SM tests with $e$, $\mu$, $\tau$ magnetic moments

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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?
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…

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

…but there was no need for it! $g=2$ stood for ~20 yrs.
Kusch and Foley 1948:

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

Schwinger 1948 (triumph of QED!):

\[
\left( \frac{g_e}{2} \right)^{\text{th}} \equiv 1 + a_e^{\text{th}} = 1.00116 \ldots
\]

We keep studying the lepton–γ vertex:

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

\[
F_1(0) = 1 \quad F_2(0) = a_l
\]
Testing new physics with the electron g-2
The QED prediction of the electron g-2

\[ a_e^{\text{QED}} = + \left( \frac{1}{2} \right) \left( \frac{\alpha}{\pi} \right) - 0.328 \, 478 \, 444 \, 002 \, 55(33) \left( \frac{\alpha}{\pi} \right)^2 \]

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

\[ A_1^{(4)} = -0.328 \, 478 \, 965 \, 579 \, 193 \, 78 \ldots \]
\[ A_2^{(4)} (m_e/m_\mu) = 5.197 \, 386 \, 68 (26) \times 10^{-7} \]
\[ A_2^{(4)} (m_e/m_\tau) = 1.837 \, 98 (33) \times 10^{-9} \]

+ 1.181 234 016 816 (11) \left( \frac{\alpha}{\pi} \right)^3

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) \left( \frac{\alpha}{\pi} \right)^4

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) \left( \frac{\alpha}{\pi} \right)^5

Complete Result! (12672 mass indep. diagrams!)

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

\[ 1.1 \times 10^{-14} \text{ in } a_e \]

NB: \( (\alpha/\pi)^6 \sim O(10^{-16}) \)

Volkov 1909.08015: \( A_1^{(10)}[\text{no lept loops}] \) at variance.
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 $\alpha$ should we use to compute $a_e^{SM}$?
The 2008 measurement of the electron g-2 is:
\[ a_e^{\text{EXP}} = 11596521807.3 \times 10^{-13} \]  
Hanneke et al, PRL100 (2008) 120801

vs. old (factor of 15 improvement, 1.8\(\sigma\) difference):
\[ a_e^{\text{EXP}} = 11596521883 \times 10^{-13} \]  
Van Dyck et al, PRL59 (1987) 26

Equate \( a_e^{\text{SM}}(\alpha) = a_e^{\text{EXP}} \) → “\( g_e \)-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 \( \alpha^{-1} = 137.035\,998\,995 \) [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 \( \alpha = 1/137.036\,999\,046\) (27) [Cs 2018], the SM prediction for the electron g-2 is:

\[
a_{e}^{\text{SM}} = 115,965,218,16.1 \times 10^{-13}
\]

The (EXP - SM) difference is:

\[
\Delta a_{e} = a_{e}^{\text{EXP}} - a_{e}^{\text{SM}} = -8.8 (3.6) \times 10^{-13}
\]

i.e. 2.4 sigma difference. Note the negative sign!

(the 5-loop contrib. to \(a_{e}^{\text{QED}}\) is \(4.6 \times 10^{-13}\))
The present sensitivity is $\delta \Delta a_e = 3.6 \times 10^{-13}$, ie $(10^{-13}$ units): 

$$
(0.1)_{\text{QED}5}, \quad (0.1)_{\text{HAD}}, \quad (2.3)\delta \alpha, \quad (2.8)\delta a_e^{\text{EXP}}
$$

$$
(0.2)_{\text{TH}}
$$

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

In a broad class of BSM theories, contributions to $a_\ell$ 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:

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

Giudice, Paradisi & MP, JHEP 2012
Testing new physics with the electron g-2 (2)

- The sensitivity in $\Delta a_e$ 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 $\Delta a_e$ 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 $\sim 250-1000$ MeV could explain the deviations in $a_\mu$ 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: \( a_\mu^{\text{EXP}} = (116592089 \pm 54_{\text{stat}} \pm 33_{\text{sys}}) \times 10^{-11} [0.5\text{ppm}] \).

- New muon g-2 experiments at:
  - Fermilab E989: aims at \( \pm 16 \times 10^{-11} \), ie 0.14ppm.  
    First two data taking completed. Analysis in progress.  
    First result expected very soon with \( \sim \) 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
The muon g-2: the QED contribution

$$a_\mu^\text{QED} = \frac{1}{2} \left( \frac{\alpha}{\pi} \right)$$  Schwinger 1948

$$+ 0.765857426 \ (16) \left( \frac{\alpha}{\pi} \right)^2$$

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

$$+ 24.05050988 \ (28) \left( \frac{\alpha}{\pi} \right)^3$$

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

$$+ 130.8780 \ (60) \left( \frac{\alpha}{\pi} \right)^4$$

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). COMPLETED²!

$$+ 750.86 \ (88) \left( \frac{\alpha}{\pi} \right)^5$$  COMPLETED!

Kinoshita et al. ‘90, Yelkhovsky, Milstein, Starshenko, Laporta,… Aoyama, Hayakawa, Kinoshita, Nio 2012, 2015, 2017 & 2019. Volkov 1909.08015: A₁[^10][no lept loops] at variance, but negligible Δ.

Adding up, I get:

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

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

with $$\alpha = 1/137.035999046(27) [0.2\text{ppb}]$$  2018
The muon g-2: the electroweak contribution

- **One-loop term:**

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

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

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

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

with \( M_{\text{Higgs}} = 125.6 \ (1.5) \) 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)

\[ K(s) = \int_0^1 dx \frac{x^2 (1 - x)}{x^2 + (1 - x)(s/m^2)} \]

\[ a_{\mu}^{\text{HLO}} = 6894.6 (32.5) \times 10^{-11} \]

\[ = 6939 (40) \times 10^{-11} \]

\[ = 6932.6 (24.6) \times 10^{-11} \]

**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

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

F. Jegerlehner, arXiv:1711.06089

Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921

Keshavarzi, Nomura, Teubner, arXiv:1802.02995
Spacelike proposal for $a_\mu^{HLO}$

- At present, the leading hadronic contribution $a_\mu^{HLO}$ is computed via the timelike formula:

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

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

- Alternatively, exchanging the x and s integrations in $a_\mu^{HLO}$

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

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

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

Lastrup, Peterman, de Rafael, 1972

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

• 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.

• State-of-the-art Si detectors: $\sim 20\mu$m hit resolution/1m $\rightarrow \sim 0.02\text{mrad}$ expected angular resolution. ECAL and $\mu$ filter at the end for PID.
• **Statistics:** With CERN’s 150 GeV muon beam M2 \((1.3 \times 10^7 \, \mu/s)\), incident on 40 15mm Be targets (total thickness 60cm), 2 years of data taking \((2 \times 10^7 \, \text{s/yr})\) \(\rightarrow\) integrated luminosity \(\mathcal{L}_{\text{int}} \sim 1.5 \times 10^7 \, \text{nb}^{-1}\).

• With this \(\mathcal{L}_{\text{int}}\) we estimate that measuring the shape of \(d\sigma/dt\) we can reach a **statistical** sensitivity of \(\sim 0.3\%\) on \(a_\mu^{\text{HLO}}\), ie \(\sim 20 \times 10^{-11}\).

• **Systematics:** Systematic effects must be known at \(\lesssim 10\text{ppm}\)!

• **Theory:** To extract \(\Delta \alpha_{\text{had}}(t)\) from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at \(\lesssim 10\text{ppm}\)!
MUonE: a proposal for a new experiment at CERN to measure the leading hadronic contribution to the muon g-2 via $\mu e$ 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…
O($\alpha^3$) contributions of diagrams containing hadronic vacuum polarization insertions:

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

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:

\[ a_μ^{HNLO}(lbl) = +80 (40) \times 10^{-11} \quad \text{Knecht & Nyffeler '02} \]
\[ a_μ^{HNLO}(lbl) = +136 (25) \times 10^{-11} \quad \text{Melnikov & Vainshtein '03} \]
\[ a_μ^{HNLO}(lbl) = +105 (26) \times 10^{-11} \quad \text{Prades, de Rafael, Vainshtein '09} \]
\[ a_μ^{HNLO}(lbl) = +100 (29) \times 10^{-11} \quad \text{Jegerlehner, arXiv:1705.00263} \]

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
The muon g-2: the Hadronic NNLO contributions (HNNLO)

- **HNNLO: Vacuum Polarization**

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

  Kurz, Liu, Marquard, Steinhauser 2014

- **HNNLO: Light-by-light**

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

  Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014
Comparisons of the SM predictions with the measured g-2 value:

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

| \( a_\mu^{\text{SM}} \times 10^{11} \) | \( \Delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} \) | \( \sigma \) |
|--------------------------------|------------------------------------------------|--------|
| 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 \( a_\mu^{\text{HNLO(Hbl)}} = 100 (29) \times 10^{-11} \) 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.
Both scalar and pseudoscalar ALPs can solve $\Delta a_\mu$ for masses $\sim [100\text{MeV}-1\text{GeV}]$ and couplings allowed by current experimental constraints.

They can be tested at present low-energy $e^+e^-$ experiments, via dedicated $e^+e^- \rightarrow e^+e^-+\text{ALP}$ & $e^+e^- \rightarrow \gamma+\text{ALP}$ searches.

Marciano, Masiero, Paradisi, MP, arXiv:1607.01022
The tau g-2: opportunities or fantasies?
The SM prediction of the tau g-2

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

\[ a_{\tau}^{SM} = 117324 \ (2) \times 10^{-8} \text{ QED} \]
\[ + \quad 47.4 \ (0.5) \times 10^{-8} \text{ EW} \]
\[ + \quad 337.5 \ (3.7) \times 10^{-8} \text{ HLO} \]
\[ + \quad 7.6 \ (0.2) \times 10^{-8} \text{ HHO (vac)} \]
\[ + \quad 5 \ (3) \times 10^{-8} \text{ HHO (lbl)} \]

Eidelman & MP 2007

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

\((m_\tau/m_\mu)^2 \sim 280\): 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 \times 10^{-13} \text{s}) makes it very difficult to determine \(a_\tau\) measuring its spin precession in a magnetic field.

- DELPHI’s result, from \(e^+e^- \rightarrow e^+e^-\tau^+\tau^-\) total cross-section measurements at LEP 2 (the PDG value):
  \[a_\tau = -0.018 (17)\]

- With an effective Lagrangian approach, using data on tau lepton production at LEP1, SLC, and LEP2:
  \[-0.007 < a_\tau^{\text{NP}} < 0.005 \ (95\% \ CL)\]
  \[\text{Gonzáles-Sprinberg et al 2000}\]

- Bernabéu et al, proposed the measurement of \(F_2(q^2=M_\gamma^2)\) from \(e^+e^- \rightarrow \tau^+\tau^-\) production at B factories.
  \[\text{NPB 790 (2008) 160}\]

- Direct probe of tau dipole moments with bent crystals:
  See Fomin’s & Ruiz Vidal’s talks
Another proposal: the $\tau$ g-2 via $\tau$ radiative leptonic decays $\tau \rightarrow e\bar{\nu}\nu\gamma$, $\tau \rightarrow \mu\bar{\nu}\nu\gamma$ comparing the theoretical prediction for the differential decay rates with precise data from high-luminosity B factories:

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

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

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

$n$: numerical errors

$(N)$: uncomputed NNLO corr.

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

$\dagger$: BABAR - PRD 91 (2015) 051103

$(\text{th})$: combined $(n) \oplus (N)$

$(\tau)$: experimental error of $\tau$

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

[Agreement with MEG’s $\mu \to e\nu\nu\gamma$ 2016]

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

Fael, Mercolli, MP, 1506.03416 (JHEP 2015)
**Electron g-2:** $\Delta a_e @ \sim 2.4 \sigma$. NP sensitivity limited only by exp uncertainties in $\alpha$ & $a_e$. The $\Delta a_e$ sensitivity will soon drop below $10^{-13} \rightarrow a_e$ will play a pivotal role in probing NP in lepton sector.

**Muon g-2:** $\Delta a_\mu \sim 3.5 - 4 \sigma$. New upcoming measurement. QED & EW ready. Lots of progress in the hadronic sector, but not yet ready. MIonE: recent proposal to measure the leading hadronic contribution to the muon g-2 via $\mu e$ scattering at CERN.

**Tau g-2:** unknown.