The new g-2 experiment at Fermilab

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Abstract. There is a long standing discrepancy between the Standard Model prediction for the muon g-2 and the value measured by the Brookhaven E821 Experiment. At present the discrepancy stands at about three standard deviations, with an uncertainty dominated by the theoretical error. Two new proposals – at Fermilab and J-PARC – plan to improve the experimental uncertainty by a factor of 4, and it is expected that there will be a significant reduction in the uncertainty of the Standard Model prediction. I will review the status of the planned experiment at Fermilab, E989, which will analyse 21 times more muons than the BNL experiment and discuss how the systematic uncertainty will be reduced by a factor of 3 such that a precision of 0.14 ppm can be achieved.

1 Introduction

The muon anomaly $a_\mu = (g - 2)/2$ is a low-energy observable, which can be both measured and computed to high precision [1, 2]. Therefore it provides an important test of the Standard Model (SM) and it is a sensitive search for new physics [3]. Since the first precision measurement of a_μ from the E821 experiment at BNL in 2001 [4], there has been a discrepancy between its experimental value and the SM prediction. The significance of this discrepancy has been slowly growing due to reductions in the theory uncertainty. Figure 1 (taken from [5]) shows a recent comparison of the SM predictions of different groups and the BNL measurement for a_μ . The a_μ determinations of the different groups are in very good agreement and show a consistent $\approx 3\sigma$ discrepancy [5–7], despite many recent iterations in the SM calculation. It should be noted that with the final E821 measurement and advances in the theoretical SM calculation that both the theory and experiment uncertainties have been reduced by more than a factor two in the last ten years [8]. The accuracy of the theoretical prediction (δa_μ^{TH} , 5×10^{-10}) is limited by the strong interaction effects which cannot be computed perturbatively at low energies. The leading-order hadronic vacuum polarization contribution, a_μ^{HLO} , gives the main uncertainty ($\sim 3 \times 10^{-10}$) [9]. It can be related by a dispersion integral to the measured hadronic cross sections, and it is known with a fractional accuracy of 0.6%, i.e. to about 0.4 ppm. The $\mathcal{O}(\alpha^3)$ hadronic light-by-light contribution, a_μ^{HLbL} , is the second dominant contribution to error in the theoretical evaluation. It cannot at present be determined from data, and relies on using specific models. Although its value is almost two orders of magnitude smaller than a_μ^{HLO} , it is much worse known

(with a fractional error of the order of 30%) and therefore it still give a significant contribution to δa_μ^{TH} (between 2.5 and 4×10^{-10}).

From the experimental side, the error achieved by the BNL E821 experiment is $\delta a_\mu^{\text{EXP}} = 6.3 \times 10^{-10}$ (0.54 ppm) [10]. This impressive result is still limited by the statistical errors, and a new experiment, E989 [11], to measure the muon anomaly to a precision of 1.6×10^{-10} (0.14 ppm) is under construction at Fermilab. If the central value remains unchanged, then the statistical significance of the discrepancy with respect to the SM prediction would be over 5σ , see Ref. [2], and would be larger than this with the expected improvements in the theoretical calculation.

2 Measuring a_μ

The measurement of a_μ uses the spin precession resulting from the torque experienced by the magnetic 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. With the assumption 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. Because electric quadrupoles are used to provide vertical focusing in the storage ring, their electric field is seen in the muon rest frame as a motional magnetic field that can affect the spin precession frequency. In the presence of both $\vec{E}$ and $\vec{B}$ fields, and in the case that $\vec{\beta}$ is perpendicular to both, the anomalous precession frequency (i.e. the frequency at which the muon's spin advances relative to its

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Figure 1. Standard model predictions of a_μ by several groups compared to the measurement from BNL (taken from [5]).

momentum) is

$$\begin{aligned}\vec{\omega}_a &= \vec{\omega}_S - \vec{\omega}_C \\ &= -\frac{q}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]\end{aligned}\quad (1)$$

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

$$a_\mu = \frac{\tilde{\omega}_a / \tilde{\omega}_p}{\lambda - \tilde{\omega}_a / \tilde{\omega}_p} = \frac{R}{\lambda - R}, \quad (2)$$

where $\lambda = \mu_\mu / \mu_p = 3.183345137(85)$ (determined experimentally from the hyperfine structure of muonium), and $R = \tilde{\omega}_a / \omega_p$. The tilde over ω_a means it has been corrected for the spread in the beam momentum (the so-called electric-field correction) and for the vertical betatron oscillations which mean that $\vec{\beta} \cdot \vec{B} \neq$ (the so-called pitch corrections): these are the only corrections made to the measurement. The magnetic field in Eq. (1) 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. This was possible in E821 where the uncertainty on the magnetic field averaged over the muon distribution was 170 ppb (parts per billion). The coefficient of the $\vec{\beta} \times \vec{E}$ term in Eq. (1) vanishes at the “magic” momentum of 3.094 GeV/c where $\gamma = 29.3$. Thus a_μ can be determined by a precision measurement of ω_a and B .

At this magic momentum, the electric field is used only for muon storage and the magnetic field alone determines the precession frequency. The finite spread in beam momentum and vertical betatron oscillations introduce small (sub ppm) corrections to the precession frequency. These are the only corrections made to the measurement.

The experiment consists of repeated fills of the storage ring, each one 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 64.4 μs , and the data collection period is typically 700 μs . The g-2 precession period is 4.37 μs , and the cyclotron period ω_C is 149 ns.

Figure 2. Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 μs [10].

Because of parity violation in the weak decay of the muon, a correlation exists between the muon spin and the direction of the high-energy decay electrons. 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. The E821 storage ring was constructed as a “super-ferric” magnet, 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 24 detector stations were placed symmetrically around the inner radius of the storage ring. The detectors were made of Pb/SciFi electromagnetic calorimeters which measured the decay electron energy and time of arrival. 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.

3 The Fermilab experiment

The E989 experiment at Fermilab plans to measure a_μ to an uncertainty of 16×10^{11} (0.14 ppm), derived from a 0.10 ppm statistical error and roughly equal 0.07 ppm systematic uncertainties on ω_a and ω_p .

The proposal efficiently uses the unique properties of the Fermilab beam complex to produce the necessary flux of muons, which will be injected and stored in the (re-located) muon storage ring. To achieve a statistical uncertainty of 0.1 ppm, the total data set must contain more than 1.8×10^{11} detected positrons with energy greater than 1.8 GeV, and arrival time greater than $30 \mu\text{s}$ after injection into the storage ring. Four out of 20 of the 8-GeV Booster proton batches in 15 Hz operational mode, each subdivided into four bunches of intensity 10^{12} p/bunch, will be used to provide muons. The proton bunches fill the muon storage ring at a repetition rate of 12 Hz, to be compared to the 4.4 Hz at BNL. The proton bunch hits a target in the antiproton area, producing a 3.1 GeV/c pion beam that is directed along a nearly 2000 m decay line, including several revolutions around the Delivery Ring, which are used to further eliminate pions and to displace secondary protons from muons using time of flight and a kicker to sweep out the protons. The resulting pure muon beam is injected into the storage ring. The muons enter the ring through a superconducting inflector magnet. At present it is envisaged that the BNL inflector will be used but there is a vigorous R&D programme underway investigating the possible use of a new large aperture inflector that would increase the number of stored muons and reduce the multiple scattering. A better optimized pulse-forming network will energize the storage ring kicker to place the beam on a stable orbit. The pion flash (caused by pions entering the ring at injection) will be eliminated owing to the long beamline, and the muon flux will be significantly increased because of the ability to take zero-degree muons.

Figure 3. The new MC-1 building at Fermilab, where the muon g-2 storage ring is being reassembled in the larger part to the left. The part to the right houses the counting room, electronics, etc, with cryogenics services further right. (Image credit: Fermilab.)

In the summer of 2013 the E821 muon storage has been moved from Brookhaven to Fermilab and it has been already relocated in the newly completed MC-1 building at Fermilab (see Figs. 3 and 4) with a stable floor and good temperature control, neither of which were available at Brookhaven.

The new experiment will require upgrades of detectors, electronic systems and data acquisition equipment to handle the much higher data volumes and slightly higher instantaneous rate and also to reduce systematic errors on the measurement of ω_a and ω_p . 24 Electromagnetic calorimeters stations with large area SiPM ($1.2 \times 1.2 \text{ cm}^2$) readout will be used. Each calorimeter is composed by 9 wide $\times$ 6 height Cerenkov lead fluoride (PbF_2) crystals wrapped in a black absorptive material (tedlar). The

Figure 4. Re-assembly of the g-2 storage-ring magnet at Fermilab, after the three superconducting coils were positioned gently on top of the newly assembled bottom ring of steel yoke segments. The coils and their complex interconnect system (top right in photo) were transported as a single unit from Brookhaven to Fermilab by land, sea and river, in 2013. (Image credit: Fermilab.)

Figure 5. Comparison of the shimming from 2015 and 2016.

high level of segmentation improves pileup recognition. Three 1500 in vacuum straw tracker tubes will be used to precisely monitor properties of the muon beam via tracking of Michel decay positrons. Also the provide data for an improvement of the electric dipole moment measurement, which can be obtained in parallel [12]. In addition an high precision laser calibration system will be used to untangling gain from other systematics and reduce gain fluctuation contribution to the systematic error at the level of 0.02 ppm. A modern data acquisition system will be used to read out waveform digitizer data at 800 MHz and to store it in order to be able to use in parallel different analysis technique. Another important contribution to reduce the error on the determination of a_μ is related to the measurement of ω_p . The storage ring magnetic field will be shimmed to an impressive uniformity. The magnet achieved full power in September 21 of 2015 with a peak to peak variation of 1400 ppm; in August 2016 the peak variation was reduced to 50 ppm (5). The goal of shimming is a peak to peak variation of 50 ppm with a muon weighted systematic uncertainty of 70 ppb, in order to improve by a factor 2 with respect to the 170 ppb of BNL.

In less than two years of running, the statistical goal of 4×10^{20} protons on target can be achieved for positive muons. A follow-up measurement using negative muons is possible. Two additional physics results will be obtained

from the same data: a new limit on the muon's electric dipole moment; and, a more stringent limit on possible CPT or Lorentz violation in muon spin precession. The first physics data-taking is expected in 2017. A BNL-level result in terms of precision is expected in 2018, while the final measurement with an uncertainty of 140 ppb (an improvement by a factor of 4 over E821) is expected in 2020.

4 Conclusion

The measurements of the muon $g-2$ have been an important benchmark for the development of QED and the Standard Model. In the recent years, following the impressed accuracy (0.54 ppm) reached by E821 experiment at BNL, a worldwide effort from different theoretical and experimental groups have significantly improved its SM prediction. At present there appears to be a 3σ difference between the theoretical (SM) and the experimental value. This discrepancy, which would fit well with SUSY expectations and other beyond the Standard Model theories, is a valuable constraint in restricting physics beyond the standard model and guiding the interpretation of LHC results. In order to clarify the nature of the observed discrepancy between theory and experiment and eventually firmly establish (or constrain) new physics effects, new direct measurements of the muon $g-2$ with a fourfold improvement in accuracy have been proposed at Fermilab by E989 experiment, and J-PARC. Data taking for the E989 experiment is expected to start in 2017.

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