TRIUMF Experiment E614

TN-42

A Monte-Carlo Study of a Pion Based Calibration Experiment

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Abstract

The purpose of this study is to evaluate the viability of using a π^+ beam from the M13 production target to produce either a polarized or an unpolarized μ^+ spectrum in the detector. This μ^+ spectrum could then be used to calibrate the detector. This study was carried out using E614 GEANT V1.2. The results of this study show that for a 65 MeV/c π^+ beam, only 1% of the incident π's result in μ's that decay in the target foil. This figure drops to 0.59% when we only consider stopped π's, and is further reduced to 0.2% when we only look at π's that stop in the target foil.

INTRODUCTION

The premise of this study is to discover whether or not it is possible to produce a polarized or unpolarized spectrum of μ's in the target foil from an incident beam of π's. This study consists essentially of two major parts: characterizing the spin distribution of daughter μ's that decay in the target foil, and examining the resultant flux of μ's that would be available to perform the experiment. Originally an incident π^+ beam momentum of 65 MeV/c was chosen because of a relatively high flux from the M13 production target (~4000 counts / uA sec) along with relatively low e^+ and μ^+ background[1].

Ideally, we would like to have the maximum number of π's stopping in the target in order to maximize the μ^+ flux in the target. The way that we achieved this is as follows. The finished detector will use a volume of an He/Ar mixture to slow the incident μ's in order to stop the maximum amount of them in the target foil. In this study, we did not

alter the He/Ar mix, but instead we increased the thickness of the scintillators to 360 microns (from 160 microns) in order to obtain a maximum number of 30 MeV/c μ stops in the target foil. Then in order to stop the more energetic π's in the target foil, we added two plastic degraders, one upstream to absorb the π's energy, and one downstream for symmetry. These degraders were varied in thickness depending on the momentum of the incoming π's.

65 MeV/c π Beam Results

The 65 MeV/c incident π^+ beam was created by E614 GEANT using the BEAM data card found in the `e614.ffcards` user input file [2]. This input allows us to select the initial beam momentum of 65 MeV/c, with a momentum spread of 0.5%. The detector geometry is already included in the E614 GEANT V1.2 package, and the only parts of the detector geometry that were modified are the scintillators and the added plastic degraders.

At 65 MeV/c, the incident π's decay along a large section of the z axis, as shown in figure 1.

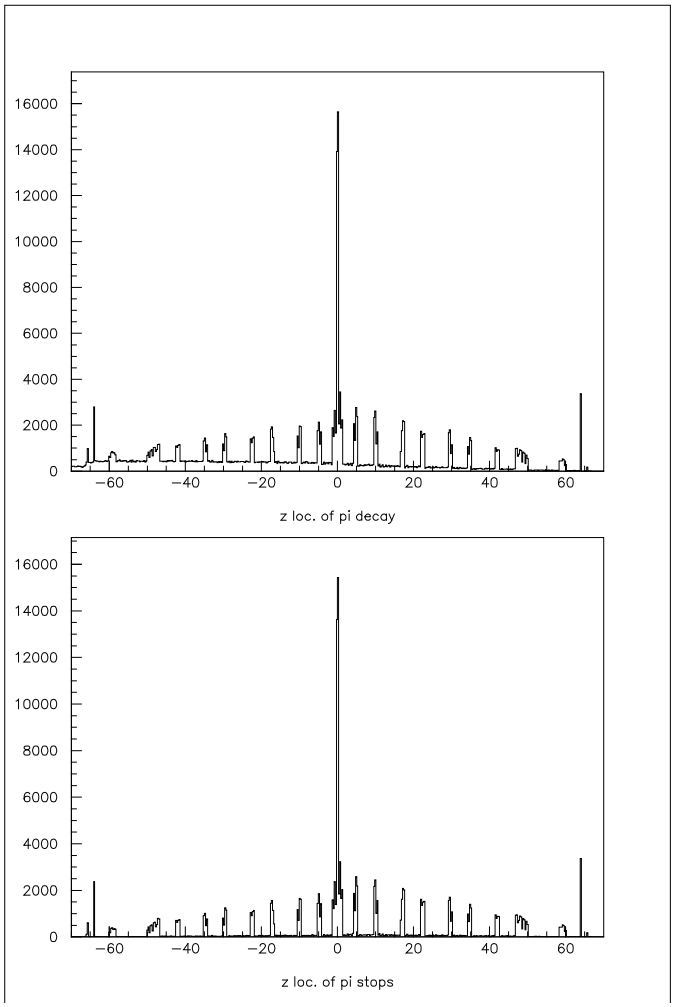

Figure 1 – Top: z location of π decays (including in flight) from –70 to 70
Bottom: z location of π stops from –70 to 70

The top graphic of figure 1 shows not only the stopping π's, but also the π's that decay in flight in the detector. The bottom graphic shows only the π's that stop. The stopping π's comprise about 31% of the incident π's. There is a noticeable baseline of in flight decays of the π's on the top figure. This baseline extends off of the graph to the left, accounting for the large fraction of the π decays that are not accounted for on the top graphic of figure one. It is also worthy to note that the stopping distribution does not appear to be exactly optimized, as the peaks to the immediate right of the stopping target are slightly larger than those peaks to the immediate left. This may be the cause of the slightly non-zero mean spin distribution that we will encounter later in this note. Figure 1 is the result of 500,000 incident π's.

Figure 2 shows a magnified view of the decay locations of π's in the scintillators and degraders. Please note the differences in scale between the four graphics.

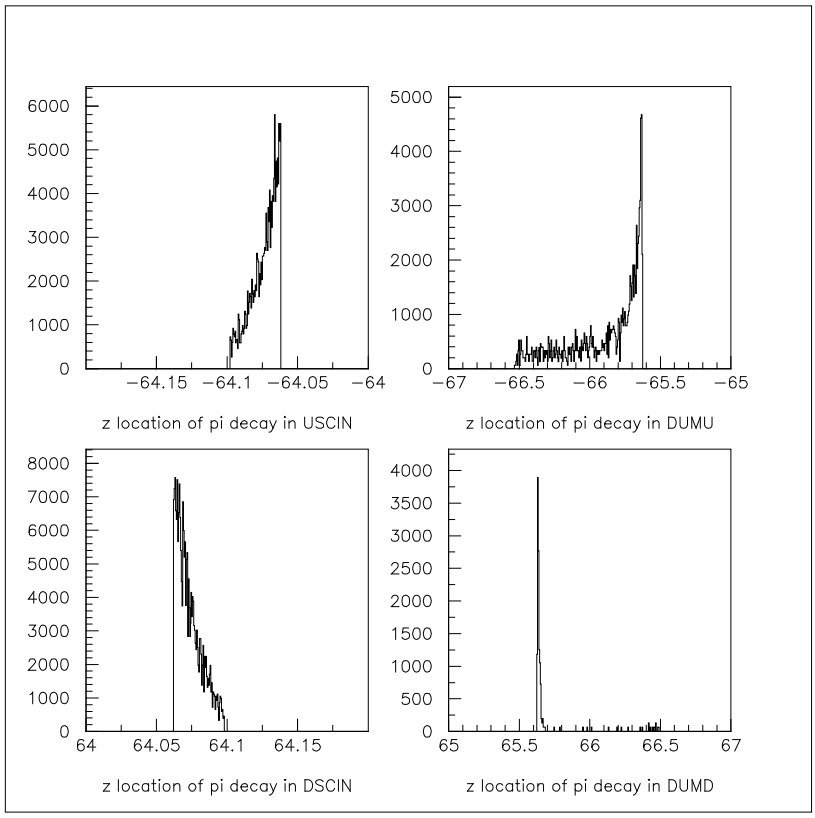

Figure 2 – z locations of π decays in the degraders and scintillators. USCIN – upstream scintillator, DSCIN – downstream scintillator, DUMU – upstream degrader, DUMD – downstream degrader

The graphics of figure 2 were created again using 500,000 incident π's. All of these graphics total less than 1.6% of the incident beam, with the downstream scintillator having the greatest proportion of the original beam at 0.67%. The detailed statistics are available in Table 1.

The graphics of figure 3 were not created using the BEAM card as in the previous graphics. In order to be able to "see" a meaningful distribution, we needed to run many more events. To save CPU time, we stored the stopping locations of the π's that decayed in the degraders and scintillators from a 500,000 event run in a data file, discarding all other decay locations. We then generated stopped π's at the stored locations, so that we had 500,000 stopped π's in only the scintillators and degraders. This is the statistical equivalent of running ~33 million incident beam π's[1].

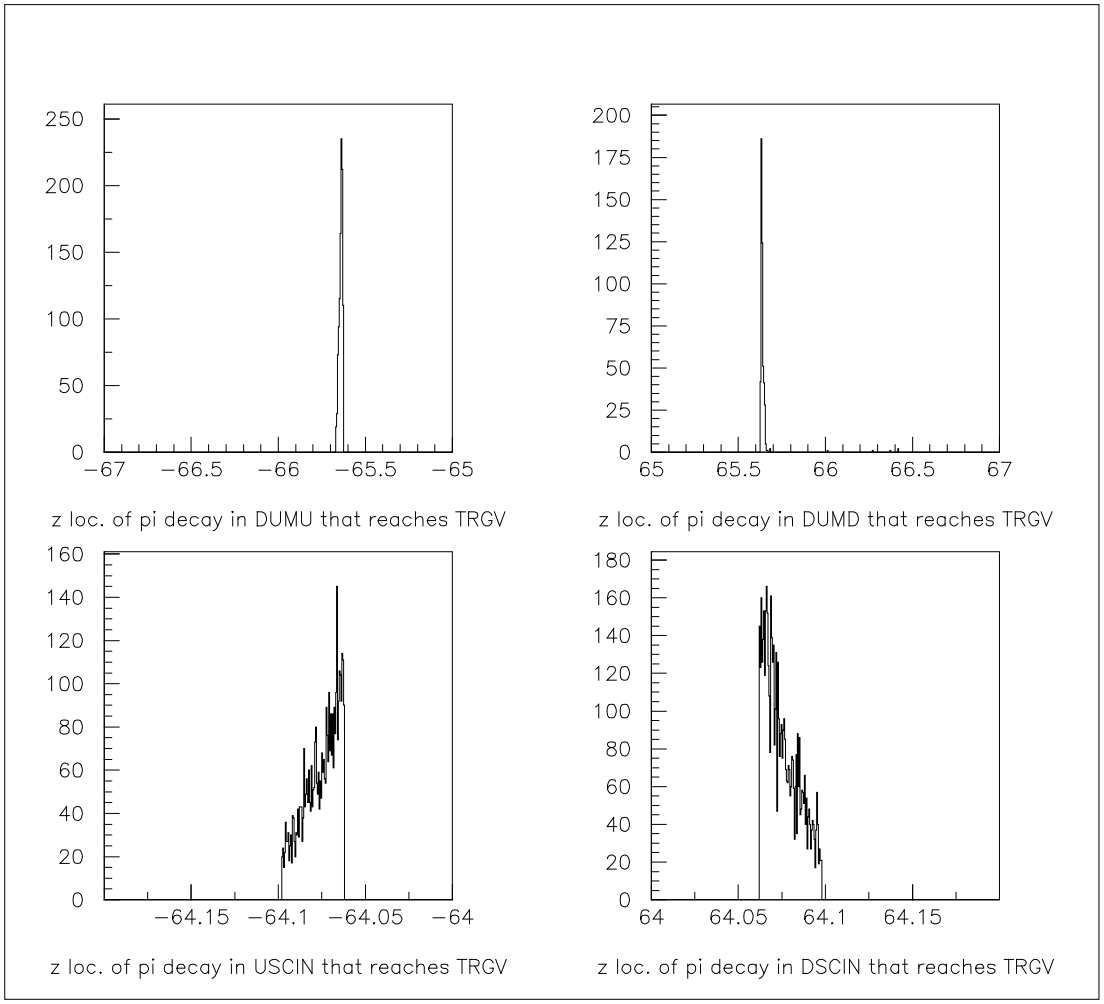

Figure 3 – z locations of π decays in scintillators and degraders that produce daughter μ's that decay in the target foil.

From the graphics of Figure 3, it seems that the flux of μ's that reach the target from the scintillators and degraders is very low, with the largest flux coming again from the downstream scintillator. The statistics are available in Table 1.

[1] A total of 7591 π's stopped in the scintillators and degraders. That is 1.52% of the original 500,000 events. A further 500,000 events were generated ONLY from this 1.52%, so the statistical equivalent of the original beam is $500{,}000/(1.52*10^{-2}) = 32.89*10^{6}$ events

Figure 4 shows the spin distribution of daughter μ's versus the z location of the π decay that produced the μ. The top graphic shows that the likelihood of a μ stopping in the target depends on its initial momentum (hence its spin) and initial z position. In the following discussion, spin[2] is often used to describe the direction of motion of the μ. For example, a μ produced in a module at z = 10cm with a spin of 0.9 will not "see" enough material in order to degrade the μ's momentum enough to stop it in the target foil. On the other hand, a μ produced at the same location with a spin of 0.1 leaves at a much larger angle than the previous case, passes through much more degrading material, and loses sufficient momentum to make stopping in the target much more probable.

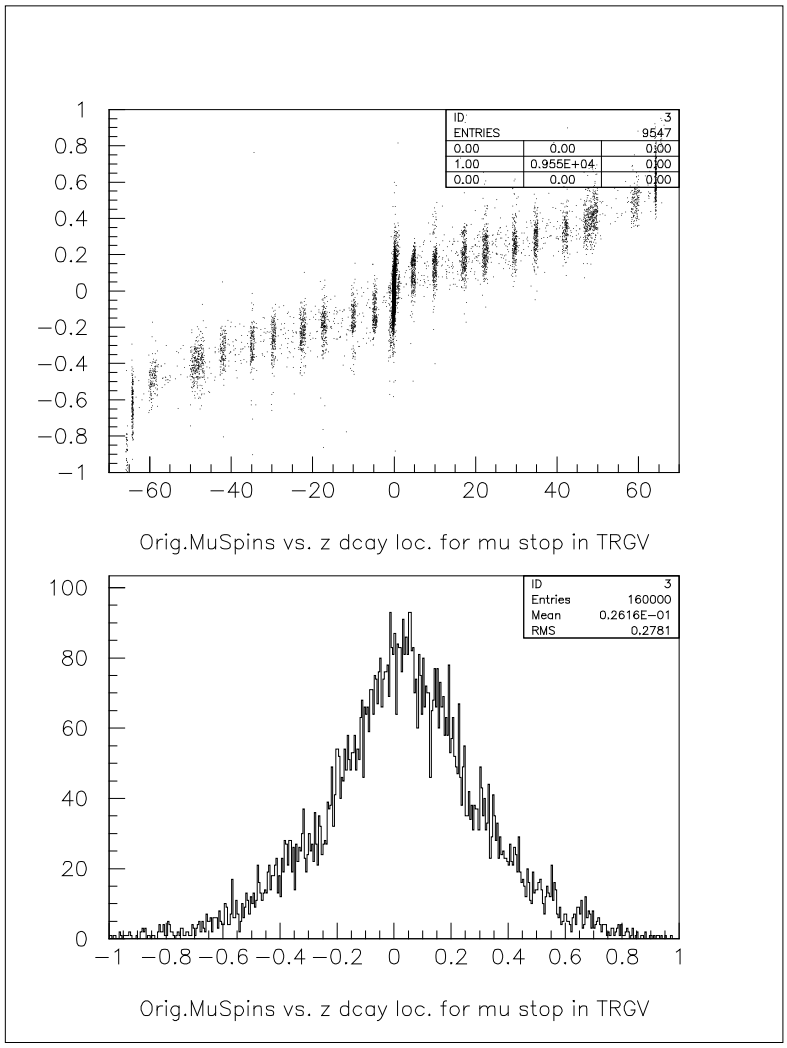

Figure 4 – Top: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay.
Bottom: Projection of top graphic onto Y-axis

[2] The term "spin" as used in this document refers to the orthogonal spin component along the z-axis. That is, μ's with spin ±1 travel parallel the z-axis, whereas a spin of 0 means the μ is moving in the x-y plane. As all μ's have the same initial momentum (29.7 MeV/c) the spin can also be used as a measure of decay angle.

The bottom graphic of figure 4 shows the projection of the top graph onto its Y-axis. The significance of this graphic is that it shows the mean spin distribution of μ's stopping in the target that originate from all over the detector body. The mean spin is $2.6*10^{-2}$, which is very close to being an unpolarized spectrum. It may be that the non-zero mean spin is a result of the error seen in the optimization of the π stopping distribution that was seen in figure 1.

Figure 5 shows the same type of histograms as the top graphic of figure 4, but figure 5 displays only the μ's that originate in the degraders. The μ's that originate in the degraders all need spins that are close to ±1, as the scintillators were optimized to stop μ's in the target foil. As the μ's come from deeper in the degraders, they need spins closer to ±1 to reach the target foil, hence the slight curvature to the histogrammed distribution.

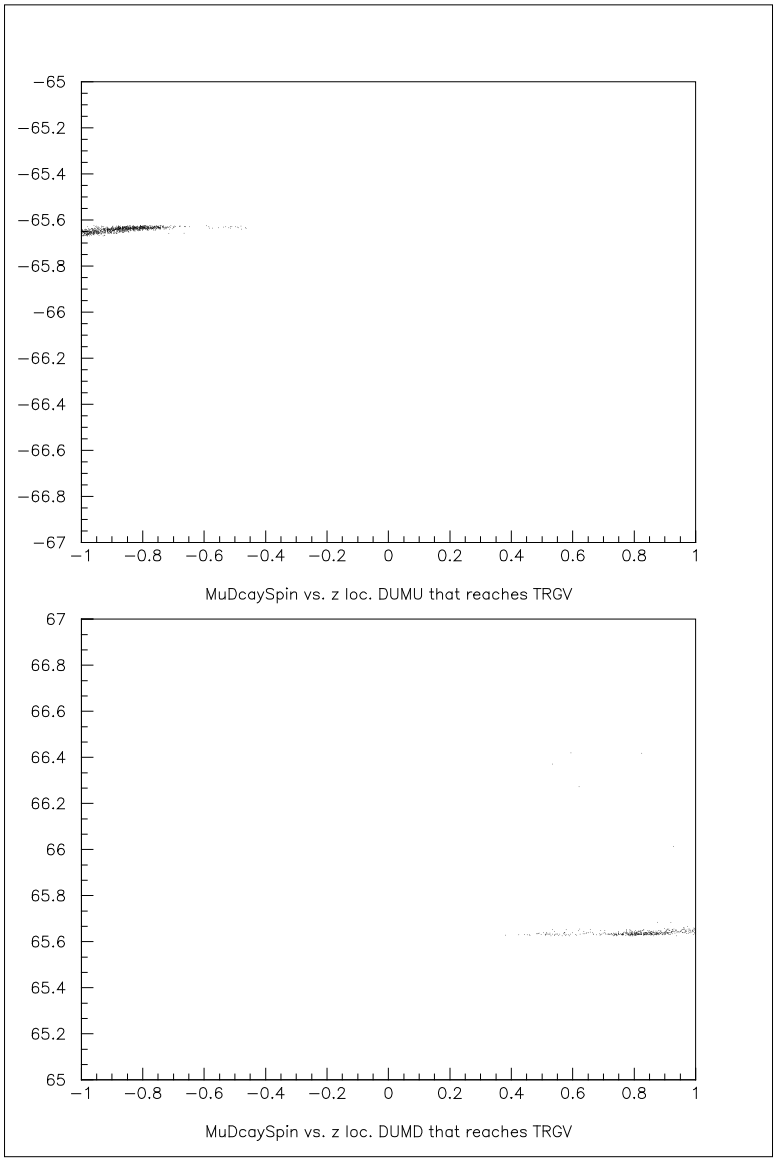

Figure 5: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay. (Degraders only)

Figure 6 is complementary to figures 4 and 5, but in this instance it is only the scintillators that are histogrammed. In figure 6 it is even more apparent that the deeper inside the scintillator the source of the μ is, the closer the spin must be to ±1.

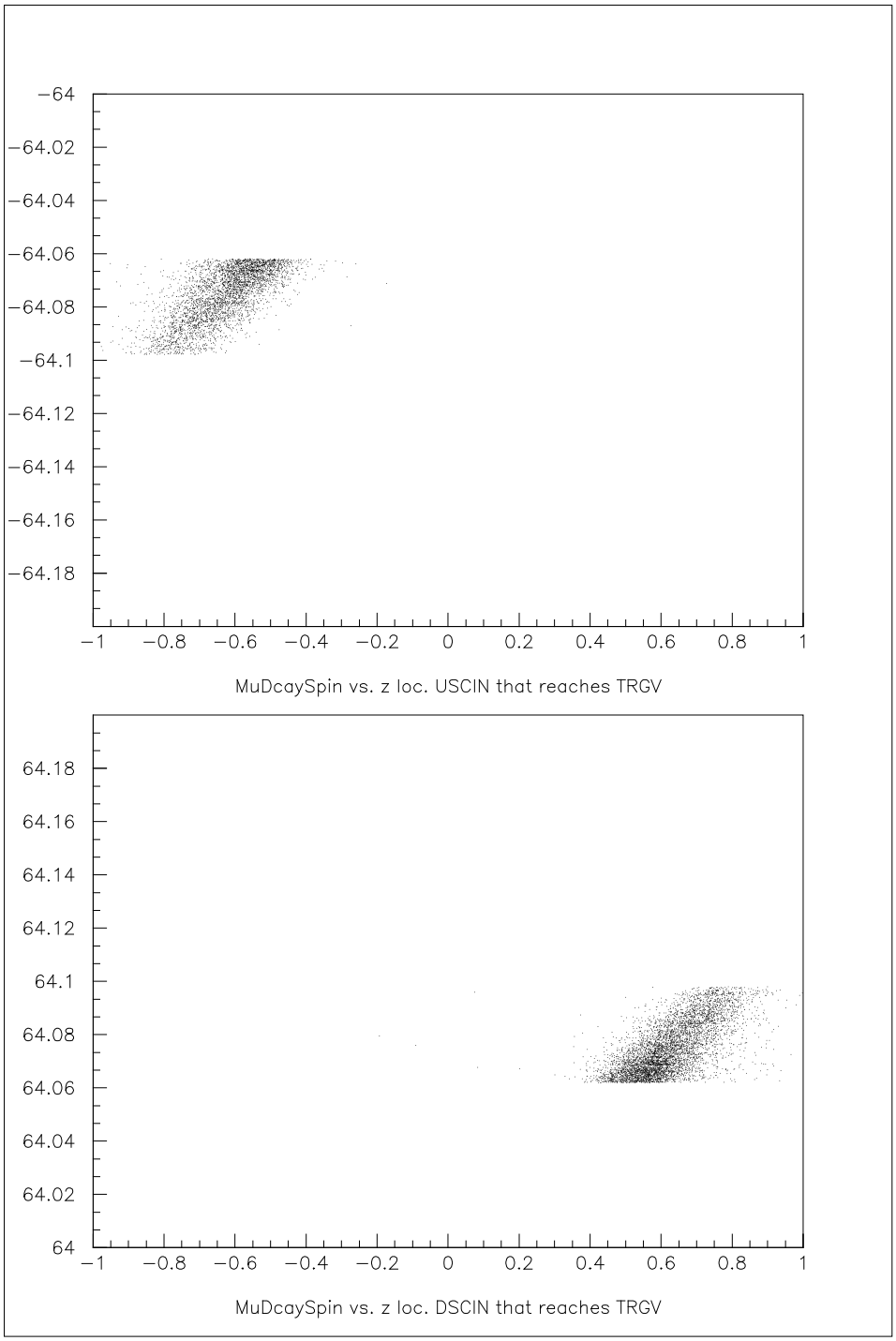

Figure 6: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay. (Scintillators only)

Figure 7 is again the same type of histogram as figures 4-6, but figure 7 shows only the μ's that stop in the target foil from parent π's that stopped in the target foil. The bottom part of figure 7 shows the projection of the top graphic onto its Y-axis. This is to show the spin distribution, along with its mean. The mean is $6.59*10^{-3}$, even closer to an unpolarized spectrum than the spectrum that was observed from all of the μ sources. Again, the non-zero value of the mean spin may be a result of error in optimizing the π stopping distribution.

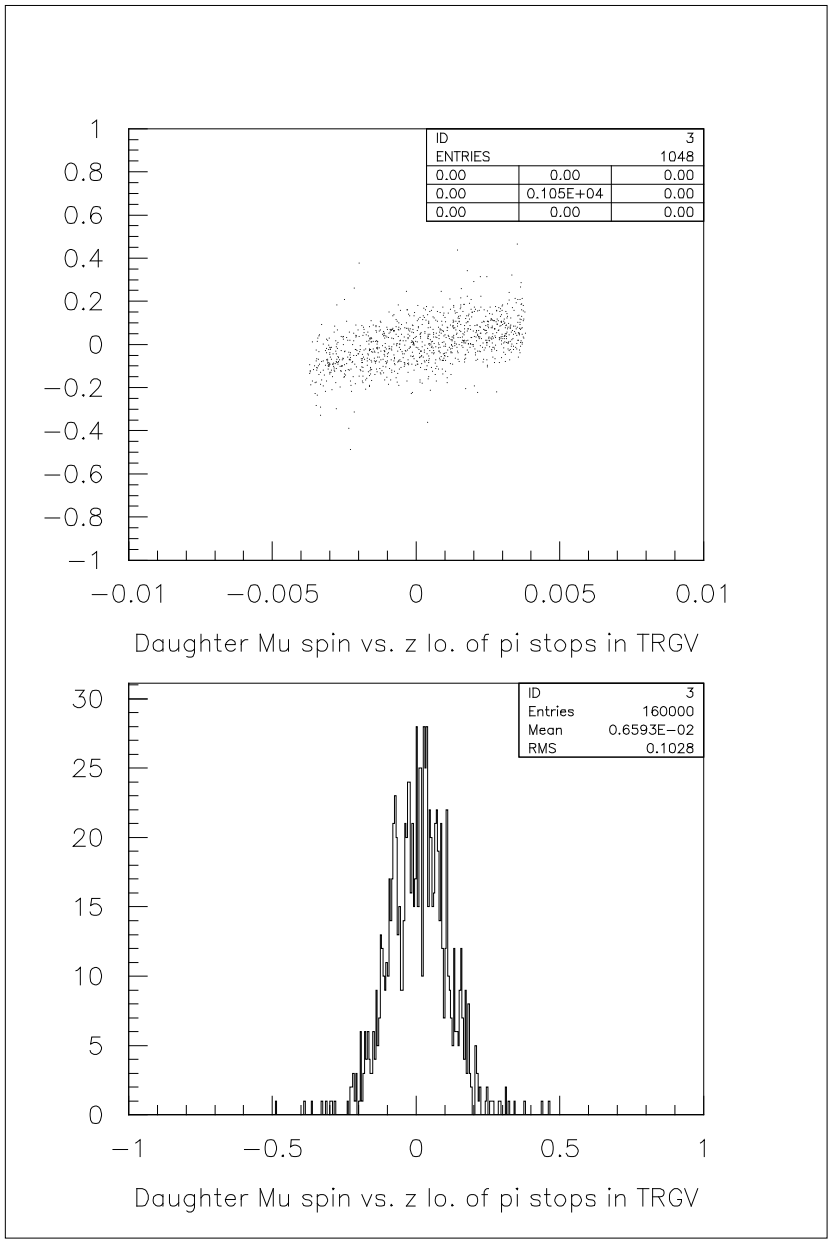

Figure 7 – Top: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay. (target only)
Bottom: Projection of top graphic onto Y-axis

Figure 8 shows the wire number in PC plane #6 (closest to target foil on the upstream side) where the incident π and the daughter μ both create a hit in the same wire. It was desirable to examine this potential problem to see if the rate at which the same wire is hit creates a significant processing problem. As these results were created from a run of 500,000 incident 65 MeV/c π's, this process of same wire hits occurs in less than 0.5%[3] of the events tracked. This may present a significant problem.

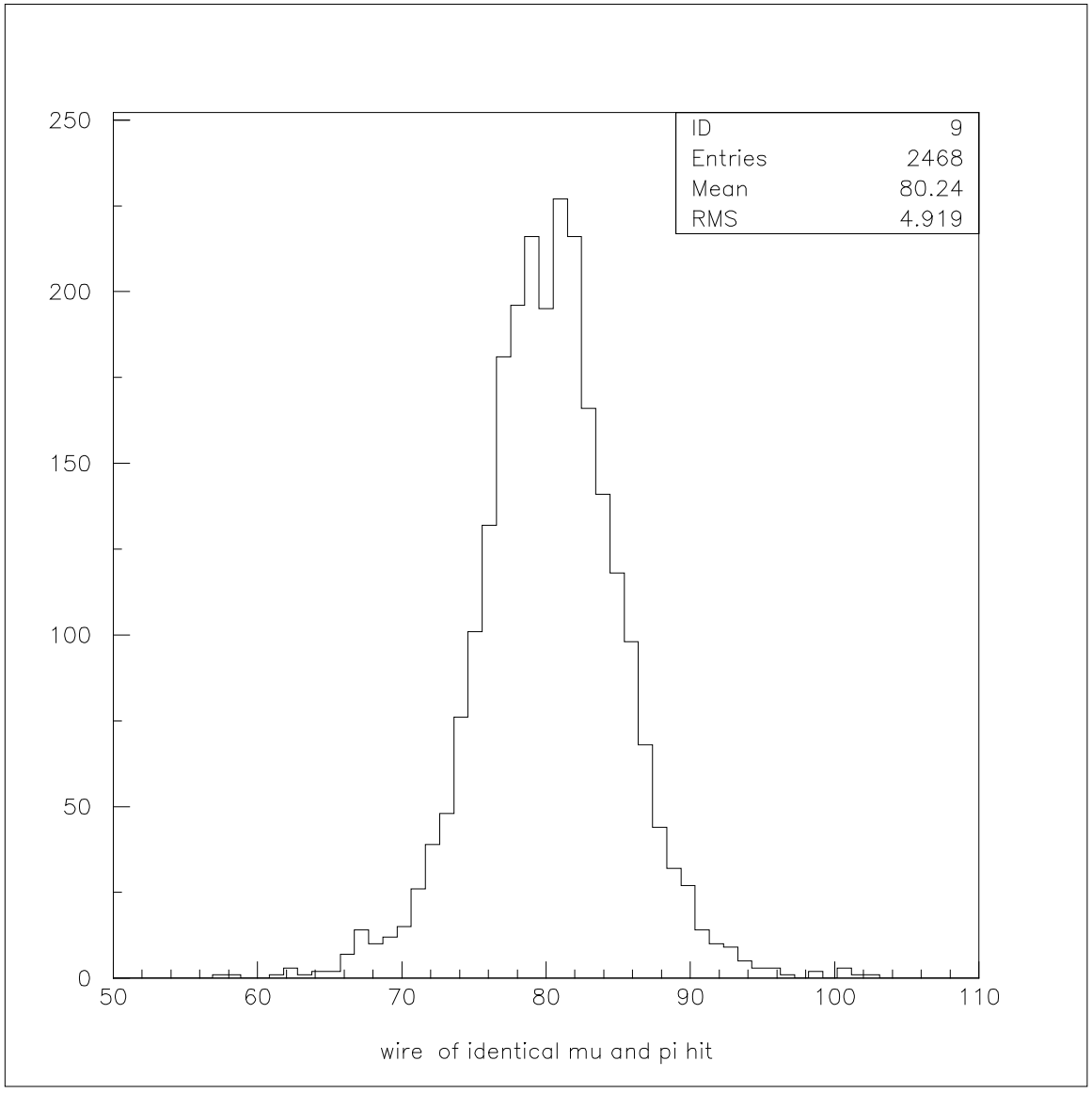

Figure 8 – Wire number in PC Plane #6 of hits from both incident parent π and daughter μ.

[3] 2468 same wire hits out of 500,000 π events. 2468/500,000 = 0.494%

Table 1 shows the majority of the statistical information gathered through the runs at an incident π momentum of 65 MeV/c. Generally, the important statistical numbers are those found under the heading "% (or fraction) of original beam". Again, all of these statistics were generated using the E614 GEANT V1.2 Monte Carlo software package, along with slight modifications for histogramming and data collection.

Statistics

Run of 65 MeV/c Beam, 500,000 events
Note: In flight pion decays are included in the statistics below

Total Pion Decays: 499,898

Pion Decay Location	# of Decays	% total beam	Mean Decay Location	RMS
Upstream Scintillator	2417	0.483%	-64.07	9.14E-03
Upstream Degrader	1632	0.326%	-65.89	0.2621
Target Foil	25,811	5.163%	1.85E-04	2.15E-03
Downstream Degrader	197	0.039%	65.71	0.2076
Downstream Scintillator	3,345	0.669%	64.07	8.82E-03
Totals	33,402	6.682%		

4841 of the resultant daughter muons from pi decays throughout the detector decay in the target
This is about 1% of the incident pion beam.

for 500,000 pion decays generated only in the scintillators and degraders,
(generated from stored locations of pion decays produced by the original 65 MeV/c beam)

Daughter Muons that reach Target foil from:	Number	% of total muons	Fraction of original Pion Beam	Mean Decay Location	RMS	Mean Spin Distribution	Spin RMS
Upstream Scintillator	4053	0.811%	1.231E-04	-64.08	9.72E-03	-0.6292	9.86E-02
Upstream Degrader	1051	0.210%	3.191E-05	-65.64	9.87E-04	-0.8626	8.76E-02
Downstream Degrader	486	0.097%	1.476E-05	65.64	6.89E-02	0.8056	0.1214
Downstream Scintillator	5583	1.117%	1.695E-04	64.08	9.61E-03	0.6248	9.95E-02
Totals	11173	2.235%	3.393E-04				

Stopped Pion Statistics

65 MeV/c incident beam 500,000 events

Pion Stopping location	# of stops	% of original incident beam	# of daughter muons that stop in target	% of original beam
Everywhere	155093	31.02%	not measured	
Target Foil	25804	5.16%	1048	0.21%

Run of 500,000 stopped pions, generated from stored locations of stopped pions produced by the original beam.

Pion Stopping location	# of daughter muons that stop in target	% of events generated	% of original beam
Everywhere	9547	1.91%	0.592%
Target Foil	3244	0.65%	0.201%
Surface of Scintillators	75	0.02%	0.005%

Table 1 – 65 MeV/c Statistics

40 MeV /c π Beam Results

As the useful μ flux available from incoming π's at 65 MeV/c is somewhat low, the next step was to test for the available flux for a π beam at 40 MeV/c. The flux of π's available from the M13 production target at 40 MeV/c is considerably lower (about a factor of 30) than the flux available at 60 MeV/c [1]. However, the π stopping distribution curve was much steeper at 40 MeV/c, so it was hoped that there would also be an increase in the flux of useful μ's that were produced. The degraders needed to optimize the stopping distribution were 530 microns thick.

From figure 9 it is seen that the majority of the π's that stop in the detector do so in the target foil. The contribution of daughter μ's from the degraders and scintillators is negligible. The π's that stop in the target are the greatest source of useful μ's. As seen in figure 10, 2839 useful μ's were produced in the target, a fraction of 0.57%. This is about a factor of 3 higher than the 65 MeV/c case. However, the total π flux is much less, so the flux of useful μ's is effectively reduced by a factor of 7 ½. An advantage to using 40 MeV/c π's is that there are fewer background sources of μ's (scintillators, degraders, modules, etc.), so it is easier on the data acquisition system.

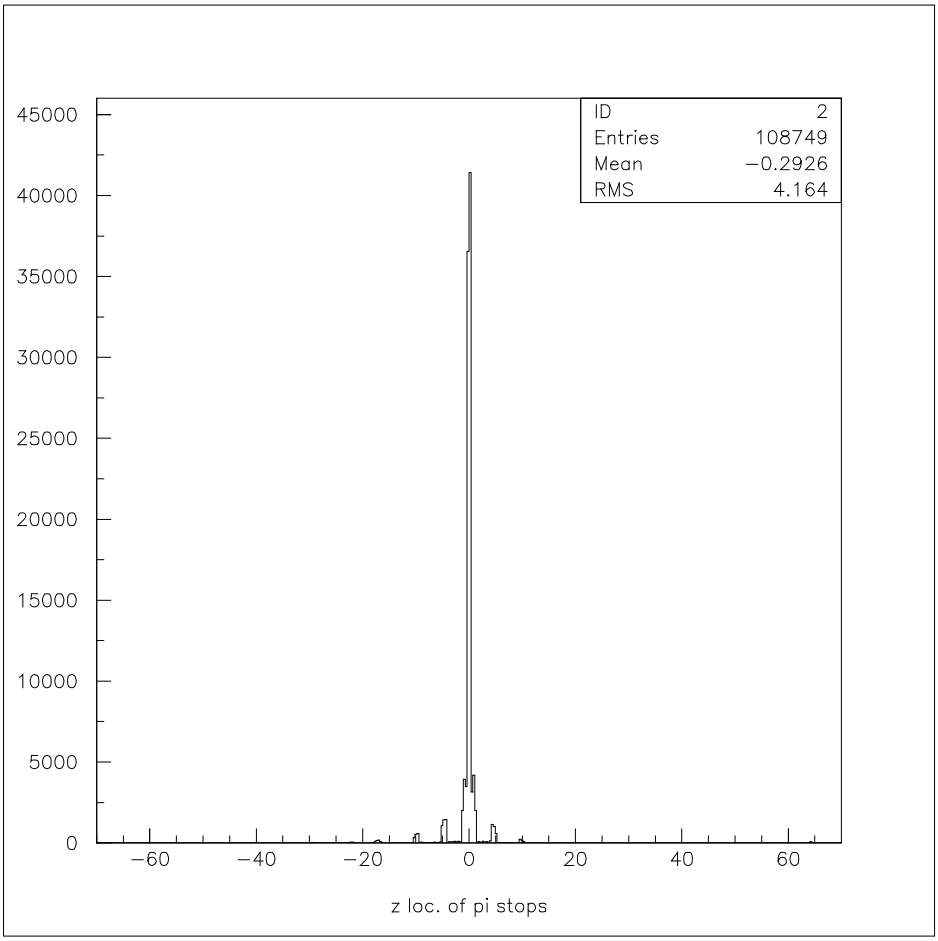

Figure 9 – z location of stopped π's (40 MeV/c)

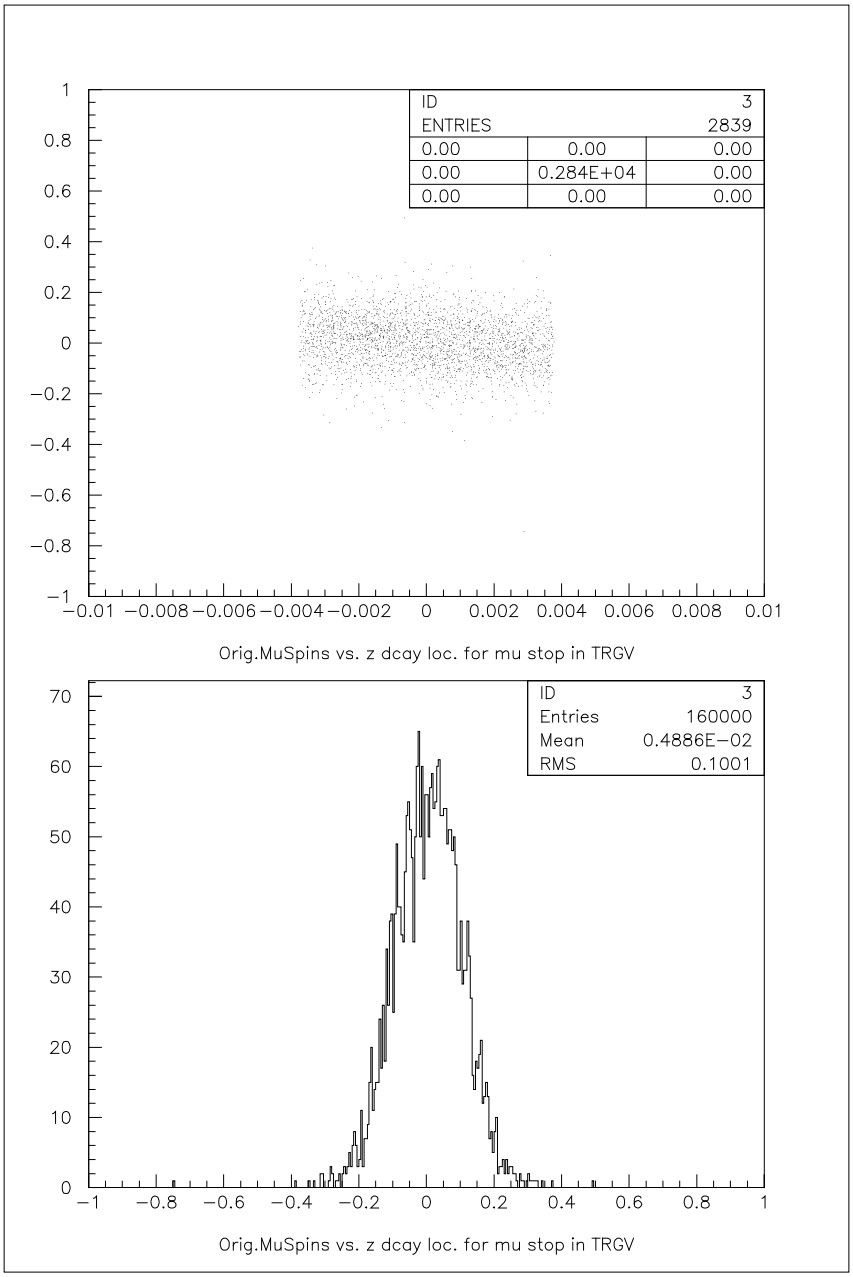

Figure 10 – Top: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay. (target only)
Bottom: Projection of top graphic onto Y-axis

The bottom part of figure 10 shows that the mean spin distribution at 40 MeV/c is as close to unpolarized as it is at 65 MeV/c.

52 MeV/c π Beam Results

In an effort to find an even better π beam momentum operating point, we tried an incident π momentum of 52 MeV/c. At this momentum, the required degrader thickness was 3.468 mm. The flux of incident π's available from the M13 production target is about a factor of four less than at 65 MeV/c [1].

In figure 11, the distribution of stopping π's is an intermediate of the two previous cases that have been discussed. There will not be as many background μ's as the 65 MeV/c case, but more than the 40 MeV/c example. The flux of incoming π's at 52 MeV/c is about a factor of 4 less than the flux at 65 MeV/c. As seen in figure 12, the flux of useful μ's available increases to 0.38% of the incident beam, just less than twice as much as at 65 MeV/c. Thus 50 MeV/c provides half of the flux of useful μ's that 65 MeV/c, but it also provides a reduction in background μ's.

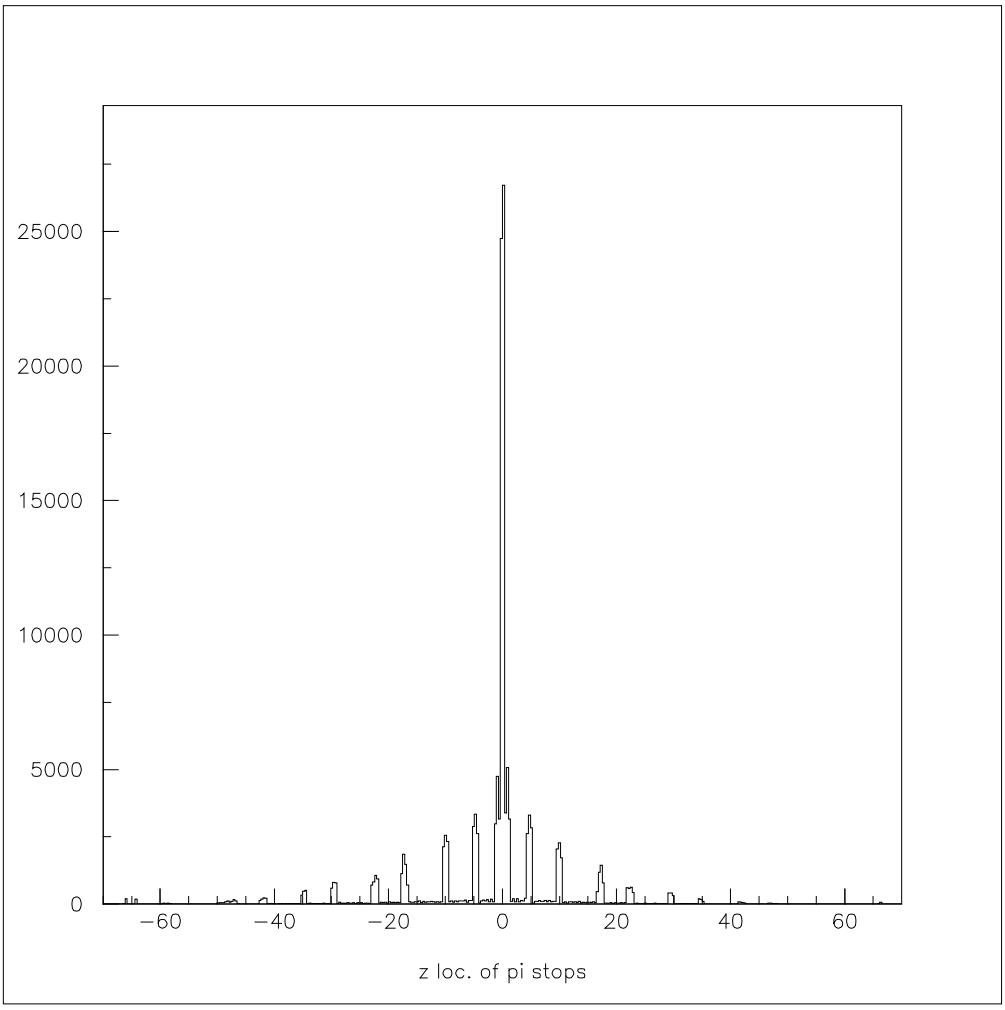

Figure 11 – z location of stopped π's (52 MeV/c)

As in both the 65 MeV/c case and the 40 MeV/c case, the mean spin distribution is close to zero, which is shown on the bottom part of figure 12.

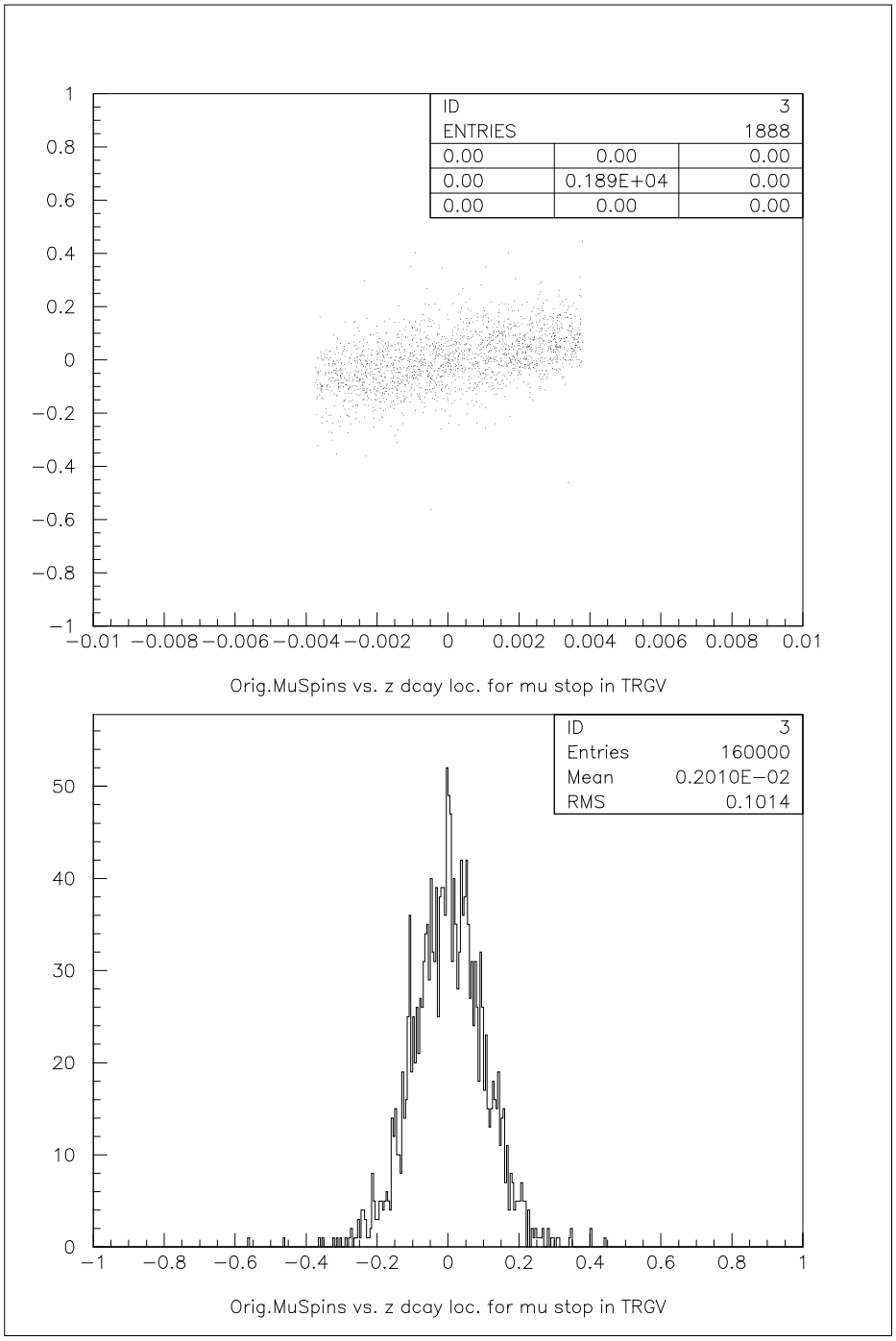

Figure 12 – Top: Spin of daughter μ's that stop in the target foil vs. z location of parent π decay. (target only)
Bottom: Projection of top graphic onto Y-axis

CONCLUSIONS

If we set as a goal to have 5,000 target foil μ events/sec, it is interesting to examine the needed flux of incident π's under different assumptions. If all of the μ's that end up stopped in the target are useful for this experiment, then at 65 MeV/c we need 500,000 incident π's/sec to have the required 5,000 target foil μ's/sec. If only the π's that stop create usable μ's in the target, then we need about 850,000 π's/sec. If we can use only the μ's in the target that are created from π's that stop in the target, the number of π's needed increases to 2.5 million π's/sec. Using a momentum of 40 or 52 MeV/c requires fewer π's/sec, but the available flux from the M13 decreases by a greater amount, so the net result is that it would take longer to accumulate 10^9 events at these lower momentums than at 65 MeV/c. The lower momentums would provide a smaller background of μ sources, as the μ sources become more concentrated around the target foil. It seems that the scintillators and degraders are not significant contributors to μ production that results in μ's in the target. Even at 65 MeV/c, only 0.03% of the incident π's decay in the scintillators and degraders to produce μ's that end up in the target foil.

Another question to answer is can we use the μ's from the surface of the scintillator for a spin experiment. Using the configuration that was utilized in this study, it is not possible. The available flux of μ's from the scintillators is much too low at only 0.005% of the incident π beam. However, it may be possible to alter the scintillator and/or degrader thicknesses along with optimizing the beam momentum in order to maximize π stops in the surface of the downstream scintillator in order to possibly perform an S_μ = +1.0 experiment using the daughter μ's.

References

1. TRIUMF Users Handbook, p. IV-18a

2. D. H. Wright, TN-29, “A Users Guide to E614 GEANT”.