Florida Institute of Technology
High Energy Physics Research Group

Spring 2010 Research Report

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Note: During September 2010, it was found that the simulation data presented here may not actually be from an MTS with an active volume height of 101 mm, but, instead, may be from an MTS with an active volume height of 170 mm. This is being inspected and will be commented on in the Fall 2010 research report.

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High-Statistics Geant4 Simulations

During the winter, Dr. Gnanvo constructed a prototype muon tomography station (MTS) at CERN and tested it throughout the semester—particularly in April. To complement the real-life testing, I simulated the actual MTS prototype using the Geant4 Monte Carlo (MC) simulation package. In this section, I will present results from high-statistics ($1.008x10^9$ events) simulations.

In the fall semester, simulations were performed to validate Geant4's reliability at a small scale. These tests can be seen in my end-of-semester report from Fall 2009.[i]

Simulating the target support plate was an issue. Dr. Gnanvo used, what I believe to be, hardboard[ii] approximately 0.508 cm thick and spanning the entirety of the x-y plane of the MTS volume. Geant4 does not seem to have any intrinsic material similar to hardboard.[iii] I used Geant4's version of PVC (G4_POLYVINYL_CHLORIDE) with a thickness of 3 cm instead of hardboard (we have available a target plate of this material and dimension). In the future, I hope to more accurately simulate the target plate; however, the scattering from the plate will be low regardless of using PVC or simulated hardboard, so it will not significantly affect the simulations for our purposes.

All other geometry aspects of the simulations are the same as already established in simulations past, thus presenting no problems. The scenarios presented have detector

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[i] http://research.fit.edu/hep_labA/archive.htm
[ii] http://en.wikipedia.org/wiki/Hardboard
[iii] http://geant4.cern.ch/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/apas09.html

gaps of 94.5 mm, and an MTS volume of 50x50x101 mm^3. Note, though, that the reconstructions of this MTS (real and MC data) are based off of a z dimension of 100mm. The CRY plane is 1x1 m^2. A target plate of thickness 3 cm made of PVC is centered at z = 0 in the MTS volume, spanning the entire x-y plane. See the configuration files available in my directory on the Cluster for more detailed information:

`/home/g4hep/geant4/examples/mytestapps/benL/`

I will now present the results from the simulations with angular dependent resolution, as this resolution is, theoretically, most representative of reality.

Scenario	Total Events	Total POCA	POCA in MTS	POCA In MTS ÷ Total POCA	Total POCA ÷ Total Events
Empty	1.008×10^9	48542	10909	0.225	4.82×10^5
Iron	1.008×10^9	47454	23580	0.497	4.71×10^5
Lead	1.008×10^9	46373	21786	0.470	4.60×10^5
Tantalum	1.008×10^9	46742	23960	0.513	4.64×10^5

Table 1 POCA efficiency for high-statistics MC with angular dependent resolution.

Now, I will present the scattering angle distributions for each scenario, normalized to 1 event for consistency. I will present two sets of plots of the same data: (1) Scattering angles from 0 to 20 degrees, and (2) scattering angles from 0 to 5 degrees. The latter shows better the difference in the “primary” distribution area, while the former shows better the tail of the distribution. The plots are on the next page.

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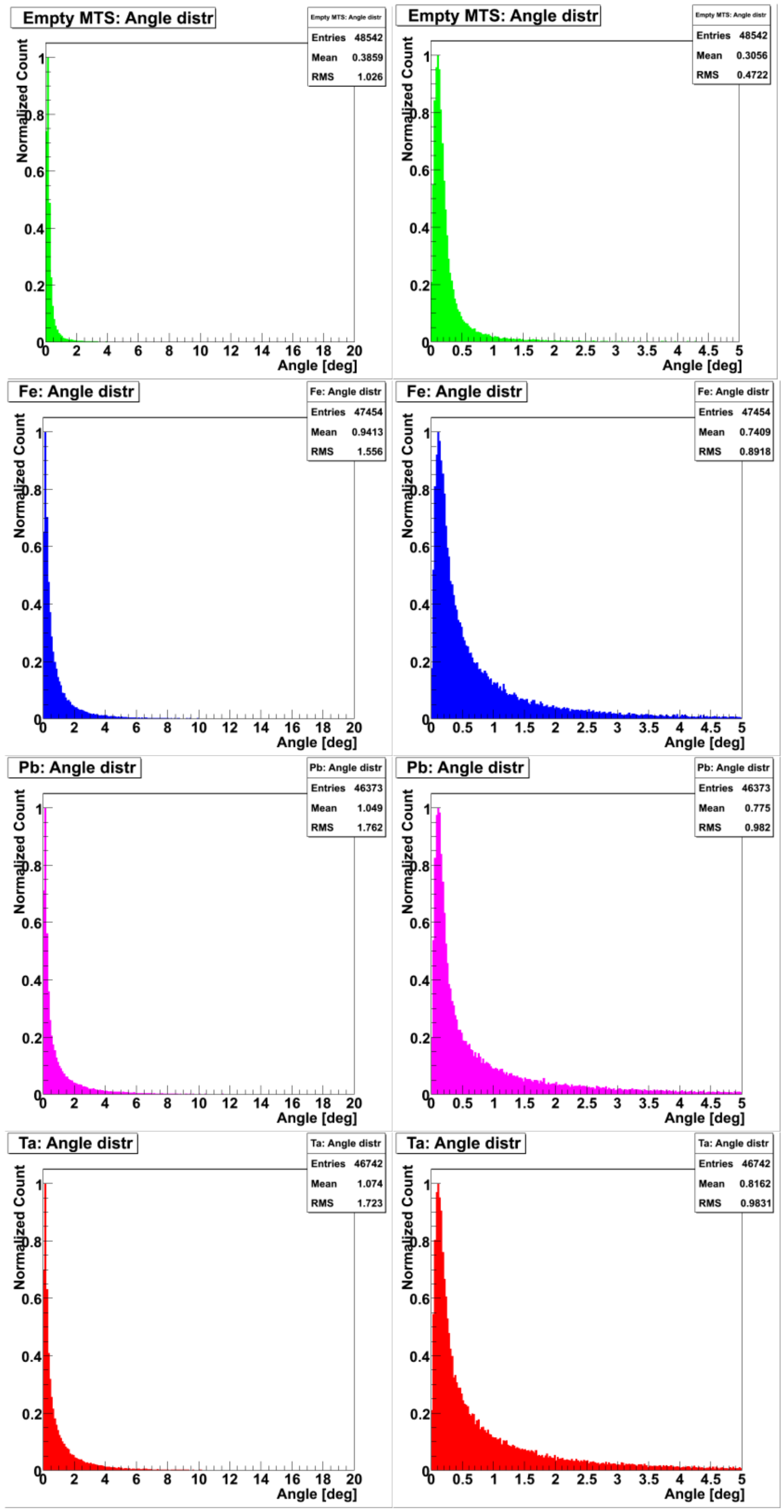

Figure 1 High-statistics scattering angle frequencies. The left column of plots ranges from 0–20 degrees and the right column from 0–5 degrees.
There are 2000 bins in every histogram.

I will recapitulate the results from the above histograms:

Scenario	0–20 Degrees		0–5 Degrees	
	Mean [deg]	**RMS**	**Mean [deg]**	**RMS**
Empty	0.3859	1.026	0.3056	0.4722
Iron	0.9413	1.556	0.7409	0.8918
Lead	1.049	1.762	0.7750	0.9820
Tantalum	1.047	1.723	0.8162	0.9831

Table 2 Mean and RMS of scattering angle frequency distributions from high-statistics MC simulations.

As you can see, the mean scattering angle is dependent on the range of the display shown, all other things held constant. Regardless of the range shown, there are marked differences between empty scenarios and any other scenario. In both ranges, systematic differences are observed for each different material's mean, that is, empty < fe < pb < ta. Do not let this be misleading in terms of the atomic numbers of theses materials. The atomic number hierarchy actually goes fe < ta < pb. Density and volume play roles here in the observed differences between materials and deviations from the hierarchy proposed by their *Z* values.

Finally, I will present the POCA reconstructions in abbreviated form. I will only present slices of the reconstruction going through the target, as it is well established that slices outside the target area show few POCA. This is easily surmised when simultaneously comparing the x-y and y-z slices. So, the only nontrivial slices are those in which the target, or part of the target, lies. Also notice the slice widths for the x-y and y-z projections. This width allows almost the entire target to be accounted for in every slice.

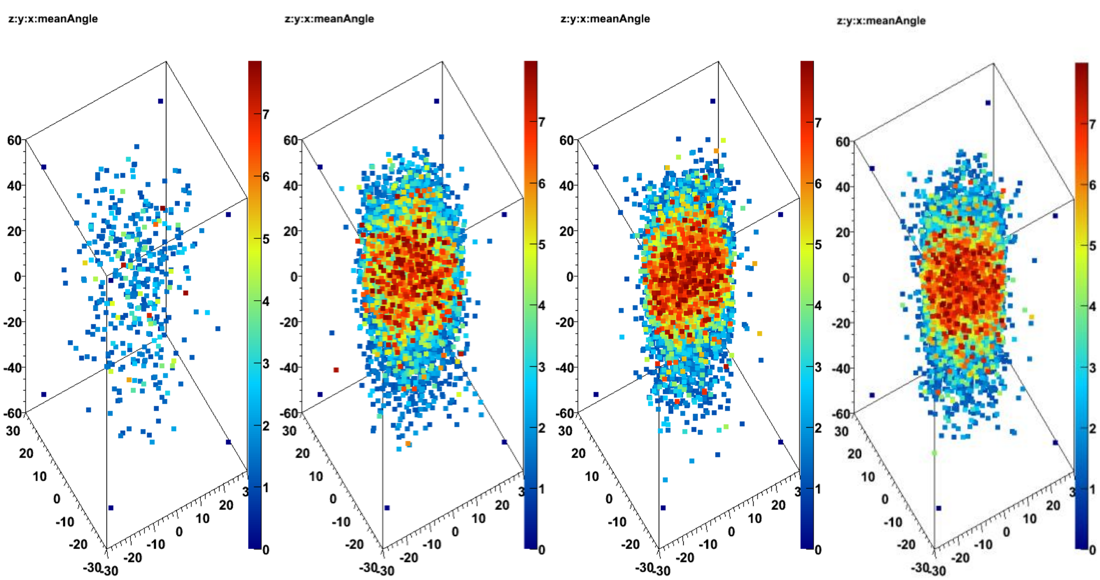

Figure 2 High-statistics 3D POCA reconstructions (from left): empty, fe, pb, and ta.

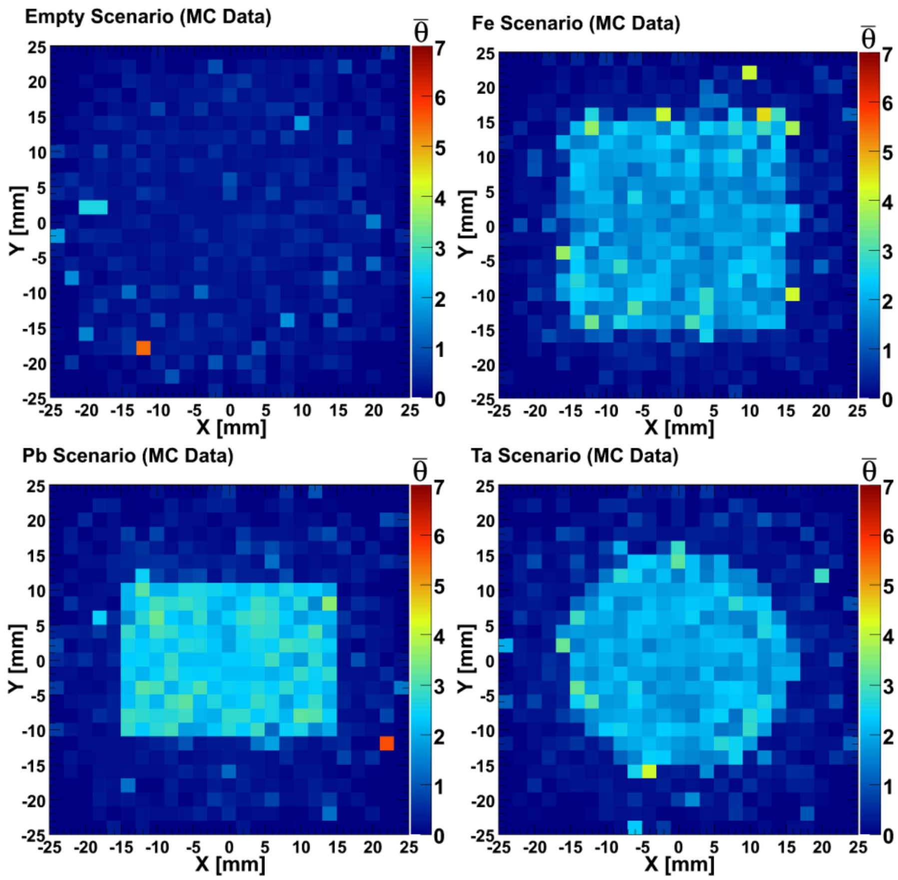

Figure 3 High-statistics 2D POCA reconstructions in x-y plane, where 10mm ≤ z ≤ 30mm.

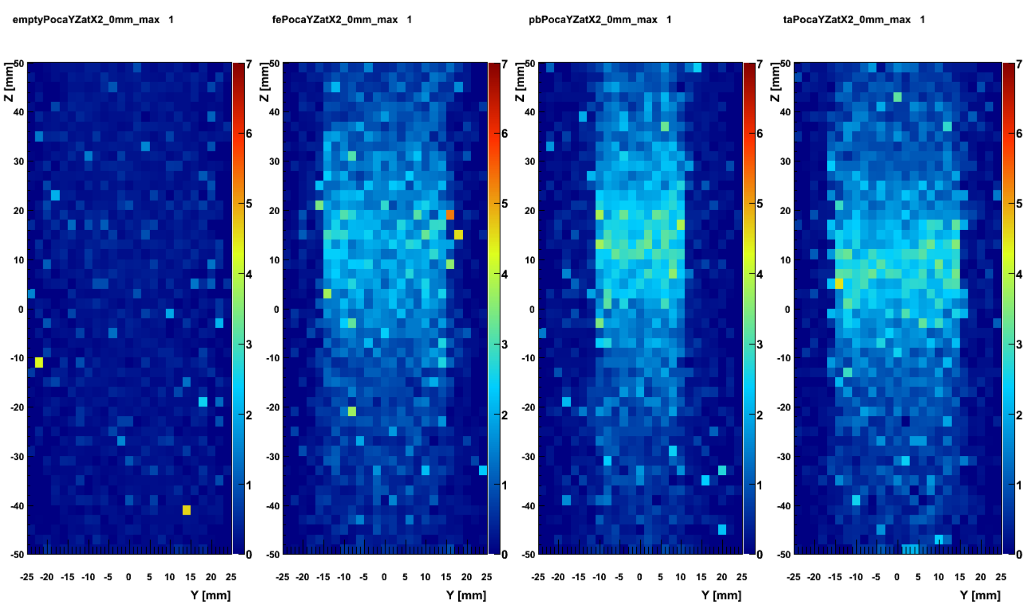

Figure 4 High-statistics 2D POCA reconstructions in y-z plane, where -5mm ≤ x ≤ 5mm. From left to right: empty, fe, pb, and ta.

As always with our high-statistics MC simulations, the x-y plane shows a well-defined picture of out targets in the correct place. And, like always, we see clutter in the y-z plane. This clutter is due to the nature of the POCA algorithm. We have always seen, and we will always continue seeing, points reconstructed outside the target in the vertical direction. Lastly, notice that the target plate does not seem to show up in any reconstruction. Later, we will observe the same behavior in the real data, justifying my approximation of the target plate with the PVC.

Low-Statistics Geant4 Simulations of Real Data

The primary objective of these simulations is to validate that our simulations of muon tomography—past, present, and future—are sufficient to model reality in a reliable and accurate way. If we have a reliable way of simulating real muon tomography, then we have a reliable (and free!) way of planning scaled-up operations and predicting the positive and negative effects of MTS geometries.

The scenarios presented below have the same geometries as the high-statistics scenarios. The MC simulations here, however, differ from the high-statistics simulations presented previously only in number of events (1.008×10^8 events vs. 1.008×10^9). Even though the MC simulations here have an order of magnitude fewer events than the ones presented above, far fewer data were taken by the real MTS. So, to compensate, only the first few data were taken from the simulations such that the numbers of simulation data and real data are the same for the analyses presented. Later I will present an analysis with the high-statistics scenarios scaled, not truncated, to match the real scenarios.

Four scenarios were tested: an empty detector (with target support plate), an iron cube (30x30x30 mm^3), a lead block (28x20x30 mm^3), and a tantalum cylinder (15 mm radius, 16 mm height). The results from these simulations are tabulated below.

Scenario	Simulation POCA			Real POCA		
	Total	In MTS	In÷Total	Total	In MTS	In÷Total
Empty	816	193	0.235	816	557	0.683
Iron	1043	508	0.487	1043	808	0.775
Lead	1473	706	0.479	1473	1125	0.764
Tantalum	2067	1061	0.512	2067	1617	0.782

Table 3 POCA efficiency for simulation and real scenarios. Simulation POCA are for angular dependent resolution. Note that the total simulation POCA is *fixed* to be the same as the real POCA total by truncating any additional data points in the simulation output.

The visualizations of these comparisons can be found on Dr. Gnanvo's 2010 SORMA poster, available on the FIT HEP website. I will reproduce the pertinent graphics from his poster below as well as scattering angle distribution histograms. Below, I will recapitulate my findings for mean scattering angles before I present the histograms of the same information.

Scenario	Simulation POCA		Real POCA	
	Mean [deg]	**RMS**	**Mean [deg]**	**RMS**
Empty	0.2562	0.2499	1.488	2.754
Iron	1.319	1.577	1.500	2.058
Lead	1.593	2.090	1.587	2.312
Tantalum	1.511	1.762	1.785	2.711

Table 4 MC vs. real POCA mean and RMS data.

As you are looking through the 2D and 3D POCA reconstructions, notice the more concentrated, sharper appearance of the MC plots. This is expected, as we know our simulation is “better” than reality. Also note that there is a filling problem with the upper and right edge bins for the x-y reconstructions. This problem has been fixed in the ROOT script (but after the production of the plots presented below).

The reconstructions below and the unmistakable inconsistencies in the numbers presented in the table above indicate that serious improvements to our MC simulations need to be made. Dr. Gnanvo suggests including the actual efficiency of the detectors in the simulation and the addition of simultaneous events. Dr. Hohlmann also wants the addition of other particles, such as electrons, that can trigger a detector, but not produce any useable data. These additions may be made to the next major simulation upgrade in addition to coding the next generation MTS geometry, designed primarily by Lenny Grasso.

Concluding this analysis, I will now present the plots associated therewith. The plots begin on the next page.

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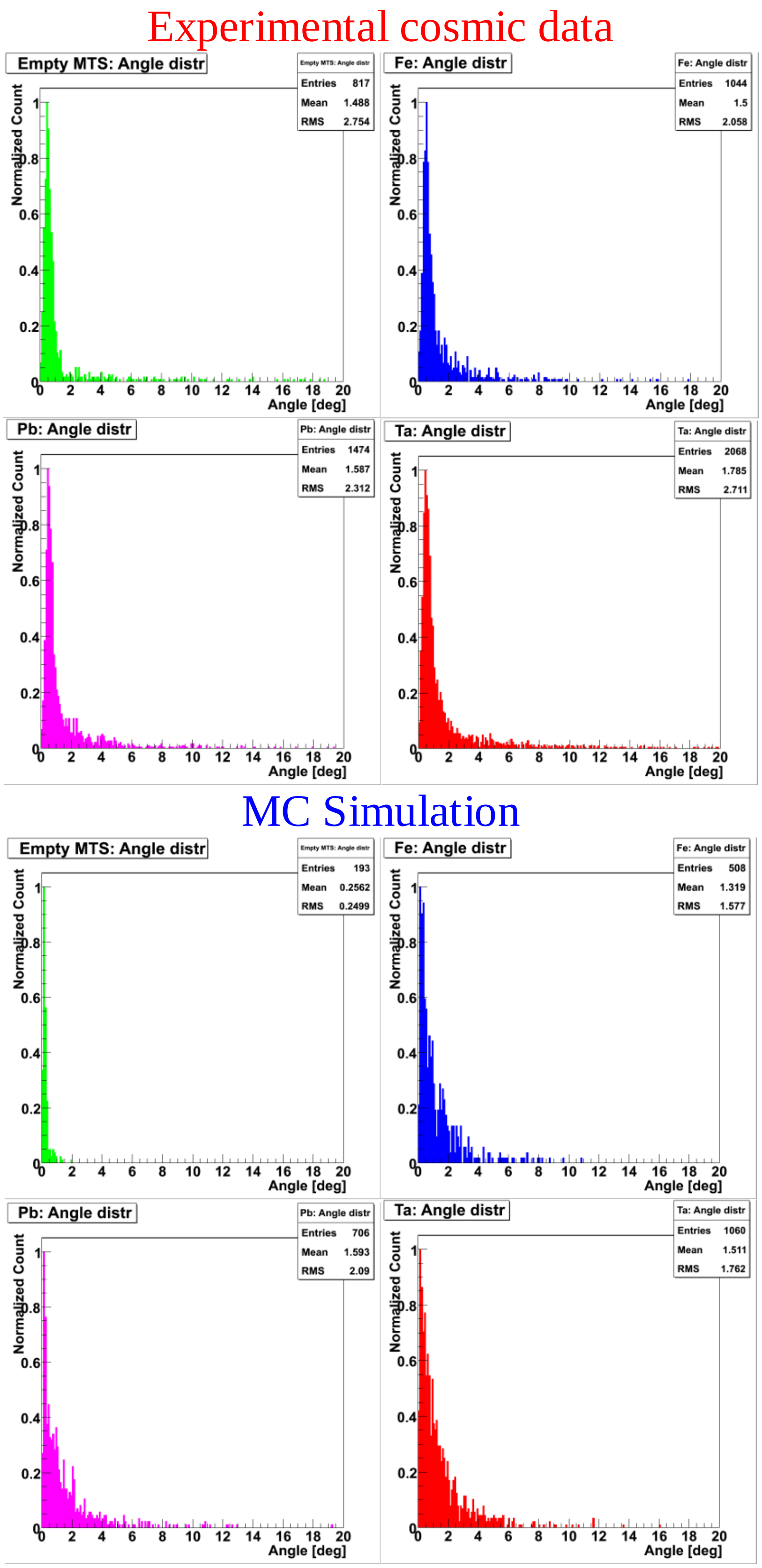

Figure 5 Scattering angle distributions for real and MC data.

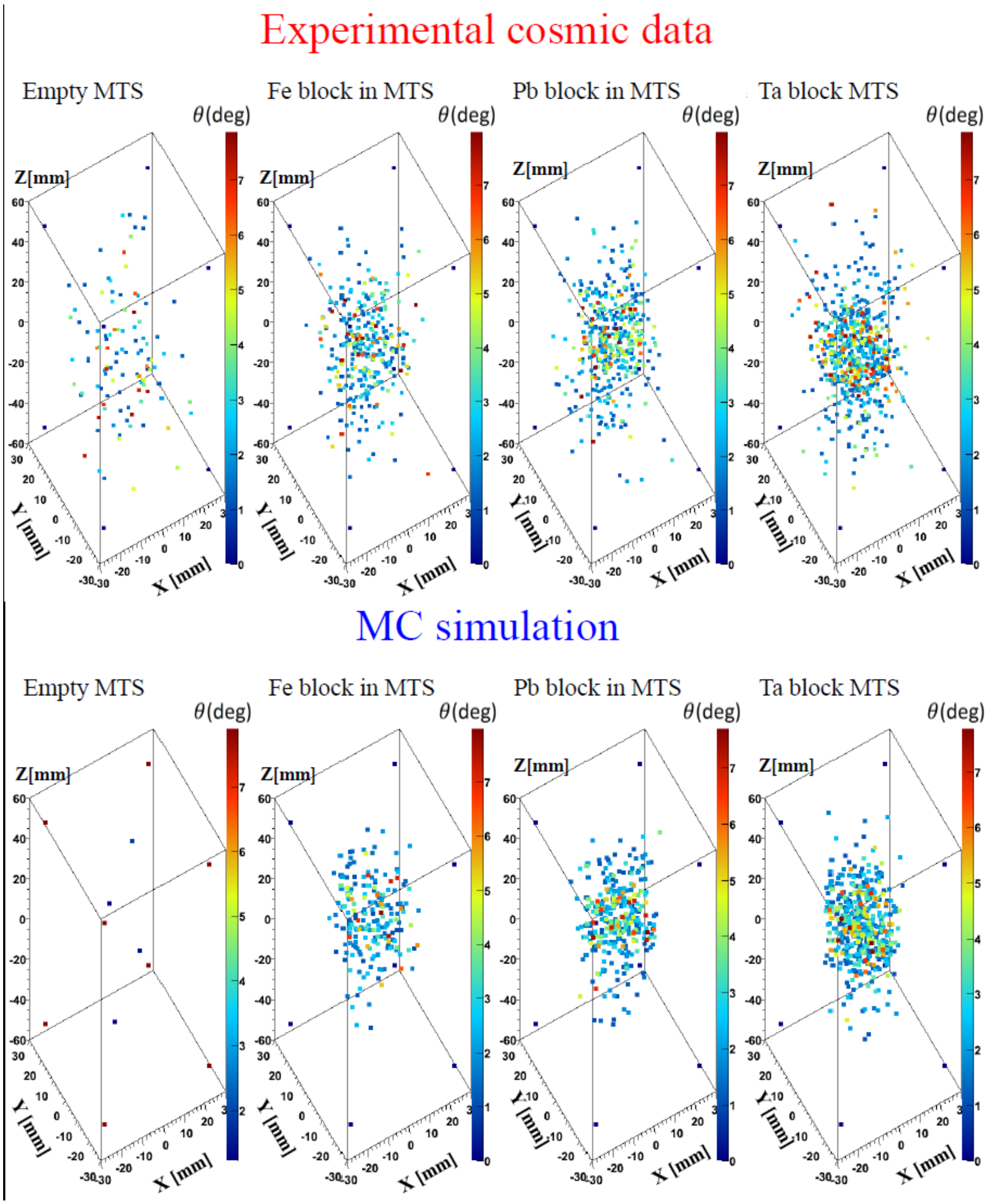

Figure 6 Low-statistics 3D POCA reconstructions for MC and real data.

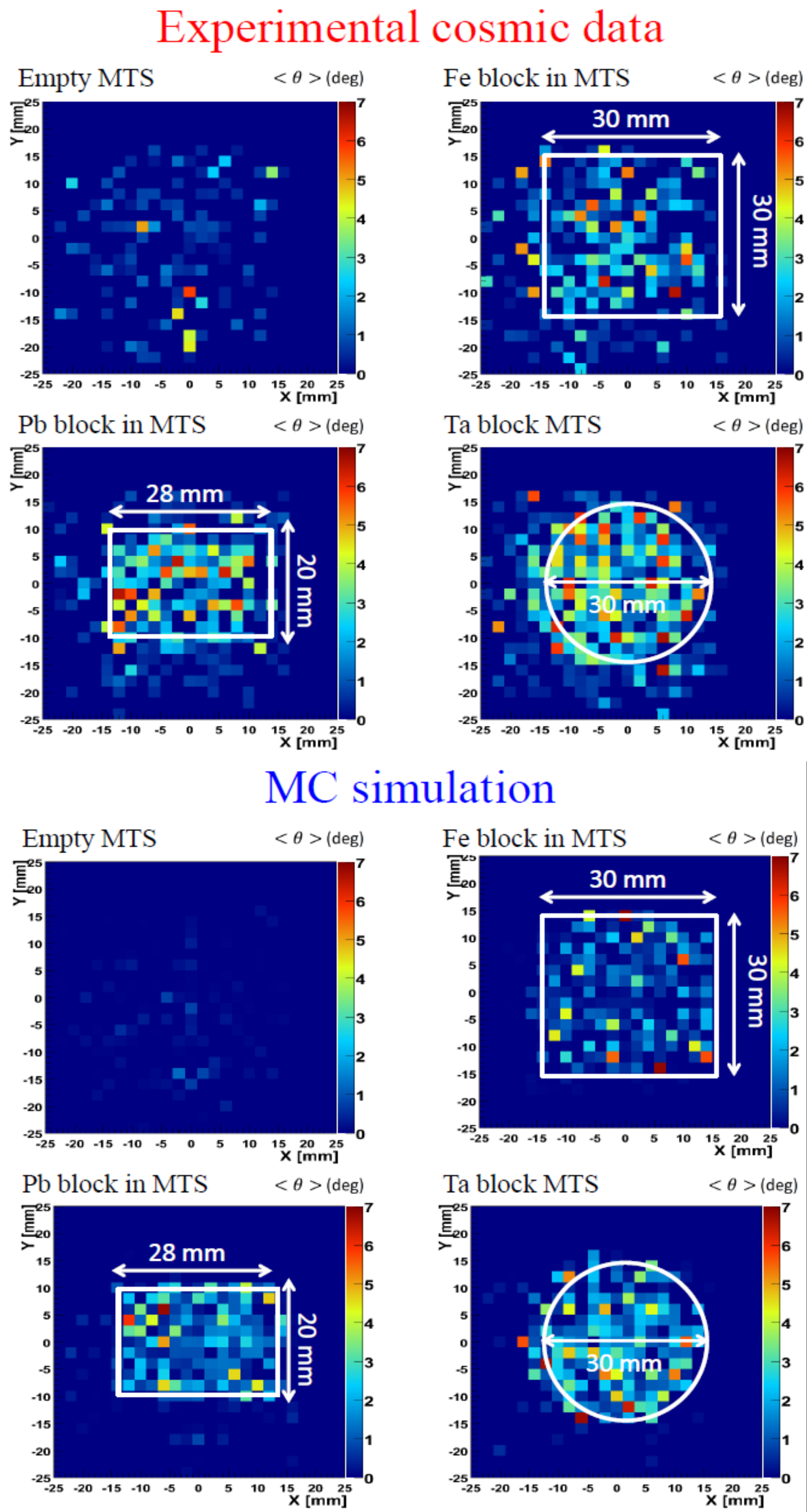

Figure 7 Low-statistics 2D POCA reconstructions in the x-y plane, where 10mm $\leq z \leq$ 30mm.

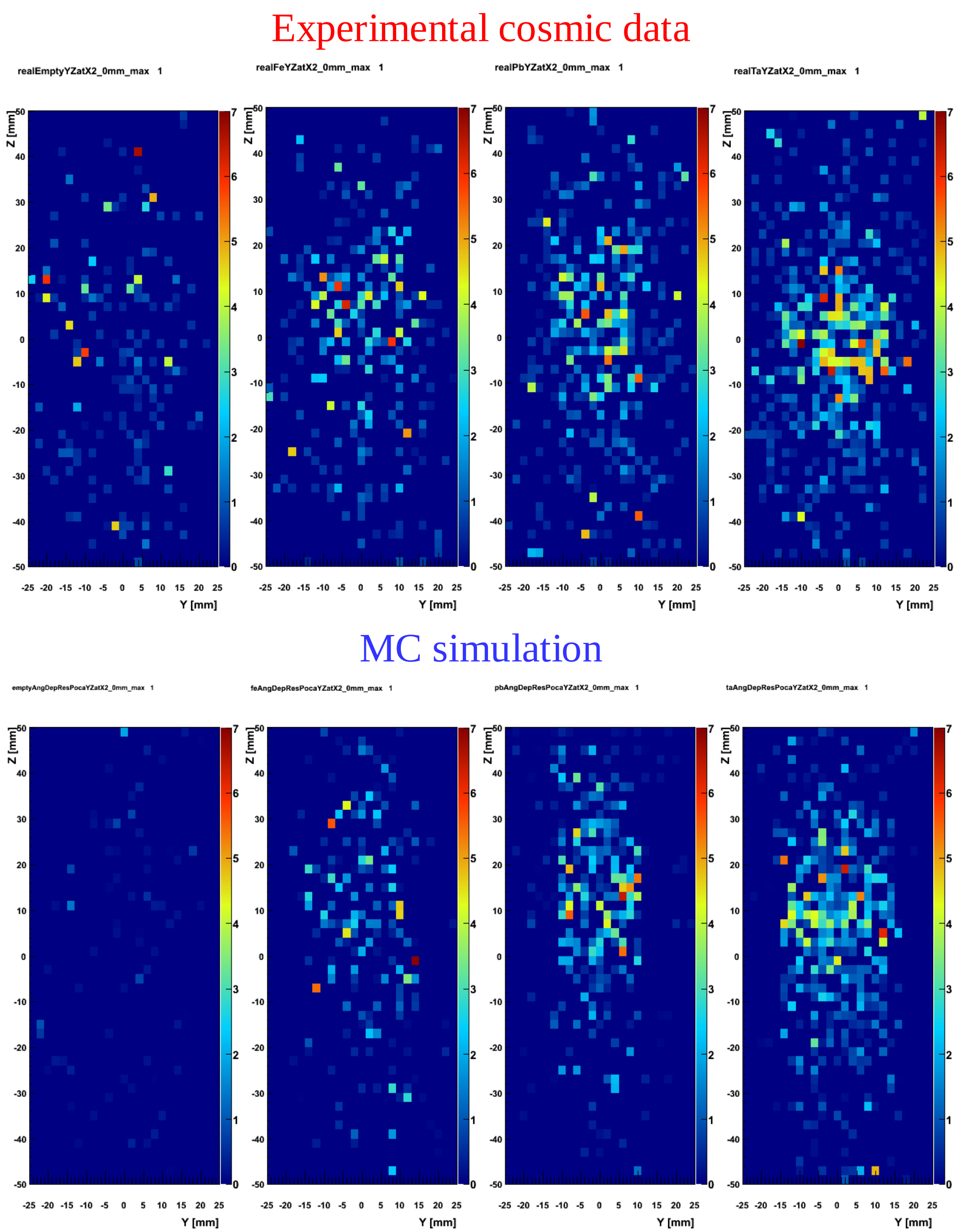

Figure 8 Low-statistics 2D POCA reconstructions in the y-z plane, where -5mm ≤ x ≤ 5mm. From left to right: empty, fe, pb, and ta.

From the y-z projections, one can see that in real life, just as in simulation, the POCA algorithm creates a significant amount of artifacts in the z direction above and below the target.

Small CRY Plane

Literature[iv] on the Cosmic-ray Shower Library (CRY) we use to simulate the natural muon flux indicates the following about CRY plane size:

> ***The lateral size of interest (meters)***
>
> *`subboxLength n`*
>
> *Particles are returned inside a box of `n` by `n`. The maximum allowed value is 300 m. Data tables are provided for 1, 3, 10, 30, 100, and 300 m. For box sizes in between these discrete values, the next largest table will be utilized and particles outside of the specified window will be dropped.*

The above implies that we should be able to use a smaller CRY plane, say 5x5 cm^2—instead of a 1x1 m^2—CRY plane, and we should get the same results as if we had run the 1x1 m^2 CRY plane for much longer.

To test this hypothesis, I simulated the empty scenario of the current MTS prototype with 100 events and with 1 million events, and each one of those with 0.05x0.05 m^2, 0.5x0.5 m^2, 1x1 m^2, and 1.5x1.5 m^2 CRY planes. The 100 event scenario provides visuals. The 1 million event scenario provides statistics. (Visualizing a 1 million event scenario requires more computing power than available and is totally unnecessary for our purposes.)

The figure below is muon tracks from the four 100 event scenarios described above. One can see the detector (2 top detectors, 2 bottom detectors, and a target plate in the middle) in yellow in the center of the pictures. The blue and red lines are muon tracks.

[iv] http://nuclear.llnl.gov/simulation/cry.pdf

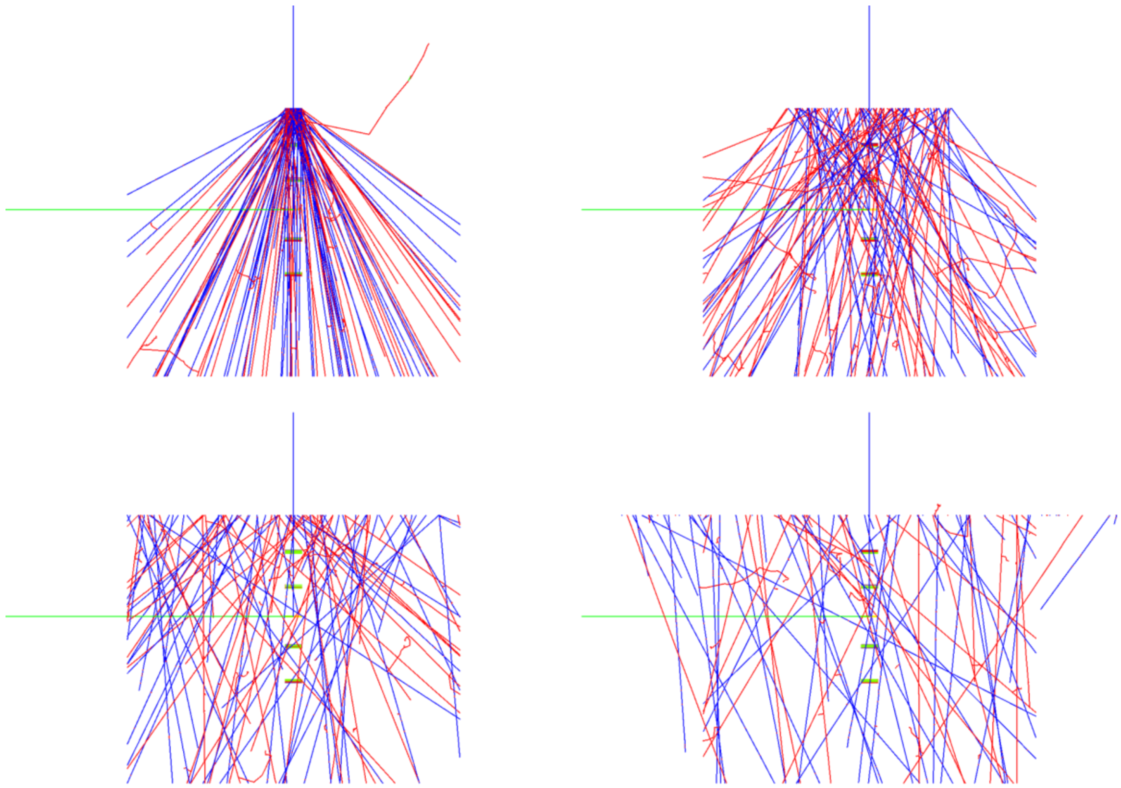

Figure 9 Muon tracks from various CRY plane sizes (clockwise from top left): 0.05x0.05, 0.5x0.5, 1x1, and 1.5x1.5 m^2.

The 100 event scenario did not produce any significant statistics. The following are the results from the 1 million event scenarios with perfect resolution detectors:

CRY Plane Size [m^2]	CPU Time [hh:mm:ss]	Total POCA (0 µm Resolution)	POCA per Second CPU Time
0.05 x 0.05	02:17:58	6266	0.76
0.5 x 0.5	00:07:50	129	0.27
1 x 1	00:05:33	37	0.11
1.5 x 1.5	00:03:33	0	0.00

Table 5 POCA efficiency for various CRY plane sizes.

Clearly, decreasing the CRY plane size does increase the POCA point efficiency as a function of time. However, observing the visualizations, one will notice that the muon shower "looks" somewhat "unrealistic" for the 0.05x0.05 m^2 CRY plane. For this reason, I do not think it is a good idea to go to such a small CRY plane. Perhaps using the 0.5x0.5 m^2 CRY plane provides a happy medium between efficiency and realism. Moving from 1x1 m^2 to 0.5x0.5 m^2 increases POCA efficiency by a factor of 2.45, while losing little realism.

Stand-Alone POCA Script

I wrote, tested, and implemented a script using the POCA code imbedded in the established Geant4 code we already use for simulation. I also found a website which displays very similar code to the one we use.[v] Perhaps the information on this website may be useful in future endeavors. This stand-alone code runs without the auspices of Geant4. It takes a data file of detector hits and produces a data file of POCA with scattering angles. These output data can be used to reconstruct real or simulated data (in fact, the script has been used to transform all real data into POCA data which can be reconstructed). The script is available on the Cluster in my directory.

The accuracy of the code was tested by comparing it with the output files of the Geant4 script we currently use for simulations of the prototype MTS. The output of the stand-alone POCA script matched exactly the output of the Geant4 code, less discrepancies in the last decimal places of some coordinates and scattering angles. The inconsistencies are *very* negligible, as a quick file-compare of a stand-alone and a Geant4 output file will demonstrate.

The code currently takes only an input file and produces an output file. Various parameters, such as the size of the MTS, etc., are hard-coded and must be changed manually and then the code recompiled. The future work on this code involves implementing a configuration file to accept these customizable features, or removing the hard-coded parameters, making the script "dumb" (that is, it performs no cuts whatsoever, and returns a POCA point for every set of input data). Furthermore, I also plan to separate out the classes I wrote for this code for use with other code, as they might be useful to my future work, as well as to everyone else's.

ROOT Script Improvements

I implemented various improvements to the ROOT script, including making 2D POCA reconstructions accurately reflecting the x-y dimensions of the MTS. Other improvements such as axis labels on the 2D plots and larger markers on the 3D plots were implemented. These changes are not consolidated to a single script yet, but are implemented on an as-needed basis. The ROOT script can be found in my directory, as mentioned in the previous section. Dr. Gnanvo made many changes as well.

Earlier in the semester, I began writing an entirely new ROOT script for data analysis, incorporating many changes that Dr. Gnanvo and I would like to see in the flexibility and power of the script for data analysis. This project was cut short when the need to analyze real data became a priority (and a reality!). Future work on this project is finishing the new ROOT script.

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[v] http://www.softsurfer.com/Archive/algorithm_0106/algorithm_0106.htm