Muon g-2 and the quest for new physics

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University of Padua

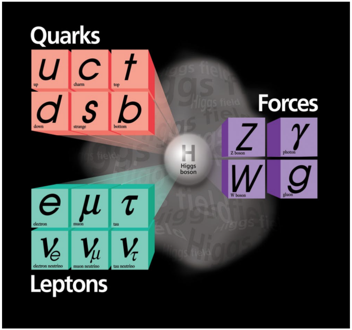
Muon g-2 or stress testing the SM
14/10/25, TVG

Plan of the talk

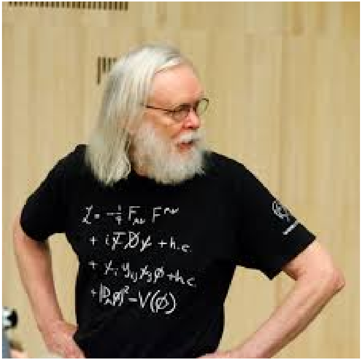
1. **The high-intensity frontier**
   - Experimental stutus/prospects
2. **The muon g-2 in the Standard Model**
3. **Direct new physics to the muon g-2**
   - Possible new physics scenarios
4. **On the“New muon g-2 puzzle”**
   - Possible new physics interpretations
   - Model independent tests of the “New muon g-2 puzzle”
5. **Conclusions and future prospects**

The Standard Model of Particle Physics

The Standard Model (SM) is a remarkably simple Quantum Field Theory (QFT) that describes well all microscopic phenomena that we observe in Nature



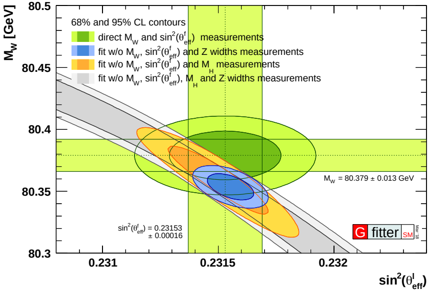
The SM describes fundamental interactions among elementary particles

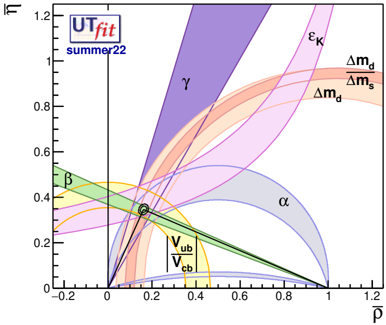


"This is short enough to write on a T-shirt!"

[John Ellis]

The SM legacy





The LEP legacy

- Z-pole observables @ the 0.1% level
- Important constraints on many BSM

The B-factories legacy

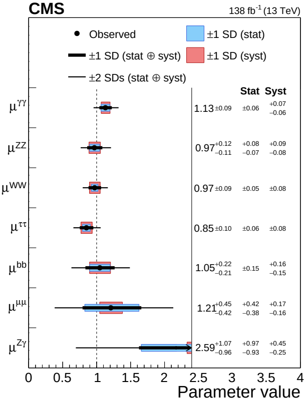
- Confirmation of the CKM mechanism
- Important constraints on many BSM

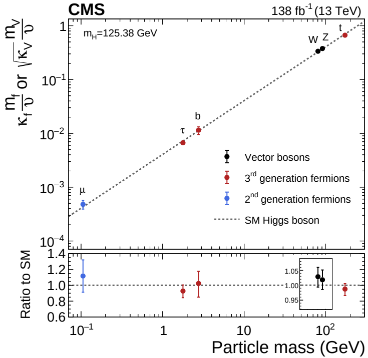
The LHC legacy (so far)

- **Higgs Boson mass** (combined LHC Run 1 + 2 results of ATLAS and CMS)

$$m_H = 124.94 \pm 0.17\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})\ \mathrm{GeV}$$

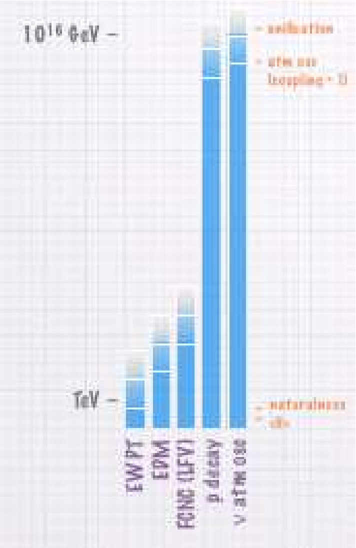
- **Higgs Boson couplings** $\mu_i^f = \dfrac{\sigma_i \times BR^f}{(\sigma_i \times BR^f)_{SM}}$ (signal strengths)





Why do we need New Physics?

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}$ GeV
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}$ GeV
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{NP} \lesssim$ TeV
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}$ GeV
- **Dark Matter (WIMP)** $\Longrightarrow$ $\Lambda_{NP} \lesssim$ TeV
- **Hierarchy problem**: $\Longrightarrow$ $\Lambda_{NP} \lesssim$ TeV



SM = effective theory at the EW scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}} \, O_{ij}^{(d)}$$

- $\mathcal{L}_{\text{eff}}^{d=5} = \frac{y_\nu^{ij}}{\Lambda_{\text{see-saw}}} L_i L_j \phi\phi$,
- $\mathcal{L}_{\text{eff}}^{d=6}$ generates FCNC operators

High-intensity frontier

Where to look for New Physics at low-energy?

- **Processes very suppressed or even forbidden in the SM**
- **Processes predicted with high precision in the SM**

....

$0\nu\beta\beta$

CPV in ν osc.

CPV and FCNC in quark sector

Precision EW tests at Z pole

Parity Violating electron scattering (Qweak, ...)

Atomic Parity Violation

....

muon g-2

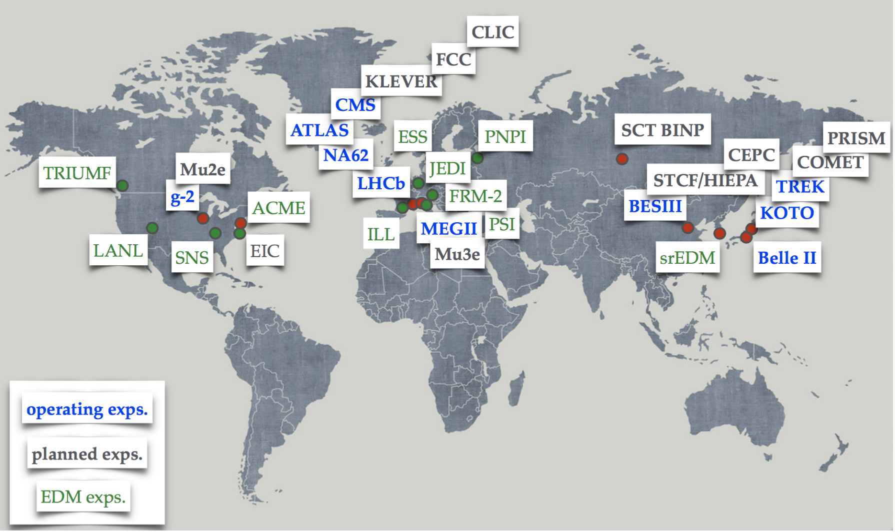
LFV in μ & τ decays

EDMs

β-decays (universality, non V-A, T violation, ...)

High-intensity frontier: A collective effort to determine the NP dynamics

High-intensity frontier / Experimental status



High-intensity frontier / Experimental bounds

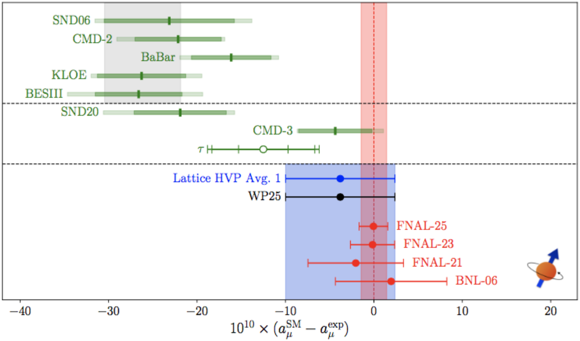
Process	Present	Experiment	Future	Experiment
$\mu \to e\gamma$	4.2×10^{-13}	MEG	$\approx 6 \times 10^{-14}$	MEG II
$\mu \to 3e$	1.0×10^{-12}	SINDRUM	$\approx 10^{-16}$	Mu3e
$\mu^-\ \text{Au} \to e^-\ \text{Au}$	7.0×10^{-13}	SINDRUM II	?	
$\mu^-\ \text{Ti} \to e^-\ \text{Ti}$	4.3×10^{-12}	SINDRUM II	?	
$\mu^-\ \text{Al} \to e^-\ \text{Al}$	$-$		$\approx 10^{-16}$	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.

- So far, only upper bounds. Still excellent prospects for exp. improvements.
- We can expect a NP signal in all above observables below the current bounds.

On the muon g-2

[*R. Aliberti et al.* – WP25, arXiv:2505.21476]
accepted on Physics Reports



- Lattice QCD a_μ^{HVP} $\longrightarrow$ no tension
- Data-driven disp. a_μ^{HVP} $\longrightarrow$ unsolved puzzle

[Evangelista, 8th Plenary Workshop of the Muon g â 2 Theory Initiative, 2025 Orsay]

Leptonic g-2: theory

- **1925: Goudsmit & Uhlenbeck propose for the electron:**

$$\boxed{\begin{aligned} \vec{\mu} &= g\frac{e}{2m}\vec{s} \\ g &= \underline{2 \quad \text{(not 1!)}} \end{aligned}}$$

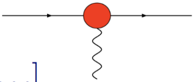
- **1928: Dirac's equation explains g=2!**
- **1948: Kusch & Foley measure g $\neq$ 2**

g/2 - 1 = a = 0.00119(5)

and Schwinger, using QED, predicts

g/2 - 1 = $\alpha/(2\pi)$ = 0.00116

- **Today we keep studying the lepton-photon vertex:**



$$\Gamma^\mu = ie[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \ldots]$$

$$\boxed{F_1(0) = 1 \qquad F_2(0) = a}$$

"$g-2$ 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]

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

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

[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]

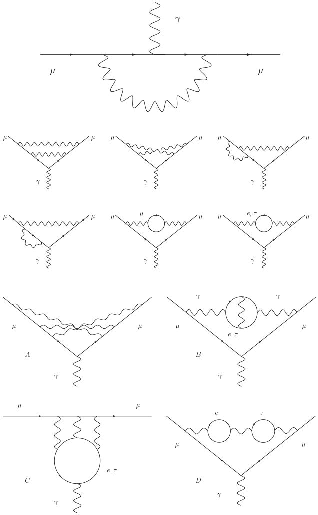
$$+\,750.86\,(88)\,(\alpha/\pi)^5 \quad \text{[Kinoshita et al. '90-'19]}$$

a_μ^{QED} = 116584718.931 (19)(100)(23) x 10^{-11}

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

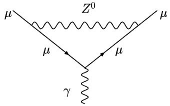
α = 1/137.035999046(27) [0.2ppb] Parker et al 2018 WP20 value

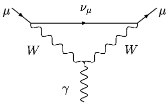
[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]

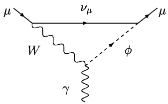


EW contribution

- **One-loop term:**







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

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

Studenikin et al. '80s

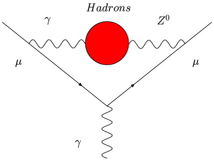
- **One-loop plus higher-order terms:**

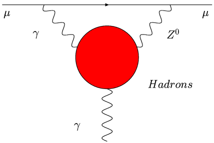
a_μ^{EW} = 153.6 (1.0) x 10^{-11}

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

WP20 value

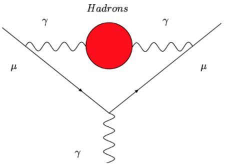
Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa,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





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

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



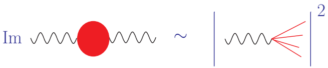
$$(a_\mu^{\mathrm{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\,\mathrm{Im}\,\Pi_{\mathrm{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\mathrm{had}}(s)$$

dispersion relations

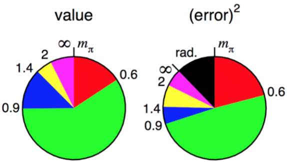
optical theorem

kernel function

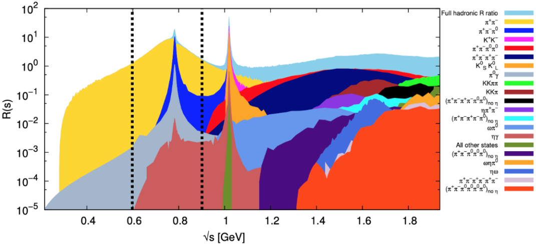
$K(s) \approx m_\mu^2/3s$ **for** $\sqrt{s} \gg m_\mu$



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



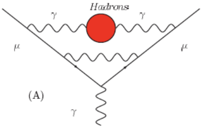
Keshavarzi, Nomura, Teubner 2018

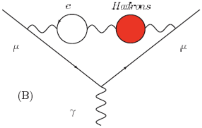


$$a_{\mu,e^+e^-}^{\mathrm{HLO}} = 6931(40) \times 10^{-11} (0.6\%)$$ [WP20]

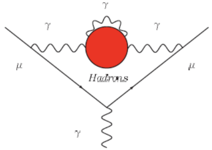
The hadronic (N)NLO VP contribution

- **$O(\alpha^3)$ contributions of diagrams containing HVP insertions:**





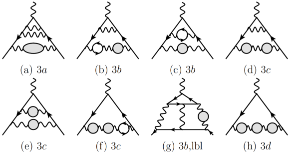
Already included in a_μ^{HLO}



$$a_\mu^{HNLO}(vp) = -98.3\ (7) \times 10^{-11}$$

Krause '96; Keshavarzi, Nomura, Teubner 2019; WP20.

- **$O(\alpha^4)$ contributions of diagrams containing HVP insertions:**



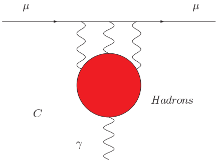
$$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$$

Kurz, Liu, Marquard, Steinhauser 2014

The hadronic (N)NLO LbL contribution

- **Hadronic light-by-light at $\mathcal{O}(\alpha^3)$**
  - Significant improvements thanks to data-driven dispersive approach
    [Colangelo, Hoferichter, Procura, Stoffer '14-'17; Pauk, Vanderhaeghen '14]
  - Lattice: RBC: $82(35) \times 10^{-11}$ [1911.08123] Mainz: $110(15) \times 10^{-11}$ [2104.02632]

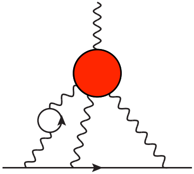
$a_\mu^{HNLO}(lbl) =$	$80\ (40) \times 10^{-11}$	Knecht & Nyffeler '02
$=$	$136\ (25) \times 10^{-11}$	Melnikov & Vainshtein '03
$=$	$105\ (26) \times 10^{-11}$	Prades, de Rafael, Vainshtein '09
$=$	$100\ (29) \times 10^{-11}$	Jegerlehner, arXiv:1705.00263
$=$	$92\ (19) \times 10^{-11}$	WP20 (phenomenology)



- **Hadronic light-by-light at $\mathcal{O}(\alpha^4)$**

$$a_\mu^{HNNLO}(lbl) = 2\ (1) \times 10^{-11}$$

[Colangelo, Hoferichter, Nyffeler, Passera, Stoffer '14]



Breakdown of SM contributions

- a_μ from WP20 (w/o BMWc lattice result)

[Colangelo EPS-HEP2021 proceeding]

Contribution	Value $\times 10^{11}$	References
Experiment (E821)	116 592 089(63)	Ref. [3]
Experiment (FNAL)	116 592 040(54)	Ref. [1]
Experiment (World-Average)	116 592 061(41)	
HVP LO (e^+e^-)	6931(40)	Refs. [6–11]
HVP NLO (e^+e^-)	−98.3(7)	Ref. [11]
HVP NNLO (e^+e^-)	12.4(1)	Ref. [12]
HVP LO (lattice, $udsc$)	7116(184)	Refs. [13–21]
HLbL (phenomenology)	92(19)	Refs. [22–34]
HLbL NLO (phenomenology)	2(1)	Ref. [35]
HLbL (lattice, uds)	79(35)	Ref. [36]
HLbL (phenomenology + lattice)	90(17)	
QED	116 584 718.931(104)	Refs. [37, 38]
Electroweak	153.6(1.0)	Refs. [39, 40]
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)	
HLbL (phenomenology + lattice + NLO)	92(18)	
Total SM Value	116 591 810(43)	
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	251(59)	

HVP LO is the bottle-neck of the SM prediction

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

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP}$$

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

- NP is at the weak scale ($\Lambda \approx v$) and weakly coupled to SM particles.*
- NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.
- NP is very light ($\Lambda \lesssim 1$ GeV) and feebly 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).

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

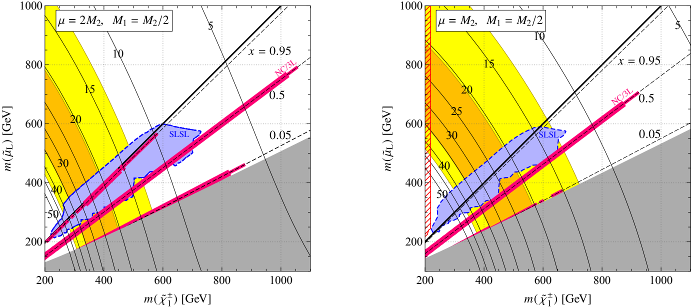


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].

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

Axion-like Particle effective Lagrangian

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

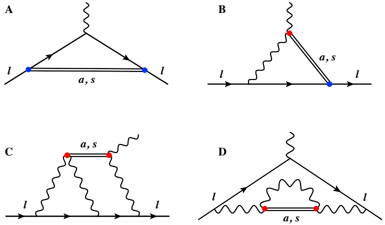


Figure: Contributions of a scalar 's' and a pseudoscalar 'a' ALP to the $(g-2)_\ell$.

[Marciano, Masiero, PP, Passera '16]

[Cornella, P.P., Sumensari '19]

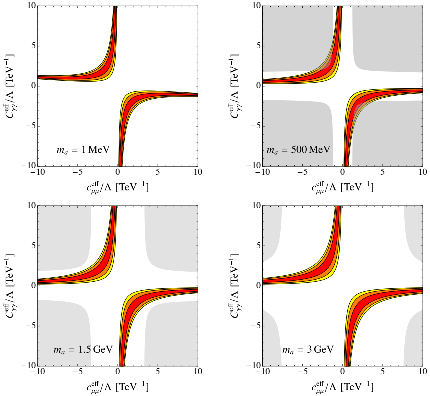


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left[\frac{12\alpha^3}{\pi} C_{\gamma\gamma}^2 \ln^2\frac{\Lambda^2}{m_\mu^2} - \frac{(c_{\mu\mu})^2}{16\pi^2} h_1\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi} c_{\mu\mu} C_{\gamma\gamma} \ln\frac{\Lambda^2}{m_\mu^2}\right]$$

- **SMEFT Lagrangian relevant for Δa_ℓ** [Buttazzo and P.P., '20]

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

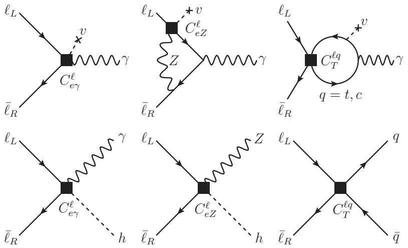


Figure: SMEFT Feynman diagrams for the g-2 (upper row) and scattering processes (lower row): $\boldsymbol{H = v + h/\sqrt{2}}$

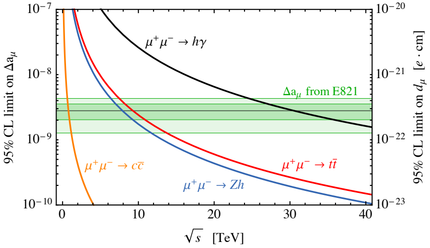
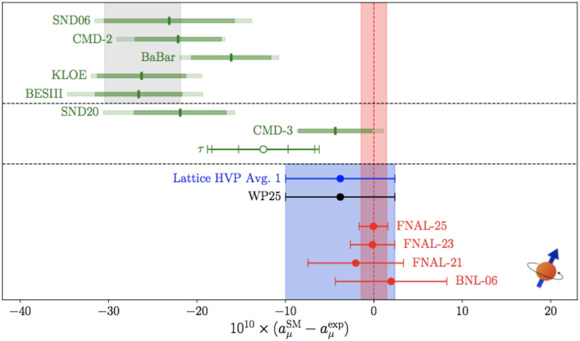


Figure: 95% C.L. reach on Δa_μ vs $\sqrt{s}$ from various processes assuming $\mathcal{L} = \left(\sqrt{s}/10\,\mathrm{TeV}\right)^2 \times 10\,\mathrm{ab}^{-1}$.

$$\Delta a_\mu \sim \frac{m_\mu v}{\Lambda^2} C_{eV,T} \qquad \Longleftrightarrow \qquad \sigma_{\mu\mu\to f} \sim \frac{s}{\Lambda^4} |C_{eV,T}|^2 \qquad (f = e\gamma, eZ, q\bar q)$$

- **At high energy $\sigma_{\mu\mu\to f}$ can compete with Δa_μ to test the very same NP!**

[*R. Aliberti et al.* – WP25, arXiv:2505.21476]
accepted on Physics Reports



- Lattice QCD $a_\mu^{\rm HVP}$ $\longrightarrow$ no tension
- Data-driven disp. $a_\mu^{\rm HVP}$ $\longrightarrow$ unsolved puzzle

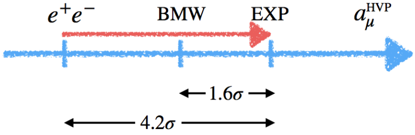
[Evangelista, 8th Plenary Workshop of the Muon g â 2 Theory Initiative, 2025 Orsay]

"New muon g-2 puzzle"

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

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

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



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

Muon g-2 $\rightleftarrows$ $\Delta\alpha$ connection

- 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 $\Delta\alpha^{(5)}_{\rm had}(M_Z)$*

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

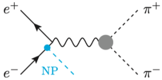
- disfavoured by the EW fit (at about 2σ), if the shift happens at $\sqrt{s} \gtrsim 1\,\mathrm{GeV}$

[Keshavarzi, Marciano, Passera, Sirlin 2020]

→ *selects light NP inducing a sub-GeV modification of $\sigma_{\rm had}$*

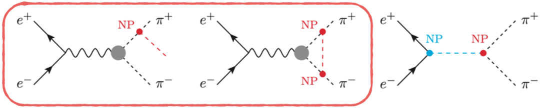
Light New Physics in $\sigma_{\rm had}$

- 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]



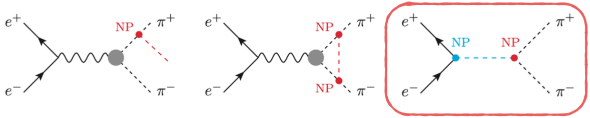
2. NP coupled only to hadrons

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*

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

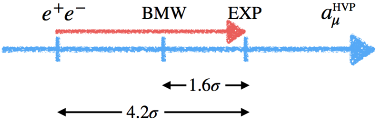
Light New Physics in σ_{had}



3. NP coupled both to hadrons and electrons

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

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



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

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)
  2. A sizeable negative interference with the SM

sub-GeV mediator

couples to u, d quarks (and electrons)

tree-level mediator

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)

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

Constraints on a new light Z' vector boson

1. Semi-leptonic processes

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

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

2. Leptonic processes

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

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

3. Iso-spin breaking observables

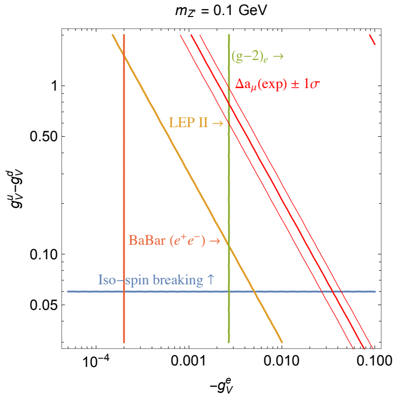
charged vs. neutral pion mass^2 difference $\Delta m^2 = m_{\pi^+}^2 - m_{\pi^0}^2$

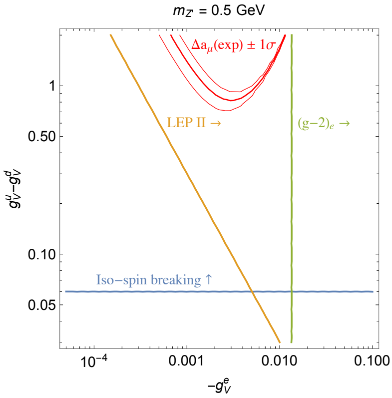
$$(\Delta m^2)_{Z'} \sim \frac{(g_V^u - g_V^d)^2}{(4\pi)^2}\Lambda_\chi^2 \qquad (\Lambda_\chi \approx 1\ \mathrm{GeV})$$

$\longrightarrow$ $|g_V^u - g_V^d| \lesssim 0.06$ [Rescaling lattice QCD calculation of Frezzotti et al 2112.01066]

$|g_V^u - g_V^d| \lesssim 0.05 \cdots 0.08, \qquad M_{Z'=(0\cdots 1)}$ GeV [Crivellin & Hoferichter, '22]

Constraints on a new light Z' vector boson





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

- The LEP bound (sum of the $q = u, d, s, c, b$ contributions) can be diluited if the Z' does not couple in a flavour-universal way. [Crivellin & Hoferichter, '22]

Model Independent Tests of the Hadronic Vacuum Polarization Contribution to the Muon $g-2$

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The hadronic vacuum polarization (HVP) contributions to the muon $g-2$ are the crucial quantity to resolve whether new physics is present or not in the comparison between the Standard Model (SM) prediction and experimental measurements at Fermilab. They are commonly and historically determined via dispersion relations using a vast catalogue of experimentally measured, low-energy $e^+e^- \to$ hadrons cross section data as input. These dispersive estimates result in a SM prediction that exhibits a muon $g-2$ discrepancy of more than 5σ when compared to experiment. However, recent lattice QCD evaluations of the HVP and a new hadronic cross section measurement from the CMD-3 experiment favor a no-new-physics scenario and, therefore, exhibit a common tension with the previous $e^+e^- \to$ hadrons data. This study explores the current and future implications of these two scenarios on other observables that are also sensitive to the HVP contributions in the hope that they may provide independent tests of the current tensions observed in the muon $g-2$.

[Di Luzio, Keshavarzi, Masiero, Paradisi, PRL '25]

On new HVP determinations

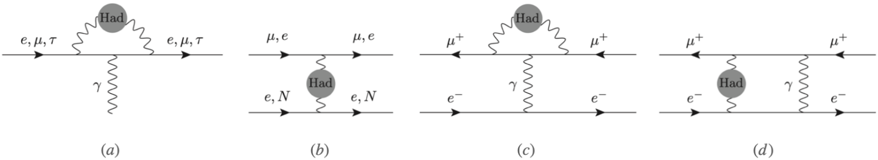
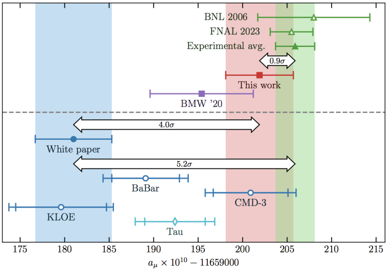


FIG. 1. Representative Feynman diagrams for observables that are sensitive to the leading HVP contribution: leptonic $g-2$ (diagram (a)), running of α and $\sin^2\theta_W$ (diagram (b)), and Muonium HFS (diagrams (c) and (d)).



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

$$K_\mu(s) = \int_0^1 dx\, \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2} \approx \frac{m_\mu^2}{3s}\,,$$

$$\delta a_\mu^{\mathrm{CMD3}} \equiv (a_\mu^{\mathrm{HVP}})_{e^+e^-}^{\mathrm{CMD3}} - (a_\mu^{\mathrm{HVP}})_{e^+e^-}^{\mathrm{KNT19}} = (21.7 \pm 3.6)\times 10^{-10}\,,$$

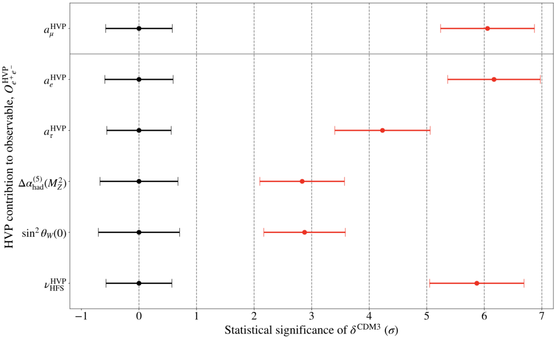
$$\delta a_e^{\mathrm{CMD3}} \approx \delta a_\mu^{\mathrm{CMD3}}\left(\frac{m_e}{m_\mu}\right)^2 \approx (5.1\pm 0.8)\times 10^{-14}\,.$$

[Di Luzio, Keshavarzi, Masiero, Paradisi, PRL '25]

On new HVP determinations

$O^{\rm HVP}_{e^+e^-}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, $\delta O^{\rm CMD3}$	Significance (σ)
$a_\mu^{\rm HVP} \times 10^{10}$	692.8 ± 2.4	714.5 ± 3.4	0.280	21.7 ± 3.6	6.1
$a_e^{\rm HVP} \times 10^{14}$	186.1 ± 0.7	192.0 ± 0.0	0.257	6.0 ± 1.0	6.2
$a_\tau^{\rm HVP} \times 10^{8}$	332.8 ± 1.4	340.2 ± 2.1	0.546	7.4 ± 1.8	4.2
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) \times 10^4$	276.1 ± 1.1	277.5 ± 1.2	0.908	1.4 ± 0.5	2.8
$\sin^2\theta_W(0) \times 10^4$	2386.0 ± 1.4	2386.4 ± 1.5	0.996	0.4 ± 0.1	2.9
$\nu^{\rm HVP}_{\rm HFS}$ (Hz)	540.5 ± 1.9	557.0 ± 2.7	0.297	16.5 ± 2.8	5.9

TABLE I. HVP contributions to the studied observables [first column] using scenario (1) KNT19 data [second column], or scenario (2) KNT19/CMD3 data [third column]. The fourth column gives the degree of correlation between scenario (1) and scenario (2) from the common KNT19 data (and other factors). The fifth column lists the difference or shift induced by the CMD-3 data as $\delta O^{\rm CMD3} \equiv (O^{\rm HVP}_{e^+e^-})^{\rm CMD3} - (O^{\rm HVP}_{e^+e^-})^{\rm KNT19}$, where the error accounts for the correlation ρ_{12}. The sixth column then quantifies the statistical significance of this shift in standard deviations.



Outlook

- The muon $g-2$ represents the most longstanding hint of New Physics now, thanks to the E989 experiment at FNAL, growing to 5.2σ.
- Lattice QCD results weaken the muon $g-2$ discrepancy to 0.9σ but they are in a strong 4.0σ tension with $e^+e^- \to$ *hadrons* experimental data.
- Light NP in $\sigma_{\rm had}$ seems to be unlikely to solve this "new g-2 puzzle".
- Eagerly await
  - New results from other Lattice QCD groups
  - Fermilab at 0.1 ppm measurement of a_μ 2025
  - J-PARC entirely new method for a_μ measurement
  - New BaBaR $e^+e^- \to$ hadrons analysis by early 2025
  - New KLOE, BES III, BELLE-II, CMD-3, SND-2 analysis
  - Independent determinations of HVP effects [Di Luzio, Keshavarzi, Masiero, Paradisi, '24]

Message: an exciting Physics program is in progress at the Intensity Frontier!