TRIUMF Experiment E614
Technical Note

Possible Methods for Optimizing Muon Polarization

R.P. MacDonald, TRIUMF

12 December, 1997

Introduction

The E614 experiment requires precise knowledge of the spin of each muon as it reaches the target, and one method of achieving this is to select only highly-polarized muons for tracking, discarding those whose spin is unsatisfactory. This requires finding parameters of muon tracks, such as position or momentum, which are strongly correlated with the muon spin, selecting muons according to some criteria (such as a slit to select position), and discarding those muon tracks which do not meet these criteria. Monte Carlo simulations, described below, have shown that a simple slit is not sufficient to select muon polarization to the precision required by the experiment. However, these same simulations may suggest more effective methods of achieving muon polarization, including optimizing the incoming M13 muon beam focus location in z, and selecting muons based on the radii of the helices they trace out as they pass through the strong magnetic field.

M13 Focus Position

The muon output from the M13 beam has a focus which can be positioned along the Z-axis by tuning the magnetic quadrupoles at the end of the beamline, or by positioning the spectrograph appropriately. It has been suspected that the optimum position for this focus is near z = -160 cm, which is approximately where the radial component B_r of the magnetic field is a maximum. (This region is also known as the "fringe field," where the magnetic field increases from zero in the beamline to a uniform 2.2 T inside the spectrometer.) One goal of the Monte Carlo studies (performed using GEANT) has been to optimize the focus location to give the most polarized muon flux at the target.

To help this process, the distance r_i from the Z-axis was plotted against the angle ψ_i between the momentum and the Z-axis, taken for each muon at z = -300 cm (where the muon tracks were started for these simulations). ψ_i was calculated as $\arctan(P_r/P_z)$ (where $P_r = \sqrt{P_x^2 + P_y^2}$). Figure 1 shows that the muons which arrived at the target with the "best" spin, $s < -0.99985$, appear to exhibit a linear relationship between r_i and ψ_i, which is consistent with the existence of an optimum focus position. This relationship remained the same regardless of where M13 beam focus was positioned, which is to be expected; this specified focus is for a mean of all of the muon tracks, whereas the relationship between r_i and ψ_i depends on the "focus" of the individual muon tracks.

If P_r is assumed to point radially towards or away from the Z-axis, then the "focus" L

of each muon track (where the track crosses the Z-axis) is given by

$$L = -300 + r_i \frac{P_z}{P_r} \tag{1}$$

where L and r_i are in centimetres. (The -300 is a correction for the fact that the muon tracks begin at -300 cm instead of at the origin.) A graph of L versus the muon spin at the target (figure 2) reveals that the muons with the best spin tend to have foci near z = -150 cm. Selecting only those muons for which $s < -.9995$, the mean value of L is $\overline{L} = -141.3$ cm, with a standard deviation of $\sigma_{\overline{L}} = 77.6$ cm; these two values may be useful when tuning the M13 beam shape.

Cuts Using Muon Track Focus L

If it were possible, a useful cut would be to measure the muon trajectory before the muon encounters the fringe field (ie. where the trajectory is linear),determine L, and only select values of L close to -150 cm. To test the feasibility of such a cut, two DC's (Drift Chambers) were constructed in the GEANT simulation and placed in the beamline, upstream of the

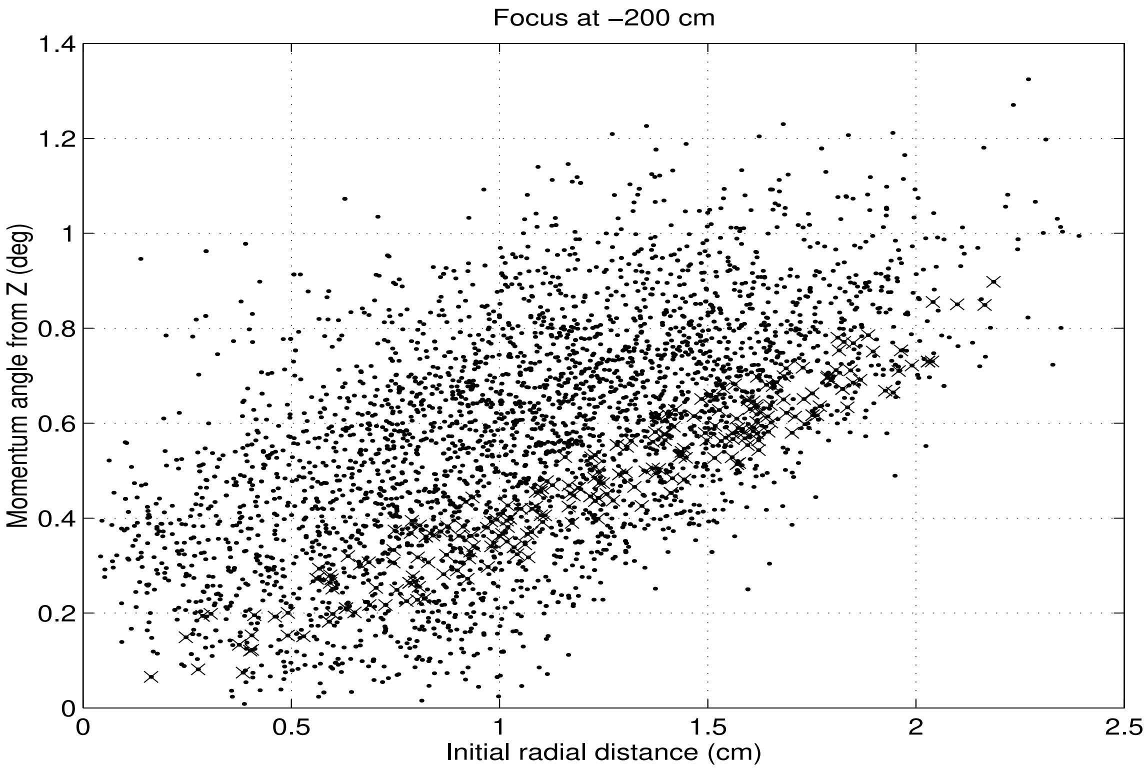

Figure 1: Initial momentum angle ψ_i vs. initial distance r_i from axis. ψ_i is the angle the initial muon momentum (taken at Z = -300 cm) makes with the Z-axis. The crosses represent muons whose final spin s at the target was better than -0.99985. Notice the apparently linear relationship between ψ_i and r_i for these muons.

fringe field. The multiple scattering[1] in these detectors modified the relationship between L and s (figure 3), so much so that L determined in this way cannot be used to make a selection.

Cuts Using Physical Slits

The simplest way to make a cut on a particle beam is to place a physical slit (of copper, lead, etc) in the path of the beam to select particles based on position. To test the effectiveness of a slit as a selection mechanism, simulations were run whose output included muon radial positions (r, the distance from the Z-axis) at several values of z, as well as the final spin of each muon as it entered the target. Most runs only considered those muons which actually stopped in the target, but a few runs were checked in which all muons were considered, and the results were the same.

[1] The mean momentum angle $\overline{\psi}$ at z = -150 cm was 0.573° with no multiple scattering, and was 3.426° with multiple scattering turned on. The mean scattering angle, then, was $3.426° - 0.573° = 2.852°$, five times the original momentum angle. This means that the muon distribution is much different at z = -150 cm than at z = -300 cm where it is measured, modifying the relationship between L and s.

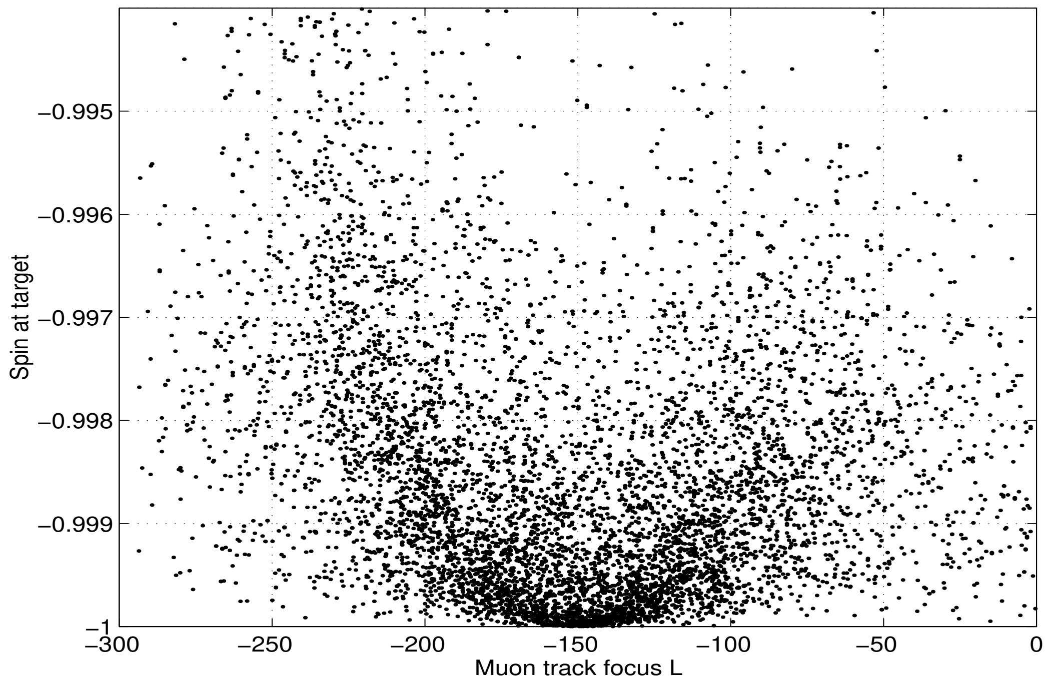

Figure 2: Spin at target vs. muon track focus L. ($L = -300 + r_i \frac{P_z}{P_r}$). The distribution of data points seems to indicate that the optimum focus position for the M13 beam would be at z = -150 cm.

The results taken at z = -150 cm will be considered here, though results were similar for all positions examined. The slit at -150 cm was inspired by the focus position results (figure 2); the idea was that incident muons "focussed" at z = -150 would be passing through this slit at the smallest radial position, while muons focussed ahead or behind this point would have larger radial positions at the slit and would thus be cut out. Narrowing the slit should select more polarized muons.

The muon spin s at the target was plotted against the radial position at z = -150 cm (figure 4). A relationship between the two is evident, but the relationship is not strong enough by itself to select a large enough sample of muons with sufficient polarization. The use of one or more slits (at different positions in the beam line and in the spectrometer) in conjunction with other selection mechanisms will be studied.

Cuts Using Helix Radii

According to the Standard Model, the spin of a muon before undergoing multiple scattering must be antiparallel to its momentum, and so momentum is the most popular candidate for selecting the muons with the best spin. Due to the magnetic field (which is approxi-

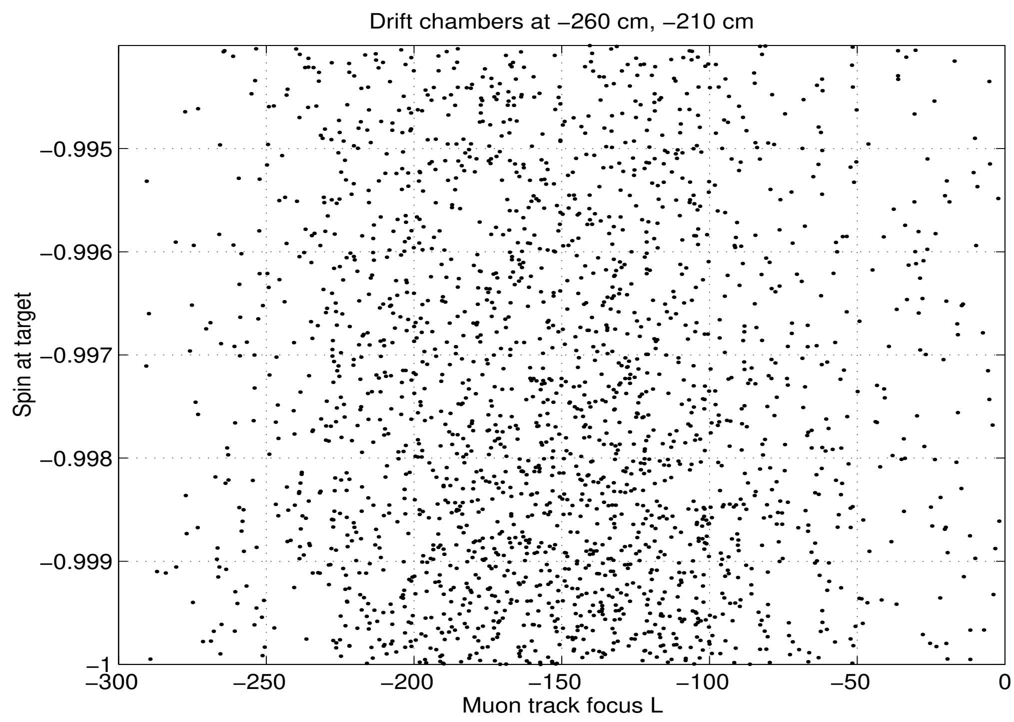

Figure 3: Spin at target vs. track focus L, DC's in beamline. The presence of drift chambers in the beamline, outside of the fringe field, drastically degrades the beam polarization, and destroys any useful relationship between L and s.

mately uniform within the proposed spectrometer) each muon will trace out a helix as it travels through the spectrometer. It can be shown [1, p.146] that, if the transverse momentum P_r is given in MeV/c and the axial component B_z of the magnetic field is given in Teslas, then the helix radius ρ in cm is $\rho = P_r/3B_z$ (the factor of 1/3 represents the conversion from MeV/cT to cm, and carries appropriate units). Using this formula, the helix radius for each muon was calculated as it entered the first drift chamber (DC) in the spectrometer. With no multiple scattering (figure 5) there is a strong correlation between the spin at the target and the helix radius, as expected. With multiple scattering on (figure 6), scattering in the vacuum windows between the beam pipe and the spectrometer, as well as in helium gaps at the front of the spectrometer, degrades the correlation between spin and momentum (and therefore between spin and helix radius) so much that helix radius alone is no longer a viable selection mechanism[2].

[2] The mean momentum angle $\overline{\psi}$ at the first drift chamber in the spectrometer was 2.162° with multiple scattering off, and 2.944° with multiple scattering on. The mean scattering angle due to the vacuum windows is then $2.944° - 2.162° = 0.782°$. These values correspond to a muon spin of $s = \cos(2.162°) = 0.99929$ with multiple scattering off, and $s = \cos(2.944°) = 0.99868$ with multiple scattering on, a difference of 0.00061 in muon spin. This is significantly higher than the desired experimental precision of ± 0.00005.

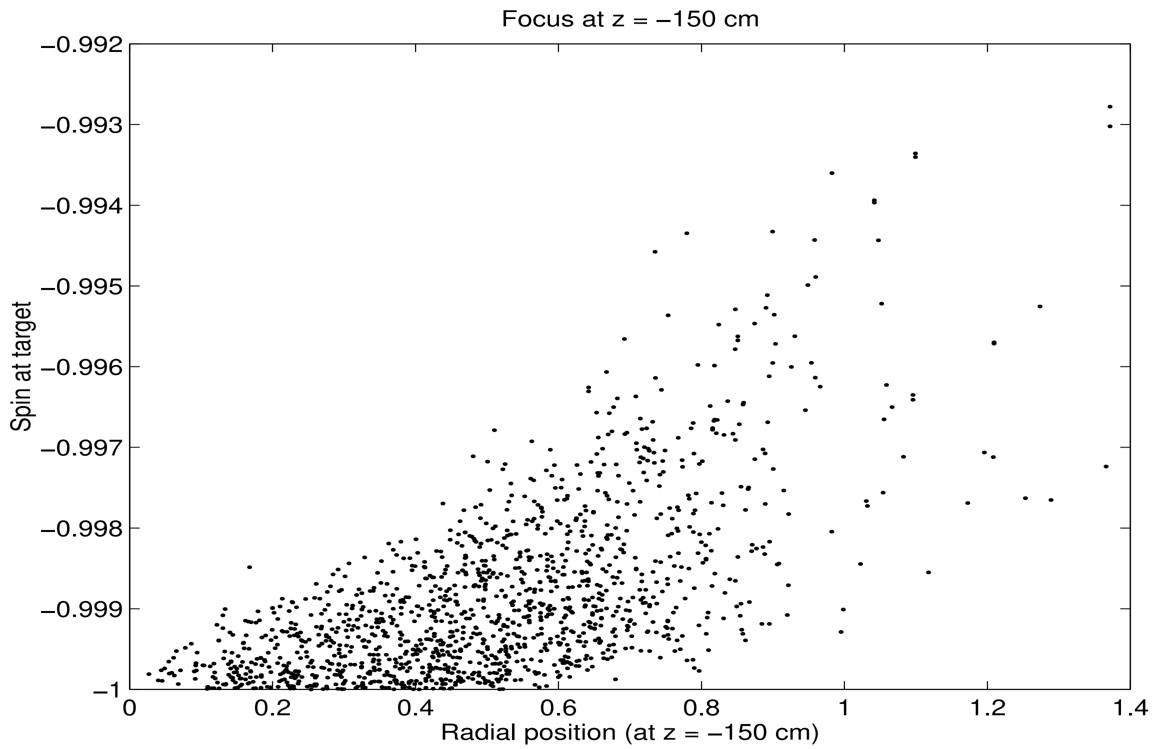

Figure 4: Spin at target vs. Radial position at z = -150 cm. There is a relationship between these two parameters, but it is not strong enough to be useful at the the precision E614 requires.

Note that to obtain helix radii from actual data (constisting entirely of position and timing information at the DC's) would require fitting a helix to hit locations at several DC's. Any helix fit would have some error associated with it, which means that selection using real data can only be less successful than the method above.

An extension of this method is under construction, in which a helix is fit to data and helicies are selected based on both radius ρ and goodness-of-fit χ^2. The idea is that the tracks selected using χ^2 have been scattered less than those which were cut out, hopefully leaving a stronger correlation between momentum (and helix radius) and final spin; a second cut would then be made based on ρ.

Conclusion

The relationships examined here suggest possible methods of selecting (through cuts) or ensuring (by tuning the M13 focus position) muon polarization. However, the relationships are weakened by multiple scattering, so that none of these methods used exclusively will result in a sufficiently polarized muon beam at the target. If these methods were to be applied in tandem (using a slit in combination with helix radius selection, for example), a

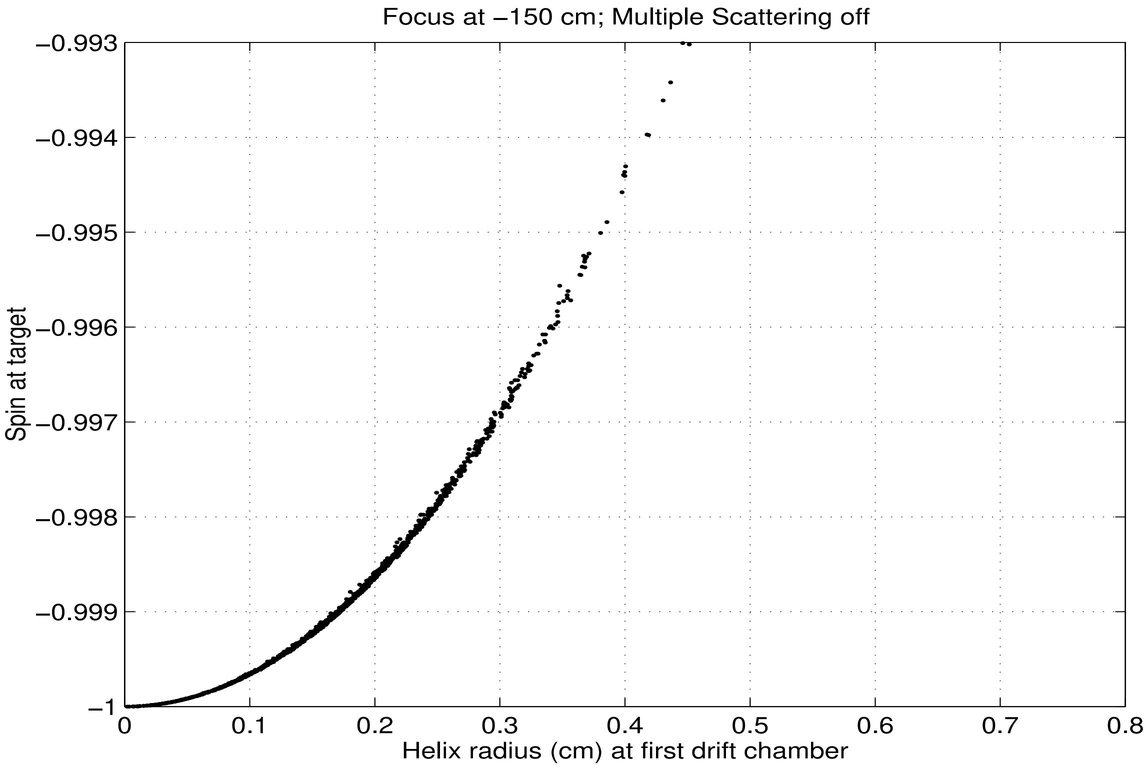

Figure 5: Spin at target vs. Helix radius, no multiple scattering. There is a strong correlation between helix radius and final spin, due to the physical connection between momentum and spin.

more successful selection scheme might be achieved. This option is being explored.

References

[1] P.D.G., *Phys. Rev.* **D54**, 1 (1996)

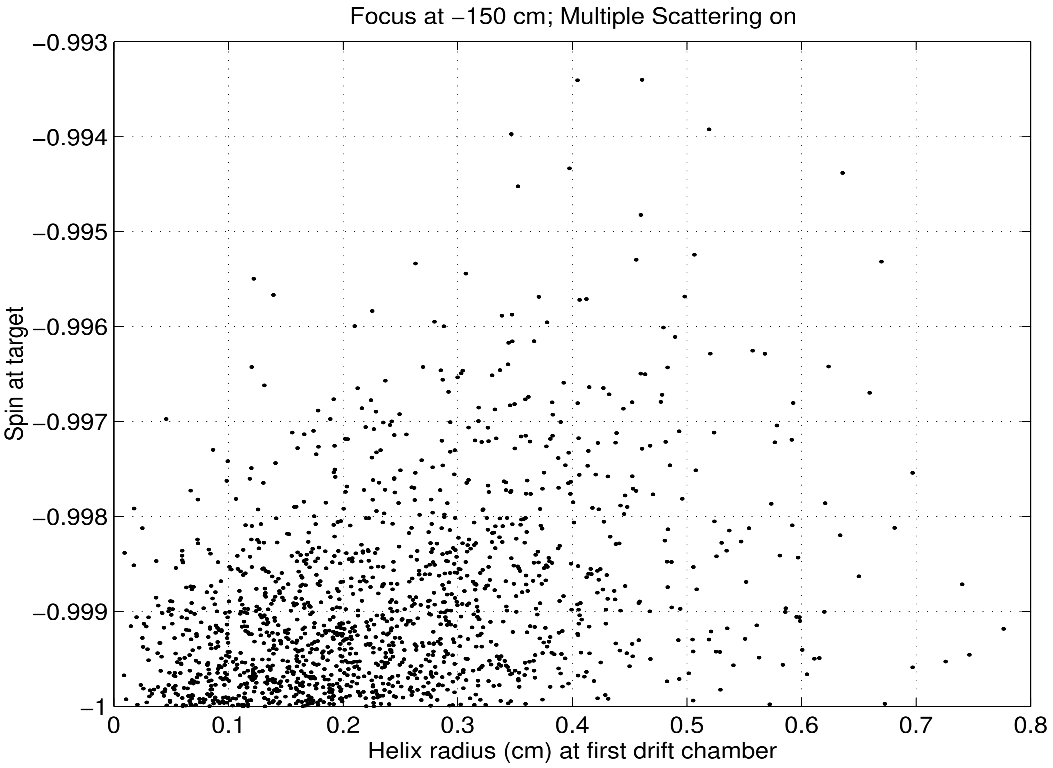

Figure 6: Spin at target vs. Helix radius, multiple scattering on. Because scattering affects the momentum of a muon but not its spin, the correlation between helix radius and spin is effectively lost. (The proportional counters (PC's) which are normally upstream of the DC's have been removed for this graph.)