The New Muon $g-2$ Experiment at Fermilab

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Experiment E989 is under preparation at Fermilab, intending to measure the anomalous magnetic moment of the muon $g_\mu - 2$ to an accuracy of 140 ppb, a fourfold improvement over the Brookhaven E821 result. The latter differs by more than 3 standard deviations from Standard Model predictions, perhaps hinting at new physics and motivating a more sensitive comparison. The techniques of the new experiment to reduce experimental statistical uncertainties by a factor four and systematics by a factor three will be described.

1 Introduction and current status of the muon $g-2$ value

The magnetic moment of a fundamental particle is given by $\vec{\mu} = g(e\hbar/2m)\vec{S}/\hbar$, where $\vec{S}$ is the spin operator and $g = 2$ was predicted by Dirac for point-like spin 1/2 particles such as the electron or muon. This leading order prediction of the Standard Model (SM) is perturbed by radiative corrections. These couple the fields of virtual particles to the muon, leading to additional contributions so g_μ deviates from 2. The sum of all such corrections is characterized by the anomalous magnetic moment $a_\mu \equiv \frac{1}{2}(g_\mu - 2)$.

The largest contribution to a_μ comes from the Schwinger term, which involves the exchange of an additional virtual photon and contributes a_μ(QED, Leading-Order)$=\alpha_{\text{QED}}/2\pi \approx 1.16 \times 10^{-3}$. The Schwinger term contribution to the electron a_e was confirmed experimentally by Kusch and Foley in 1947.

The modern SM prediction for a_μ includes QED contributions calculated to order α^5_{QED} [1], weak interaction contributions calculated to 2 loops [2], and hadronic contributions. The latter are usually described in terms of a leading-order (LO) hadronic vacuum polarization (HadVP) and higher-order HadVP, where the LO HadVP is best determined from a dispersion relation and measurements of e^+e^- scattering into hadronic final states made by BABAR, KLOE, CMD2, and SND (see [3, 4] for details and references). The hadronic light-by-light contribution (Had-LBL) is determined from the "Glasgow Consensus" and is discussed in [5].

Abundant hadronic decay data of τ from LEP and CLEO can be used with isospin breaking corrections and the assumption of CVC to evaluate the LO HadVP contribution to a_μ. Since the τ data just has the isovector part of the contribution, the isoscalar part from e^+e^- scattering must be introduced by hand, so e^+e^- and τ evaluations of LO HadVP are not fully independent. Early τ-based evaluations were different from those based on e^+e^- scattering. Recently it has been shown that after properly accounting for $\gamma - \rho$ mixing the results are consistent [6].

The SM prediction is compared with the experimental result from Brookhaven E821 [7] in Table 1, where a 3.6 σ difference is observed. Using a different evaluation of the LO HadVP contribution, $(6949.1 \pm 42.7) \times 10^{-11}$, from [8], reduces the discrepancy to 3.3 σ.

There is great interest in this discrepancy since the Standard Model is incomplete, and many models of physics beyond the Standard Model, such as supersymmetry (SUSY), predict new particles which contribute to the muon anomaly and naturally cause such a discrepancy. For instance, given a mass scale Λ, the SUSY contribution in terms of $\tan\beta$ and the SUSY μ-parameter is [9] (see Fig. 1):

$$a_\mu(\mathrm{SUSY}) \approx \mathrm{sign}(\mu) \times 130 \times 10^{-11} \times \tan\beta \times \left(\frac{100\ \mathrm{GeV}}{\Lambda}\right)^2 .$$

Thus a_μ measurements are potentially sensitive to SUSY interactions at the TeV scale. Technicolor models and models with extra spatial dimensions also predict contributions to a_μ. The muon anomaly is sensitive to new physics in a manner which is unique and complementary to other searches for new physics. It is more sensitive to new physics than the electron anomaly by a factor $(m_\mu/m_e)^2 \approx 43{,}000$. Anomaly contributions come from interactions which are CP- and flavor-conserving, chirality-flipping, and which appear in loops. This complements LHC searches for new physics since those observables are typically chirality-conserving. Further, the tanβ parameter and sign(μ) parameter which are important in many SUSY models are difficult to measure at the LHC, and determined better by a precision $g-2$ measurement [9]. Lower energy precision tests such as electric dipole moment (EDM) searches are sensitive to CP-violating interactions, and searches such as $\mu \rightarrow e$ conversion are flavor-violating. Muon $g-2$ is primarily sensitive to leptonic couplings so it complements precision s and B physics experiments that search for the hadronic couplings of new physics.

Whether the discrepancy between theory and experiment for a_μ is an indication of new physics can only be resolved by reducing the uncertainties. New precision measurements and analysis of e^+e^- scattering data from BESIII, Novosibirsk, and Frascati, and lattice QCD calculations of LO HadVP [10] should reduce the theoretical uncertainties. The discrepancy also motivates the new high rate, next generation $g_\mu - 2$ experiment E989 at Fermilab [11].

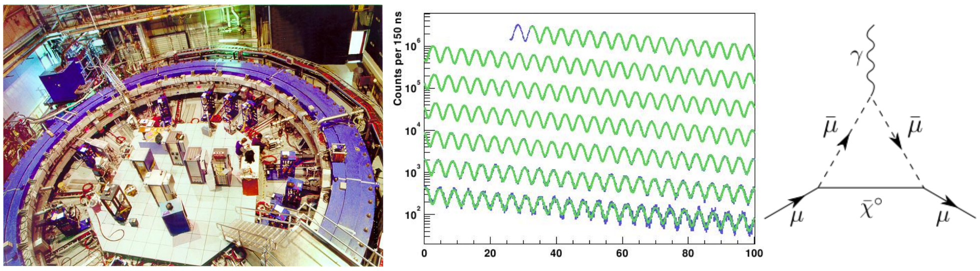

Figure 1: Left: The BNL E821 storage ring. Center: The BNL E821 “wiggle” plot showing the anomalous precession ω_a. Right: A one-loop SUSY contribution to a_μ from a smuon and chargino loop.

2 Overview of experimental technique

The experiment E989 will inject polarized muons through a superconducting inflector into a 7.1 m radius magnetic storage ring with electric quadrupoles for vertical focusing and scraping

Source		Contribution	Uncertainty
a_μ(QED)	=	116 584 718.951	$\pm$ 0.080 (α^5)
a_μ(HadVP; LO)	=	6 923	$\pm$ 42 (Exp)
a_μ(HadVP; HO)	=	-98.4	$\pm$ 0.6 (Exp) $\pm$ 0.4 (Rad)
a_μ(Had-LBL)	=	105	$\pm$ 26
a_μ(Weak; 1 loop)	=	194.8	
a_μ(Weak; 2 loop)	=	-41.2	$\pm$ 1 (Had) $\pm$ 2$\to$ 0 (Higgs)
a_μ(SM Theory)	=	116 591 802	$\pm$ 49 $\times 10^{-11}$ (0.42 ppm)
a_μ(E821 Expt.)	=	116 592 089	$\pm$ 63 $\times 10^{-11}$ (0.54 ppm)
Δ(Expt.-Theory)	=	287	$\pm$ 80 $\times 10^{-11}$ (3.6 σ)

Table 1: Standard model prediction from M. Davier *et al.* [4] for a_μ in units of 10^{-11}, and the experimental result from BNL E821 [7].

(essentially a Penning trap, see Fig. 1) [7, 11]. A magnetic kicker is pulsed on during the first turn, resulting in $\approx 10^4$ muons on a stable orbit per fill. While stored, the muon spin vector precession frequency ω_S is faster than the momentum vector cyclotron frequency ω_C. The difference frequency ω_a is proportional to a_μ:

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{mc}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{1}$$

where $B = 1.45$T is the storage ring magnet field, and $\vec{E}$ is the electric field from the electrostatic quadrupoles. The electric field dependence cancels by using muons at the magic momentum $p_{\text{magic}} = m_\mu c/\sqrt{a_\mu} \approx 3.094$ GeV$/c$, $\gamma \approx 29.3$.

To extract a_μ from Eq. 1, experiment FNAL E989 is required to measure two quantities precisely (i) the anomalous muon spin frequency precession frequency $\omega_a \approx 2\pi \times 229$ kHz and (ii) the magnetic field $\vec{B}$ averaged over the muon distribution in the ring. The magnetic field is measured using pulsed NMR [12, 13] and expressed in terms of the Larmor precession frequency a free proton would exhibit in the same field, $\omega_p \approx 2\pi \times 61.79$ MHz, using the relation $\hbar\omega_p = 2\mu_p B$.

The anomalous precession frequency ω_a is measured by detecting positrons from the decay of stored μ^+. Parity violation in this weak decay leads to a correlation between the positron emission direction and the muon spin direction. The lab frame positron energy is given approximately in terms of the rest frame energy E^* and rest frame angle between muon spin and positron direction θ^* by $E_{\text{lab}} \approx \gamma E^*(1+\cos\theta^*)$. Detecting decay e^+ above 1.9 GeV corresponds to to a cut on θ^* and allows the reconstruction of the muon spin direction as a function of time. The resulting positron spectrum $N(t) \approx N_0 e^{-t/(\gamma\tau)}[1 + A\cos(\omega_a t + \phi)]$ from BNL E821 is seen in Fig. 1. Corrections are applied for muons not at the magic momentum, and for the pitching motion from vertical betatron oscillations.

The positron energies and arrival times will be determined by 24 calorimeters in the interior of the storage ring. The calorimeters have a 6×9 array of PbF_2 Čerenkov crystals with attached SiPMs read by 12 bit ADCs digitizing at 800 MSPS. Timing resolution is better than 100 ps, and spatial/temporal separation resolves e^+ arriving >5 ns apart. Gain stability over a fill of 0.1% requires a precision laser calibration system and mV SiPM bias stability. Information about the muon spatial and momentum distribution in the ring will come from fiber beam monitors, a fast-rotation analysis [7], and from several sets of straw tracking chambers. The latter will also be used for an improved limit on the electric dipole of the muon. The systematics on the extraction of ω_a will be held to 70 ppb.

A significant, 20-fold improvement in detected positrons comes from several advantages of FNAL over BNL. First a more intense muon beam will be injected into the ring at a rate of about 12 Hz versus < 0.5 Hz at BNL. Unlike BNL, the muon beam will be free of pion contamination due the much longer decay line used - this yields much smaller backgrounds and allows the detectors to remain on during muon injection. Other improvements in the overall efficiency lead to an expected statistical precision of 100 ppb.

The magnetic field measurement will be improved by upgrades to the NMR measurement system, improved NMR probes and procedures, coupled with a more homogeneous and stable storage ring magnetic field, in part from an experimental hall with $\pm 1^\circ$C stability. The goal is a field measurement with an accuracy on the equivalent precession frequency of a free proton weighted by the muon distribution $\tilde{\omega}_p$ to 70 ppb.

3 Summary

The E989 experiment is under construction at Fermilab, intending to measure the anomalous magnetic moment of the muon a_μ to an accuracy of 140 ppb. Comparison of the experimental result with theoretical predictions yields a precise check of the Standard Model, with sensitivity to new physics. The first stored muons are expected around 2017.

Acknowledgments

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