The Muon g-2 Experiment Overview and Status as of June 2016

Jenny Holzbauer
University of Mississippi, University, Mississippi 38677, USA
E-mail: jholzbau@fnal.gov

Abstract. The Muon g-2 Experiment at Fermilab will measure the anomalous magnetic moment of the muon to a precision of 140 parts per billion, which is a factor of four improvement over the previous E821 measurement at Brookhaven. The experiment will also extend the search for the muons electric dipole moment (EDM) by approximately two orders of magnitude, with a sensitivity down to 10^{-21} e.cm. Both of these measurements are made by combining a precise measurement of the 1.45T storage ring magnetic field with an analysis of the modulation of the decay rate of the higher-energy positrons from the (anti-)muon decays recorded by 24 calorimeters and 3 straw tracking detectors. The recent progress in the alignment of the electrostatic quadrapole plates and the trolley rails inside the vacuum chambers and in establishing the uniform storage ring magnetic field will be described.

1. Introduction

In 2006, an experiment at BNL, E821, reported a final measured value of g-2 to high precision and it was found that the value was approximately 3 sigma away from the theoretical value [1]. In recent years, this tension has remained despite improvements in the theoretical calculation [2]. To help resolve this tension, two new experiments are being built or planned. One is E34, an ultra-cold muon beam experiment in Japan [3, 4]. The other is an improved version of E821, the Muon g-2 Experiment [5, 2], which has reference number E989. In this proceedings, we will discuss the physics of g-2 and the current standard model (SM) value, the new experiment procedure and setup, and discuss progress in building the new experiment.

2. Standard Model and Current Experimental Value

The quantity g is a constant which relates particle spin and magnetic moment. In Dirac theory, the value of g is exactly 2 [6]. However, higher order effects will alter this value. For example, new physics which interacts weakly, such as a new heavy W, could contribute in this way in SUSY models [7]. The muon is studied rather than the electron in this experiment because the muon is much heavier and thus is more sensitive to higher order corrections but still long lived enough to study. The experiment specifically studies what is known as the anomaly, which is a_μ =(g-2)/2.

The standard model theory calculation breaks down into four main components: quantum electrodynamics (QED) [8], electroweak (EW) [9], hadronic vacuum polarization (HVP) [10, 11] and hadronic light-by-light (HLbL) [12]. The first two, the QED and EW components are well known with relatively small uncertainties. As can be seen in Table 1, the QED component is the largest contribution to the standard model value but has the smallest uncertainty, while the hadronic terms are less well known. The hadronic vacuum polarization can be obtained from studies of e+e- to hadrons data from various experiments (or tau to hadrons). There is also work ongoing to include lattice information. The hadronic light by light term is particularly tricky and not obtainable directly from data. Data can be used to indirectly add constraints but the value is obtained from diagram calculations or from lattice calculations.

Table 1. Standard model components of the anomaly, taken directly from [2]. Two values are shown for HVP to reflect two recent estimates. The terms lo and ho indicate lower order and higher order, respectively. Other terms are defined in the text.

	Values in 10^{-11} units
QED ($\gamma + l$)	$116584718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077$
HVP(lo) [10]	6923 ± 42
HVP(lo) [11]	6949 ± 43
HVP(ho) [11]	-98.4 ± 0.7
HLbL	105 ± 26
EW	153.6 ± 1.0
Total SM [10]	$116591802 \pm 42_{\mathrm{H-LO}} \pm 26_{\mathrm{H-HO}} \pm 2_{\mathrm{other}}$ ($\pm 49_{\mathrm{tot}}$)
Total SM [11]	$116591828 \pm 43_{\mathrm{H-LO}} \pm 26_{\mathrm{H-HO}} \pm 2_{\mathrm{other}}$ ($\pm 50_{\mathrm{tot}}$)

The value of the anomaly from the BNL experiment [1], corrected for updated constants [13] and given in [2], is $a_\mu^{E821} = 116592089 \pm 63 \times 10^{-11}$ (54 ppm). The uncertainty is roughly twice as large as the standard model calculation uncertainty. The new experiment is expected to reduce this uncertainty by a factor of four to 0.14 ppm, which would give a 5 sigma deviation from the standard model calculation, assuming the central value remains the same for both the standard model calculation and the measurement. If the standard model uncertainty also improves, the deviation could be around 8 sigma under these same central value assumptions.

3. The Muon g-2 Experiment Plans and Status

The Muon g-2 Experiment is located at Fermilab. It reuses the BNL storage ring, which was moved carefully from BNL to Fermilab. Most parts, like vacuum chambers, could be shipped by normal means, but the 15 ton cryostat ring was trickier. It is large, heavy and the superconducting coils cannot flex more than approximately 3 mm. This portion was moved by the Emmert Corportation, which used a barge and a large truck. In 2015, the magnet and related cryo-systems were tested, and the magnet was cooled and powered at Fermilab. The required 1.45 Tesla field was achieved and the transportation was deemed a success.

The muons for the storage ring are produced by the Fermilab accelerator complex. The source protons are produced and moved by reused Tevatron equipment, and they collide with a lithium target to produce pions. These pions enter a long delivery ring where they decay to muons and neutrinos. The polarized, positively charged muon beam is then injected into the storage ring. The long delivery ring helps to reduce proton/pion contamination, which was an issue at BNL. The new experiment expects a factor of 20 increase in muon statistics over the BNL experiment and which will reduce the statistical error to 0.1 ppm.

In brief, the experiment consists of a cryo-system surrounding dipole magnets, which contain vacuum chambers with electrostatic quadrapole plates. The magnets and quadrapole plates work in tandem to keep the muons in the proper location. There are other parts like the

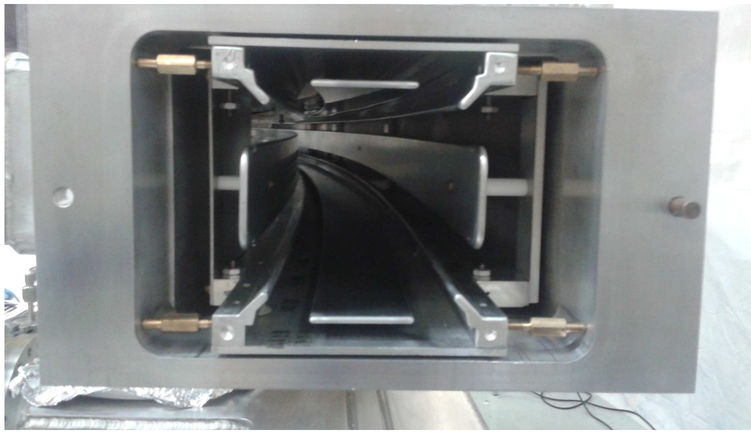

Figure 1. View of the cage with trolley rails and (most interior) four electrostatic quadrapole plates, from a vacuum chamber end flange.

inflector, kickers, collimators and a beam monitoring system, as well as a trolley that rides around inside of the ring to measure the field. Detector systems include both straw trackers and lead crystal calorimeters. Trackers were not used in the BNL experiment and should add valuable information to the new g-2 data. Additionally, the calorimeters now have multiple read out channels to reduce pileup.

The measurement consists of two quantities, ω_a and ω_p. The term ω_a is the precession frequency measured with high energy decay positrons and ω_p is the magnetic field (B) normalized to the proton lamour frequency. The spin and cyclotron frequencies can be combined to give the anomaly in terms of ω_a, B, and the charge over mass ratio (e/m). This can be rewritten in terms of ω_a/ω_p and the muon, proton magnetic moment ratio from hyperfine splitting. There is an additional electric field term which is removed by choosing the appropriate momenta of the muons, 3.09 GeV/c, known colloquially as the magic momentum. Not all muons will have exactly this momentum, which introduces some uncertainties and corrections into the analysis. Alignment efforts to ensure conformity of the muons are particularly important.

3.1. Status of the Ring Installation

The vacuum chambers contain the electrostatic quadrapole plates, as mentioned earlier. These plates are mounted to a cage structure which contains rails the B field measurement trolley will ride on, see Figure 1. The quadrapole plates are aligned to the design value to within $\pm$0.5 mm (top/bottom) or $\pm$0.75 mm (sides) over the length of the chamber, with larger $\pm$2.0 mm deviations allowed on shorter length scales. The cage rails are aligned to within $\pm$0.5 mm vertically to allow the trolley to ride smoothly, and the cage (and plates) is positioned radially to be centered on the magic radius, 7112 mm, the location where there muons will have the magic momentum value. The vertical alignment is done using a Hamar laser system along with a retroreflector, which allows a final measurement of the vertical alignment in vacuum, through a clear plexiglass flange. Digital calipers and micrometers are used for quadrapole plate alignment, for absolute vertical alignment before the use of the relative laser system, and for the radial alignment.

3.2. Status of the Magnetic Field Uniformity

To produce a uniform magnetic field, iron shims are strategically added throughout the ring. The field is measured and shims are added iteratively. Measurements use a shimming cart

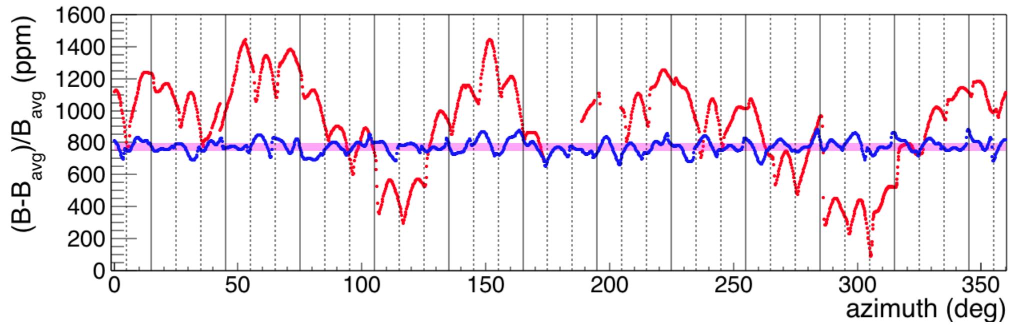

Figure 2. Magnetic field variation versus azimuth for the first survey (red) and a more recent June 2016 survey (blue) with the variation goal shown in a magenta band. Additional improvements to the field uniformity will continue through August 2016.

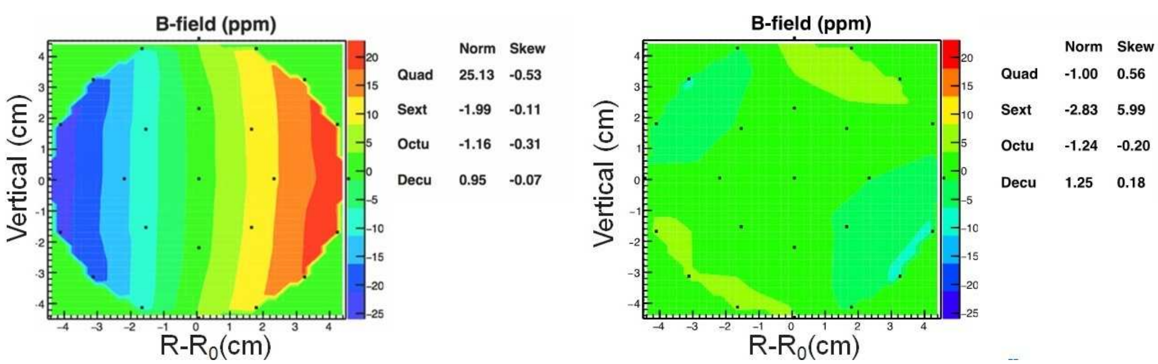

Figure 3. Azmuthally averaged magnetic field variation for the first survey (left) and a more recent June 2016 survey (right). Additional improvements to the field uniformity will continue through August 2016.

containing 25 nuclear magnetic resonance (NMR) probes and 4 capacitative gap sensors as well as 4 position sensors to give the cart location in r, θ, and z.

The initial field measurements when the magnet was first powered up were similar to those at BNL when it was first powered up. A variation was found of ±700 ppm in the field vs azimuth and ±25 ppm in the azimuthally averaged field. As of June 2016, the variation of the field has been reduced to ±200 ppm (RMS of about 40 ppm), as shown in Figure 2 and the azimuthally averaged field variation is reduced to ±6 ppm, as shown in Figure 3. These are much closer to the target field variations of ±25 ppm and $\pm < 1$ ppm, even before the planned laminated shims are applied. This application is expected to finish in August of 2016.

4. Summary

The Muon g-2 Experiment at Fermilab is well under way in terms of its construction and assembly. It is expected that the new experiment will improve the uncertainty on the measured value versus the previous measurement by a factor of four. The collaboration is very active and working hard to install the various ring components to ensure a uniform B field and correct muon location. Detector systems will be installed soon as well and data taking is expected in 2017, with the potential to resolve the tension of the previous result and the standard model calculation.

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