PROCEEDINGS OF SCIENCE

The Next-generation Muon $(g-2)$ Experiment

B. Lee Roberts[*][†]
Department of Physics
Boston University
Boston, MA 02216 USA E-mail: `roberts@bu.edu`

The muon $(g-2)$ experiment at the Brookhaven AGS achieved a relative precision on the muon anomalous magnetic moment, a_μ, of ± 0.54 ppm. The anomaly is sensitive to a wide range of physics beyond the standard model such as supersymmetry, and thus can help constrain the interpretation of any "new physics" found at the Large Hadron Collider. It is desirable to improve the precision of the experiment and of the theoretical (standard-model) value. A new experiment to improve the precision of a_μ to ± 0.14 ppm is being discussed for Fermilab or J-PARC. The existing precision muon storage ring would be moved to one of these facilities. In parallel, a significant worldwide effort to improve the uncertainty on the standard model value is underway, and over the next several years could produce a significant improvement in the theory uncertainty.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

PoS(NuFact08)102

---

[*] Speaker.

[†] This work supported in part by the US National Science Foudation.

1. Introduction

A charged particle with $q = \pm e$ and spin $\vec{s}$ has a magnetic moment $\vec{\mu}_s = g_s(q/2m)\vec{s}$; an anomaly $a \equiv (g_s - 2)/2$; and $\mu = (1+a)e\hbar/2m$; where g_s is the spin g-factor. The g-value is exactly 2 for a point-like fermion in the Dirac equation, but radiative corrections give rise to a non-zero value for the anomaly a. The lowest order (QED) correction, first calculated by Schwinger[1], gives $a = \alpha/2\pi$. The standard model predicts contributions from QED, the electroweak gauge bosons, and from strongly interacting hadrons in vacuum polarization loops that couple to the photon.

For the muon, radiative corrections from QED, virtual hadrons (quarks), and weak gauge bosons are important at the level of measurement[2]. The QED contribution has been calculated through order $(\alpha/\pi)^4$, with significant progress made on the next order contribution[3]. The electro-weak contributions have been calculated through second order, with the leading logs estimated for the next order[2, 5]. Both of these contributions are now known to a precision that would easily support an order of magnitude improvement in the experimental value.

On the other hand, the hadronic contribution cannot be calculated directly, because of the problems with low-energy QCD. Analyticity and the optical theorem give a dispersion relation[6, 2], which relates the hadronic vacuum polarization to the measured cross-section for e^+e^- annihilation to hadrons,

$$a_\mu(\mathrm{Had};1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s); \;\; R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma_{\mathrm{tot}}(e^+e^- \to \mu^+\mu^-)}, \tag{1.1}$$

with experimental data used as input. The factor s^{-2} in the dispersion relation means that values of $R(s)$ at low energies (the ρ resonance) dominate the determination of $a_\mu(\mathrm{Had};1)$. In principle, this information could be obtained from hadronic τ^- decays such as $\tau^- \to \pi^-\pi^0\nu_\tau$, which can be related to e^+e^- annihilation through the CVC hypothesis and isospin conservation. However, for a number of years, the two methods had inconsistencies, independent of the value of a_μ, that disagreed[5]. In order to compare the hadronic tau decay data with the e^+e^- data, it is necessary to make corrections for isospin violation (which is a work in progress[7]) and include the isoscalar contribution "by hand" since the tau data do not show the $\rho - \omega$ interference, the dominant feature in the e^+e^- data. Benayoun et al.[8], claim that this $\tau - e^+e^-$ difference goes away if the correct mixing of the vector mesons is included.

During the time between NuFact08 and the writing of this paper, new $e^+e^- \to \pi\pi$ data have become available from KLOE[9] and from BaBar[11]. The integral and features of the new KLOE data agrees with that from the e^+e^- data from CMD-2 and SND[10] The preliminary BaBar data seem to disagree with them, but when taken alone, give a larger value for the hadronic contribution. The new BaBar data were presented as preliminary, so we will have to wait for a paper from the BaBar collaboration before drawing any conclusions.

Experiment E821 at the Brookhaven Alternating Gradient Synchrotron attained a relative precision of 0.54 ppm[4](e)(f) on a_μ. Since the electroweak contribution is 1.3 ppm of a_μ, the experimental precision is now adequate to begin probing the weak scale. Since the first precise result from E821 was reported in 2001[4](c), there has remained a difference between theory and experiment of between two and three standard deviations when the hadronic contribution is taken from e^+e^- data. When hadronic τ-decay and CVC theory is used to determine the hadronic contribution, the discrepancy is smaller[5].

Motivated by this potential discrepancy, and the special role a_μ can play in guiding the interpretation of "new physics" that might be found at the LHC, a new collaboration is being formed to explore opportunities to improve the experimental precision by a factor of ~ 4 to 5 at either Fermilab or J-PARC. Whether there is a disagreement with the standard model or not, the value of the muon anomaly will provide an important constraint on the interpretation of new physics.

The technique is based on the fact that because $a_\mu > 0$ the spin precesses faster than the momentum vector as the muon travels transversely to the field. Muons were injected into and stored in a superferric storage ring that used electrostatic focusing and operated at "magic" value of $\gamma = 29.3$ (explained below). The difference frequency between the momentum precession (cyclotron) frequency and the muon spin precession frequency, $\omega_a = \omega_S - \omega_C = -\left[(g-2)/2\right](qB/m)$, is the frequency with which the spin precesses relative to the momentum, and is proportional to the anomaly, rather than to g. When the velocity is transverse to the magnetic field ($\vec{\beta}\cdot\vec{B} = 0$) with both an electric and a magnetic field present, the spin difference frequency is given by

$$\vec{\omega}_a = -\frac{q}{mc}\left\{a_\mu\vec{B} - \left[a_\mu - \frac{1}{(\gamma^2-1)}\right]\vec{\beta}\times\vec{E}\right\}. \tag{1.2}$$

Electric quadrupoles were used for vertical focusing, taking advantage of the "magic" $\gamma = 29.3$, where the quantity in square brackets is zero, so the electric field does not contribute to the spin motion relative to the momentum. A precision measurement of a_μ requires precision measurements of the muon spin precession frequency ω_a, and the magnetic field, which is expressed as the free-proton (Larmor) precession frequency ω_p in the storage ring magnetic field. These two (average) frequencies plus the fundamental constant $\lambda = \mu_\mu/\mu_p$ give the anomaly: $a_\mu = (\omega_a/\omega_p)/(\lambda - \omega_a/\omega_p)$.

The experimental signal is the $e^\pm$ from $\mu^\pm$ decay, detected by lead-scintillating fiber calorimeters. Since the highest energy $e^\pm$ are correlated with the muon spin, if one counts high-energy $e^\pm$ as a function of time, one gets an exponential from muon decay modulated by the $(g-2)$ precession frequency. The expected form for the positron time spectrum is $f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$, however in analyzing the data it is necessary to take a number of small effects into account[4].

The values obtained for a_μ by E821 are shown in Fig. 1, along with the theory value obtained using the average of e^+e^- data-based evaluations for the lowest-order hadronic contribution[2]. The discrepancy with theory is 3.4 standard deviations when using the e^+e^- data for the hadronic contribution, and about one-third of this when using the τ-data. The improvement of the e^+e^- data, and the understanding of the related theoretical issues is under active study worldwide[12].

2. A New Upgraded Experiment

The E821 uncertainty on a_μ of 0.54 ppm is dominated by the statistical error of 0.46 ppm. For our last data set the systematic uncertainties on the knowledge of $\langle B\rangle$ and ω_a were 0.17 ppm and 0.21 ppm respectively, for a total systematic uncertainty of 0.27 ppm.

The goal of a new experiment is to obtain equal statistical and systematic errors of 0.1 ppm each. The improvement in systematic errors will require an improvement of about a factor of three over those obtained in the final (2001) E821 data collection period. The significant improvement in the statistical error must come from a more intense muon flux in the secondary beam, along

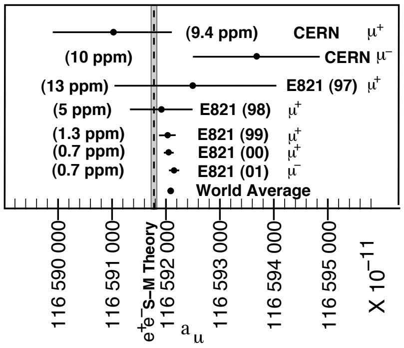

Figure 1: Measurements of a_μ. The strong interaction and other standard model contributions are taken from reference [2].

with improved efficiency in storing these muons. A benchmark is provided by the E821 beam parameters. In the 2001 run, the AGS proton beam was divided into 12 bunches around the ring, with a bunch intensity of 5×10^{12} protons per bunch. The bunches were extracted at 33 ms intervals, with about 10^4 muons stored per injection of the ring. The total AGS cycle time was 2.7 s.

The statistical goal requires 21 times the number of analyzed muon decays as were analyzed in E821. This requires a significant increase in stored muons per fill, or many more muon fills per hour, at a lower rate. From the pulse pile-up point of view, the latter approach is preferable. We believe that the instantaneous rate could be increased by at most a factor of five over that obtained in E821, and still use the counting technique of E821. It also might be possible to develop a new integral technique that takes the entire time spectrum of muon decays after injection, rather than counting the decays individually. New, very dense calorimeters using tungsten sheets and flat ribbons of scintillating fibers have been prototyped[14] and could be used in either method,.

An important beam issue is the muon beam purity. The E821 beam contained an equal number of muons and pions. Upon injection into the storage ring, the pions produced significant hadronic backgrounds that gave long-lasting baseline shifts to detectors in the storage ring just around from the injection point. Thus new experiment needs to have significantly better beam purity. A "backward" muon beam would be ideal, since the 3.1 GeV/c muons are easily separated from the 5.3 GeV/c pions. Another alternative is a much longer decay line, so that the pion contamination can decay away.

The inflection and injection into the storage ring needs to be improved. The superconducting inflector magnet that permitted the muon beam to arrive at the edge of the storage region undeflected[13] had superconductor over the beam channel which caused about half of the beam to be lost from multiple scattering. A new inflector would have to be produced with open ends to eliminate these losses. The fast muon kicker[15] did not provide the full kick needed to store the maximum number of muons, which would need to be improved in the new experiment.

A new collaboration is being formed, and we are exploring options at J-PARC and Fermilab. BNL does not appear to be a viable option. J-PARC could provide a backward muon beam, which would be pion free, but the instantaneous rates in the detectors would be challenging to handle. At Fermilab the 8 GeV booster accelerator could provide a better time structure, (more pulses of less intensity per second) but only forward muons are a possibility with the 8 GeV proton beam energy.

3. Summary and Conclusions

The present measurement of the muon anomalous magnetic moment has a precision of ±0.54 ppm, and may have a significant difference with the standard-model value. Before the new BaBar data presented in September, the difference was 3.6 σ. We will have to wait to see how the BaBar results are combined with the other available data.

The experiment can be improved significantly at Fermilab or J-PARC, and we are actively exploring these options.

Acknowledgments: I wish to thank Michel Davier, Graziano Venanzoni, and Ivan Logashenko for helpful discussions on the measurements of $R(s)$. Thanks to David Hertzog for his reading of the manuscript and for useful discussions.

References

[1] J. Schwinger, Phys. Rev. **73**, 416L (1948), and Phys. Rev. **76** 790 (1949). The former paper contains a misprint in the expression for a_e that is corrected in the longer paper.

[2] J.P. Miller, E. de Rafael and B.L. Roberts, hep-ph/0703049, and Rep. Prog. Phys. **70** (2007) 795-881.

[3] T. Kinoshita, Nucl. Phys. (Proc. Suppl.) **B 144** 206 (2005), T. Kinoshita and M. Nio Phys. Rev. **D 73** 053007 (2006), and references therein.

[4] $(g-2)$ Collaboration: (a) R.M. Carey et al., Phys. Rev. Lett. **82** (1999) 1632; (b) H.N. Brown et al., Phys. Rev. **D 62** (2001) 091101; (c) H.N. Brown, et al., Phys. Rev. Lett. **86** (2001) 2227; (d) G.W. Bennett, et al., Phys. Rev. Lett. **89**, 101804 (2002); (e) G.W. Bennett, et al., Phys. Rev. Lett. **92**, 161802 (2004). (f) G.W. Bennett, et al., Phys. Rev. **D 73** (2006) 072003.

[5] M. Davier and W.J. Marciano, Ann. Rev. Nucl. and Part. Phys. **54**, 115 (2004)

[6] C. Bouchiat and L. Michel, J. Phys. Radium **22** (1961) 121, S. Brodsky and E. de Rafael, Phys. Rev. **168** (1968) 1620.

[7] See the talk by Lopez-Castro at Tau2008, http://tau08.inp.nsk.su/

[8] M. Benayoun, P. David, L. Del Buono, O. Leitner, H.B. O'Connell, Eur. Phys. J. **C 55**, 199-236 (2008).

[9] F. Ambrosino, et al., (KLOE Collaboration) arXiv:0809.3950 [hep-ex] Sept. 2008, which supersedes A. Aloisio, et al., Phys. Lett. **B 606** (2005) 12.

[10] R.R Akhmetshin, et al., (CMD-2) Phys. Lett. **B 648** (2007) 28; M.N. Achasov, et al., (SND) J. Exp. Theor. Phys. **103** (2006) 380.

[11] M. Davier at Tau'08 http://tau08.inp.nsk.su/ Budker Institute, September 2008.

[12] See http://www.ippp.dur.ac.uk/old/MuonMDM/ for an example.

[13] A. Yamamoto, et al., Nucl. Inst. and Meth. **A496**,8-25 (2002).

[14] R. McNabb, et al., Submitted to Nucl. Instr. Meth. (Aug. 2008).

[15] E. Efstathiadis, et al., Nucl. Inst. and Meth. **A496**,(2002) 8.