# SPIN CORRELATIONS STUDY FOR THE NEW g-2 EXPERIMENT AT FERMILAB*

J. D. Crnkovic†, W. M. Morse, V. Tishchenko, BNL, Upton, New York, USA
D. Stratakis[1], FNAL, Batavia, USA
[1]also at BNL, Upton, New York, USA

*Abstract*

The muon g-2 experiment executed at Brookhaven concluded in 2001 and measured a discrepancy of more than three standard deviations compared to the Standard Model (SM) calculation. A new initiative at the Fermilab is under construction to improve the experimental accuracy fourfold. Achieving this goal, however, requires the delivery of highly polarized 3.094 GeV/c muons with a narrow ±0.5 % $\Delta p/p$ acceptance to the g-2 storage ring. In this study, we examine systematic errors that can arise from correlations between muon spin and transverse coordinates for the new g-2 experiment. To achieve this goal we perform end-to-end spin tracking simulations from the production target up to the ring injection point and compare our findings against the results from the Brookhaven experiment. We detail similarities and differences.

## INTRODUCTION

The final CERN muon g-2 storage ring experiment [1] used pion injection with electro-static quadrupoles that provided weak vertical focusing. The electric field does not precess the muon spin at the so-called "magic momentum" of 3.094 GeV/c. A pion beam with central momentum $(0.7 \pm 2)$ % above the magic momentum was injected into the storage ring. There were 350 muons stored per $3 \times 10^6$ pions injected into the ring [1].

The first run [2] of the Brookhaven National Laboratory experiment [3] (E821) used pion injection, since the storage ring kicker was not yet ready. The muons have spin and coordinate phase-space correlations, since the pions come in from the high radius side of the ring, pass through the center, and are then lost on the low radius side. The muon spin starts precessing in the storage ring magnetic field as soon as it is produced by the pion decay.

E821 used direct muon injection, resulting in an order of magnitude greater storage efficiency. The E821 beamline length was 122 m, which was only 70 % of the pion decay length of 174 m. The pion beam momentum was $(1.7 \pm 0.5)$ % above the magic momentum. Pions were rejected just before the storage ring, while muons with magic momentum ±0.5 % were injected into the storage ring.

The Fermi National Accelerator Laboratory (Fermilab) Muon g-2 Experiment [4] (E989) has a long beamline, where effectively all of the pions decay before the storage ring. Clearly, the pion decay kinematics affects the stored muon phase-space differently in the above experiments.

## SPIN AND TRANSVERSE COORDINATE CORRELATIONS

Muons produced from pion decays are polarized in the pion rest-frame due to linear and angular momentum conservation along with the **V-A** nature of Weak interactions. E821 and E989 produce polarized muon beams by accepting the forward and rejecting the backward muons from pion decays.

The lab-frame muon momentum vector arises from the pion decay kinematics:

$$\begin{aligned} p_\mu^z &= p_\pi\,[0.21\,(1+\cos\Theta)+0.58] \\ p_\mu^T &= P_\mu \sin\Theta \\ p_\mu^x &= p_\mu^T \sin\Phi \\ p_\mu^y &= p_\mu^T \cos\Phi, \end{aligned} \quad (1)$$

where $p$ is lab-frame momentum, $P$ is pion rest-frame momentum, $\Theta$ is pion rest-frame momentum polar angle, $\Phi$ is pion rest-frame momentum azimuthal angle. The muon spin is along the momentum in the pion rest-frame. The polarization component transverse to the lab momentum is given by

$$\Sigma^T = \frac{\gamma_\pi \beta_\pi}{\gamma_\mu \beta_\mu} \sin\Theta = \left(\frac{2m_\mu}{m_\pi^2 - m_\mu^2}\right) p_\pi \sin\theta, \quad (2)$$

where $\gamma$ is the lab-frame Lorentz factor, $\beta$ is the lab-frame muon speed divided by the speed of light, $m$ is the mass, and $\theta$ is the lab-frame muon momentum polar angle.

Figure 1 illustrates the relationship between muon momentum and spin in the pion rest-frame. There is a correlation between $p_\mu^T$ and $\Sigma^T$, as seen in Eqs. (1) and (2).

Figure 2 shows the $x$-$x'$ phase-space admittance in the center of a FODO horizontally defocusing quadrupole magnet for the E821 beamline. In pion decay,

$$\Delta x' \equiv x'_\pi - x'_\mu = \sin\theta \sin\phi, \quad (3)$$

where $\phi$ is the lab-frame muon momentum azimuthal angle. Figure 2 also shows a central momentum pion decay to a magic momentum muon in the horizontal plane. There is a correlation between the signs of $\Delta x'$, $x'_\mu$, and $\Sigma^T$, as seen in Eqs. (2) and (3). The correlations between spin and the transverse coordinates decrease as the distance between the magnets decreases.

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† jcrnkovic@bnl.gov

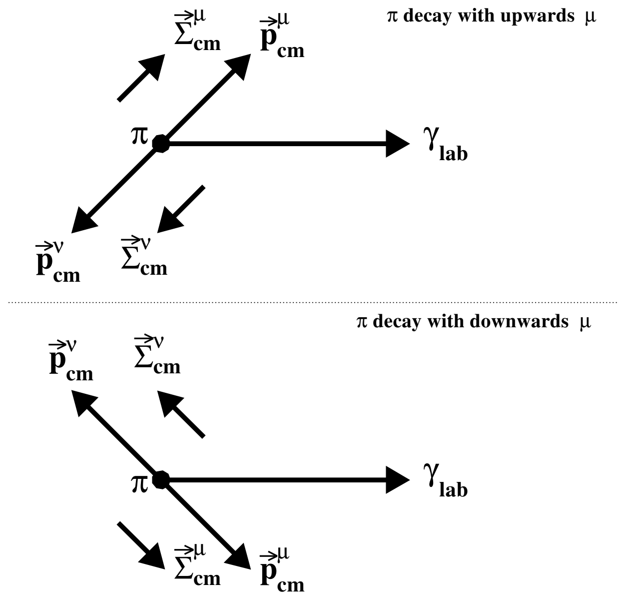


Figure 1: Cartoon illustrating the correlation between muon momentum and spin in the pion rest-frame.

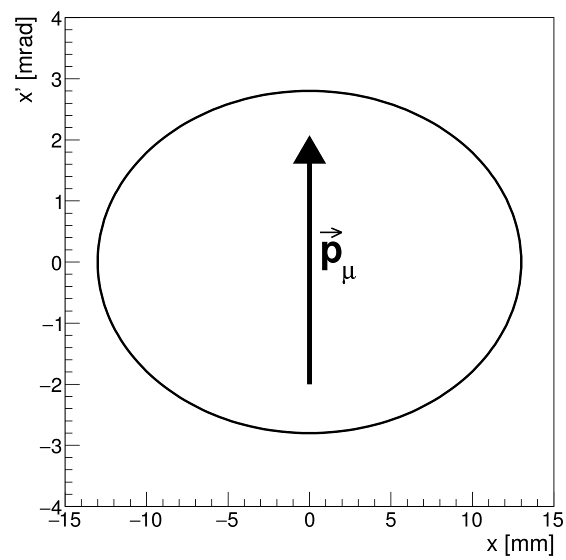


Figure 2: E821 $x$-$x'$ phase-space admittance in the center of a FODO horizontally defocusing quadrupole magnet. The $\Delta x'$ is shown for a central momentum pion decaying to a magic momentum muon in the horizontal plane. The signs of $x'_\mu$ and $\Sigma^T$ are correlated.

The spin and transverse coordinate correlations are expected to be more dominant in E821 compared to E989. E821 rejected pions just before beam injection into the storage ring, where this also rejected the muons with $\Theta \approx 0°$. The inclusion of the $\Theta \approx 0°$ muons in E989 will increase the muon storage efficiency and diminish the spin and transverse coordinate correlations. Most of the muons with horizontal spin components come from pion decays around the FODO vertically focusing quads in the E821 beamline. Likewise, most of the muons with vertical spin components come from pion decays around the FODO horizontally focusing quads. This is less of an effect for E989, because there are more quads closer together and thus smaller beta functions.

## MC SIMULATION ESTIMATIONS

A MC simulation of the muon beam just after injection into the muon storage ring exists for E821 [5]. In order to access information on the spin and transverse coordinate correlations for E989, we incorporate G4Beamline, a code that includes basic physical processes such as spin tracking and muon decay, into our simulation. We initiate our simulation at the g-2 target and track the muon beam up to the entrance of the inflector [6]. At this point we examine the spin correlations, where the muon $z$-$x$ spin angle is given by $\phi_a = \tan^{-1}\left(\Sigma^x_\mu/\Sigma^z_\mu\right)$. A selection cut of $\pm 1$ % $\Delta p/p$ with respect to the magic momentum is applied to the simulation data. The $z$-$x$ spin angle vs. $x$ or $x'$ are shown in Figs. 3 and 4. The average precession angle increases in a roughly linear fashion with respect to the transverse coordinates $x$ or $x'$. The linear fits indicate that the correlations are an order of magnitude greater for E821 compared to E989.

## CONCLUSIONS

The E821 and E989 beamlines produce muon spin and transverse coordinate correlations. However, the E989 beamlines have suppressed beta functions compared to E821, due to the larger density of magnets. As a result, E989 is found to have correlations that are consistent with zero or small compared to the correlations for E821. These correlations will produce a differential decay systematic error in the measurement of the muon anomalous magnetic moment [7]. These systematic effects are presently being calculated for E989, while they have already been estimated as being small compared to the E821 total systematic error.

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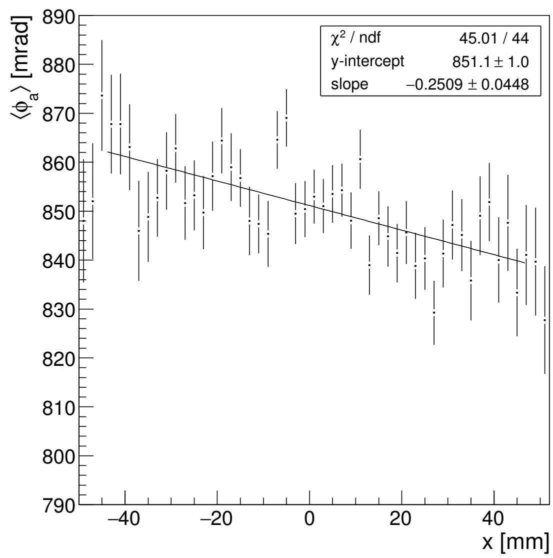
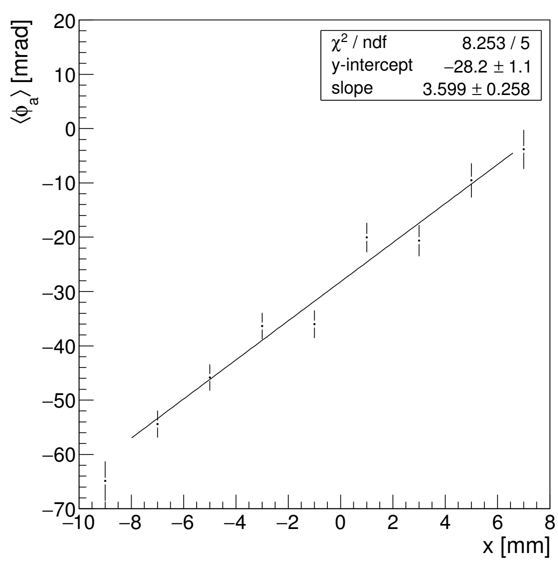
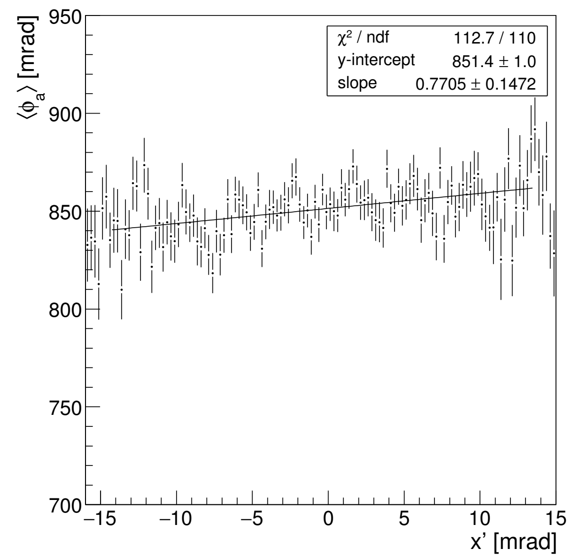



(a)

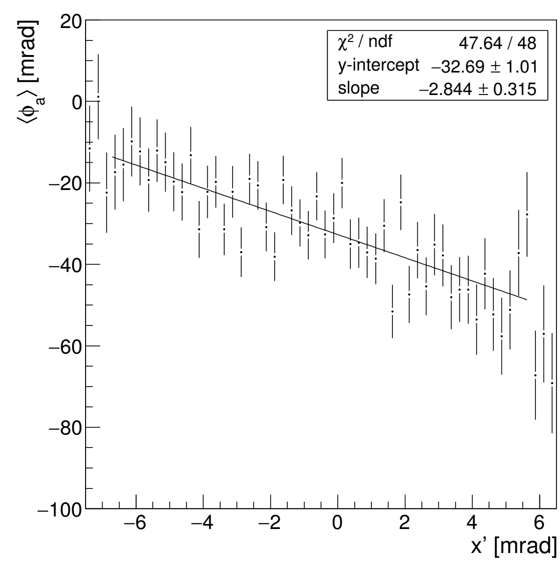



(b)

Figure 3: MC simulation of average $z$-$x$ spin angle ($\langle\phi_a\rangle$) vs. $x$: (a) E989 and (b) E821.




(a)




(b)

Figure 4: MC simulation of average $z$-$x$ spin angle ($\langle\phi_a\rangle$) vs. $x' = dx/ds$: (a) E989 and (b) E821.

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