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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 comparable accuracy between experiment and theory. Two new proposals at Femilab and J-PARC plan to improve the experimental uncertainty of a factor 4, and there are good motivation to expect a further reduction of the error from the theoretical side. I will review the status of the proposal to Fermilab, E989, and discuss how the goal of 0.14 ppm on the muon anomaly can be achieved, by collecting more than 21 times the statistics of the BNL measurement, and obtaining a factor of 3 reduction in the overall systematic error.

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). Therefore it provides an important test of the Standard Model (SM) and it is sensitive search for new physics 2). Since the first precision measurement of a_μ from E821 experiment at BNL in 2001 3), there has been a discrepancy between its experimental value and the SM prediction. This discrepancy has been slowly growing due to impressive theory and experiment recent achievements. Figure 1 (from 4)) shows an up-to-date comparison of the SM predictions of different groups and the BNL measurement for a_μ. Evaluation of different groups are in very good agreement, showing a persisting $3\,\sigma$ discrepancy (as, for example, $26.1 \pm 8.0 \times 10^{-10}$ 4)), despite many changes in the recent history. It should be noted that both theory and experiment uncertainties have been reduced by more than a factor two in the last ten years[1]. 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 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 $\mathrm{O}(\alpha^3)$ hadronic light-by-light contribution, a_μ^{HLbL}, is the second dominant error to the theoretical evaluation. It cannot at present be determined from data, and relies on same specific models. Although its value is almost one order 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 significantly 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) 6). This impressive result is still limited by the statistical errors, and a new experiment, E989 7) at Fermilab, to measure the muon g-2 to a precision of 1.6×10^{-10} (0.14 ppm) has received a CD0 approval, and funding from the DOE has begun. CD1 is expected in mid 2013.

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[1] In 2001 this discrepancy was $(23.1 \pm 16.9) \times 10^{-10}$ 5).

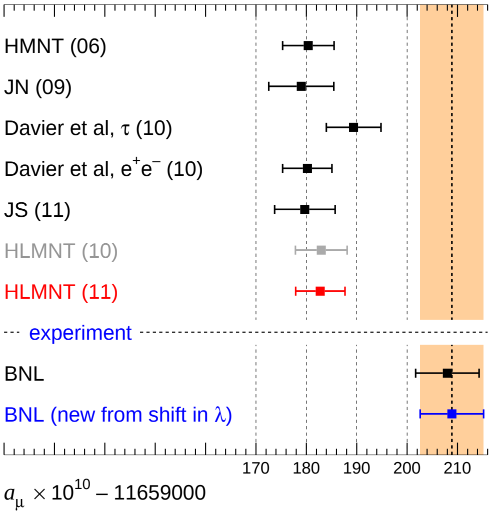

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL (taken from $^{4)}$).

2 Recent results and expected improvement on the hadronic contribution

Differently from the QED and Electroweak contributions to a_μ, which can be calculated using perturbation theory, and therefore are well under control, the hadronic ones (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 a direct connection with data and therefore only model-dependent estimates exist. As the hadronic sector dominates the uncertainty on the theoretical prediction $a_\mu^{\rm TH}$, considerable effort has been put by on it by the experimental and theoretical groups, reaching the following main achievements:

- A precise determination of the hadronic cross sections at the e^+e^- colliders (VEPP-2M, DAΦNE, BEPC, PEP-II and KEKB) which allowed a determination of $a_\mu^{\rm HLO}$ with a fractional accuracy below 1%. These efforts led to the development of dedicated high precision theoretical tools, like Radiative Corrections (RC) and the non-perturbative hadronic contribution to the running of α (i.e. the vacuum polarisation, VP) in Monte Carlo (MC) programs used for the analysis of the data [8];

- The use of '*Initial State Radiation*' (ISR) which opened a new way to prcisely obtain the electron-positron annihilation cross sections into hadrons at particle factories operating at fixed beam-energies [9].
- A dedicate effort on the evaluation of the Hadronic Light-by-Light contribution (see for example [10]), where two different groups [11, 12] obtained results consistent on the size of the contribution (with sligthly different errors), and therefore strengthening our confidence in the reliability of these estimates;
- an impressive progress on lattice, where an accuracy of $\sim 2\%$ were reached on on the two-flavor QCD correction to $a_\mu^{\rm HLO}$ [13];
- A better agreement between the e^+e^-- and the $\tau-$ based evaluation of $a_\mu^{\rm HLO}$, thanks to improved isospin corrections [14]. These two sets of data are eventually in agreement (with τ data moving towards e^+e^-- data) after including vector meson and $\rho-\gamma$ mixing [15, 16, 17].

For sure further improvements are expected on the hadronic contribution to a_μ on the timescale of the new g-2 experiments at Fermilab and J-PARC. On the experimental side more data are expected from current and future e^+e^- colliders. From the theory, the lattice calculation has already reached a mature stage and has real prospects to match experimental precision below 1%. From both activities a further reduction of the error on $a_\mu^{\rm HLO}$ can be expected. What about $a_\mu^{\rm HLBL}$? With the expected reduction of the error on $a_\mu^{\rm HLO}$ and the planned improved precision of the new g-2 experiments, it is clear that it will become the main subject of future theoretical investigations. Although there isn't a direct connection with data, $\gamma-\gamma$ measurements perfomed at e^+e^- colliders will help us to constrain on-shell form factors [18]. Lattice calculation would help for 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. Assuming 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 feld is seen in the muon rest frame as a motional magnetic feld 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

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

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

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

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 electric-field and pitch ($\vec{\beta} \cdot \vec{B} \neq 0$) corrections [3]. 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 time 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.

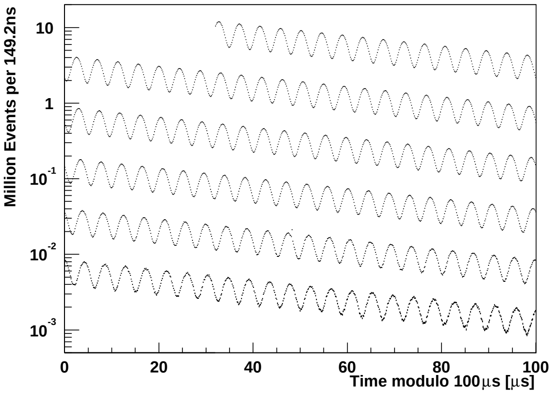

Figure 2: Distribution of electron counts versus time for the 3.6 billion muon decays. The data are wrapped around modulo 100 μs [6].

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. The plan uses 6 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. The proton bunches fill the muon storage ring at a repetition rate of 18 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 900 m decay line. The resulting pure muon beam is injected into the storage ring. The muons will enter the ring through a new superconducting inflector magnet, which will replace the existing one, which is wound in such a manner that the coils intercept the beam on both ends of the magnet. The new inflector will result in a higher muon storage efficiency. Once entering the ring, a better optimized pulse-forming network will energize the storage ring kicker to place the beam on a stable orbit. The pion flashes (caused by pions entering the ring at injection) will be decreased by a factor of 20 from the BNL level, and the muon flux will be significantly increased because of the ability to take zero-degree muons. The stored muon-per-proton ratio will be increased by a factor of 5 to 10 over BNL.

The E821 muon storage will be relocated to Fermilab, in a new building 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. 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. The storage ring magnetic feld will be shimmed to an even more impressive uniformity, and improvements in the feld-measuring system will be implemented. The systematic error on the magnetic field is halved by better shimming, relocations of critical NMR probes, 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 run using negative muons is possible, depending on future scientic motivation. Two additional physics results will be obtained from the same data: a new limit on the muon's electric dipole moment (up to 100 times better); and, a more stringent limit on possible CPT or Lorentz violation in muon spin precession. A technically driven schedule permits data taking to begin in 2016.

5 Conclusion

The measurements of the muon g-2 have been a 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, 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. E989 has received a CD0 approval in September 2012 and the

CD1 is expected in mid 2013. First results could be available around 2017/18.

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