Abstract

The Fermilab Muon g-2 experiment aims to measure the muon anomalous magnetic moment \(a_\mu\) with an unprecedented precision of 140 parts per billion (ppb), a four-fold improvement over the 540 ppb precision obtained by the BNL Muon g-2 experiment. This study presents preliminary work on estimating the muon losses by using double coincidences in the calorimeters.

INTRODUCTION

The muon magnetic moment is related to the muon spin via a dimensionless proportionality constant known as the muon g-factor \((g)\). Dirac theory predicts that \(g = 2\) for spin-1/2 point particles such as the muon, while Standard Model (SM) Quantum Field Theory predicts that \(g \neq 2\). The fractional deviation of \(g\) from 2 is known as the magnetic anomaly. The final Brookhaven National Laboratory (BNL) muon \(a\) measurement \([1]\) is

\[
a_\mu \equiv \frac{g - 2}{2} = 116592091 \,(54\,(33) \times 10^{-11},
\]

with statistical and systematic errors quoted respectively within the parentheses. The BNL measurement has a more than 3\(\sigma\) difference \([1,2]\) from the SM prediction, indicating the possibility of physics beyond the SM. The Fermi National Accelerator Laboratory (Fermilab) Muon g-2 experiment has the goals of increasing the statistics by more than a factor of 20 and reducing systematic errors by a factor of 3.

The Fermilab Muon Campus \([3]\) produces a high intensity and highly polarized muon beam that is injected into the storage ring. The muon beam is injected into the storage ring via the inflector magnet which is designed to minimize perturbations to the very uniform storage ring magnetic field. Fast magnetic kickers transfer the injected orbit muons onto the central orbit. The Fermilab Muon g-2 experiment uses 24, 6 \times 9 segmented \(\text{PbF}_2\) Cherenkov crystal calorimeters \([4,5]\) which measure decay positron energy and arrival time. The muon anomaly can be determined by a precise measurement of the muon spin precession \(\omega_\mu\) in the storage ring and the magnetic field \(B\). When excluding systematic effects, the decay positron counts \((N)\) can be described by a 5-parameter fit function \([6,7]\),

\[
N(t) = (N_0/\tau) \times e^{-t/\tau} [1 - A \cos(\omega_\mu t + \phi)],
\]

where \(t\) is the arrival time of the positrons from the muon decays, \(N_0\) is normalization, \(\tau\) is the lab-frame muon lifetime, \(A\) is asymmetry, and \(\phi\) is the initial phase of the muon polarization. Muons at the edge of the phase space are favorably lost at early times, leading to a deviation from pure exponential muon decay in Eq. 2. The average spin of the lost muons can differ from that of the fully stored muons, if these 2 muon populations are created at different points in the production beamline. This difference in average spin phase can cause a shift in the measured \(\omega_\mu\). The Fermilab experiment has a goal of keeping the relative number of lost muons below \(10^{-4}\) per \(\tau\).

The Fermilab Muon g-2 experiment is currently in the first physics data taking run. This discussion presents lost muon studies based on preliminary experimental data that uses double coincident events in the calorimeters. These studies were in part used to avoid muon storage ring beta-ion resonances \([8]\) when establishing the voltages for the electrostatic quadrupole system (EQS) that provide vertical focusing and determine the n-value for the storage ring dynamics.

DETECTION OF LOST MUONS

The BNL experiment measured lost muons by searching for three-fold coincidences in consecutive calorimeters. The energy deposited by MIPs were far below the hardware threshold of the calorimeters used by the BNL experiment. The BNL experiment used scintillator detectors mounted on the front of the calorimeters. Thanks to better calorimeter segmentation and timing precision, the Fermilab experiment is developing lost muon measurement techniques based on either two or three-fold coincidences in consecutive calorimeters. This discussion only covers lost muon detection techniques using two-fold coincidences. The red line shows an example decay electron trajectory while the blue line shows a lost muon trajectory. Two detection coincidences in adjacent calorimeters are used to select muon candidates, where the calorimeters are located every 15 degrees around the storage ring. The 3 GeV lost muons typically...
Figure 1: Diagram [6] of a lost muon detected by finding three-fold coincidences among three consecutive calorimeters. The red line shows example decay electron trajectories while the blue line shows a lost muon trajectory.

A muon cluster is formed by calculating energy weighted position and time (as given by Eq. 3) of the crystal hits in a calorimeter:

\[ (X,Y,t) = \frac{\sum E_{\text{cal}} \times (X,Y,t)_{\text{cal}}}{\sum E_{\text{cal}}} \]

(3)

Three selections [9] have been used to reduce correlated single \( e^+ \) backgrounds:

1. \( E_{\text{frac}} = E_{\text{max}} / E_{\text{total}} > 0.8 \).
2. Spatial distance between the cluster centers in two consecutive calorimeters \( X_2 - X_1 < 0 \).
3. Number of crystal hits in a cluster < 3.

Cut (1) shows the fraction energy in a cluster where \( E_{\text{max}} \) is the maximum energy in a single crystal and \( E_{\text{total}} \) is the total energy in that cluster. Cut (1) provides a goodlost muon signal selection as \( E_{\text{frac}} \) should be ~1 for muon candidates. Cut (2) removes the positrons side-entering into the adjacent calorimeter therefore mostly hitting the crystals closest to the storage volume. Cut (3) removes background decay positrons as they produce electromagnetic shower hitting more crystals in a cluster compared to the muons hitting fewer than three crystals. Figure 2 shows the azimuthal distribution of the lost muon signal with > 30 μs after applying the above-mentioned cuts. The EQS scraping [7] reduces lost muons during the measurement period. The storage ring horizontal and vertical tunes are effectively determined by the EQS operating voltages [7, 10]. Storage ring betatron resonances increase the number of lost muons, and so it is desirable to find EQS operating voltages that avoid the large betatron resonances. Figure 3 shows a scan of lost muons per decay electron in the first calorimeter and with energy > 1.8 GeV as a function EQS storage set-point voltage. A large increase in lost muons is clearly seen from the betatron resonances centered near 18.8 and 21.2 kV. These data were taken without beam scraping, and corresponding decreases in the number of observed decay \( e^+ \) are also seen near these EQS storage set-point voltages [8].
Figure 3: Fraction of lost muons as a function of EQS storage set-point voltage for calorimeter 1. An increased lost muon rate is observed from the betatron resonances centered near 18.8 and 21.2 kV. These resonances are due to $3Q_y = 1$ and $Q_x + 2Q_y = 2$ line in the tune plane.

CONSTRUCTION OF THE LOSS FUNCTION

Figure 4 shows the loss function ($L(t)$) providing the rate at which muons are lost from the ring as a function of time after injection, constructed from double coincidences. The losses are normalized with a pure exponential with the expected lifetime of 64.4 µs and an amplitude determined from the number of decay electrons with energies $> 1.8$ GeV measured in the first calorimeter in a double coincidence. The ratio of lost muons to decay positrons is expected to be much higher at early times than at late times. The loss function ($\Lambda(t)$ [6]) is a correction factor to $N_0$ (see Eq. (2)) that accounts for muon losses.

$$\Lambda(t) = 1 - Ce^{-t_0/\tau} \int_{t_0}^{t} (L(t')) e^{t'/\tau} dt', $$

where the integral can be evaluated numerically with $\tau = 64.4$ µs, $t_0$ is the canonical fit start time and the parameter C is allowed to float in the fit, thereby including a sixth parameter into Eq. 2.

Figure 5 shows an example of the loss function using data integrated over $t_0 = 30$ µs to $t = 300$ µs.

CONCLUSION

The Fermilab Muon g-2 experiment is currently in the first physics data taking phase. Lost muon systematic effects causes a systematic effect on $\omega_d$ when extracting from the 5-parameter fit. MC simulation of the muon beam and storage ring has been used to optimize the lost muon signal by taking advantage of highly segmented calorimeters to distinguish the lost muons from the much larger decay positron backgrounds. Preliminary physics data have been used to determine electrostatic quadrupole operating voltages by looking at fractional muon losses and estimate the rate of losses over time using double coincidence calorimeter events.
REFERENCES


