The Muon $g-2$ Experiment at Fermilab*

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Abstract

There remains a tantalizing discrepancy between the Standard Model prediction for the muon $g-2$, and the value measured by the Brookhaven E821 Experiment. This discrepancy has driven designs for multiple experiments. Here I present current progress on the construction of the Fermilab E989 experiment which will improve on the Brookhaven experiment by a factor of four, to a combined uncertainty of 0.14 ppm.

INTRODUCTION

Understanding the anomalous magnetic moment of the muon has consumed the energies of generations of physicists, from the likes of Dirac and Schwinger, down to the present day. Advances in the theory and measurement of $g-2$ have fed off each other and have productively informed all other subfields of particle and nuclear physics.

The most recent chapter closed at the Brookhaven National Laboratory (BNL) in the United States at the turn of the century, followed by publication of the final report of the Muon $g-2$ Experiment E821 [1]. This experiment reached an ultimate combined uncertainty of 0.54 ppm. This precision is sufficiently high to access the very small electroweak contributions present at second order. Parallel developments at the same precision have

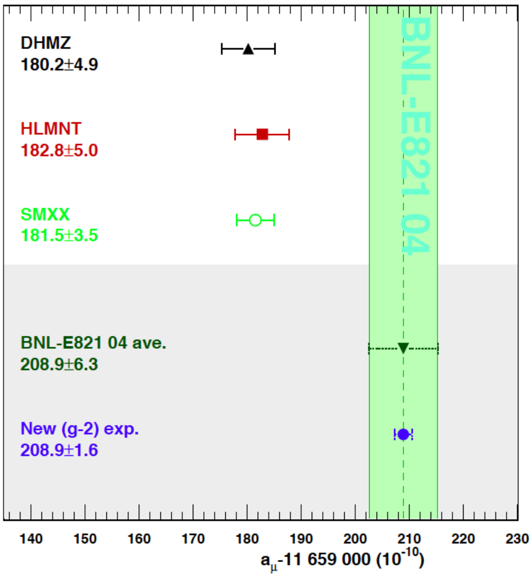

FIG. 1: This plot summarizes the current discrepancy between the consensus Standard Model theory prediction for the muon anomaly and the BNL E821 experimental result.

been required in the theory. Consensus among contributors to the ongoing theory efforts makes it appear likely that the results of E821 show a discrepancy from the Standard Model prediction, at the level of 3.6 standard deviations; see Figure 1.

This unresolved state-of-affairs fairly begs for significant continued effort on both the theoretical and experimental fronts. The US High Energy Physics community has recognized the importance of this measurement: Recommendation 22 in the recent report of the Particle Physics Project Prioritization Panel (P5) [2] recommends completing the Fermilab E989 Muon $g-2$ project under all funding scenarios. Here, I describe the current progress on bringing this next generation storage ring experiment to the data taking stage. Other contributions in this workshop present progress on a radically different method for measuring the muon magnetic anomaly at the Japan Proton Accelerator Research Center (JPARC).

THE METHOD

Modern electron g-factor experiments have dramatically improved uncertainties by going to smaller experiments with very large observation times on individual particles in cyclotron traps [3]. The brief muon lifetime prevents that approach, so muon experiments have by necessity proceeded by a different path: the last four precision $g-2$ experiments all utilized storage ring techniques, to measure time dependent ensemble spin precession. Understanding this method is key to understanding the design of the experiment.

Muon beams are naturally highly polarized: muons are born in a two-body decay of spin-zero pions via the $V-A$ (left-handed) weak interaction. As neutrinos are only observed in left-handed chirality, angular momentum conservation demands that all muons have the same spin orientation. In the case of muon $g-2$, we maximize and utilize that beam ensemble polarization to effect our measurement.

To produce a muon beam, a proton beam impinges upon a pion production target. Those pions are collected, momentum selected, and transported through a decay channel, along which they decay to muons. Those muons are then injected into a storage ring with an extremely uniform magnetic field. For those muons which are stored in the ring, the momentum will precess at the cyclotron frequency

$$\omega_C = \frac{eB}{mc\gamma} \ ,$$

while the spin undergoes both Larmor and Thomas precession

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{mc\gamma} \ .$$

The difference between these two frequencies,

$$\omega_a = \omega_S - \omega_C = \frac{g-2}{2}\frac{eB}{mc} = a_\mu \frac{eB}{mc} \ ,$$

is known as the anomaly frequency. Measuring all quantities in this expression (in particular, ω_a and B) gives the anomaly directly.

In practice, things are of course not so simple. Muons will not remain in a storage ring with only a single uniform magnetic field. This field will retain particles by focusing in the plane perpendicular to the field, but will do nothing to prevent vertical losses (along the field direction). Since we want an extremely uniform magnetic field across the entire volume of stored muons, we can not use magnetic fields to perform vertical focusing. Instead, we utilize an electrostatic quadrupole focusing system; the induced horizontal defocusing is overcome by the magnetic field.

In the presence of vertical motions and the electric fields, our previous expression relating ω_a to a_μ must be modified:

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} - a_\mu \frac{\gamma}{\gamma + 1} \left(\vec{\beta} \cdot \vec{B} \right) \vec{\beta} \right] \ ,$$

The first term in the square brackets is our original result. The second encodes the effect of the electrostatic quadrupoles. The final term comes from the vertical momentum component. Since the deviations from the horizontal plane will be small, let me ignore the final term for now; in the experiment, we must correct for the vertical motions, but this *pitch correction* is small and well controlled. The key insight here is that the electric field effects vanish for a particular "magic" value of the momentum, given by

$$\gamma_{\text{magic}} = \sqrt{1 + \frac{1}{a_\mu}} \ .$$

For muons this corresponds to a momentum $p_{\text{magic}} = 3.091\,\text{GeV/c}$. Producing large numbers of muons at this momentum demands only quite modest proton beam energy; at Fermilab, we will use an 8 GeV beam. Of course since there is a distribution of momenta in the stored beam, corrections must be applied to the final result; again, this *E-field correction* turns out to be small and well controlled.

Key to the experiment then is measurement of ω_a. The chiral structure of the weak interactions gives us direct access to the spin direction, at least on a statistical basis. In the three body decay of the muon, the electron is not emitted isotropically. In the rest frame of the muon, with the spin aligned along a coordinate axis, the differential decay distribution for the electron momentum direction is given (in units of the dimensionless electron energy $y = E_{\mathrm{e}}/E_{\mathrm{max}}$) by

$$\frac{\mathrm{d}^2\Gamma_{\mu^\pm}}{\mathrm{d}y\mathrm{d}\Omega} = n(y)\,(1 \mp a(y)\cos\theta)\ ,$$

with $n(y) = y^2(2-y)$ and $a(y) = (2y-1)/(3-2y)$. This results in the highest energy positrons (electrons) being emitted preferentially parallel (anti-parallel) to the muon spin orientation. In the lab frame the combination of spin precession and energy dependent asymmetry is observed as a sinusoidal variation in the observed number of positrons (electrons) above a threshold energy

$$f(t) = N_0(E_{\mathrm{thresh}})e^{-t/\tau}\left[1 + A(E_{\mathrm{thresh}})\cos(\omega_a t + \phi)\right] \tag{1}$$

This threshold is chosen to maximize the statistical power of the collected data, which is proportional to the asymmetry $A(E)$ (rising with energy) and the square of the observed number of electrons $N(E)$ (falling with energy); $A(E)$ and $N(E)$ are the integrals of $a(y)$ and $n(y)$ from the chosen threshold to E_{max}. During analysis, we will provide a multi-level blinding process to the analysis so that neither the Collaboration as a whole, nor the analyzers individually, will be able to steer (whether intentionally or not) the analysis toward a “preferred” value.

To extract the anomaly, we must know the absolute value of the magnetic field distribution, integrated over the storage volume, in addition to ω_a. A number of pulsed NMR probes, including fixed, plunging, and traveling, are used to measured the proton Larmor precession frequency in the field

$$\omega_P = \frac{eB}{2m_P}g_p$$

Like the ω_a analysis, this frequency is also hidden by a blinding procedure, further protecting from unintentional bias.

The combination of ω_a and ω_P allows calculation of a_μ.

$$a_\mu = \frac{\omega_a/\omega_P}{\mu_\mu/\mu_P - \omega_a/\omega_P}\ , \tag{2}$$

TABLE I: A summary of the ω_a systematics in both the BNL E821 and expected improvements for the FNAL E989 experiment [4].

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Detector Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
Coherent Betatron Oscillations	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
Field and pitch corrections	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

where the ratio of magnetic moments was measured at the Los Alamos National Laboratory (LANL) in the United States utilizing the same spherical calibration probe used in the E821 NMR calibration procedure.

IMPROVING THE SYSTEMATICS

To improve the overall error relative to E821 by a factor of four will require improvements not only in statistics (a factor of at least twenty), but also systematics. In the BNL experiment, systematic errors contributed 0.28 ppm, and statistics 0.46 ppm, to the final, combined 0.54 ppm result.

When discussing improvements to the systematics, it helps to recall that we are performing two parallel measurements - ω_a and ω_P- and we divide our systematic studies along these lines. We intend to improve substantially on both of these, to better than 0.1 ppm in each category. The major ω_a systematics are illustrated in Table I, and ω_P systematics in Table II.

What do we need to do to reach these goals? Since it is impossible to discuss the

TABLE II: A summary of the ω_P systematics in both the BNL E821 and expected improvements for the FNAL E989 experiment [4].

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

experimental requirements along with all of our plans in the short space available here, I choose to concentrate on just a few issues. It should be understood, however, that much more work has been done to date than I have room to discuss.

Implementation details

The FNAL implementation of the experiment is an evolutionary upgrade of the E821 model. The majority of the major devices, in fact, have been transplanted from BNL to FNAL, and form the backbone of the experiment. Despite this, nearly all of the subsystems are undergoing major upgrades in functionality and/or precision to meet the stringent new requirements.

At FNAL, the experiment is part of a larger muon physics program - which includes the muon-to-electron conversion (Mu2e) search experiment - in a new Muon Campus facility close to Wilson Hall. The $g-2$ experiment occupies the new MC1 experimental hall and is served by a new beamline. Proton delivery to the muon campus requires modest upgrades to the accelerator complex which are compatible with the ongoing neutrino program. Protons will continue to be accelerated by the Booster ring to 8 GeV. Bunches will be extracted from the Booster and transported to the Recycler ring. After extraction from the Recycler, the protons will impinge on an upgraded production target in the AP0 hall - occupying the former Tevatron antiproton production facility. Pions will be focused by a lithium lens and momentum selected by a pulsed dipole; these devices served the antiproton program and required significant upgrades to operate reliably with the more demanding $g-2$ pulse rates. Pions will be sent to the Delivery ring - which will serve as part of an 800 m long decay line, effectively eliminating pions from the beam - and will be extracted after one turn for delivery to the $g-2$ storage ring. Upgrades to the Delivery ring (the former antiproton Debuncher) are designed to accommodate both single-turn muon extraction for $g-2$ and resonant proton extraction for Mu2e. Extracted beam will traverse a new line to the $g-2$ Storage Ring, which was moved - with much fanfare - from BNL to FNAL in the summer of 2013 [5].

Once the muons have reached the storage ring, the work of the accelerator physicists gives way to the particle physicists. Of course, the beam must be transported from the outside to the inside of the ring; the storage volume is a torus with radius 7.11 m, with an unobstructed circular cross sectional of diameter 90 mm. Over this region, the storage field, averaged over azimuth and the weighted by the muon storage distribution, must be uniform to better than 1 ppm. To reach the storage region, the fringe fields must be cancelled without destroying the field uniformity in the neighboring storage region. This key task is the job of a superconducting magnetic inflector. The baseline design for the FNAL experiment is to refurbish and reuse the E821 inflector. This device is a truncated double cosine magnet with an external superconducting shield that both maintained a field free channel within the fringe field of the storge ring and reduced the impact of the injection channel field on the storage field at the required level. Despite the success of this device, some design choices - in particular, that windings cover the ends of the beam channel - significantly impact the efficiency of beam injection. Signficant R&D is ongoing to design a new inflector with open ends and a wider bore as a possible option should scope contingency be available at a later date.

The exit of the E821 inflector is centered 77 mm from the center of the storage region. Without additional work, the muon ensemble would not store. The task of moving the beam on-orbit is handled by three fast kicker modules, each consisting of a pair of plates and a high voltage, high-speed pulse forming network. The current sheets created during the kick locally suppress the magnetic field by an amount sufficient to deflect magic momentum muons by 10.8 mrad, sufficient to move the distribution onto the nominal orbit. New fast kicker modules are being designed for the FNAL effort, based on a Blumlein triaxial transmission line design. This should enable a signifiantly shorter, higher amplitude current pulse, improving storage efficiency. Simultaneously, the new design will retain significant margin to allow a higher kick for compatibility with the proposed increase in the inflector bore, which will shift the centroid of the muon bunch further outward radially, requiring a stronger kick deflection.

As mentioned in the overview above, maintaining a stored beam requires electrostatic quadrupole fields for vertical focusing. This is accomplished by a four quadrant system, which will be largely reused. A number of upgrades are in progress to improve various aspects of the system. Of perhaps greatest importance, the system will be operated at a higher field index to move the frequency of coherent betatron oscillations far away from the second harmonic of the $g-2$ oscillation frequency. Second, during injection, the BNL muon beam passed through the first outer quadrupole plate and insulating supports; ongoing redesign of this part of the system should significantly reduce losses resulting from scattering.

The decay electrons have lower energy than the muons, with correspondingly smaller orbital radii in the magnetic storage field. Therefore, decay positron paths will curve inward, towards the center of the ring. The magnet yoke is C-shaped, with the open side toward the ring center, and the beam vacuum vessel is scalloped to minimize scattering during the inward spiral. Twenty-four segmented PbF_2 calorimeters will be located symmetrically around the ring. The output signal waveforms from each segment will be digitized and stored. Offline processing produces the energy and time histograms needed to fit the physics and extract ω_a.

Analysis improvements

In E821, oscillation spectra were constructed from individual event timings, the so called "T-method" of analysis. The output signals from the calorimeters were waveform digitized, zero suppressed, and the over-threshold samples were stored in onboard RAM until read out by the data acquisition system. Individual pulses were fit to a template, below threshold pulses were rejected, and histograms were built. Construction cost and memory limitations were severe constraints when the digitizer modules were designed necessitating this approach.

In the intervening years, the impact of Moore's law on transient and persistent data storage, network data transmission, and computation resources, have been very large, while the physics have changed little. These gains permit us to reimagine the entire data collection and processing scheme. We building a new set of highly segmented calorimeters, and custom waveform digitizers which will be able to store and readout every sample during the measurement period, for every segment of every calorimeter. Advances in parallel and distributed computation and in high speed networks promise significantly higher throughput data acquisition and offline analysis systems.

Access to the full data record for each channel enables fabulous possibilities undreamed of at the E821 design stage. We intend to again pursue the T-method, but access to the full data stream enables many improvements in the areas of threshold and pedestal stability tracking, as well as vast improvements in pileup reconstruction. In addition, the full data stream permits a new integrated charge collection, or "Q method" approach. Here, we integrate data from all data samples from early to late, and fit the resulting oscillatory signal. Because this method sums over all data samples, it is impacted differently by various systematic errors. The complementarity of these two methods combined with the blinded analysis will provide significant strength to our final result.

IN CONCLUSION

As of this workshop, the Fermilab Muon $g-2$ Project had reached a number of important milestones: the ring had been shipped from BNL to FNAL and installed in the new MC1 experiment hall at the Fermilab Muon Campus. As the workshop got underway, the storage ring superconducting magnets had just been energized for the first time in fourteen years, validating the condition of the full system; a few small issues had been discovered and fixes were being planned and scheduled, and the field shimming plans for 2015 were being finalized. A host of other construction and R&D activities were underway at many Laboratory and University sites both inside and outside the USA. Under the current budget profile, the experiment will begin full commissioning and data taking at the beginning of calendar year 2017, followed by three years of data taking.

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