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PAST AND FUTURE OF THE MUON G-2 EXPERIMENTS

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Abstract

The most recent high precision measurement of the anomalous magnetic moment of the muon, $a_\mu = (g_\mu - 2)/2$ was performed at the Brookhaven National Laboratory (BNL) by the experiment E-821 and deviates from the Standard model of particle physics calculation by approximately three standard deviations. Since this disagreement could be evidence for new physics, two new Muon $g-2$ experiments are underway to measure a_μ with improved precision. Experiment E-989, located at the Fermi National Accelerator Laboratory (FNAL), will measure a_μ by injecting a beam of polarized positive muons at the "magic momentum" inside the same magnetic storage ring used at BNL. The experiment is currently in commissioning phase and aims to start taking data in 2018. Experiment E-34, planned to be located at the Japan Proton Accelerator Research Complex (J-PARC), will use a novel approach based on an ultra-cold muon beam. After a brief review of the status of the theoretical calculation and the E-821 result, this contribution discusses the status of the new Muon $g-2$ experiments.

1 Introduction

The magnetic moment of the muon is a property of the particle that quantifies the strength of its interaction with the magnetic field, and is given by:

$$\vec{\mu} = g_\mu \frac{e}{2m} \vec{s} \tag{1}$$

where e is the electron charge, m and s are the mass and the spin of the muon. The proportionality factor g_μ is predicted to be exactly two in the Dirac theory. In the framework of the standard model of particle physics (SM) contributions from quantum electrodynamics (QED), electroweak (EW) and quantum chromodynamics (QCD) effects are such that:

$$a_\mu^{\text{theo.}} = \frac{1}{2}(g_\mu^{\text{SM}} - 2_{\text{Dirac}}) = \mathcal{O}(10^{-3})_{\text{QED}} + \mathcal{O}(10^{-9})_{\text{EW}} + \mathcal{O}(10^{-7})_{\text{QCD}}, \tag{2}$$

Table 1: *Current theoretical values of a_μ with all the Standard Model contributions detailed (from [1]). Leading-order and higher-orders are indicated with (lo) and (ho) respectively. For HVP (lo) are quoted the values of two recent evaluations. A new reevaluation is reported in [7].*

Contribution		$a_\mu^{\text{theo.}}(\times 10^{-11})$			
QED		116584718.95	±	0.08	
EW		154	±	1	
QCD	HVP (lo)	6923	±	42	[4]
QCD	HVP (lo)	6949	±	43	[5]
QCD	HVP (ho)	−98.4	±	0.7	[5]
QCD	HLbL	105	±	26	
Total SM		116591802	±	49	[4]
Total SM		116591828	±	50	[5]

where a_μ is called muon anomaly. The value of each term for the current prediction of $a_\mu^{\text{theo.}}$ are summarized in Table 1. The QED [2] and EW [3] terms are very well known, while the QCD terms (the hadronic vacuum polarization, HVP [4] [5], and the hadronic light-by-light, HLbL [6]) are the dominant contribution on the overall theoretical uncertainty. The relative precision for the current theoretical value of the anomalous magnetic moment of the muon is about 0.42 ppm [1].

Experimentally, a_μ was measured several times at CERN and more recently at BNL (experiment E-821). The current best experimental measurement was published in 2006 by the E-821 collaboration and is $a_\mu^{E821} = 116592089$
$\pm\ 63 \times 10^{-11}$ [8]. This value is larger that the expected SM prediction by about 3 standard deviations (3σ) and it has a relative precision of 0.54 ppm. Since this discrepancy might be a signal of new physics, it is necessary to confirm it. The new $g-2$ experiments are aiming to achieve a level of precision four times higher than the one of E-821, approximately 0.14 ppm. If the discrepancy remains the same, this precision will provide 5 standard deviations, and with improvements on the theoretical uncertainties could reach 8σ of significance [1].

2 The experimental measurement method

The muon anomaly is measured by injecting polarized muons into a magnetic storage ring. In the presence of both magnetic ($\vec{B}$) and electric ($\vec{E}$) fields the muon anomaly introduces an anomalous precession frequency that could be written as:

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{3}$$

where e is the electron charge, m is the mass of the muon, γ is the Lorentz factor and $\vec{\beta}$ is the particle velocity in units of speed of light c. If the electric field term of Equation (3) cancels out, a_μ can be determinated by precise measurements of ω_a and ω_p (*i.e.*, the magnetic field B in units of proton Larmor frequency) as follows:

$$a_\mu = \frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}\frac{\omega_a}{\omega_p}. \tag{4}$$

In Equation (4) the electron-to-proton magnetic moment ratio $\mu_e/\mu_p = -658.2109866(20)$, the muon-to-electron mass ratio $m_\mu/m_e = 206.7682826(46)$ and the gyromagnetic moment of the electron $g_e/2 =$

−2.00231930436182(52) are obtained from other experiments with relative precision of 3.0 ppb, 22 ppb and 0.00026 ppb, respectively [9].

Two different approaches are used to eliminate the term that depends on the electric field term. The first approach, which was used by the CERN-III, the BNL E-821 experiments and will be used by the FNAL E-989 experiment, consists of injecting muons with $\gamma = 29.3$ (*i.e.*, muons at the so-called magic momentum of 3.09 GeV/c). The second approach will be implemented by the J-PARC E-34 experiment, and consist of employing an ultra-cold muon beam for which the focusing electric field is not necessary.

3 The E-989 Experiment

The Muon $g-2$ experiment at Fermilab (E-989) is an improved version of the BNL E-821 experiment. The main limitation of the BNL experiment was statistical. The FNAL accelerator complex will provide a muon beam with higher rate and reduced contamination than the BNL beam, resulting in a projection of a factor of 20 increase in muon statistics. The muon beam will be produced by collecting the 3.1 GeV/c polarized and positively-charged muons which decay from pions. The pions are generated by colliding a 8 GeV proton beam with an Inconel target. The muon beam will be injected by means of an inflector magnet, which locally cancels the magnetic field, into the 15-ton and 14-m diameter cryostat ring that was transported from Brookhaven (New York) to Fermilab (near Chicago) in the summer 2013. The ring consists of rectangular vacuum chambers surrounded by a cryo-system and a C-shaped dipole magnets which provide a vertical magnetic field of 1.4 T. The magnetic field inside the storage ring is as uniform as possible (this was obtained by a careful shimming procedure), and it is kept mechanically and thermally stable. The injected muons are moved on the center of the storage ring's orbit by kicker magnets and are vertically contained by the electrostatic quadrupoles plates. The ring is also instrumented with collimators to remove the off-momentum muons and a beam monitoring system.

The measurement of the magnetic field (ω_p), is performed using approximately 400 fixed NMR probes located in the vacuum chambers outside the muon storage ring. Periodically, a trolley travels inside the ring orbit and measures the magnetic field in the muon storage ring. By combining the two measurements it is possible to obtain a precise map of the magnetic field experienced by the stored muons around the ring.

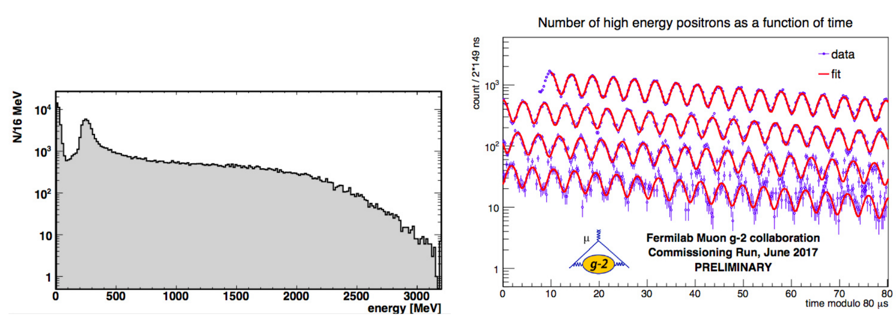

Figure 1: *a) Energy distribution from Summer 2017 data recorded in the calorimeters. The low energy peaks are from proton and lost muons. b) Time distribution of the positrons from muon decay from two weeks of data accumulated during the Summer 2017 run.*

To measure ω_a, the positrons from the decay of the stored muon are detected by 24 highly segmented lead-fluoride electromagnetic calorimeters and 3 straw tracker chambers positioned around the inside of the storage ring. The detectors will record the energy and the arrival time of these decay positrons. These informations are then used to build the so-called wiggle plot, in which the number of positrons with an energy above a threshold are collected as a function of the time from the injection into the ring. Since the high energy positrons are preferentially emitted with momentum aligned with the muon spin, it is possible to extract ω_a from the wiggle plot. Figure 1a) shows the energy distribution measured by the calorimeters, while figure 1b) the wiggle plot with a preliminary analysis fit. These data were acquired during a 5 week commissioning run performed in summer 2017 to test the experiment. Despite that during this run the rate of muons delivered by the accelerator complex was lower than the one planned for physics runs, the wiggle plot contains approximately 700,000 positrons collected during 2 weeks of the run, and corresponds to about the same statistics of the $g-2$ CERN-II experiment result [10].

4 The E-34 Experiment

The new $g-2$ experiment at J-PARC (E-34) proposes to measure a_μ by injecting an ultra-cold beam of positive muons inside a storage ring. The ultra-cold muon beam will be produced by colliding a 3 GeV/c^2 proton beam into a 20 mm graphite target to produce pions. These positive pions will be stopped on the surface of the target and they will decay into muons. The low-momentum polarized positive muons (called surface muons) will be collected and stopped into a second target to form muonium (μ^+-electron) atoms. At room-temperature, some of these muonium atoms diffuse into the target material and reach its surface where they will be ionized using laser pulses. The resulting ultra-cold muons are then accelerated to 300 MeV/c by a LINAC and injected into the storage ring. The transverse dispersion of the beam is expected to be 10^{-5} thanks to the cold-muon source, then there is no need of a focusing electric field inside the storage ring. Moreover, because of the low momentum (300 MeV/c) of the muons, the storage ring will be a compact 66-cm diameter solenoid with 3.0 T of magnetic field. The positrons produced by the muon decay will be detected with a silicon strip tracker located in the center of the solenoid. The E-34 experiment is at present developing all the components and it is expecting to start data-taking in 2020 [11].

5 Conclusions

The 3 standard deviations between the current theoretical calculation and the most recent experimental measurement of the muon's anomalous magnetic moment may be a hint of new physics. Two new $g-2$ experiments, the E-989 experiment at Fermilab and the E-34 experiment at J-PARC, are aiming to improve the experimental precision to 0.14 ppm. The E-989 experiment successfully completed a commissioning run in Summer 2017 and plans on starting to collect physics data in 2018. The E-34 will provide a measurement of a_μ using a new experimental method, which will be an independent cross-check of the previous measurements. These new direct measurements and a new improved SM prediction will have the potential to definitively confirm (or constrain) new physics effects.

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