implying $\Lambda \lesssim$ *few* x 100 TeV, beyond the direct production reach of any foreseen collider.
- **Weakly coupled NP:** $C^\mu_{e\gamma}, C^{\mu t}_T \lesssim 1/16\pi^2$ implying $\Lambda \lesssim 20$ TeV maybe within the direct production reach of a very high-energy Muon Collider

Minimal extensions of the SM to account for the $(g-2)_\mu$ anomaly

Addition of a **SINGLE NEW FIELD**:

i) The addition of a **single fermion** cannot explain this anomaly ;

(C. Biggio 2008; Freitas, Lykken, Kell, Westhoff 2014; Biggio, Bordone 2014)

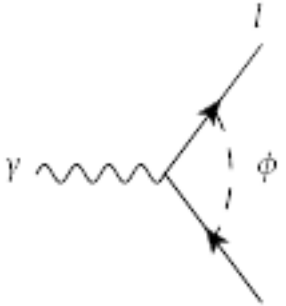
ii) The addition of a **single scalar** can account for the discrepancy if the new scalar is:

a **new Higgs doublet**; (Freitas, Lykken, Kell, Westhoff 2014; Broggio, Chun, Passera, Patel, Vempati 2014; Biggio, Bordone 2014; Cherchiglia, Kneschke, Stockinger, Stockinger-Kim 2017)

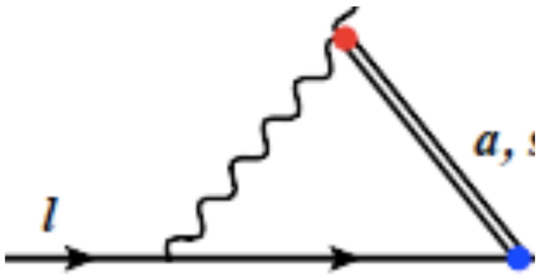
one of the two **leptoquarks**: $S^{1/3}(3, 1, -1/3; Q= -1/3)$; $D^{7/6}(3,2, 7/6; Q = 5/3, 2/3)$ Chakraverty, D. Choudhuri, Datta 2001; Biggio, Bordone 2014; Queiroz, Shepherd 2014; Coluccio Leskow, D'Ambrosio, Crivellin, Muller 2017

- **iii)** one massive **vector boson**: only possibility → abelian gauge extensions – Z', dark photon (Biggio, Bordone, Di Luzio, Ridolfi 2016; Davoudiasl, H.-S.Lee, Marciano 2014; Altmannshofer, C.-Y. Chen, Dev, Soni 2016;)
- **iv) ALPs (ALP-photon photon + ALP Yukawa interactions with leptons)**

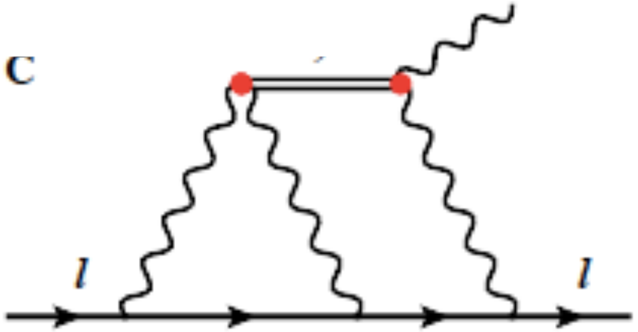
$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi}\gamma_5\psi$$

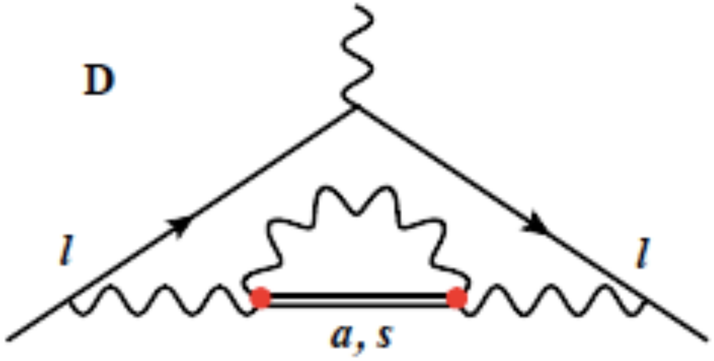


Chen, Davoudiasl, Marciano, Zhang 2016



One-loop contribution

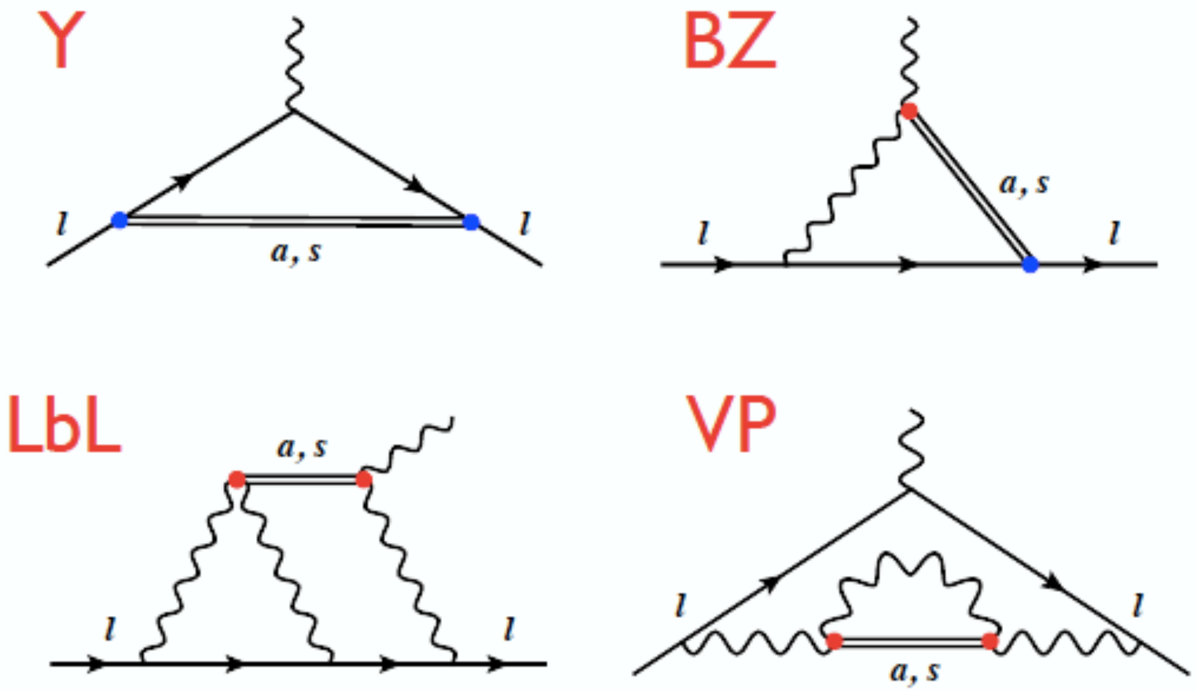




Two-loop contributions

Marciano, AM, Paradisi, Passera 2016

ALPs contributions to the muon g-2?



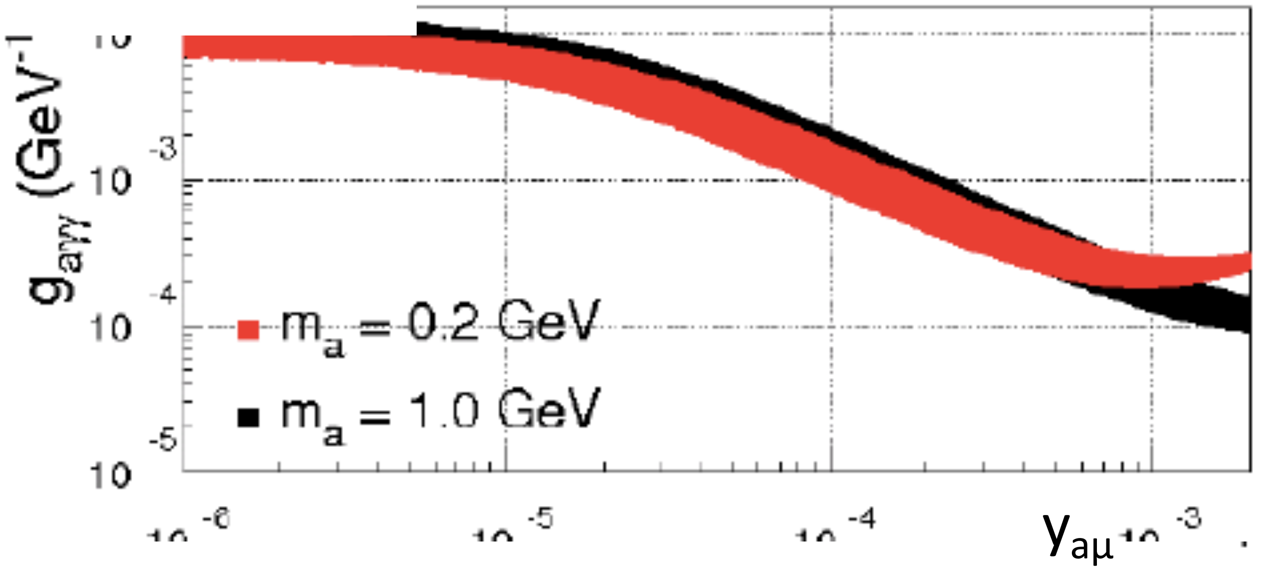
Marciano, AM, Paradisi, Passera 2016;
Bauer, Neubert, Thamm 2017

- **Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.**

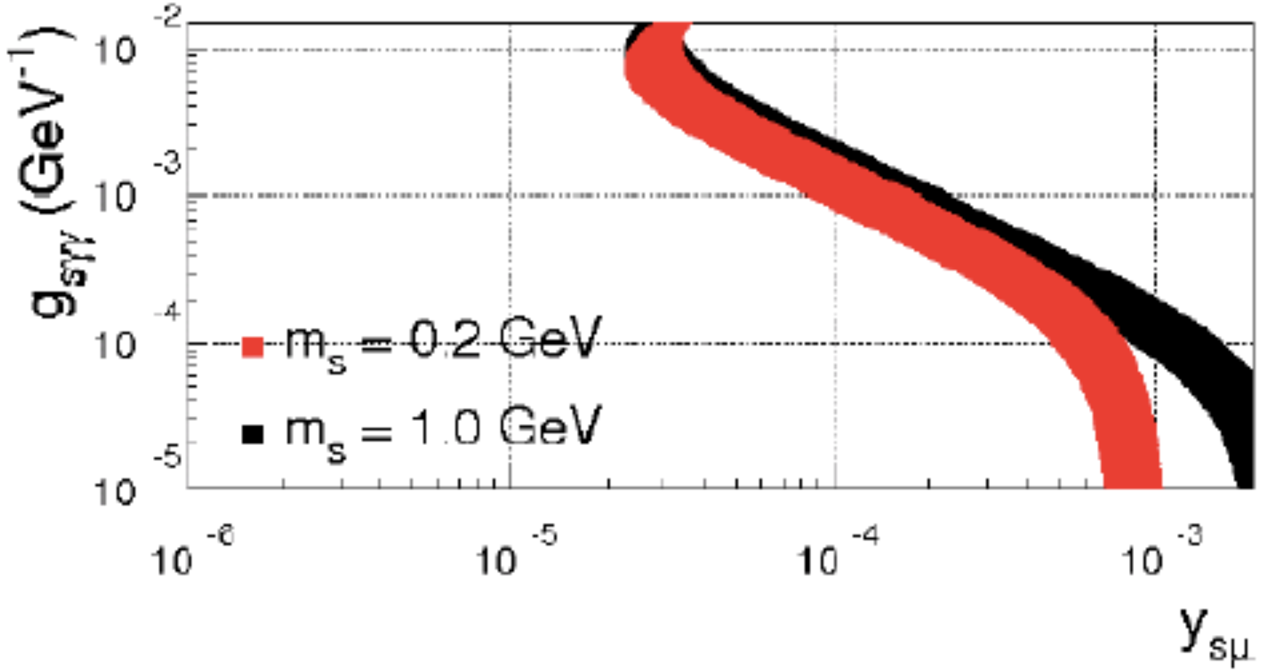
- **They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \to e^+e^-$+ALP & $e^+e^- \to \gamma$+ALP searches.**

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

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



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



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

MMPP 2016

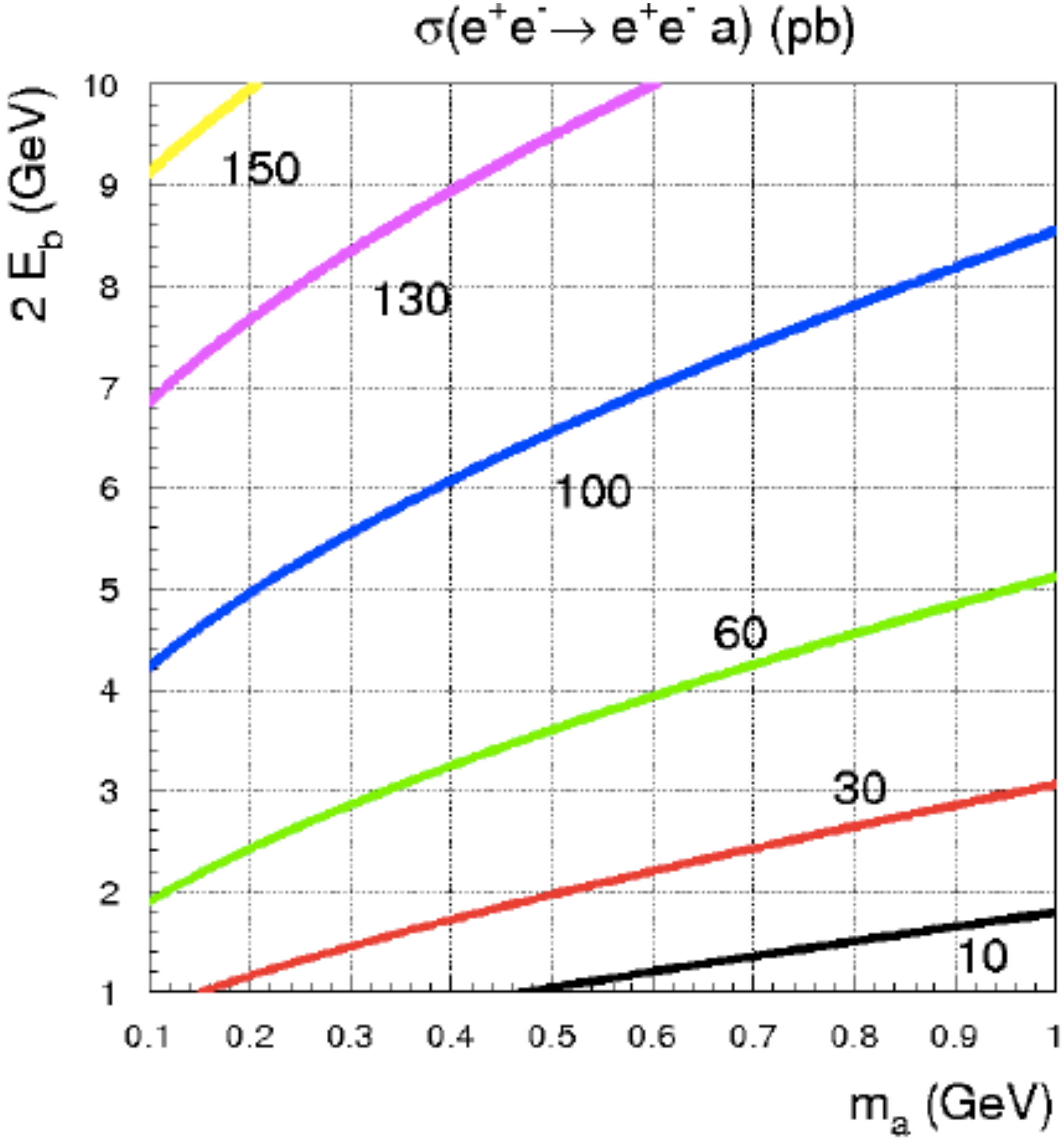
Experimental tests at e^+e^- colliders

MMPP 2016

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^- a\,,$$
$$e^+e^- \rightarrow \gamma^* \rightarrow \gamma a\,,$$

$$\sigma_{eea} \simeq \frac{\alpha^2}{4\pi}\, g^2_{a\gamma\gamma} \left(\ln \frac{E_b}{m_e}\right)^2 f\left(\frac{m_a}{2E_b}\right)$$
$$E_b \equiv \sqrt{s}/2$$

$$\sigma_{eea}(\sqrt{s} = 1\,\mathrm{GeV}) \approx 31\,\mathrm{pb}\,\left(\frac{g_{a\gamma\gamma}}{10^{-2}\,\mathrm{GeV}^{-1}}\right)^2,$$
$$\sigma_{\gamma a}(\sqrt{s} = 1\,\mathrm{GeV}) \approx 9\,\mathrm{pb}\,\left(\frac{g_{a\gamma\gamma}}{10^{-2}\,\mathrm{GeV}^{-1}}\right)^2,$$



Model-independent predictions

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

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 10^{-28} \left(\frac{\phi_e^{CPV}}{10^{-4}} \right) \, e\,\mathrm{cm}\,,$$

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

- **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!

[Giudice, P.P., & Passera, '12]

DM and g-2 as windows to New Physics

- **Minimal extensions of the SM to account for the DM**: one additional field that being neutral and stable might have been in thermal equilibrium interacting with ordinary matter and today have the correct density to account for the DM
- **Minimal extensions of the SM to account for the g-2 anomaly**: one single additional field (leptoquark or additional Higgs doublet or ALPs) coupling sizeably to leptons and/or photons
- Is it possible to have just one single additional field to account for both the DM **and** the g-2 anomaly? No, the DM fields in these minimal SM extensions decay too quickly to ordinary matter particles. **One needs at least two new fields** (for instance one additional fermion and one additional scalar)

Calibbi, Ziegler, Zupan 2018

Muon-electron scattering: The MUonE Project

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

EPJC 2017 - arXiv:1609.08987

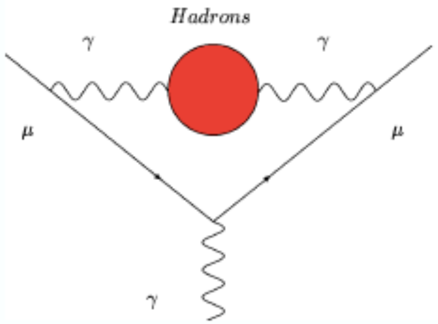
A new approach to a_μ^{HLO}

C. Carloni Calame, MP, L. Trentadue, G. Venanzoni

PLB 2015 - arXiv:1504.02228

Spacelike proposal for a_μ

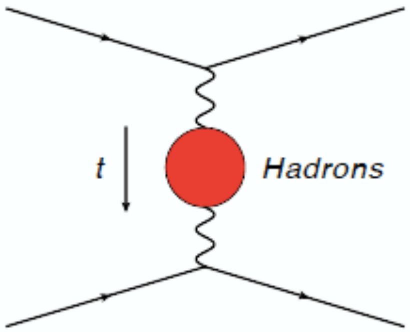
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the **timelike** formula:



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

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

- 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

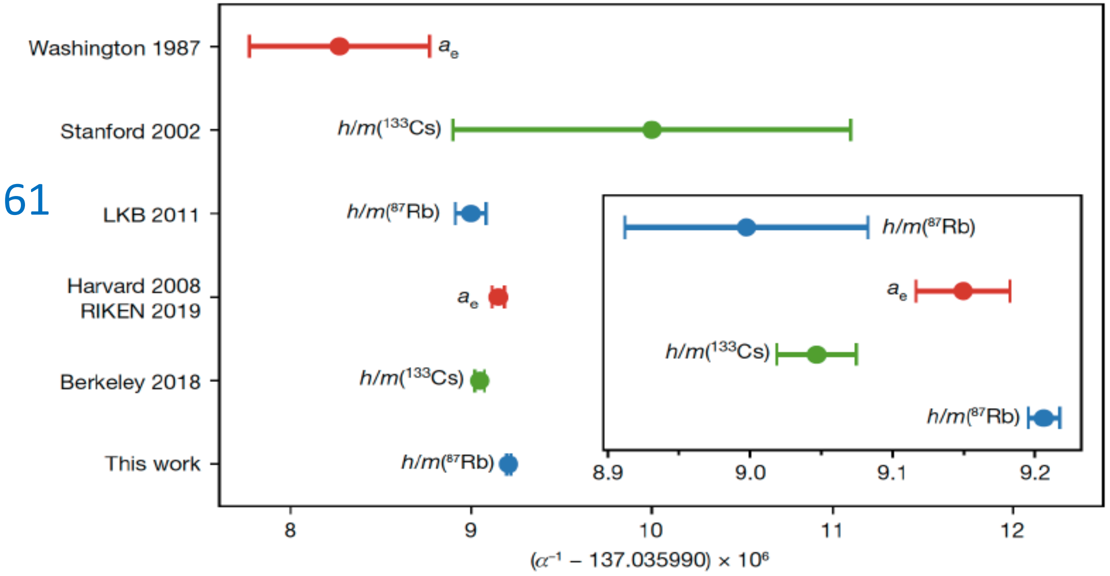
→ **NO, NP cannot spoil the validity of such extraction**

A new life for an old protagonist: the g-2 of the ELECTRON

$a_e^{EXP} = 115\,965\,218\,07.3\,(2.8) \times 10^{-13}$ Hanneke et al, PRL 2008

The g-2 of the electron no longer provides the best determination of α

Morel et al., Nature 588 (2020) 61



$\Delta a_e = a_e^{EXP} - a_e^{SM} = -8.9\,(3.6) \times 10^{-13}$ [2.5σ] [Cs18]

$= +4.7\,(3.0) \times 10^{-13}$ [1.6σ] [Rb20]

The $(g\text{-}2)_e$ exp. error may soon become $< 10^{-13}$ →
(g-2)e can soon play a pivotal role in probing NP in the leptonic sector

- In a broad class of BSM theories, contributions to a_l scale as

$$\frac{\Delta a_{\ell_i}}{\Delta a_{\ell_j}} = \left(\frac{m_{\ell_i}}{m_{\ell_j}}\right)^2$$

This Naive Scaling leads to:

$$\Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}; \qquad \Delta a_\tau = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.8 \times 10^{-6}$$

Giudice, Paradisi, Passera 2012

Testing new physics with the electron g-2 (2)

e

- The sensitivity in Δa_e may soon drop below 10^{-13}! This will bring a_e to play a pivotal role in probing new physics in the leptonic sector.

- NP scenarios exist which violate Naive Scaling. They can lead to larger effects in Δa_e and contributions to EDMs, LFV or lepton universality breaking observables.

Giudice, Paradisi & MP, JHEP 2012
Crivellin, Hoferichter, Schmidt-Wellenburg, PRD 2018

- One real scalar with a mass of ~ 250−1000 MeV could explain the deviations in a_μ and a_e, through one- and two-loop processes, respectively.

Davoudiasl & Marciano, PRD 2018

…some final thoughts on the leptonic g-2

- **$(g\text{-}2)_\mu$ certainly represents the most longstanding possible hint (constantly at the 3 – 4 σ significance level) of NP BSM (now, thanks to this last exp. result, growing to 4.2 σ)**
- the recent **BMW remarkable ab initio lattice computation** of $(g\text{-}2)_\mu$ is nicely quite close to the experimental value of $(g\text{-}2)_\mu$, however its discrepancy w.r.t. the traditional dispersive relation **cannot** be accounted for by Δσ(s) shifts **above ~ 1GeV** (otherwise the global EW fit is ruined) and by shifts **below ~1GeV** to avoid conflicts with the quoted exp. error of σ(s)
- An important (g-2) leptonic synergy: **$(g\text{-}2)_\mu$ and $(g\text{-}2)_e$**
- The NP accounting for $(g\text{-}2)_\mu$ can lead to potentially relevant enhancements in **leptonic EDMs and LFV physics**
- **MUonE** can soon provide an **independent determination** of the leading hadronic contributions to a_μ alternative to both the dispersive and lattice methods