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The Fermilab Muon g-2 experiment

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Abstract

The anomalous magnetic moment of the muon can be both measured and computed to a very high precision, making it a powerful probe to test the standard model and search for new physics. The previous measurement by the Brookhaven E821 experiment found about three standard deviation discrepancy from the predicted value. The Muon g-2 experiment at Fermilab will improve the precision by a factor of four through a factor of twenty increase in statistics and a threefold reduced systematic uncertainty with an upgraded apparatus. The experiment will also carry out an improved measurement of the muon electric dipole moment. Construction at Fermilab is well underway.

1 Introduction and theoretical background

The muons magnetic moment $\vec{\mu}$ is given by,

$$\vec{\mu} = g\frac{q}{2m}\vec{s} \tag{1}$$

where the gyromagnetic ratio g of the muon is predicted to be 2 in case of structureless spin 1/2 particle of mass m and charge q, according to Dirac theory. Experimentally it is measured to be greater than 2. The muon anomaly a_μ, given by (g-2)/2 arises due to radiative corrections (RC), which couple the muon spin to virtual fields. These mainly include quantum electrodynamic processes (QED), electroweak loops, hadronic vacuum polarization (HVP) etc. as shown in Fig.1.

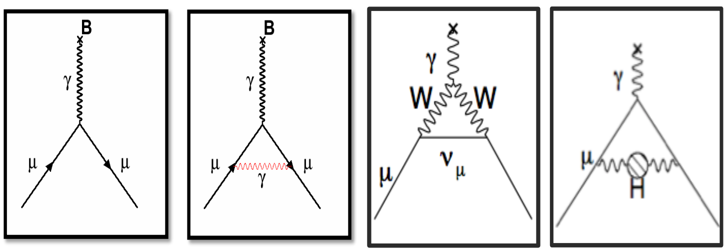

Figure 1: The SM correction in a_μ from QED, electroweak loops, HVP.

The leading RC from the lowest order QED process from the exchange of a virtual photon in Fig.1 i.e. the "Schwinger term", is calculated to be $a_\mu = (\alpha/2\pi) = 0.00116$ [1]. The difference between experimental and theoretical values of a_μ especially at sub-ppm precision, explores new physics well above the 100 GeV scale for many standard model extensions [2].

A difference of 3.6 σ [3] between theory and experiment, could indicate several possible models or any new model. These new models, can be generally illustrated using a relation discussed in [4] in which new physics (N.P.) contributions scale as [5] $\delta a_\mu(N.P.) = \mathcal{O}[C(N.P.)] \times (m_\mu/M)^2$ where M is the N.P. mass scale and C is the model's coupling strength, related to any N.P. contributions to the muon mass, $C(N.P.) \equiv (\delta m_\mu(N.P.)/\delta m_\mu)$. In the multi-TeV scale, a muon mass is generated by radiative effects (shown in green in Fig.2). The other possible models could be due to Z′, W′, universal extra dimensions, littlest Higgs assume a typical weak-interaction scale coupling (shown in red in Fig.2) [5]. The purple band in this figure represents unparticles, extra dimension models or SUSY with enhanced coupling [6]. Existence of dark photons or dark Z [7] from very weakly interacting and very light particles would correspond to a narrow band in the 10 - 100 MeV mass range, having an extremely small coupling, is not shown in this figure. In Fig.2 the yellow band represents the difference between theory and experiment and the blue band represents the improvement with combined theory and experimental error. Improved precision of measurement in a_μ to 140 parts per billion will continue to constrain or validate the energy scale of the models, which is the goal of "The E989 Muon g-2 Experiment". This requires 21 times more statistics than the previous Brookhaven E821 experiment and a threefold reduction of the systematic error.

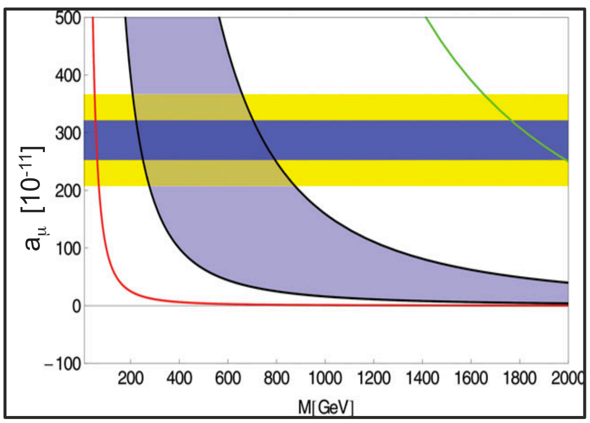

Figure 2: Generic classification of mass scales vs. a_μ contributions from new physics sources. Various possibilities are explained in Sec.1.

2 Storage ring technique

A polarized muon beam (from pion decay) of energy of 3.1 GeV is injected (through the inflector shown in Fig.3) in a storage ring of uniform magnetic field of 1.45 T with a cyclotron frequency of ω_c. Fig.3 shows the entire storage ring with the kickers (K1-K3), and the quadrupoles (Q1-Q4), the collimators (C), the NMR trolley garage and the fiber harps. An electron calorimeter is placed at a position indicated by the calorimeter number (1 to 24). We essentially measure the muon spin precession frequency ω_s relative to the cyclotron frequency i.e. $\omega_a = \omega_s - \omega_c$.

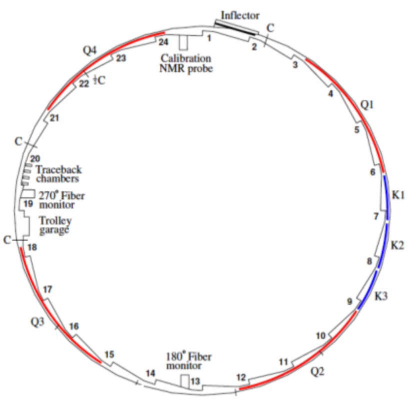

Figure 3: The layout of the storage ring from the E821 experiment.

These frequencies including Larmor and Thomas precession are approximately given by,

$$\begin{aligned} \omega_c &= \frac{e}{m\gamma} B \\ \omega_S &= \frac{e}{m\gamma} B(1 + \gamma a_\mu) \\ \omega_a &= \frac{eB}{m} a_\mu \end{aligned} \tag{2}$$

Thus, a_μ is extracted from ω_a, provided the magnetic field B is measured via NMR and recast a_μ in terms of proton precession frequency ω_p,

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} \tag{3}$$

The measurement of a_μ also requires an accurate value of μ_μ/μ_p as seen in Eq.3. The muons decay to positrons preferentially in direction of muon spin which are detected by the 24 calorimeters shown in Fig.3. The time spectrum of these positrons is given by,

$$N(t) = N_0 e^{-t/\tau}(1 + Acos(\omega_a t)) \tag{4}$$

with which ω_a is extracted. But care needs to be taken into account for the distortions in this spectrum due to pileup, gain instabilities, beam losses.

3 Experimental progress and details

The storage ring layout is shown in Fig.3 of the previous section. Here we emphasize on the details of the improvements required to achieve our goal. Several improvements are required to collect 21 times more muons than the previous effort at Brookhaven E821 experiment. This is accomplished by improved muon storage and using a long decay channel to produce muons that requires improvement of existing tunnels and building new ones. The usage of a delivery ring to get rid of pions would eliminate early unwanted background. The improved beam structure will have 4 batches of 4×10^{12} protons to the Recycler in 1.33 s supercycle with a frequency of 15 Hz. A proton batch is divided into four proton bunches of intensity 10^{12}. Thus, the experiment will receive 16 proton bunches per supercycle, i.e. a rate of 12 Hz.

We aim for enhanced improvements to the muon precession systematics due to calorimeters and trackers. To achieve this the calorimeter should resolve multiple particles and have high gain stability. Each calorimeter is made up of 9×6 PbF_2 Cherenkov crystals that are read by SiPMs (Silicon Photo Multipliers) which improves the resolution and pileup protection. A laser calibration system will be used for the accurate calibration of the calorimeters. We will develop a high-performance laser calibration system and use it for on-line monitoring of the SiPM gain fluctuations during the run. This laser calibration system must have a relative accuracy at sub-per mil level to achieve the goal of our experiment. The tracker should improve positron tracking (use much thinner straws) and inform muon beam dynamics more effectively.

We further aim for improvements to the proton precession systematics by using new set of NMR probes and generating a more uniform magnetic field with improved shimming of magnets. A uniform field is essential as the signal degrades more quickly in high gradients. The magnetic field is measured using pulsed proton NMR with a goal of 70 ppb accuracy. The factor of 2.4 improvement over BNL E821 will come from higher magnetic field uniformity and stability, new lower noise NMR electronics with higher frequency resolution, new NMR probes with higher signal to noise ratio and improved calibration probes and calibration techniques.

4 Summary

The Muon g-2 experiment under construction at Fermilab aims for a fourfold improvement from Brookhaven E821 in the measurement of the muon g-2. This is essential for the understanding of QED and the Standard Model and evidence of any new physics beyond the Standard Model. Significant efforts in the theory of e^+e^- measurements are also leading to an improvement in the uncertainty in HVP along with a lot of progress on Lattice calculations too. This will improve the theoretical calculation of g-2. Efforts to enhance and investigate the performance of all detector systems are taking place, along with testing the best methods of data acquisition. We plan further installations in 2^{nd} half of 2016 and expect data taking with muons in 2017 and initial results in 2018.

Acknowledgments

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References

1. J. Schwinger, Phys. Rev. 73, 416 (1948).
2. G.W. Bennett, et al. Phys.Rev.D73:072003, 2006
3. Davier et al. 2011
4. A. Czarnecki and W. J. Marciano, Phys. Rev. D64, 013014 (2001)
5. D. Hertzog, Ann. Phys (Berlin) 2015., courtesy D. Stockinger
6. T. P. Gorringe and D. W. Hertzog, doi: 10.1016/j.ppnp.2015.06.001
7. H. Davoudiasl, et al. Phys. Rev. D **86** (2012) 095009