EPJ Web of Conferences 96, 01002 (2015)
DOI: 10.1051/epjconf/20159601002

The Muon *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 a comparable accuracy between experiment and theory. 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 ($\delta a_\mu^{\mathrm{TH}}$, between 5 and 6 $\times 10^{-10}$) 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 (between 4 and 5 $\times 10^{-10}$). It can be related by a dispersion integral to the measured hadronic cross sections, and it is known with a fractional accuracy of 0.7%, i.e. to about 0.4 ppm. The O(α^3) hadronic light-by-light contribution, a_μ^{HLbL}, is the second dominant 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 $\delta a_\mu^{\mathrm{TH}}$ (between 2.5 and 4 $\times 10^{-10}$).

From the experimental side, the error achieved by the BNL E821 experiment is $\delta a_\mu^{\mathrm{EXP}} = 6.3 \times 10^{-10}$ (0.54 ppm) [9]. This impressive result is still limited by the statistical errors, and a new experiment, E989 [10], 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 then 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

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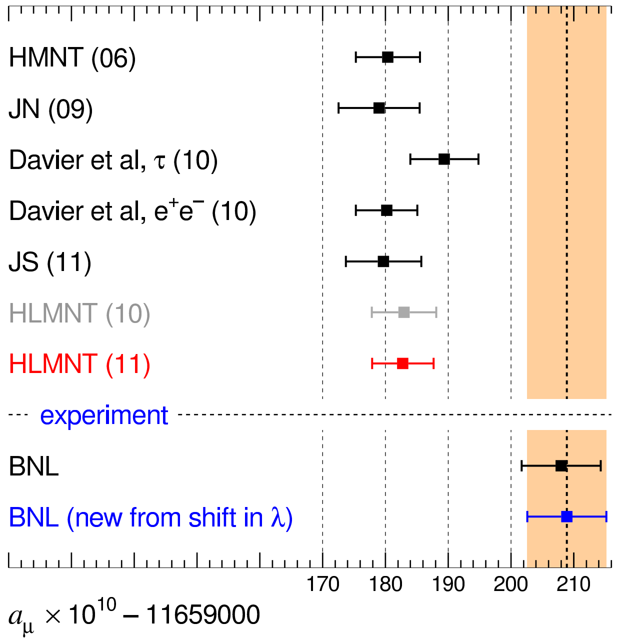

Figure 1. Standard model predictions of a_μ by several groups compared to the measurement from BNL (taken from [5]).

both, the anomalous precession frequency (*i.e.* the frequency at which the muon's spin advances relative to its momentum) is

$$\begin{aligned}\vec{\omega_a} &= \vec{\omega_S} - \vec{\omega_C} \\ &= -\frac{q}{m}\Big[a_\mu \vec{B} - \Big(a_\mu - \frac{1}{\gamma^2 - 1}\Big)\frac{\vec{\beta} \times \vec{E}}{c}\Big] \end{aligned} \qquad (1)$$

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

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

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 $< B >_{\mu-dist}$ to sub-ppm precision. This was possible in E821 where the uncertainty on the magnetic field averaged over the muon distribution was 30 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.

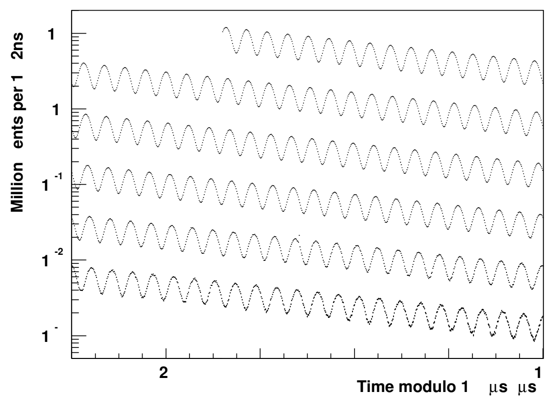

Figure 2. Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 μs [9].

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.

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