Ph.D. Dissertation Prospectus

Measurement of the Magnetic Anomaly of the Muon to X parts per billion in Run 1 of the Fermilab Muon $g-2$ Experiment

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Overview

The Fermilab Muon $g-2$ Experiment (E989) is measuring the anomalous magnetic moment of the muon a_μ to high precision. The goal is 140 parts per billion, which represents a four-fold improvement over the the previous best experimental measurement of 540 parts per billion, made by the E821 collaboration at Brookhaven National Laboratory in 2001. There is currently a $3\,\sigma$ to $4\,\sigma$ discrepancy between theory and experiment, which the new measurement has been designed to resolve or confirm. The difference between theoretical and experimental values might be attributed to new physics. The new measurement is based upon the same principles as the last experiment, and if it measures the same central value, the discrepancy would be pushed over the 5σ level needed to classify it as a discovery. The experiment is located at Fermi National Accelerator Laboratory which has the facilities necessary to produce the large number of muons for the measurement, corresponding to about 2×10^{11} detected decay positrons above some energy threshold. In Run 1 of the experiment, E989 gathered about 1×10^{10} decay positrons for a precision comparable to the BNL result.

The experiment principle is summarized as follows: Polarized muons are injected into a highly uniform magnetic storage ring. The injected muons will orbit around the ring at the cyclotron frequency, and their spins will turn at the Larmor precession frequency. The difference between these two frequencies, ω_a, is directly proportional to a_μ and the magnetic field of the ring. a_μ is then determined by measurements of the magnetic field and

ω_a. The magnetic field is measured by many nuclear magnetic resonance (NMR) probes located around the ring which monitor the field at all times. Separately a set of 17 NMR probes periodically measure the magnetic field where the muons live. ω_a is measured by taking advantage of the parity violating nature of the weak decay of the muon, which produces a correlation between the muon spin at the time of the decay and the decay positron direction and momentum. The positrons, which spiral inward, are measured by calorimeters placed on the inside of the storage ring. The number of positrons above some energy threshold is modulated by ω_a, which can be extracted.

The experiment is designed to store a large number of muons in the ring at a time for many time-dilated muon lifetimes. For Run 1 this was ∼10,000 injected muons per measurement period (a single "fill"). The muons decay with a lifetime of 64.4 µs and data are gathered for approximately 10 muon lifetimes. Muons are produced by the accelerator complex and injected into the uniform magnetic field of the $g - 2$ storage ring. The injected muons are kicked onto the right orbit within the ring using a magnetic kicker. Muons are focused vertically within the ring using electrostatic quadrupoles. The combination of these elements, the phase distribution of the injected muons, and the natural motion of the individual muons leads to a coherent motion of the beam as a whole. This is important to consider when extracting ω_a or measuring the magnetic field. In the former the number of detected positrons above threshold will depend on the beam movement, and in the latter the desired value of the magnetic field is that which the muons see over the course of their lifetimes. There is a specialized detector system involving straw trackers which facilitates the measurement of the muon beam dynamics in order to account for these effects.

The main part of my thesis involves the fitting of the positron data and the extraction of the ω_a frequency. I use a specific analysis technique called the Ratio Method which has the advantage of reducing slowly time varying effects in the data to provide a more robust estimate of ω_a. The method involves splitting, time-shifting, and dividing the data in such a way that the exponential nature of the hit time spectrum is eliminated and slow effects are reduced, while preserving the ω_a oscillation. Many checks are made in the ω_a extraction to make sure the fit behaves properly, time varying effects have been sufficiently accounted for, subsets of the data corresponding to individual calorimeters or run conditions are understood, etc. Many systematic effects which would pull the value of ω_a are studied, such as pileup in the detectors, energy response of the detectors, changing beam dynamics, etc. Only after everything has been checked extensively can the final value of ω_a be trusted and unblinded.

The second part of my thesis focuses on the track fitting, which is part of the track reconstruction chain that determines the muon beam distribution and dynamics. Track reconstruction is performed in several stages: First, individual hits in the tracker are clustered into distinct tracks. Second, a best fit track is made to those clusters of hits. Finally, third, the track is extrapolated back into the storage ring. The fitting stage I wrote utilizes error propagation code contained within a Geant4 simulation, called Geane (Geometry and error propagation). Geane propagates particles in the simulation forwards or backwards along average trajectories, and calculates transport and error matrices for the track which describe the changes and spread in track parameters respectively. These matrix objects are plugged into a relatively simple χ^2 minimization algorithm which incorporates material correlations between measurement planes, calculates a covariance matrix for the track, and finally produces a best fit track. This process typically converges after three iterations of the fitting procedure.

The collaboration expects to publish the results from the Run 1 analysis sometime in late 2019. At this point the ω_a and field analyses should be complete and consistent between different analyzers, and the combination between the two finished to provide the final value of a_μ. The result should be comparable in precision to the BNL result, which ideally would give confidence in the previously measured discrepancy or resolve it. By 2021 the necessary statistics should be captured for a four times more precise measurement.

Outline

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- Magnetic moments of particles
- Standard Model contributions to a_μ
- QED
- Electroweak

- Hadronic
- Experimental value and discrepancy with theory
- Beyond the Standard Model

2 Principle Techniques of E989

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- Measuring the magnetic field
- Production and injection of polarized muons
- Storage of muons
- Muon beam dynamics
- Corrections to the precession frequency

3 Detector Systems

- Auxiliary Detectors
- Calorimeters
- Laser calibration system
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4 Track Reconstruction and Analysis

- Track finding
- Track fitting
- Track extrapolation
- Muon beam measurements

5 Precession Frequency Analysis

- Hit reconstruction
- Fitting with the Ratio Method
- Stability vs fit start time
- Individual calorimeter fits
- Systematic studies vs pileup
- Systematic studies vs gain
- Systematic studies vs beam dynamics
- Systematic studies vs muon losses
- Systematic studies vs other

6 Conclusion

- Summary of systematic errors
- Final value of a_μ
- Looking forward to the next runs