

## 57. Muon Anomalous Magnetic Moment

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The Dirac equation predicts a muon magnetic moment,  $\vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S}$ , with gyromagnetic ratio  $g_\mu = 2$ . Quantum loop effects lead to a small calculable deviation from  $g_\mu = 2$ , parameterized by the anomalous magnetic moment

$$a_\mu \equiv \frac{g_\mu - 2}{2} . \quad (57.1)$$

That quantity can be accurately measured and, within the Standard Model (SM) framework, precisely predicted. Hence, comparison of experiment and theory tests the SM at its quantum loop level. A deviation in  $a_\mu^{\text{exp}}$  from the SM expectation would signal effects of new physics, with current sensitivity reaching up to mass scales of  $\mathcal{O}(\text{TeV})$  [1,2]. For recent and thorough muon  $g - 2$  reviews, see Refs. [3–5].

The E821 experiment at Brookhaven National Lab (BNL) studied the precession of  $\mu^+$  and  $\mu^-$  in a constant external magnetic field as they circulated in a confining storage ring. It found [7]<sup>1</sup>

$$\begin{aligned} a_{\mu^+}^{\text{exp}} &= 11\,659\,204(6)(5) \times 10^{-10} , \\ a_{\mu^-}^{\text{exp}} &= 11\,659\,215(8)(3) \times 10^{-10} , \end{aligned} \quad (57.2)$$

where the first errors are statistical and the second systematic. Assuming CPT invariance and taking into account correlations between systematic uncertainties, one finds for their average [6,7]

$$a_\mu^{\text{exp}} = 11\,659\,209.1(5.4)(3.3) \times 10^{-10} . \quad (57.3)$$

These results represent about a factor of 14 improvement over the classic CERN experiments of the 1970's [8]. Improvement of the measurement by a factor of four by setting up the E821 storage ring at Fermilab, and utilizing a cleaner and more intense muon beam is in progress with the commissioning of the experiment having started in 2017.

The SM prediction for  $a_\mu^{\text{SM}}$  is generally divided into three parts (see Fig. 57.1 for representative Feynman diagrams)

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}} . \quad (57.4)$$

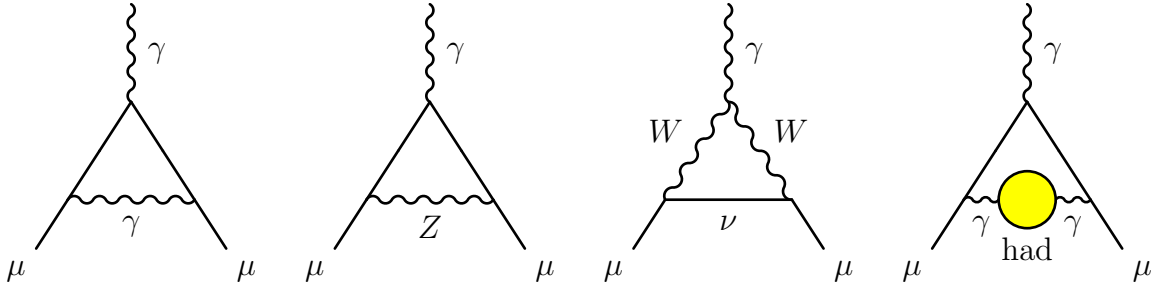
The QED part includes all photonic and leptonic ( $e, \mu, \tau$ ) loops starting with the classic  $\alpha/2\pi$  Schwinger contribution. It has been computed through 5 loops [9]

$$\begin{aligned} a_\mu^{\text{QED}} &= \frac{\alpha}{2\pi} + 0.765\,857\,425(17) \left(\frac{\alpha}{\pi}\right)^2 + 24.050\,509\,96(32) \left(\frac{\alpha}{\pi}\right)^3 \\ &+ 130.879\,6(6\,3) \left(\frac{\alpha}{\pi}\right)^4 + 753.3(1.0) \left(\frac{\alpha}{\pi}\right)^5 + \dots \end{aligned} \quad (57.5)$$

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<sup>1</sup> The original results reported by the experiment have been updated in Eqs. (57.2) and (57.3) to the newest value for the absolute muon-to-proton magnetic ratio  $\lambda = 3.183\,345\,107(84)$  [6]. The change induced in  $a_\mu^{\text{exp}}$  with respect to the value of  $\lambda = 3.183\,345\,39(10)$  used in Ref. 7 amounts to  $+1.12 \times 10^{-10}$ .

## 2 57. Muon anomalous magnetic moment



**Figure 57.1:** Representative diagrams contributing to  $a_\mu^{\text{SM}}$ . From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

with no change in the coefficients since our previous update of this review in 2013. Employing<sup>2</sup>  $\alpha^{-1} = 137.035\,999\,049(90)$ , obtained [6] from the precise measurements of  $h/m_{\text{Rb}}$  [11], the Rydberg constant and  $m_{\text{Rb}}/m_e$  [6], leads to [9]

$$a_\mu^{\text{QED}} = 116\,584\,718.95(0.08) \times 10^{-11}, \quad (57.6)$$

where the small error results mainly from the uncertainty in  $\alpha$ .

Loop contributions involving heavy  $W^\pm$ ,  $Z$  or Higgs particles are collectively labeled as  $a_\mu^{\text{EW}}$ . They are suppressed by at least a factor of  $\frac{\alpha}{\pi} \frac{m_\mu^2}{m_W^2} \simeq 4 \times 10^{-9}$ . At 1-loop order [12]

$$\begin{aligned} a_\mu^{\text{EW}}[1\text{-loop}] &= \frac{G_\mu m_\mu^2}{8\sqrt{2}\pi^2} \left[ \frac{5}{3} + \frac{1}{3} (1 - 4\sin^2\theta_W)^2 \right. \\ &\quad \left. + \mathcal{O}\left(\frac{m_\mu^2}{M_W^2}\right) + \mathcal{O}\left(\frac{m_\mu^2}{m_H^2}\right) \right], \\ &= 194.8 \times 10^{-11}, \end{aligned} \quad (57.7)$$

for  $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2 \simeq 0.223$ , and where  $G_\mu \simeq 1.166 \times 10^{-5} \text{ GeV}^{-2}$  is the Fermi coupling constant. Two-loop corrections are relatively large and negative [13]. For a Higgs boson mass of 125 GeV [13]

$$a_\mu^{\text{EW}}[2\text{-loop}] = -41.2(1.0) \times 10^{-11}, \quad (57.8)$$

where the uncertainty stems from quark triangle loops. The 3-loop leading logarithms are negligible [13,14],  $\mathcal{O}(10^{-12})$ , implying in total

$$a_\mu^{\text{EW}} = 153.6(1.0) \times 10^{-11}. \quad (57.9)$$

<sup>2</sup> In early versions of this review we used the precise  $\alpha$  value determined from the electron  $a_e$  measurement [9,10]. With the new measurement [11] of the recoil velocity of Rubidium,  $h/m_{\text{Rb}}$ , an  $a_e$ -independent determination of  $\alpha$  with sufficient precision is available and preferred.

## 57. Muon anomalous magnetic moment 3

Hadronic (quark and gluon) loop contributions to  $a_\mu^{\text{SM}}$  give rise to its main theoretical uncertainties. At present, those effects are not precisely calculable from first principles, but such an approach, at least partially, may become possible as lattice QCD matures [15]. Instead, one currently relies on a dispersion relation approach to evaluate the lowest-order (*i.e.*,  $\mathcal{O}(\alpha^2)$ ) hadronic vacuum polarization contribution  $a_\mu^{\text{Had}}[\text{LO}]$  from corresponding cross section measurements [16]

$$a_\mu^{\text{Had}}[\text{LO}] = \frac{1}{3} \left( \frac{\alpha}{\pi} \right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R^{(0)}(s), \quad (57.10)$$

where  $K(s)$  is a QED kernel function [17], and where  $R^{(0)}(s)$  denotes the ratio of the bare<sup>3</sup> cross section for  $e^+e^-$  annihilation into hadrons to the pointlike muon-pair cross section at center-of-mass energy  $\sqrt{s}$ . The function  $K(s) \sim 1/s$  in Eq. (57.10) gives a strong weight to the low-energy part of the integral. Hence,  $a_\mu^{\text{Had}}[\text{LO}]$  is dominated by the  $\rho(770)$  resonance.

Currently, the available  $\sigma(e^+e^- \rightarrow \text{hadrons})$  data give a leading-order hadronic vacuum polarization (representative) contribution of [18]

$$a_\mu^{\text{Had}}[\text{LO}] = 6\,931(33)(7) \times 10^{-11}, \quad (57.11)$$

where the first error is experimental (dominated by systematic uncertainties), and the second due to perturbative QCD, which is used at intermediate and large energies to predict the contribution from the quark-antiquark continuum. New data in particular from the BABAR and VEPP-2000 experiments have led to a reduction by about 20% in the uncertainty of the hadronic contribution compared to the 2013 PDG value.

Alternatively, one can use precise vector spectral functions from  $\tau \rightarrow \nu_\tau + \text{hadrons}$  decays [20] that can be related to isovector  $e^+e^- \rightarrow \text{hadrons}$  cross sections by isospin symmetry. Analyses replaced  $e^+e^-$  data in the two-pion and four-pion channels by the corresponding isospin-transformed  $\tau$  data, and applied isospin-violating corrections [19]. Owing to the progress in the precision of the  $e^+e^-$  data, the  $\tau$  data are now less precise and less reliable due to additional theoretical uncertainties. The  $\tau$ -based result was therefore not updated in the most recent  $a_\mu^{\text{Had}}[\text{LO}]$  evaluation [18].

Higher order hadronic contributions are obtained from dispersion relations using the same  $e^+e^- \rightarrow \text{hadrons}$  data [28], giving  $a_\mu^{\text{Had,Disp}}[\text{NLO}] = (-98.7 \pm 0.9) \times 10^{-11}$  and  $a_\mu^{\text{Had,Disp}}[\text{NNLO}] = (12.4 \pm 0.1) \times 10^{-11}$  [29], along with model-dependent estimates of the hadronic light-by-light scattering contribution,  $a_\mu^{\text{Had,LBL}}[\text{NLO}]$ , motivated by

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<sup>3</sup> The bare cross section is defined as the measured cross section corrected for initial-state radiation, electron-vertex loop contributions and vacuum-polarization effects in the photon propagator. However, QED effects in the hadron vertex and final state, as photon radiation, are included.

## 4 57. Muon anomalous magnetic moment

large- $N_C$  QCD [30–36].<sup>4</sup> Following [34], one finds for the sum of the three terms

$$a_\mu^{\text{Had}}[\text{N(N)LO}] = 19(26) \times 10^{-11}, \quad (57.12)$$

where the error is dominated by hadronic light-by-light uncertainty.

Adding Eqs. (57.6), (57.9), (57.11) and (57.12) gives the representative  $e^+e^-$  data based SM prediction

$$a_\mu^{\text{SM}} = 116\,591\,823(1)(34)(26) \times 10^{-11}, \quad (57.13)$$

where the errors are due to the electroweak, lowest-order hadronic, and higher-order hadronic contributions, respectively. The difference between experiment and theory

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11}, \quad (57.14)$$

where the errors are from experiment and theory prediction (with all errors combined in quadrature), respectively, represents an interesting but not conclusive discrepancy of 3.5 times the combined  $1\sigma$  error. All the recent estimates for the hadronic contribution compiled in Fig. 57.2 exhibit similar discrepancies.

An exciting interpretation is that  $\Delta a_\mu$  may be a new physics signal with supersymmetric particle loops as the leading candidate explanation. Such a scenario is quite natural, since generically, supersymmetric models predict [1] an additional contribution to  $a_\mu^{\text{SM}}$

$$a_\mu^{\text{SUSY}} \simeq \pm 130 \times 10^{-11} \cdot \left( \frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \tan\beta, \quad (57.15)$$

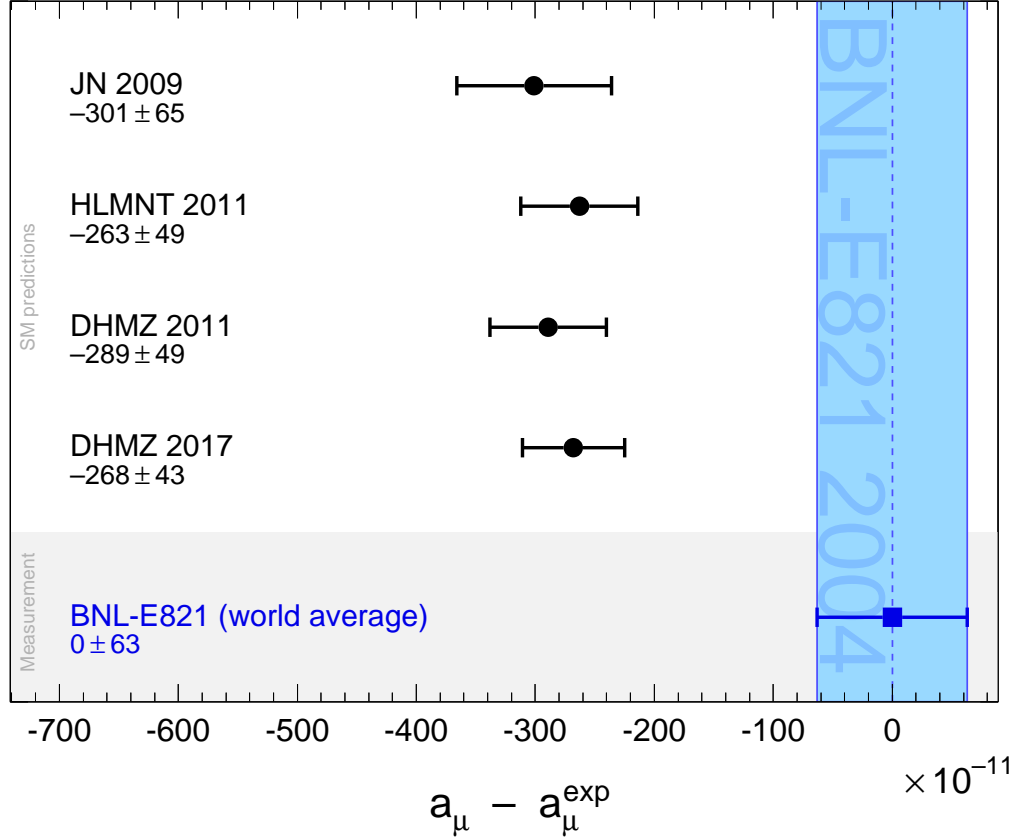
where  $m_{\text{SUSY}}$  is a representative supersymmetric mass scale,  $\tan\beta \simeq 3\text{--}40$  a potential enhancement factor, and  $\pm 1$  corresponds to the sign of the  $\mu$  term in the supersymmetric Lagrangian. Supersymmetric particles in the mass range 100–500 GeV could be the source of the deviation  $\Delta a_\mu$ . If so, those particles should be directly observable at the Large Hadron Collider at CERN. So far, there is however no direct evidence in support of the supersymmetry interpretation.

New physics effects [1] other than supersymmetry could also explain a non-vanishing  $\Delta a_\mu$ . A popular scenario involves the “dark photon”, a relatively light hypothetical vector boson from the dark matter sector that couples to our world of particle physics through mixing with the ordinary photon [38,39,40]. As a result, it couples to ordinary charged particles with strength  $\varepsilon \cdot e$  and gives rise to an additional muon anomalous magnetic moment contribution

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_\mu), \quad (57.16)$$

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<sup>4</sup> Some representative recent estimates of the hadronic light-by-light scattering contribution,  $a_\mu^{\text{Had,LBL}}[\text{NLO}]$ , that followed after the sign correction of [32], are:  $105(26) \times 10^{-11}$  [34],  $110(40) \times 10^{-11}$  [30],  $136(25) \times 10^{-11}$  [31].



**Figure 57.2:** Compilation of recent published results for  $a_\mu$  (in units of  $10^{-11}$ ), subtracted by the central value of the experimental average (57.3). The shaded band indicates the size of the experimental uncertainty. The SM predictions are taken from: JN 2009 [4], HLMNT 2011 [23], DHMZ 2011 [19], DHMZ 2017 [18]. Note that the quoted errors in the figure do not include the uncertainty on the subtracted experimental value. To obtain for each theory calculation a result equivalent to Eq. (57.14), the errors from theory and experiment must be added in quadrature.

where  $F(x) = \int_0^1 2z(1-z)^2 / [(1-z)^2 + x^2z] dz$ . For values of  $\varepsilon \sim 1-2 \cdot 10^{-3}$  and  $m_V \sim 10-100$  MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon  $g-2$  discrepancy. However, recent experimental constraints disfavor such a scenario [41] under the assumption that the dark photon decays primarily into charged lepton pairs. Direct searches for the dark photon continue to be well motivated [42]; but with guidance coming from phenomena outside the muon anomalous magnetic moment discrepancy.

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## 57. Muon anomalous magnetic moment 7

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