SM tests with e, μ, τ magnetic moments

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INFN Padova

Workshop on electromagnetic dipole moments
of unstable particles
Milano 3-4 Oct 2019

- e: **Testing new physics with the electron g-2**
- μ: **The muon g-2: recent theory progress**
- τ: **The tau g-2: opportunities or fantasies?**

g = 2

- **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.

g ≠ 2

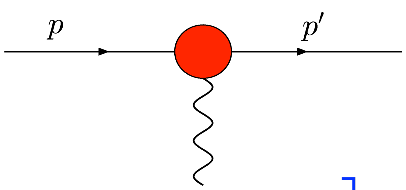
- **Kusch and Foley 1948:**

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

- **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!

Testing new physics with the electron g-2

The QED prediction of the electron g-2

$a_e^{QED} = + (1/2)(\alpha/\pi) - 0.328\,478\,444\,002\,55(33)\,(\alpha/\pi)^2$

Schwinger 1948 Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; CODATA Mar '12

$A_1^{(4)} = -0.328\,478\,965\,579\,193\,78\ldots$

$A_2^{(4)}\,(m_e/m_\mu) = 5.197\,386\,68\,(26) \times 10^{-7}$

$A_2^{(4)}\,(m_e/m_\tau) = 1.837\,98\,(33) \times 10^{-9}$

O(10^{-18}) in a_e

$+\ 1.181\,234\,016\,816\,(11)\,(\alpha/\pi)^3$

O(10^{-19}) in a_e

Kinoshita; Barbieri; Laporta, Remiddi; … , Li, Samuel; MP '06; Giudice, Paradisi, MP 2012

$A_1^{(6)} = 1.181\,241\,456\,587\ldots$

$A_2^{(6)}\,(m_e/m_\mu) = -7.373\,941\,62\,(27) \times 10^{-6}$

$A_2^{(6)}\,(m_e/m_\tau) = -6.5830\,(11) \times 10^{-8}$

$A_3^{(6)}\,(m_e/m_\mu, m_e/m_\tau) = 1.909\,82\,(34) \times 10^{-13}$

$-\ 1.9113213917\,(12)\,(\alpha/\pi)^4$

O(10^{-20}) in a_e

Kinoshita & Lindquist '81, … , Kinoshita & Nio '05; Aoyama, Hayakawa, Kinoshita & Nio 2015 & 2017; Kurz, Liu, Marquard & Steinhauser 2014. Laporta, arXiv:1704.06996 (mass independent term)

$+\ 6.73\,(16)\,(\alpha/\pi)^5$ **Complete Result! (12672 mass indep. diagrams!)**

Aoyama, Hayakawa, Kinoshita, Nio, 2012, 2019. Volkov 1909.08015: $A_1^{(10)}$[no lept loops] at variance.

1.1 10^{-14} in a_e NB: $(\alpha/\pi)^6 \sim O(10^{-16})$

The SM prediction of the electron g-2

- The SM prediction is:

$$a_e^{SM}(\alpha) = a_e^{QED}(\alpha) + a_e^{EW} + a_e^{HAD}$$

- The EW (1&2 loop) term is: Czarnecki, Krause, Marciano '96, Jegerlehner 2017

$$a_e^{EW} = 0.3053\,(23) \times 10^{-13}$$

- The Hadronic contribution, at LO+NLO+NNLO, is:

Nomura & Teubner '12, Jegerlehner 2017; Krause'97; Kurz, Liu, Marquard & Steinhauser 2014

$$a_e^{HAD} = 16.93\,(12) \times 10^{-13}$$

$$a_e^{HLO} = +\,18.490\,(108) \times 10^{-13}$$

$$a_e^{HNLO} = [-2.213(12)_{vac} + 0.37(5)_{lbl}] \times 10^{-13}$$

$$a_e^{HNNLO} = +\,0.28\,(1) \times 10^{-13}$$

- Which value of α should we use to compute a_e^{SM}?

$(g\text{-}2)_e$ no longer gives the best value of α

- The 2008 measurement of the electron g-2 is:

  $a_e^{EXP} = 11596521807.3\ (2.8) \times 10^{-13}$ Hanneke et al, PRL100 (2008) 120801

  vs. old (factor of 15 improvement, 1.8σ difference):

  $a_e^{EXP} = 11596521883\ (42) \times 10^{-13}$ Van Dyck et al, PRL59 (1987) 26

- Equate $a_e^{SM}(\alpha) = a_e^{EXP}$ → "g_e-2" determination of alpha:

$$\alpha^{-1} = 137.035\,999\,150\,(33) \quad [0.24 \text{ ppb}]$$

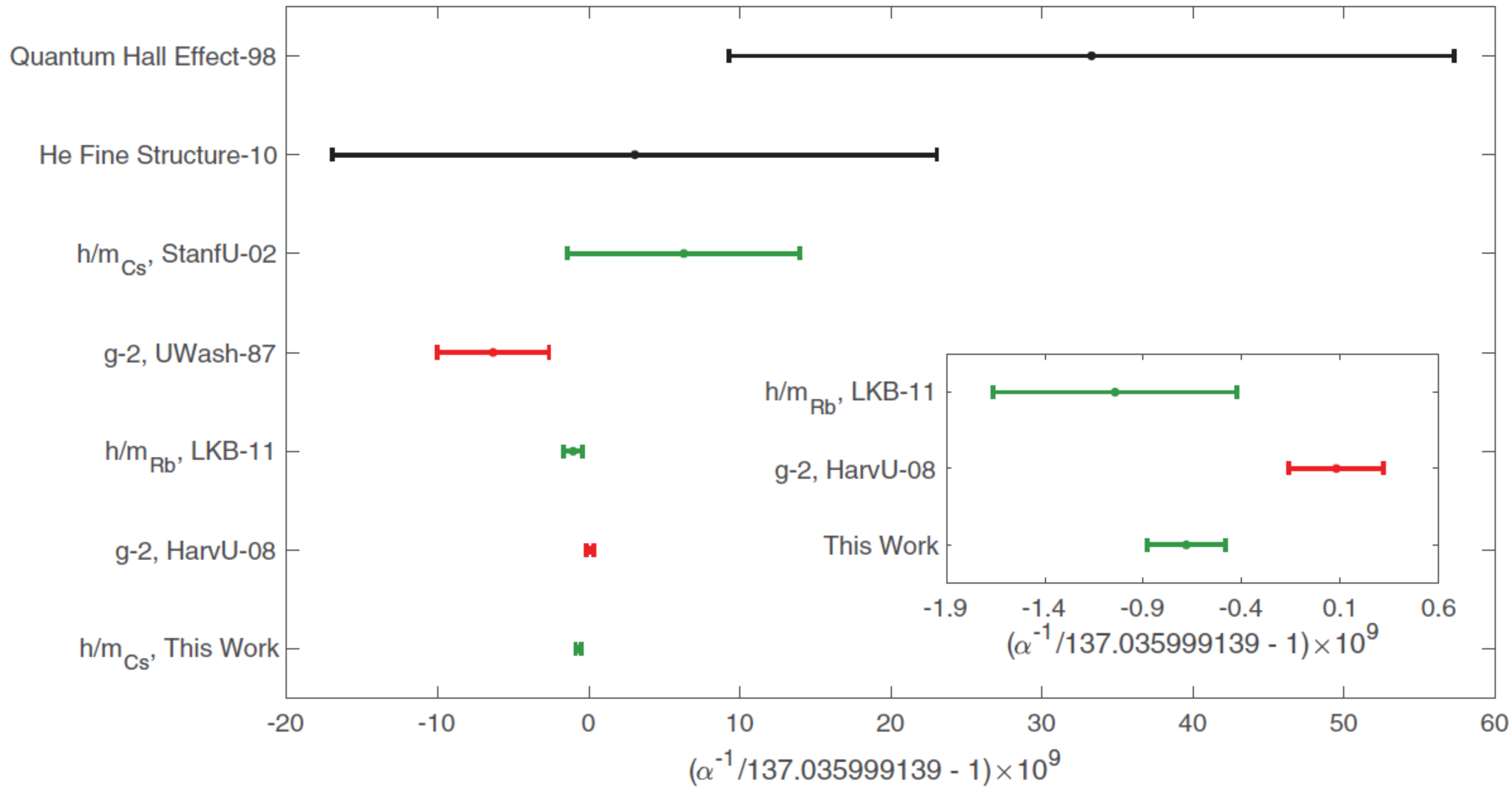
- Compare it with the present best determination of alpha:

$$\alpha^{-1} = 137.035\,999\,046\,(27) \quad [0.20 \text{ ppb}]$$ Science 360 (2018) 191 (Cs)

(was α^{-1} =137.035 998 995 (85) [0.62 ppb] PRL106 (2011) & CODATA 2016)

2.4 sigma discrepancy

Determinations of alpha



Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, Holger Müller
Science 360 (2018) 191

- Using α = 1/137.036 999 046 (27) [Cs 2018], the SM prediction for the electron g-2 is:

$$a_e^{SM} = 115\,965\,218\,16.1\,(0.1)\,(0.1)\,(2.3) \times 10^{-13}$$

δC_5^{qed} δa_e^{had} from $\delta\alpha$

- The (EXP - SM) difference is:

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

i.e. 2.4 sigma difference. Note the negative sign!
(the 5-loop contrib. to a_e^{QED} is 4.6×10^{-13})

- The present sensitivity is $\delta\Delta a_e = 3.6 \times 10^{-13}$, ie ($10^{-13}$ units):

$$\underbrace{(0.1)_{\rm QED5}, \quad (0.1)_{\rm HAD},}_{(0.2)_{\rm TH}} \quad (2.3)_{\delta\alpha}, \quad (2.8)_{\delta a_e^{\rm EXP}}$$

- The $(g\text{-}2)_e$ exp. error may soon drop below 10^{-13} and work is in progress to further reduce the error induced by $\delta\alpha$ →

sensitivity below 10^{-13} may be reached with ongoing exp work

- 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 & MP, JHEP 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.

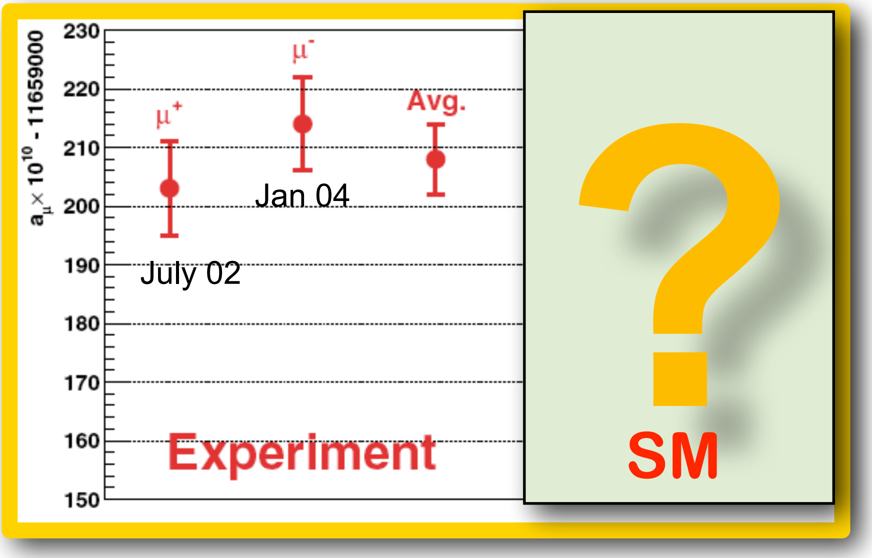
Giudice, Paradisi & MP, JHEP 2012
Crivellin, Hoferichter, Schmidt-Wellenburg, PRD 2018

- 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

The muon g-2: recent theory progress

The muon g-2: experimental status



- BNL 821: a_μ^{EXP} = (116592089 ± 54_{stat} ± 33_{sys})x10^{-11} [0.5ppm].
- New muon g-2 experiments at:
  - Fermilab E989: aims at ± 16x10^{-11}, ie 0.14ppm.
    First two data taking completed. Analysis in progress.
    First result expected very soon with ~ BNL E821 precision.
  - J-PARC proposal: phase-1 start with 0.46ppm (TDR 2017).
- Are theorists ready for this (amazing) precision? Not yet!

See Venanzoni's talk

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

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

Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; MP '04

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

Remiddi, Laporta, Barbieri … ; Czarnecki, Skrzypek; MP '04; Friot, Greynat & de Rafael '05, Mohr, Taylor & Newell 2012

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

Kinoshita & Lindquist '81, … , Kinoshita & Nio '04, '05; Aoyama, Hayakawa,Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015; Steinhauser et al. 2013, 2015 & 2016 (all electron & τ loops, analytic); Laporta, PLB 2017 (mass independent term). COMPLETED[2]!

$+ \; 750.86\,(88)\,(\alpha/\pi)^5$ **COMPLETED!**

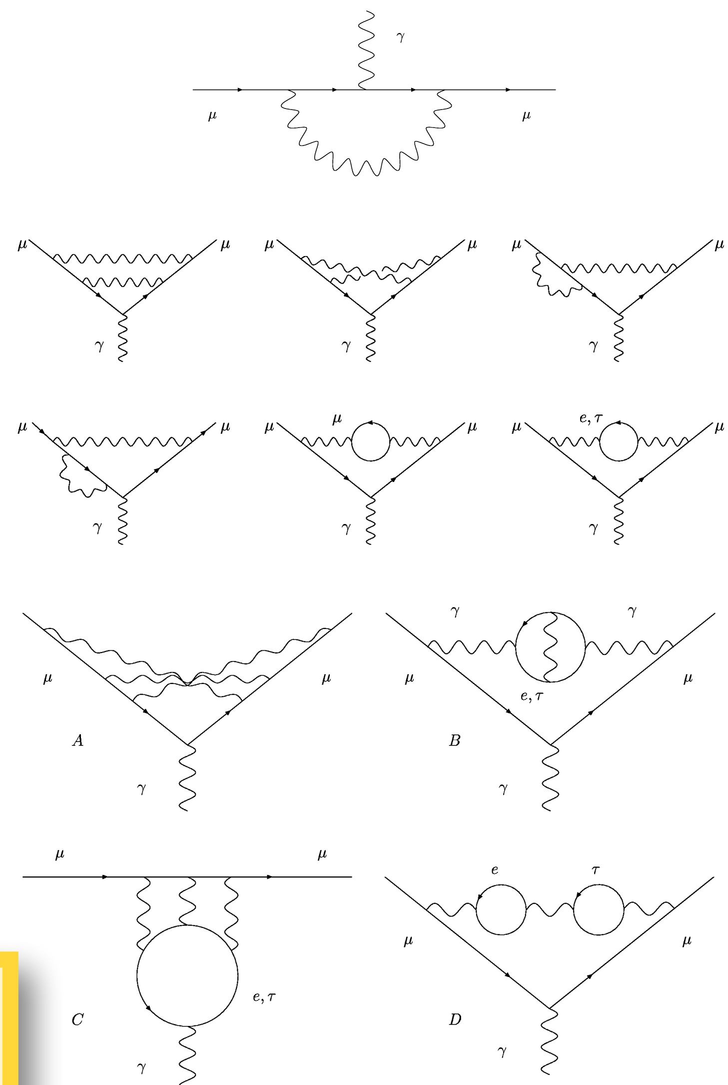
Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,… Aoyama, Hayakawa, Kinoshita, Nio 2012, 2015, 2017 & 2019.
Volkov 1909.08015: $A_1^{(10)}$[no lept loops] at variance, but negligible Δ.

Adding up, I get:

$a_\mu^{QED} = 116584718.933\,(20)(23) \times 10^{-11}$

from coeffs, mainly from 4-loop unc ↲ ↳ from α (Cs)

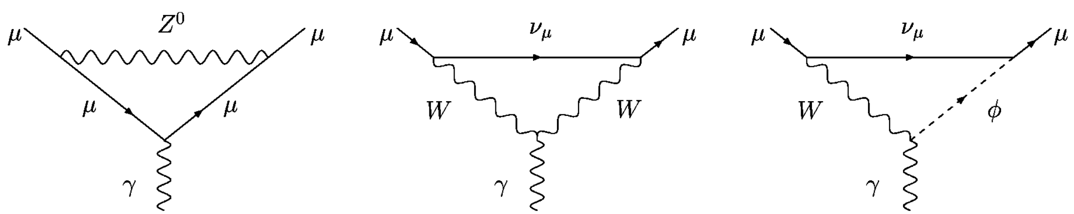
with $\alpha = 1/137.035999046(27)$ [0.2ppb] 2018



...

The muon g-2: the electroweak contribution

- **One-loop term:**



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

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

Studenikin et al. ’80s

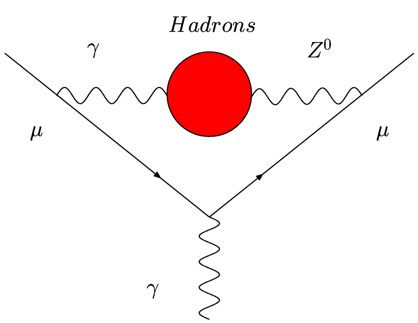
- **One-loop plus higher-order terms:**

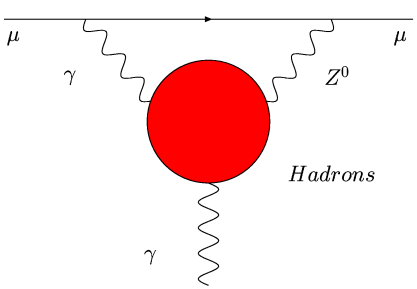
$a_\mu^{\rm EW} = 153.6\ (1.0) \times 10^{-11}$

with $M_{\rm Higgs}$ = 125.6 (1.5) GeV

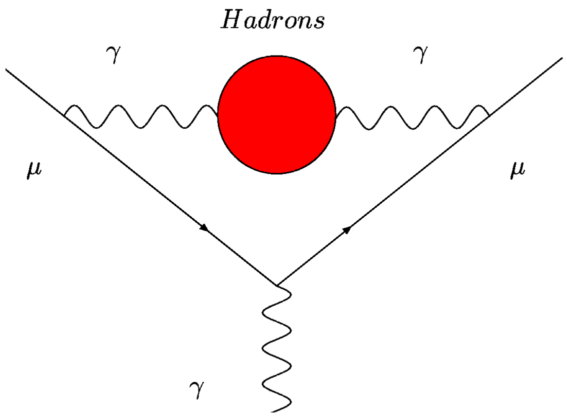
Hadronic loop uncertainties and 3-loop nonleading logs.

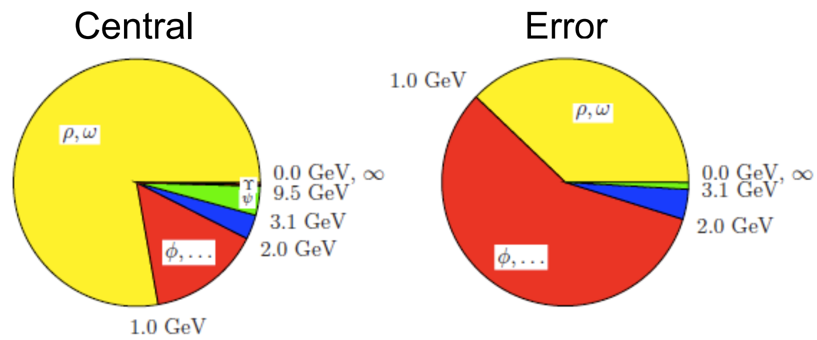
Kukhto et al. ’92; Czarnecki, Krause, Marciano ’95; Knecht, Peris, Perrottet, de Rafael ’02; Czarnecki, Marciano and Vainshtein ’02; Degrassi and Giudice ’98; Heinemeyer, Stockinger, Weiglein ’04; Gribouk and Czarnecki ’05; Vainshtein ’03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa, Yasui, 2019: 152.9(1.0)e-11.





The muon g-2: the Hadronic LO contribution (HLO)





F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \, \frac{x^2(1-x)}{x^2 + (1-x)(s/m^2)} \qquad a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds \, K(s)\, \sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s) R(s)$$

$a_\mu^{\rm HLO} = 6894.6\ (32.5) \times 10^{-11}$ F. Jegerlehner, arXiv:1711.06089

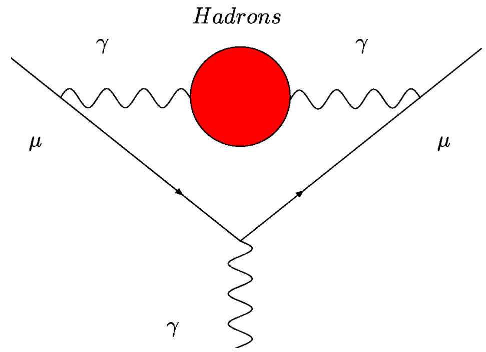
$= 6939\ (40) \times 10^{-11}$ Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921

$= 6932.6\ (24.6) \times 10^{-11}$ Keshavarzi, Nomura, Teubner, arXiv:1802.02995

- **Radiative Corrections are crucial.** S. Actis et al, Eur. Phys. J. C66 (2010) 585
- **Lots of progress in lattice calculations.** Muon g-2 Theory Initiative

Spacelike proposal for a_μ^{HLO}

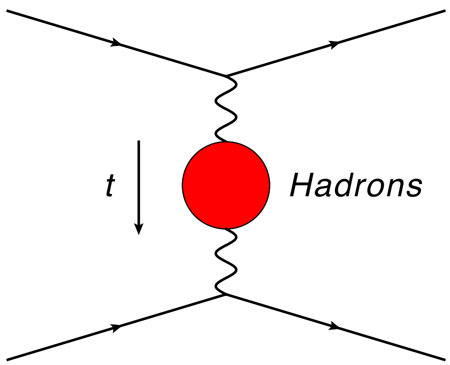
- **At present, the leading hadronic contribution a_μ^{HLO} is computed via the timelike formula:**



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

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

- **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!

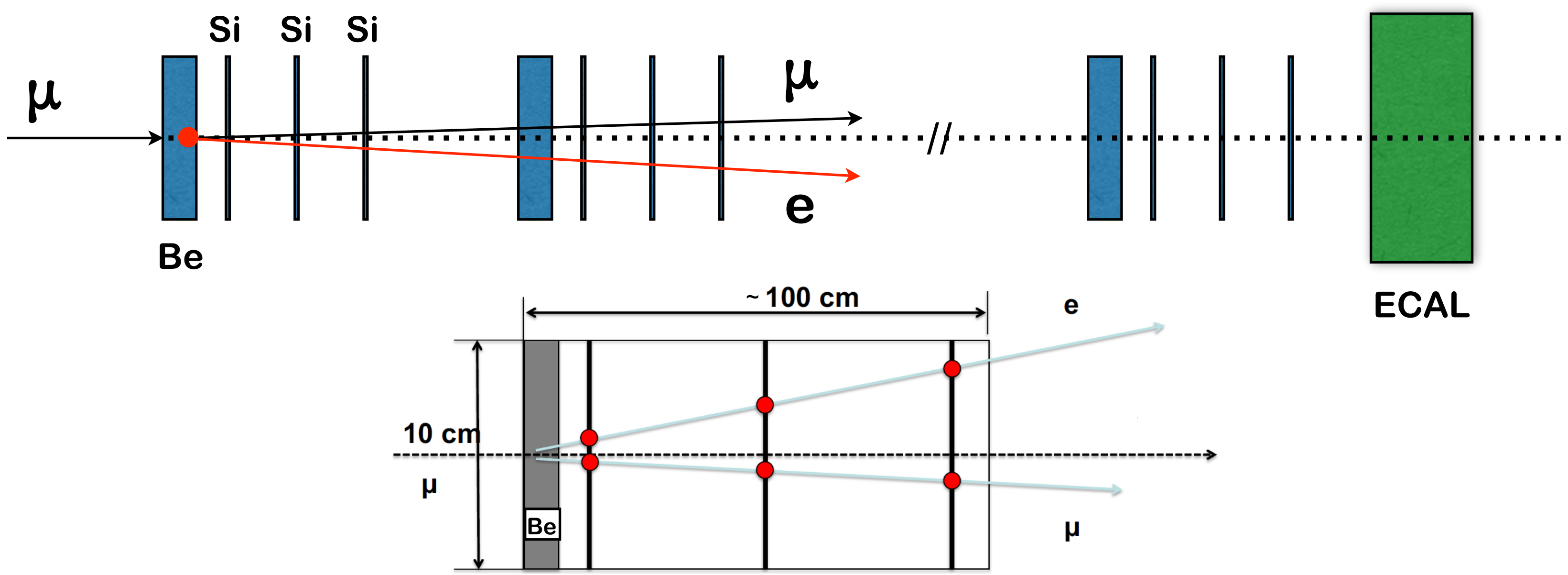
Carloni Calame, MP, Trentadue, Venanzoni, 2015

Muon-electron scattering: The MUonE Project

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

EPJC 2017 - arXiv:1609.08987

- $\Delta\alpha_{had}(t)$ can be measured via the elastic scattering μ e → μ 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.



- State-of-the-art Si detectors: ~20μm hit resolution/1m → ~0.02mrad expected angular resolution. ECAL and μ filter at the end for PID.

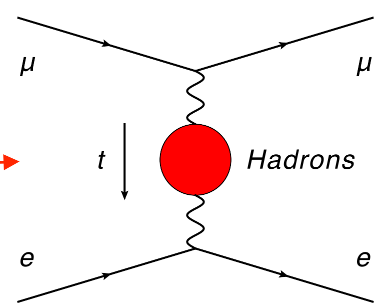
MUonE (2)

- **Statistics:** With CERN's 150 GeV muon beam M2 (1.3×10^7 μ/s), incident on 40 15mm Be targets (total thickness 60cm), 2 years of data taking (2×10^7 s/yr) → integrated luminosity $\mathcal{L}_{int} \sim 1.5 \times 10^7\ nb^{-1}$.

- With this $\mathcal{L}_{int}$ we estimate that measuring the shape of $d\sigma/dt$ we can reach a <u>statistical</u> sensitivity of ~0.3% on a_μ^{HLO}, ie $\sim 20 \times 10^{-11}$.

- **Systematics:** Systematic effects must be known at ≲ 10ppm!

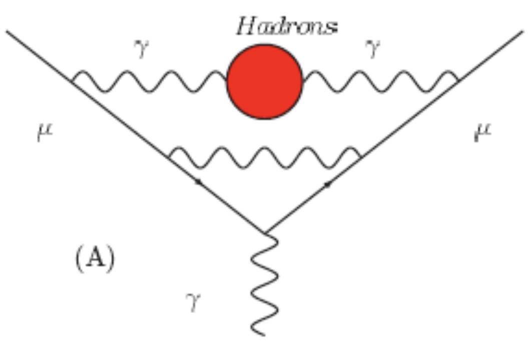
- **Theory:** To extract $\Delta\alpha_{had}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at ≲ 10ppm!

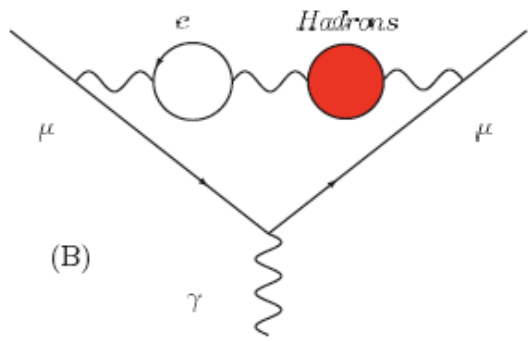


MUonE (3)

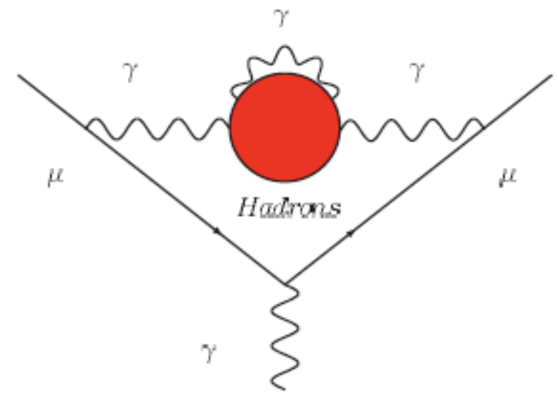
- MUonE: a proposal for a new experiment at CERN to measure the leading hadronic contribution to the muon g-2 via μe scattering.
- Very challenging experiment! Test beams @ CERN in 2017 & 2018
- Positive report from CERN's "Physics Beyond Colliders" WG.
- June 2019: Letter of Intent submitted to CERN's SPSC for Pilot Run in 2021. Under review.
- Lots of ongoing experimental & theoretical progress…

HNLO: Vacuum Polarization





Already included in a_μ^{HLO}

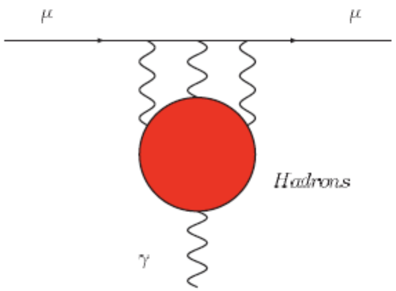


O(α^3) contributions of diagrams containing hadronic vacuum polarization insertions:

$$a_\mu^{HNLO}(vp) = -98.2\,(4) \times 10^{-11}$$

Krause ’96, Alemany et al. ’98, Hagiwara et al. 2011, Jegerlehner 2017, Keshavarzi, Nomura, and Teubner 2018

HNLO: Light-by-light contribution



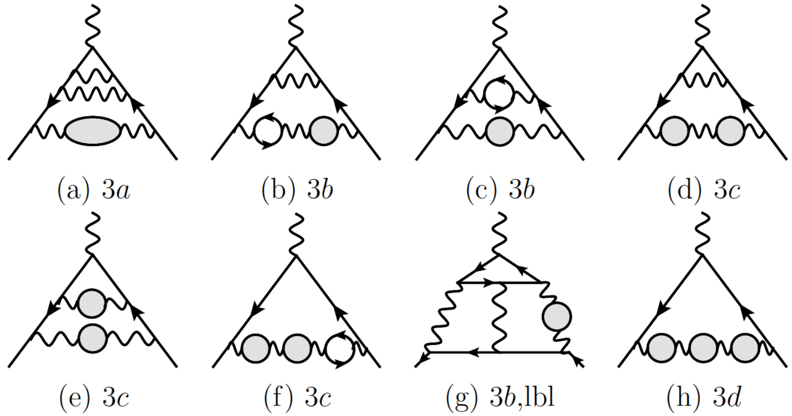
- This term had a troubled life! Nowadays:

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

Results based also on Hayakawa, Kinoshita '98 & '02; Bijnens, Pallante, Prades '96 & '02

- Improvements expected in the π^0 transition form factor A. Nyffeler 1602.03398
- The HLbL contribution can be expressed in terms of observables in a dispersive approach. Colangelo et al, 2014-15-17; Vanderhaeghen et al, 2014.
- Lots of progress on the lattice. See Muon g-2 Theory Initiative

HNNLO: Vacuum Polarization



$O(\alpha^4)$ contributions of diagrams containing hadronic vacuum polarization insertions:

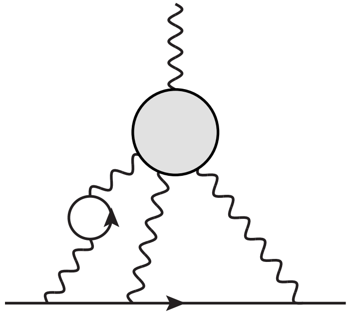
$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$

Kurz, Liu, Marquard, Steinhauser 2014

HNNLO: Light-by-light

$a_\mu^{HNNLO}(lbl) = 3\ (2) \times 10^{-11}$

Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014



Comparisons of the SM predictions with the measured g-2 value:

$a_\mu^{EXP} = 116592091\ (63) \times 10^{-11}$

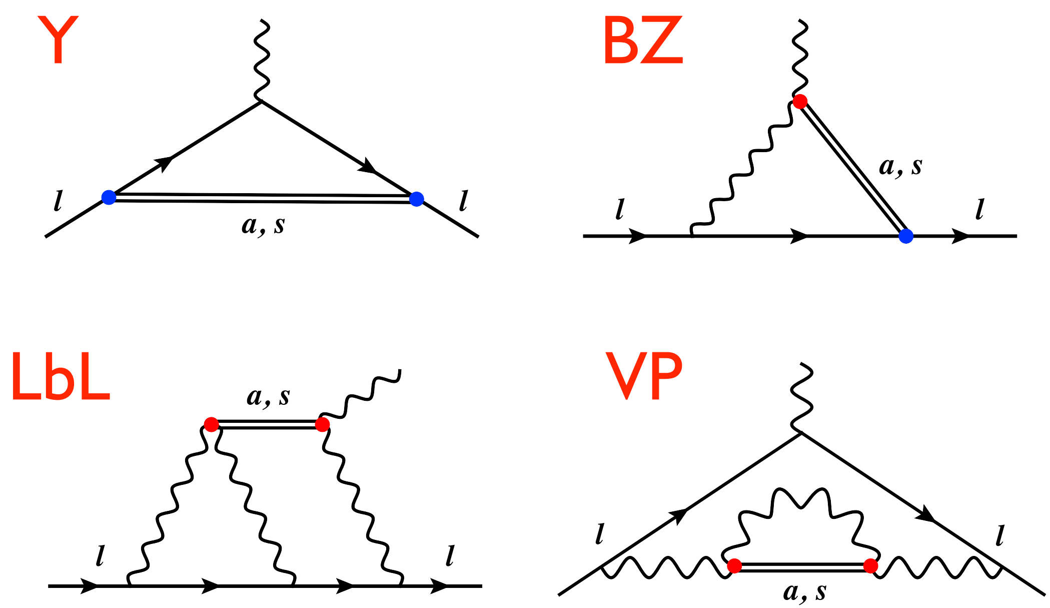
E821 – Final Report: PRD73 (2006) 072 with latest value of $\lambda=\mu_\mu/\mu_p$ from CODATA'10

$a_\mu^{SM} \times 10^{11}$	$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM}$	σ
116 591 784 (44)	$307\ (77) \times 10^{-11}$	4.0 [1]
116 591 829 (49)	$262\ (80) \times 10^{-11}$	3.3 [2]
116 591 822 (38)	$269\ (74) \times 10^{-11}$	3.6 [3]

with the hadronic light-by-light $a_\mu^{HNLO}(lbl) = 100\ (29) \times 10^{-11}$ of F. Jegerlehner arXiv:1705.00263, and the hadronic leading-order of:

[1] F. Jegerlehner, arXiv:1711.06089.
[2] Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921.
[3] Keshavarzi, Nomura, Teubner, arXiv:1802.02995.

ALPs contributions to the muon g-2?



- **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.**

Marciano, Masiero, Paradisi, MP, arXiv:1607.01022

The tau g-2: opportunities or fantasies?

- The Standard Model prediction of the tau g-2 is:

a_τ^{SM}	=	117324	(2)	x 10^{-8}	QED
	+	47.4	(0.5)	x 10^{-8}	EW
	+	337.5	(3.7)	x 10^{-8}	HLO
	+	7.6	(0.2)	x 10^{-8}	HHO (vac)
	+	5	(3)	x 10^{-8}	HHO (lbl)

$$a_\tau^{SM} = 117721\ (5) \times 10^{-8}$$

Eidelman & MP 2007

- $(m_\tau/m_\mu)^2 \sim 280$: great opportunity to look for New Physics, and a "clean" NP test too…

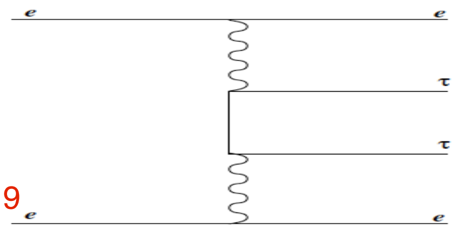
	Muon	Tau
a_{EW} / a_H	1/45	1/7
$a_{EW} / \delta a_H$	3	10

… if only we could measure it!!

The tau g-2: experimental bounds

- **The very short mean life of the tau (2.9×10^{-13} s) makes it very difficult to determine a_τ measuring its spin precession in a magnetic field.**

- **DELPHI's result, from $e^+e^- \to e^+e^-\tau^+\tau^-$ total cross-section measurements at LEP 2 (the PDG value):**



$$a_\tau = -0.018\ (17)$$

PDG 2019

- **With an effective Lagrangian approach, using data on tau lepton production at LEP1, SLC, and LEP2:**

$$-0.007 < a_\tau^{NP} < 0.005 \quad (95\%\ CL)$$

Gonzáles-Sprinberg et al 2000

- **Bernabéu et al, proposed the measurement of $F_2(q^2{=}M_\Upsilon^2)$ from $e^+e^- \to \tau^+\tau^-$ production at B factories.** NPB 790 (2008) 160

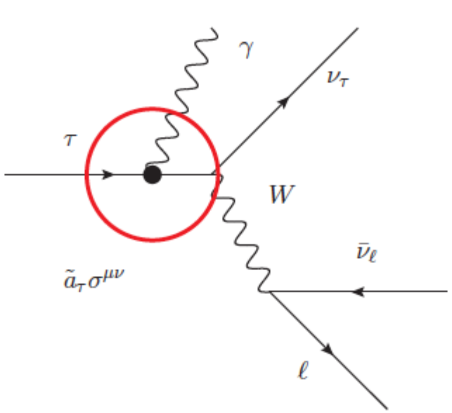
- **Direct probe of tau dipole moments with bent crystals:**

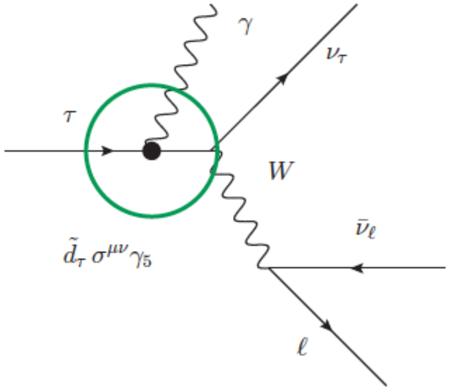
See Fomin's & Ruiz Vidal's talks

Another proposal: the τ g-2 via τ radiative leptonic decays

- a_τ via the radiative leptonic decays $\tau \to e\bar{\nu}\nu\gamma,\ \tau \to \mu\bar{\nu}\nu\gamma$ comparing the theoretical prediction for the differential decay rates with precise data from high-luminosity B factories:

$$d\Gamma = d\Gamma_0 + \left(\frac{m_\tau}{M_W}\right)^2 d\Gamma_W + \frac{\alpha}{\pi} d\Gamma_{\rm NLO} + \tilde{a}_\tau\, d\Gamma_{\rm a} + \tilde{d}_\tau\, d\Gamma_{\rm d}$$





- Detailed feasibility study performed in Belle-II conditions: we expect a (modest) improvement of the present PDG bound.

Eidelman, Epifanov, Fael, Mercolli, MP, arXiv:1601.07987 (JHEP 2016)

Radiative leptonic tau decays: branching ratios

τ

B.R. of radiative τ leptonic decays ($\omega_0 = 10$ MeV)	$\tau \to e\bar{\nu}\nu\gamma$	$\tau \to \mu\bar{\nu}\nu\gamma$
$\mathcal{B}_{\text{LO}}$	1.834×10^{-2}	3.663×10^{-3}
$\mathcal{B}^{\text{Inc}}_{\text{NLO}}$	$-1.06\,(1)_n(10)_N \times 10^{-3}$	$-5.8\,(1)_n(2)_N \times 10^{-5}$
$\mathcal{B}^{\text{Exc}}_{\text{NLO}}$	$-1.89\,(1)_n(19)_N \times 10^{-3}$	$-9.1\,(1)_n(3)_N \times 10^{-5}$
$\mathcal{B}^{\text{Inc}}$	$1.728\,(10)_{\text{th}}(3)_\tau \times 10^{-2}$	$3.605\,(2)_{\text{th}}(6)_\tau \times 10^{-3}$
$\mathcal{B}^{\text{Exc}}$	$1.645\,(19)_{\text{th}}(3)_\tau \times 10^{-2}$	$3.572\,(3)_{\text{th}}(6)_\tau \times 10^{-3}$
$\mathcal{B}^{\dagger}_{\text{EXP}}$	$1.847\,(15)_{\text{st}}(52)_{\text{sy}} \times 10^{-2}$	$3.69\,(3)_{\text{st}}(10)_{\text{sy}} \times 10^{-3}$

$\mathcal{O}$(10%) RC ☛

(n): numerical errors

(N): uncomputed NNLO corr.

$\sim (\alpha/\pi) \ln r \ln(\omega_0/M) \times \mathcal{B}^{\text{Exc/Inc}}_{\text{NLO}}$

†BABAR - PRD 91 (2015) 051103

(th): combined $(n) \oplus (N)$

(τ): experimental error of τ lifetime: $\tau_\tau = 2.903(5) \times 10^{-13}$ s

[Agreement with MEG's μ→eννγ 2016]

	$\tau \to e\bar{\nu}\nu\gamma$	$\tau \to \mu\bar{\nu}\nu\gamma$
Δ^{Exc}	$2.02\,(57) \times 10^{-3} \to 3.5\sigma$	$1.2\,(1.0) \times 10^{-4} \to 1.1\sigma$

Fael, Mercolli, MP, 1506.03416 (JHEP 2015)

Conclusions

- **Electron g-2:** Δa_e @ "$-$" 2.4 σ. NP sensitivity limited only by exp uncertainties in α & a_e. The Δa_e sensitivity will soon drop below 10^{-13} $\rightarrow$ a_e will play a pivotal role in probing NP in lepton sector.

- **Muon g-2:** Δa_μ ~ 3.5 - 4 σ. New upcoming measurement. QED & EW ready. Lots of progress in the hadronic sector, but not yet ready. MUonE: recent proposal to measure the leading hadronic contribution to the muon g-2 via μe scattering at CERN.

- **Tau g-2:** unknown.