New physics behind the new muon g-2 puzzle?

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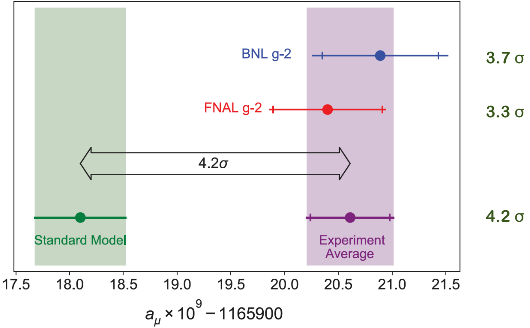
Based on Di Luzio, Masiero, Paradisi and Passera, PLB **829** (2022).

Experimental status

- **April 7th 2021: Muon $g-2$ experiment at 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 4 runs completed, 5th in progress.**
- **Muon $g-2$ proposal at J-PARC: Phase-1 with similar BNL precision.**

"Old muon g-2 puzzle"

- **Status of $a_\mu \equiv \frac{g_\mu - 2}{2}$ as of April $7^{\rm th}$ 2021 (with $a_\mu^{\rm SM}$ based on $a^{\rm HLO}_{\mu,\,e^+e^-}$)**

$$a_\mu^{\rm EXP} = 116592061(41) \times 10^{-11} \quad \text{[BNL + FNAL]}$$
$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-11} \quad \text{[WP20]}$$

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

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

  - 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.

- **Low-energy determinations of Δa_μ assume that systematic and hadronic uncertainties are under control at the outstanding level of $\Delta a_\mu < 10^{-9}$!**

New Physics for the muon $g-2$: at which scale?

- **Δa_μ discrepancy at $\sim 4.2\,\sigma$ level:**

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = (2.51 \pm 0.59) \times 10^{-9}$$

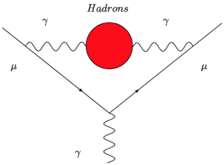
$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

  - NP is at the weak scale ($\Lambda \approx v$) and weakly coupled to SM particles.*
  - 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.

*Favoured by the *hierarchy problem* and by a WIMP DM candidate but disfavoured by the LEP and LHC bounds (supersymmetry being the most prominent example).

HLO contribution from $e^+e^- \to hadrons$

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



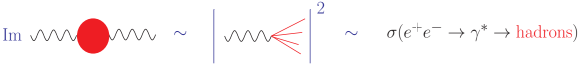
$$(a_\mu^{\mathrm{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\,\mathrm{Im}\,\Pi_{\mathrm{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\mathrm{had}}(s)$$

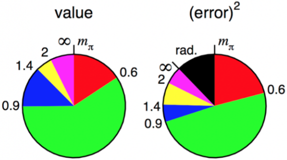
dispersion relations

optical theorem

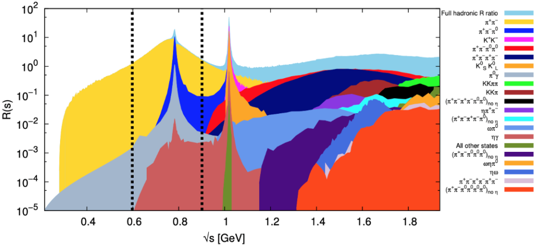
kernel function

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





Keshavarzi, Nomura, Teubner 2018



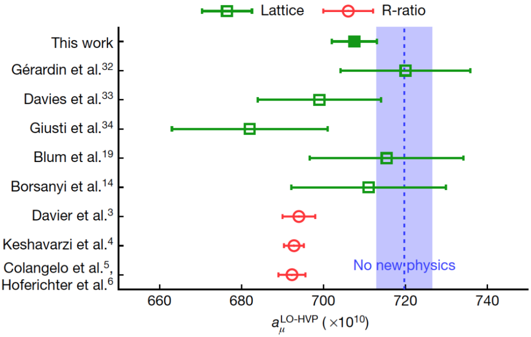
$$a_{\mu,e^+e^-}^{\mathrm{HLO}} = 6931(40) \times 10^{-11} (0.6\%)$$ [WP20]

HLO contribution from lattice QCD

- **Great progress also in lattice QCD, where spacetime is modeled as a discrete grid of points. The BMW collaboration reached a 0.8% precision!**

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

- **2–2.5σ tension with the "data-driven" evaluations.**



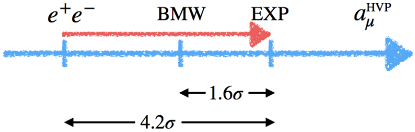
Borsanyi et al (BMWc), Nature 2021

"New muon g-2 puzzle"

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

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

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



"new puzzle": if BMW is correct, the "old" g-2 discrepancy (4.2σ) would be basically gone

→ *however, this brings in a new tension with e^+e^- data (2.2σ)*

Here, NP in $\sigma_{\rm had}(e^+e^- \to \text{hadrons})$ such that [LDL, Masiero, Paradisi, Passera 2112.08312]

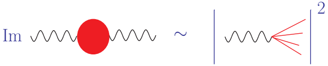
1. $(a_\mu^{\rm HVP})^{\rm WP20}_{e^+e^-} \approx (a_\mu^{\rm HVP})_{\rm EXP}$
2. the approximate agreement between BMW and EXP is not spoiled
3. w/o a direct contribution $a_\mu^{\rm NP}$ (i.e. NP not in muons)

Consequences of the BMW result

- **Can Δa_μ be due to missing contributions in $\sigma(e^+e^- \to had)$?**
  - An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha^{(5)}_{\rm had}(M_Z)$ defined by:

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

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



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

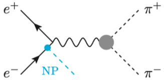
- **A change in $\sigma(e^+e^- \to had)$ is strongly disfavoured by:**
  - **EW-fit for $\sqrt{s} \gtrsim 1$ GeV** [Marciano, Passera, Sirlin, '08, Keshavarzi, Marciano, Passera, Sirlin, '20, Crivellin, Hoferichter, Manzari, Montull, '20]. A shift of $\sigma(e^+e^- \to had)$ to accomodate the Δa_μ anomaly would necessarely require new physics to show up in the EW-fit!

- **A check of the BMW results by other lattice QCD (LQCD) coll. is worth.**

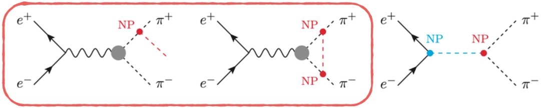
- **LQCD coll. should provide $\Delta\alpha^{\rm LQCD}_{\rm had}$ to be compared with $\Delta\alpha^{e^+e^-}_{\rm had}$.**

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

- Light new physics inducing a sub-GeV modification of $\sigma_{\rm had}$ 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]



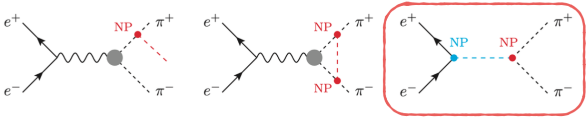
2. NP coupled only to hadrons

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

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

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

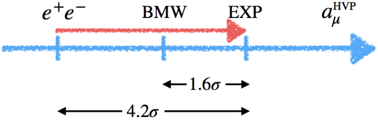
Light New Physics in σ_{had}



3. NP coupled both to hadrons and electrons

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

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



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

should be "subtracted" by NP,
since NP does not contribute to HVP at the LO
(but it contributes at the LO to the x-section)

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

A new light Z' vector boson

- Requirements:

  1. σ_{had} modified at $\sqrt{s} \lesssim 1\,\text{GeV}$ (mostly $\pi^+\pi^-$ channel) → sub-GeV mediator; → couples to u, d quarks (and electrons)
  2. A sizeable negative interference with the SM

     sizeable → tree-level mediator

     negative interference → couples via a vector current

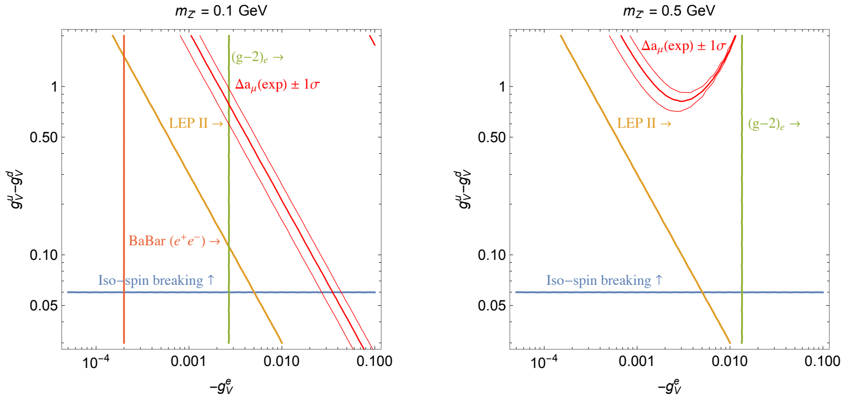
→ *a light spin-1 mediator with vector couplings to first generation SM fermions*

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

- It can be shown that (neglecting iso-spin breaking corrections due to NP)

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

A new light Z' vector boson

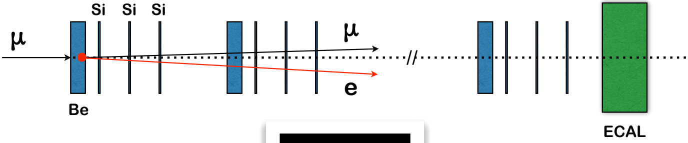


At least two independent bounds prevent to solve the "new muon g-2 puzzle"!

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.



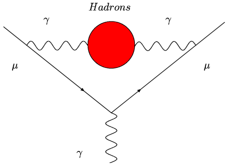
Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna, Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

[Courtesy by M. Passera]

- Letter of Intent submitted to CERN SPSC in 2019: Test run approved for 2022

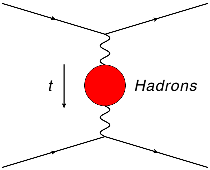
- **The leading hadronic contribution a_μ^{HLO} computed via the timelike formula:**



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

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

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



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

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

Lautrup, Peterman, de Rafael, 1972

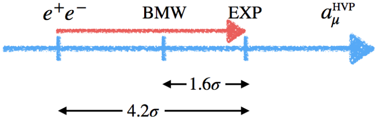
$\Delta\alpha_{\rm had}(t)$ is the hadronic contribution to the running of α in the spacelike region: a_μ^{HLO} can be extracted from scattering data!

- **The extraction of $\Delta\alpha_{\rm had}$ is not contaminated by NP!** [Masiero, PP, Passera, 2020]

Outlook

- Fermilab's Muon g-2 experiment confirms BNL's result
- The BMWc lattice result weakens the exp-SM discrepancy, but brings in a tension with e^+e^- data

→ *"new muon g-2 puzzle"*



- Here, we considered the possibility this is due to NP (not in muons) that modifies σ_{had}

→ *excluded by a number of exp. constraints*

other ways in which NP can address this puzzle ? → [Darmé, Grilli di Cortona, Nardi 2112.09139 NP in Bhabha scattering ? → backup slides]

- Alternative confirmations of HVP contributions will be crucial (lattice, MUonE, ...)