

Status of the Fermilab muon ($g-2$) experiment^{*}

B. Lee Roberts^{1,2;1)}

¹ Department of Physics, Boston University, Boston, MA 02215, USA

² On behalf of the New Muon ($g-2$) Collaboration

Abstract The New Muon ($g-2$) Collaboration at Fermilab has proposed to measure the anomalous magnetic moment of the muon, a_μ , a factor of four better than was done in E821 at the Brookhaven AGS, which obtained $a_\mu = [116\,592\,089(63)] \times 10^{-11} \pm 0.54$ ppm. The last digit of a_μ is changed from the published value owing to a new value of the ratio of the muon-to-proton magnetic moment that has become available. At present there appears to be a difference between the Standard-Model value and the measured value, at the $\simeq 3$ standard deviation level when electron-positron annihilation data are used to determine the lowest-order hadronic piece of the Standard Model contribution. The improved experiment, along with further advances in the determination of the hadronic contribution, should clarify this difference. Because of its ability to constrain the interpretation of discoveries made at the LHC, the improved measurement will be of significant value, whatever discoveries may come from the LHC.

Key words measurement, muon anomalous magnetic moment

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1 Introduction

The anomalous magnetic moment (anomaly) of the e, μ or τ lepton is defined by

$$a_{e,\mu,\tau} = \frac{(g_{e,\mu,\tau} - 2)}{2}; \quad \vec{\mu}_{e,\mu,\tau} = g_{e,\mu,\tau} \left(\frac{Qe}{2m_{e,\mu,\tau}} \right) \vec{s}, \quad (1)$$

where $\vec{\mu}$ is the magnetic dipole moment, and the factor g is equal to 2 in the Dirac theory. One of the important discoveries on the path to the development of QED, and then the Standard Model, was the measurement by Kusch and Foley [1] which showed definitively that $g_e > 2$. Almost simultaneously, Schwinger showed that this difference could be explained by the (one-loop in modern language) radiative correction with the value $\alpha/2\pi \simeq 0.00116\dots$, independent of the lepton mass.

The Standard-Model value of a_μ arises from loop contributions containing virtual photons, leptons, gauge bosons, and hadrons in vacuum polarization loops. Other talks at this meeting have discussed the Standard-Model contributions in some detail. For a general review the reader is referred to the review article by Miller, et al., [3].

The muon anomaly has been measured in a series of experiments that began over fifty years ago [4], the most recent, E821 at the Brookhaven AGS, achieving a precision of ± 0.54 parts per million (ppm) [5, 6]:

$$a_\mu = [116\,592\,089(63)] \times 10^{-11} \pm 0.54 \text{ ppm}. \quad (2)$$

The result has been slightly adjusted from the value reported in Refs. [5, 6] because the value of the fundamental constant $\lambda = \mu_\mu/\mu_p$, the muon to proton magnetic moment ratio, (see Eq. (6)), has changed [7]. The statistical error in the anomaly is ± 0.46 ppm and the systematic error is ± 0.28 ppm. The goal of the new Fermilab experiment [8] is equal statistical and systematic errors of ± 0.1 ppm, for a combined error of 0.14 ppm.

Interestingly enough, the measured muon anomaly seems to be slightly larger than the Standard-Model value of [9]

$$a_\mu^{\text{SM}}[e^+e^-] = 116\,591\,834(49) \times 10^{-11}, \quad (3)$$

which uses e^+e^- annihilation into hadrons to determine the hadronic contribution, and the value of Prades et al., [10] for the hadronic light-by-light contribution. There is a difference of $\sim 3.2\sigma$ between

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1) E-mail: roberts@bu.edu

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the two. If hadronic τ decays are used to determine the lowest-order hadronic contribution (a determination that relies on significant isospin corrections), the difference drops to $\sim 2\sigma$ [11].

Non-Standard-Model contributions could come from muon substructure, supersymmetry or extra dimensions, to name a few possibilities. Excellent reviews on this topic have been written by Stöckinger [12], and Czarnecki and Marciano [13]. The SUSY contribution depends on $\tan\beta$ and the sign of the μ parameter [12, 13]:

$$a_\mu^{\text{SUSY}} \simeq \text{sgn } \mu \, 130 \times 10^{-11} \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \tan\beta. \quad (4)$$

Both $\tan\beta$ and the μ parameter will be difficult to determine at LHC. The sign of the deviation of a_μ from the Standard Model gives the sign of μ , and the plot below illustrates the sensitivity of LHC and a_μ to $\tan\beta$. It assumes that the SPS1a scenario is realized at LHC [12]. The difference between the Standard Model and the result from E821 is assumed to be $\Delta_{a_\mu} = (255 \pm 80) \times 10^{-11}$. The band labeled “Fermilab” assumes the same Δ_{a_μ} but with an error of $\pm 34 \times 10^{-11}$. The improved error comes from the projected 0.14 ppm experimental error, and improved knowledge of the hadronic contribution to a_μ . See Ref. [12] for more details.

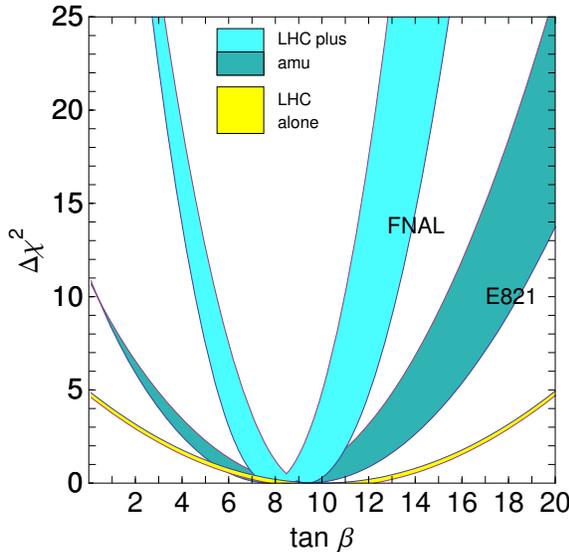


Fig. 1. A “blueband” plot showing the LHC and muon ($g-2$) sensitivities to $\tan\beta$. The (Figure courtesy of D. Stöckinger)

2 Measuring a_μ

The measurement of a_μ uses the spin precession resulting from the torque experienced by the mag-

netic moment when placed in a magnetic field. An ensemble of polarized muons is introduced into a magnetic field, where they are stored for the measurement period. Assuming that the muon velocity is transverse to the magnetic field ($\vec{\beta} \cdot \vec{B} = 0$), the rate at which the spin turns relative to the momentum vector is given by the difference frequency between the spin precession and cyclotron frequencies. With an electric field present as well as a magnetic one, the difference frequency becomes

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{Qe}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right], \quad (5)$$

where $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$. (The reason for introducing an electric field will become apparent in the next section.) The experimentally measured numbers are the muon spin frequency ω_a and the magnetic field, which is measured with proton NMR, calibrated to the Larmor precession frequency, ω_p , of a free proton. The anomaly is related to these two frequencies by

$$a_\mu = \frac{\tilde{\omega}_a / \omega_p}{\lambda - \tilde{\omega}_a / \omega_p} = \frac{\mathcal{R}}{\lambda - \mathcal{R}}, \quad (6)$$

$\lambda = \mu_\mu / \mu_p = 3.183345137(85)$, and $\mathcal{R} = \tilde{\omega}_a / \omega_p$. The tilde over ω_a means it has been corrected for the electric-field and pitch ($\vec{\beta} \cdot \vec{B} \neq 0$) corrections [3]. The ratio λ is determined experimentally from the hyperfine structure of muonium, the μ^+e^- atom [7, 14]. As mentioned above, the recommended value of λ has changed slightly since the final results of E821 were published [5, 6], increasing the value of a_μ by 9×10^{-11} , which is reflected in Eq. (2).

2.1 The Magic- γ technique

In the 2001 data set, the systematic errors on the magnetic field were reduced to 0.17 ppm. A number of contributions went into this small error, but one which we wish to emphasize here is the average magnetic field experienced by the muon ensemble. The magnetic field in Eq. (5) is an average that can be expressed as an integral of the product of the muon distribution times the magnetic field distribution over the storage region. Since the moments of the muon distribution couple to the respective multipoles of the magnetic field, either one needs an exceedingly uniform magnetic field, or exceptionally good information on the muon orbits in the storage ring, to determine $\langle B \rangle_{\mu\text{-dist}}$ to sub-ppm precision. Thus traditional magnetic focusing used in storage rings, which involves magnetic quadrupole and higher multipoles, will cause large uncertainties in the knowl-

edge of $\langle B \rangle_{\mu\text{-dist}}$. This problem was mitigated in the third CERN experiment [15], and in E821, by using electrostatic quadrupoles to provide the vertical focusing, freeing the magnetic-field design to be as close to a uniform dipole field as possible. Examination of Eq. (5) shows that for $\gamma = 29.3$, called “the magic γ ,” an electric field will not contribute to ω_a . The electric-field effect vanishes for particles with the central momentum equal to $p_{\text{magic}} = 3.09 \text{ GeV}/c$, and is a small (sub-ppm) correction for other stored muons [6].

The CERN experiment used a rectangular aperture, which at their 7.3 ppm level of precision did not cause problems in determining the average field. However, the large moments of a rectangular beam were not acceptable for the BNL experiment, which aimed at a factor-of-twenty improvement. Thus a circular beam aperture was chosen for E821, which resulted in a systematic error on $\langle B \rangle_{\mu\text{-dist}}$ of 0.03 ppm, certainly adequate for the experiment now proposed at Fermilab.

The experiment consists of repeated fills of the storage ring, each time introducing an ensemble of muons into a magnetic storage ring, and then measuring the two frequencies ω_a and ω_p . The muon lifetime is given by $\gamma\tau_\mu = 64.4 \mu\text{s}$, and the data collection period is typically ~ 10 muon lifetimes in the ring. The $(g-2)$ precession period is $4.37 \mu\text{s}$, and the cyclotron period is 149 ns . As the μ^- (or μ^+) decay, e^- (e^+) are emitted in the decay $\mu^- (\mu^+) \rightarrow e^- (e^+) + \nu_\mu (\bar{\nu}_\mu) + \bar{\nu}_e (\nu_e)$. The high-energy decay electrons (positrons) carry information on the muon spin direction at the decay. Thus as the spin turns relative to the momentum, the number of high-energy decay electrons is modulated by the frequency ω_a , as shown in Fig. 2.

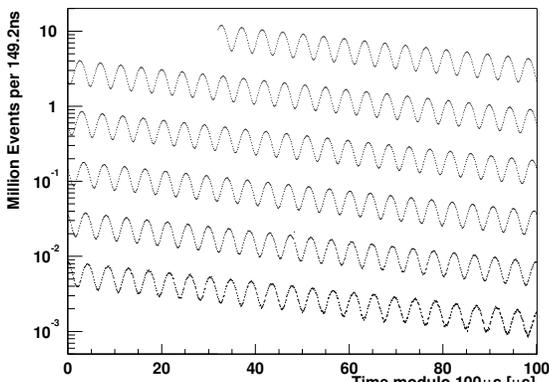


Fig. 2. The time spectrum of decay electrons from the 2001 E821 running period, when μ^- were stored. (From Ref. [5])

The E821 storage ring was constructed as a “super-ferric” magnet [16], meaning that the iron determined the shape of the magnetic field. Thus B_0 needed to be well below saturation and was chosen to be 1.45 T. The resulting ring had a central orbit radius of 7.112 m, and 12 detector stations were placed symmetrically around the inner radius of the storage ring. The detector geometry and number were optimized to detect the high-energy decay electrons, which carry the largest asymmetry, and thus information on the muon spin direction at the time of decay. In this design, many of the lower-energy electrons miss the detectors, reducing background and pileup. The electrostatic quadrupoles [17] cover 43% of the ring, leaving significant gaps for the fast muon kicker [18] and other objects in the ring.

While alternate schemes for measuring a_μ have been proposed, the magic γ technique has a number of things in its favor. One of the most important is that since E821, it is quite well understood and offers a straightforward path to a 0.1 ppm measurement, or perhaps somewhat beyond. Its features are:

- 1) high muon polarization and decay asymmetry;
- 2) large storage ring with ample room for detectors, field mapping, kickers, etc.;
- 3) muon injection, which has been shown to work;
- 4) rates in the detectors that are easily handled with conventional technology;
- 5) data are fit over many $(g-2)$ cycles, which is a powerful tool to unmask systematic errors that depend on time;
- 6) precision magnetic field techniques which are well understood;
- 7) well understood systematic errors.

3 The Fermilab proposal: P989

The Fermilab proposal [8] uses the magic γ in the precision storage ring developed for E821, with new detectors, electronics, along with improved magnetic field measurement and control. Central to the new proposal is the use of features unique to Fermilab that will provide copious proton bunches of $\sim 10^{12}$ protons at 10 to 20 ms intervals. This compares with $\sim 4-5 \times 10^{12}$ protons per bunch at BNL, with a maximum of 12 bunches per machine cycle time of 2.7 s. The effective fill rate at BNL was 4.4 Hz, compared with a projected rate of 18 Hz at Fermilab.

At BNL, pions 1.7% above the magic momentum decayed in an 80 m long FODO line, producing a beam that contained an equal number of pions, muons and electrons. A large hadronic “flash” accompanied

the injection into the ring causing a significant baseline shift in the detectors near the injection point.

At Fermilab, the Recycler Ring will be used to re-bunch each proton batch from the Booster into four bunches with $\sim 10^{12}$ protons each. These will be extracted one at a time to a production target at the location of the present antiproton target. The antiproton debuncher ring will be used as a 900 m long pion decay line. The resulting pion flash will be decreased by a factor of 20 from the BNL level, and the muon flux will be significantly increased because of the ability to take zero-degree muons. The stored muon-per-proton ratio will be increased by a factor of 5 to 10 over BNL. Segmented detectors [19] and new electronics should easily be able to handle the increased data rates per fill of the ring.

The plan is to move the E821 muon storage ring to Fermilab, and install it in a new building near the existing AP0 hall. An optimistic schedule has the ring moved, re-assembled and shimmed by 2014. We estimate that in two years of running on μ^+ , we could achieve the goal of the ± 0.14 ppm error. Most of this running would be simultaneous with NOVA, using the extra Booster batches that cannot be used by the Main Injector program. If the Main Injector program is down, then $(g-2)$ can use the full Booster beam. With further running we might be able to approach the 0.1 ppm level. During the Project X era, we could

achieve a a comparable error for μ^- .

4 Summary and conclusions

The muon anomalous magnetic moment has played an important role in the development of the Standard Model, and in constraining theories of physics beyond the Standard Model. E821 at the Brookhaven Lab AGS achieved a factor of 13.5 in precision over the famous CERN experiments of the 1970s, and reached a relative precision of ± 0.54 ppm. The New Muon $(g-2)$ Collaboration has proposed to improve the error by a factor of four at Fermilab. Given the sensitivity of a_μ to a number of proposed extensions to the Standard Model, a more precise measurement, especially when combined with improvements in the knowledge of the hadronic contribution that are on the horizon, will provide valuable information for the interpretation of new phenomena that might be discovered at LHC.

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