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The muon $(g-2)$ experiment at Fermi National Laboratory

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Summary. — The E-989 experiment planned at Fermi National Laboratory in Batavia, IL, USA, has a goal to measure the anomalous magnetic moment of the muon (a_μ) to 0.14 ppm. This will be a fourfold improvement over the previous measurement of $a_\mu^{exp} = 116\,592\,089\,(63) \times 10^{-11}$ (0.54 ppm) made at Brookhaven National Laboratory in 2001. This measurement compared to the current theoretical results differ by more than 3σ. It is imperative that we reduce the errors on both the experimental measurement and the theoretical value to better understand this difference. This paper covers the Brookhaven experiment as well as the upgrades that are planned for the Fermilab experiment.

PACS 13.40.Em – Electric and magnetic moments.
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1. – Introduction

The magnetic moment ($\vec{\mu}_s$)of any elementary particle can be related to its intrinsic spin($\vec{S}$) by the gyromagnetic ratio (g): $\vec{\mu}_s = g\frac{q}{2m}\vec{S}$. Historically our measurement of g shows that our understanding of it is either wrong or incomplete. In the 1920s, it was known experimentally that g for the electron was 2, but it was not understood mathematically why that was the case. In 1928, Dirac saved the day uniting concepts from relativity and quantum mechanics to determine that g for a spin 1/2 particle is in fact two.

This concept held for about 20 years until the experiments were repeated with more precision. Kusch and Foley [1] measured g_e to be $g_e = 2.00238(6)$. At this point the "anomaly" is introduced and is defined as, $a = \frac{g-2}{2}$. They found $a_e = 0.1\%$. At the same time, Schwinger [2] was using his time trying to understand the empty space. His work showed us that the empty space is not really empty and radiative corrections change the prediction for g by exactly the right amount. The first order correction is $\frac{\alpha}{2\pi}$.

The anomaly for the electron agrees with the standard model prediction to the part-per-trillion level. The muon is more sensitive to loop corrections and you have to add in the corrections from QED, Hadronic and Electroweak loops. If there were some new

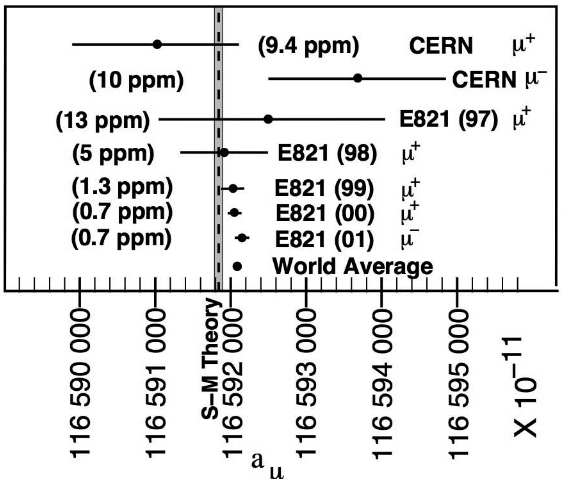

Fig. 1. – Experimental value of a_μ over time compared with the theoretical value shown as the dotted line. The errors are within the grey band for the theory and smaller than the point for the final experimental value.

physics this would also have to be added to calculation. Taking the difference in the experimental measurement and the theoretical calculation in the muon system, $a_\mu^{exp} - a_\mu^{theory} = 287(80) \times 10^{-11}$ [3, 4] shows a 3σ difference. Also note, that the difference is on order of the electroweak contribution meaning that if there were new physics in the loops it could be on the order of the Electroweak scale. Figure 1 shows the progression of the experimental measurement vs the SM prediction.

More investigation from both the theory and the experiment is required in order to understand this difference.

2. – Status of the theoretical predication

The different contributions to the theoretical predication mentioned in the Introduction are broken down in table I. Note that the hadronic component is broken down further to: Hadronic Vacuum Polarization [HVP] (Leading and Higher Order) and Hadronic Light-By-Light [HLbyL].

The two components with the largest contribution to the uncertainty are the HVP-LO

Table I. – *Theoretical contributions* [3].

Contribution	Result in 10^{-11} units
QED (leptons)	$116\,584\,718.09 \pm 0.15$
HVP (LO) $[e^+e^-]$	$6\,923 \pm 42$
HVP (HO)	-98.4 ± 0.7
HLbyL	105 ± 26
EW	153 ± 1
Total	$116\,591\,801 \pm 49$

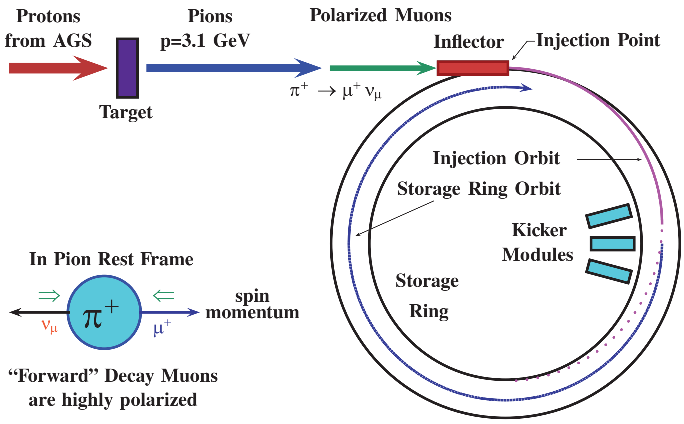

Fig. 2. – Experimental setup at Brookhaven National Laboratory for E821.

and the H-LbyL. Over the next five years there needs to be improvement in these two components. The value for the Leading Order HVP term is determined from experimental cross section measurements of $e^+e^- \to hadrons$. As more experiments produce results for this measurement the error will continue to drop (over the past 15 years the error has dropped by a factor of 4 just by more experiments getting involved). The input for the HVP-LO does not yet have experimental input, but an updated experiment at KLOE-2 which is starting a two photon physics program will aid in reducing the uncertainty.

Lattice-QCD is also getting involved in both of these measurements [5] and over the next 5 years will have errors on the order of 5% on the HVP-LO term which will be an independent check of the experimental determination. The Lattice will also work on a measurement for he HLbyL term. Errors on the order of 10-15% are possible but not without more computing power.

3. – Experimental result from Brookhaven National Laboratory

The setup for the Brookhaven experiment can be seen in fig. 2. The general idea is that polarized muons coming from pion decay are injected into a storage ring. After entering the ring through an inflector, they are kicked into the central orbit by three kickers located 90 degrees downstream from injection. The storage ring has a uniform dipole magnetic field of 1.45 T. Electrostatic quadrupoles provide weak vertical focusing.

The muon spin will precess about the magnetic field with the frequency ω_a:

$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma_\mu^2 - 1}\right)\vec{\beta} \times \vec{E}\right]. \tag{1}$$

The second term in eq. (1) is necessary from the influence of the electric quadruples. Conveniently, the dependence on this term can be removed by storing muons which have a "magic" gamma of 29.3, which corresponds to a momentum of 3.09 GeV. The anomaly, a_μ can then be extracted just by knowing the precession frequency and the magnetic field. The magnetic field is measured in units of the free proton precession frequency, ω_p. To eliminate the uncertainty on the mass of the muon, the anomaly can be measured in

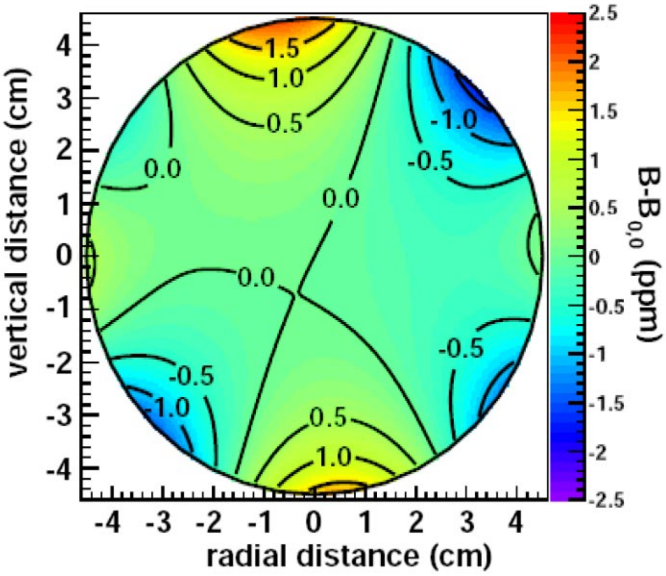

Fig. 3. – Magnetic field map from the E821 experiment. The contours represent deviations (in ppm) from the magnetic field at 1.45 T.

terms of the free proton precession frequency, ω_p:

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} \,. \tag{2}$$

This eliminates the uncertainty on the mass of the muon from entering the calculation of a_μ. The value μ_μ/μ_p is determined by the muon hyperfine structure and is known to the part-per-billion levels [6]. Independent analyses measure ω_a and ω_p.

To measure the magnetic field to a high precision, the E821 experiment used a combination of fixed NMR probes on the top and bottom of the ring as well as 17 NMR probes on a trolley which mapped the field at 6000 azimuthal positions. The result of these measurements showed a magnetic field that was consistent across the aperture of the muon storage ring to 1 part-per-million. The field map can be seen in fig. 3.

The highest energy decay positrons coming from $\mu^+ \to e^+\nu_e\bar{\nu}_e$ were detected using lead-scintillation fiber calorimeters located at 24 positions around the ring. The direction of the positron are preferentially pointed in the direction of the muon spin due to parity violation in the weak decay. Positrons above an energy threshold exhibit a muon decay spectrum given by

$$N(t) = N_0 e^{-t/\tau} \left[1 + A\cos\left(\omega_a t + \phi\right)\right[\,. \tag{3}$$

The distribution of the decay electrons from the 2001 run (this measurement used μ^- rather than μ^+) can be seen in fig. 4.

The final results from E821 [7] was a measurement of: $a_\mu = 116\,592\,089\,(63) \times 10^{-11}$.

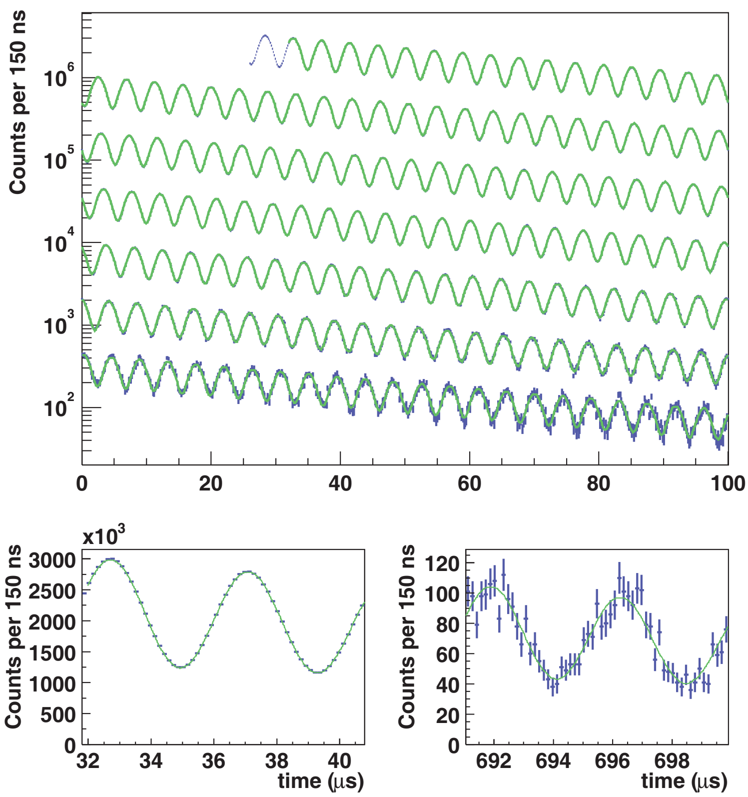

Fig. 4. – Time distribution of electrons with $E > 1.8$ GeV from the 2001 run of E821. Note that the green line is the fit while the blue points are the data points.

4. – Status of E989, a new $g-2$ experiment at Fermi National Laboratory

In order to understand the 3σ difference between theory and experiment the uncertainties on the experimental measurement must be reduced and thus improving upon the Brookhaven experiment is necessary. The E-989 experiment at Fermilab has mission need approval (CD0) from the Department of Energy to go forward with this experiment. A lot of the equipment from the Brookhaven experiment will be reused, but several improvements will be put into place in order to drop the uncertainty to a goal of 0.14 part-per-million, a four-fold improvement.

There is a new muon program at Fermilab, of which the muon $g-2$ experiment is an integral component. There is existing infrastructure in the form of beam lines and antiproton sources that are available for use. The immediate effect of this is that it will give the muon $g-2$ experiment about 20 times more statistics than the Brookhaven Experiment. This paired with the fact that the beam line will be $20\times$ longer, lowering the pion contamination in the beam as well as the hadronic flash when the bunch enters the storage ring, will result in a statistical error drop from 0.4 ppm to ~ 0.1 ppm.

The goal for lowering the systematic errors on the measurement of ω_p is from 0.18 ppm to 0.07 ppm. This projection is based on known techniques and current equipment as well as adding in more NMR probes, better calibration, better shimming of the magnet

TABLE II. – *Systematic uncertainty improvements.*

Uncertainty associated with ω_a	E821 uncertainty [ppm]	Improvement Plan	E989 goal [ppm]
Lost muons	0.09	Long beam line eliminates non-standard muons	0.02
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
E-Field& Pitch	0.05	Improved measurement with tracking detectors	0.03
Total	0.12		0.07

and implementing temperature control. The systematic improvements associated with the ω_a measurement can be seen laid out in table II.

One of the biggest improvements to the $g-2$ experiment at Fermilab will be the inclusion of tracking detectors at one or two positions around the ring. While the Brookhaven experiment did have tracking detectors, they were placed outside of the vacuum, truncating the scallop region in the process.

The addition of the tracking detectors will give feedback on the beam itself. The electron decay can be tracked back to the point of tangency of the muon orbit to determine the muon's momentum. This will aid in the systematic uncertainty on the momentum of the muon since not all muons are exactly at the "magic" momentum. Due to betatron motion of the beam, having the ability to get a good sense of the beam profile will help with these systematics as well. Millimeter resolution of the beam profile is needed in order for the systematics to be lowered to the desired amount. These components are the last listed in table II, the E-Field and Pitch corrections. In addition to these corrections the tracking detector can also provide assistance to the pileup corrections as it will be more heavily segmented and directly in front of the calorimeters.

The calorimeters will also be upgraded with segmented calorimeters, which will help with the pileup systematic uncertainties. The collaboration had a beam test for the calorimeters in April of 2012 where they tested crystal calorimeters. The readout devices being tested currently are silicon photomultipliers. The crystals and the photomultiplier can be seen in fig. 5.

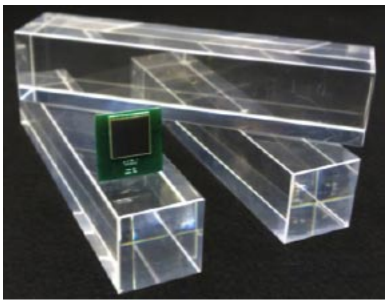

Fig. 5. – Crystal calorimeters and silicon photomultiplier being tested for the E989 experiment.

Since the Fermilab E989 experiment will reuse several pieces of experimental equipment from the previous experiment it has to be moved to the Fermilab campus from the Brookhaven campus. This includes the $50'$ diameter cryostat that cannot be taken apart. The majority of the equipment has been moved from Brookhaven to Fermilab. This includes the continuously wound cryostat which made the move over the summer of 2013. It traveled by truck, barge and then truck again to get from the Brookhaven campus to the Fermilab Campus where arrived at the end of July.

5. – Conclusions

Currently there is three sigma difference between the theoretical prediction and experimental measurement for the value of the muon $g-2$. In order to see if this difference is real the uncertainties on both the theoretical value and the experimental measurement must drop. The theory side will continue to work on the Hadronic Vacuum Polarization term. The experimental side is repeating the measurement at Fermilab with a goal of dropping the uncertainty by a factor of four. The planned start for data taking at Fermilab is 2016. If the uncertainty drops and the central value stays the same, the difference between the two will be over 5σ making the difference very interesting.

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