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The New 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, 6, 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 ($\delta a_\mu^{\rm TH}$, between 5 and 6×10^{-10}) is limited by the strong interaction effects which cannot be computed perturbatively at low energies. The leading-order hadronic vacuum polarization contribution, $a_\mu^{\rm HLO}$, gives the main uncertainty (between 4 and 5 $\times10^{-10}$). 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, $a_\mu^{\rm HLbL}$, 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 $a_\mu^{\rm HLO}$, it is much worse known (with a fractional error of the order of 30%) and therefore it still give a significant contribution to $\delta a_\mu^{\rm TH}$ (between 2.5 and 4 $\times10^{-10}$).

From the experimental side, the error achieved by the BNL E821 experiment is $\delta a_\mu^{\rm EXP} = 6.3\times10^{-10}$ (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 signif-

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icance 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.

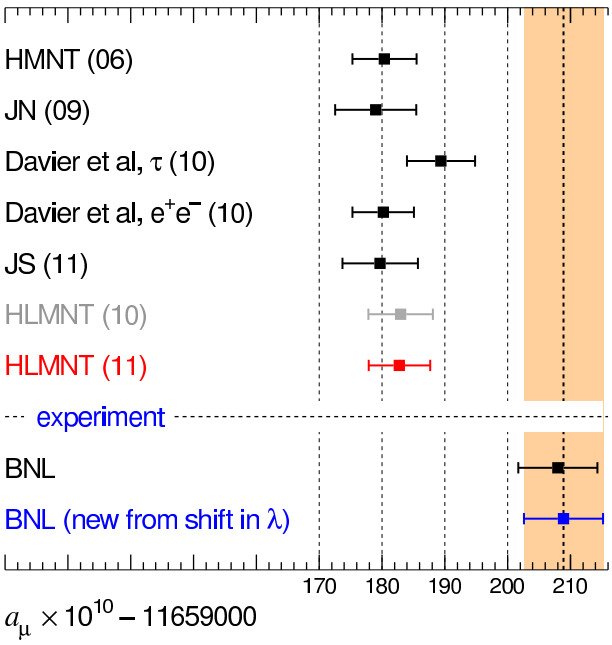

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL (taken from [5]).

2. Recent results and expected improvement on the hadronic contribution

In contrast to the QED and Electroweak contributions to a_μ, which can be calculated using perturbation theory, and therefore are well under control, the hadronic contributions (LO VP and HLbL) cannot be computed reliably using perturbative QCD. The hadronic contribution $a_\mu^{\rm HLO}$ can can be computed from hadronic e^+e^- annihilation data via a dispersion relation, and therefore its uncertainty strongly depends on the accuracy of the experimental data. For the Hadronic Light-by-Light contribution $a_\mu^{\rm HLbL}$ there is no direct connection with data and therefore only model-dependent estimates exist. As the hadronic sector dominates the uncertainty on the theoretical prediction $a_\mu^{\rm TH}$, it has been the subject of considerable recent activity from both experimental and theoretical groups, with the following outcomes:

- A precise determination of the hadronic cross sections at the e^+e^- colliders (VEPP-2M, DAΦNE, BEPC, PEP-II and KEKB) has allowed a determination of $a_\mu^{\rm HLO}$ with a fractional accuracy below 1%. These efforts have led to the development of dedicated high precision theoretical tools such as the addition of Radiative Corrections (RC) and the non-perturbative hadronic contribution to the running of α (i.e. the vacuum polarisation, VP) into the Monte Carlo (MC) programs used for the analysis of the experimental data [11];
- The use of '*Initial State Radiation*' (ISR) data [12, 13, 14] which has opened a new way to precisely obtain the electron-positron annihilation cross sections into hadrons at particle factories operating at fixed beam-energies [15, 16].
- A dedicated effort on the evaluation of the Hadronic Light-by-Light contribution (see for example [17]), where two different groups [18, 6] have obtained consistent values (with slightly different errors), and therefore strengthened the confidence in the reliability of these estimates.
- Impressive progress on the lattice, where an accuracy of $\sim 4\%$ has been reached on the four-flavour calculation of $a_\mu^{\rm HLO}$ [19];
- A better agreement between the e^+e^-- and the $\tau-$based evaluation of $a_\mu^{\rm HLO}$, due to improved isospin corrections [7]. These two sets of data are now broadly in agreement (with τ data moving towards e^+e^-- data) after including vector meson and $\rho-\gamma$ mixing [20, 21].

Further improvements are expected on the calculations of the hadronic contribution to a_μ on the timescale of the new g-2 experiments at Fermilab and J-PARC and this will be augmented, on the experimental side, by more data from current and future e^+e^- colliders. From the theoretical side, the lattice calculation has already reached a mature stage and has real prospects to match the experimental precision. From both activities a further reduction of the error on $a_\mu^{\rm HLO}$ can be expected and thus progress on $a_\mu^{\rm HLbL}$ will be required. Although for the HLbL contribution there isn't a direct connection with data, $\gamma-\gamma$ measurements performed at e^+e^- colliders will help constrain the on-shell form factors [22, 23] and lattice calculations will help better determine the off shell contributions.

3. 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 muons spin advances relative to its 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

$$a_\mu = \frac{\tilde{\omega_a}/\omega_p}{\lambda - \tilde{\omega_a}/\omega_p} = \frac{R}{\lambda R}, \quad (2)$$

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 $< B >_{\mu-dist}$ 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.

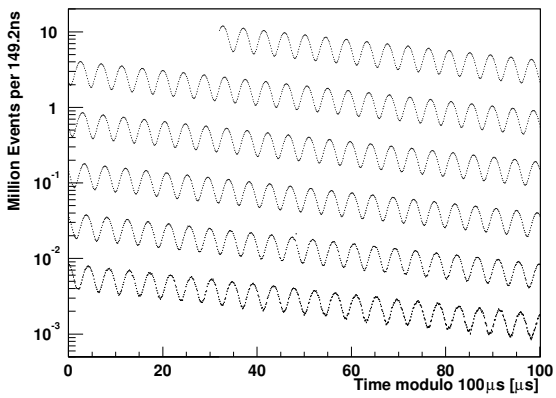

Figure 2: Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 μs [9].

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.

4. The FERMILAB PROPOSAL: E989

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 (relocated) 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 μs 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.

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, electronics and data acquisition equipment to handle the much higher data volumes and slightly higher instantaneous rates. Electromagnetic calorimeters made of lead fluoride (PbF2) crystals, with large area (1.2×1.2 cm) Silicon Photo-Multiplier (SiPM) readout will be used. A prototype matrix made of 28 crystals together with SiPM bias power supply and a laser diode based monitoring system has been successfully tested at the SLAC National Accelerator Laboratory (SLAC) test beam facility [24]. In-vacuum straw drift tubes will be used to measure the characteristics of the muon beam, and provide data for an improved muon electric dipole moment measurement, which can be obtained in parallel [25]. A modern data acquisition system will be used to read out waveform digitizer data and store it so that both the traditional event mode and a new integrating mode of data analysis can both be used in parallel. The systematic uncertainty on the precession frequency is expected to improve by a factor 3 thanks to the reduced pion contamination, the segmented detectors, and an improved storage ring kick of the muons onto orbit.

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.)

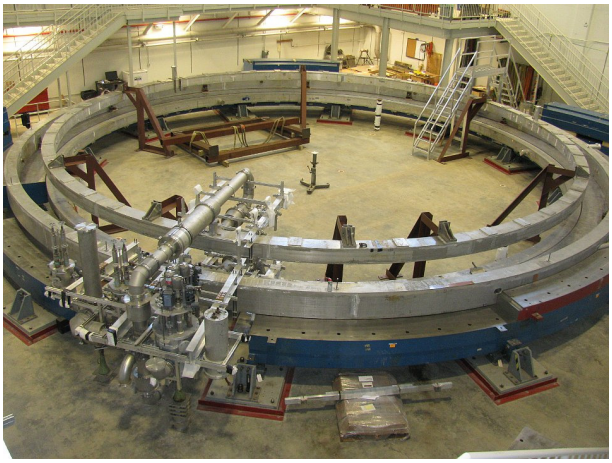

Figure 4: Re-assembly of the g-2 storage-ring magnet at Fermilab, after the three superconducting coils were positioned gently on top of the newly assembled bottom ring of steel yoke segments. The coils and their complex interconnect system (top right in photo) were transported as a single unit from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

The storage ring magnetic field will be shimmed to an even more impressive uniformity, and improvements in the field-measuring system will be implemented. The systematic error on the magnetic field is halved by better shimming, and other incremental changes. 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 early 2017. The next critical milestone will be the cooling of the superconducting coils and the powering of the storage-ring magnet, which is expected by the spring of 2015.

5. 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 significant 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. First results from E989 are expected around 2017/18.

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