

Comparisons of Pion Simulations for the MOLLER Experiment

Dominic C. Lunde *California Lutheran University*

W. Deconinck and D. Armstrong *College of William and Mary, Physics Dept.*

August 29, 2016

Abstract

The MOLLER experiment at Jefferson Lab will measure the parity-violating asymmetry in Møller scattering, the scattering of electrons from electrons. A precise measurement of this parity-violating asymmetry will allow us to determine the weak charge of the electron with a precision that improves over the E158 experiment at SLAC. The experiment will scatter electrons from a 11 GeV beam from atomic electrons in a liquid hydrogen target. The detected particles will include inelastically produced pions, which will be a background to our measurements. In this work we investigate the validity and accuracy of two available pion physics models in order to estimate the uncertainty in the size of the pion background in the simulation. Currently there are two methods of pion models implemented. The LUND model is based on the Pythia event generator and has been used with success in simulations for the SoLID experiment. The Wiser model is based on data from previous pion scattering experiments. Comparison of the rates, cross sections, particle momentum, scattering angles, and other parameters show that both models produce consistent results for the parameters that were studied in this work, within the range of energies and scattering angles of interest to the MOLLER experiment. ¹

¹This work was supported in part by the National Science Foundation under Grant Nos. PHY-1359364 and PHY-1405857.

1 Introduction

The Standard Model describes three different forces: electromagnetic, strong, and weak force. There are many physical parameters that must be measured in order to precisely calculate the charges of these forces. One of these parameters is the parity violation in the weak force which only is violated in the weak force. This parity violation means that the spin of the electron determines the probability of the particles interacting through the weak force as opposed to the electromagnetic force. A precise measurement of this difference in probabilities is necessary in calculating the weak charge of the particles involved. This asymmetry is what the MOLLER experiment is going to measure. The experiment will be measuring the parity-violating asymmetry Møller scattering, which is the scattering of electrons from electrons. This measurement will improve the accuracy of calculation of the weak charge of the electron.

$$A_{PV} = \frac{S_R - S_L}{S_R + S_L} \approx \frac{M_Z}{M_\gamma} \cdot Q_W(e) \quad (1)$$

[2]

In the equation above A_{PV} stands for the parity violating asymmetry, S_R and S_L stands for the rates for the right and left polarized electron beams, M_Z stands for the scattering amplitude of a Z boson interaction, M_γ stands for the scattering amplitude of the electromagnetic interactions, $Q_W(e)$ stands for the weak charge of the electron. As seen above, a more precise measurement of A_{PV} will allow a more precise calculation of the weak charge of the electron. An experiment was run many years ago at the Stanford Linear Accelerator Center in order to measure the parity-violating asymmetry of Møller scattering. The MOLLER experiment will improve upon this result.

However, these parity-violating interactions occur very rarely. Therefore in order to measure precisely the experiment needs detect many of these events because the error is $\frac{1}{\sqrt{N}}$, where N stands for the number of scattering events.. In order to achieve that the MOLLER experiment will be run with a 11 GeV electron beam for multiple years. When using a such a high current beam many different scattering events will occur besides just Møller. One such event will be inelastic collisions between electrons and nuclei of the target atoms producing pions. These pions, specifically nega-

tive pions, will be bent by the magnetic fields of the MOLLER apparatus and will collide upon the main detector. The negative pions will flood the measurements and ultimately be a background to the parity-violating measurement. Therefore it is necessary to design an accurate pion detector so that this background can be removed from the final measurements. In order to prepare for the experiment a simulation has been created. An accurate model of pions generation is necessary in order to design this detector. There are two models available to the MOLLER experiment: the LUND model and the Wiser model. The LUND model is based on the Pythia event generator and has been used with success in simulations for the SoLID experiment. The Wiser model is based on data from previous pion scattering experiments. My project was to test these two different generation models of pions within the MOLLER simulation and determine which model would be best to be used within the MOLLER parameters.

2 Procedure

2.1 Re-factoring the Code

The project began by getting up to speed with the MOLLER simulation. I learned how to use Root, brushed up on my C++ skills, and started familiarizing myself with the MOLLER simulation. Initially the LUND generator was not built into the simulation. My first task was to understand the code flow and build in the connections so that the LUND generator would work.

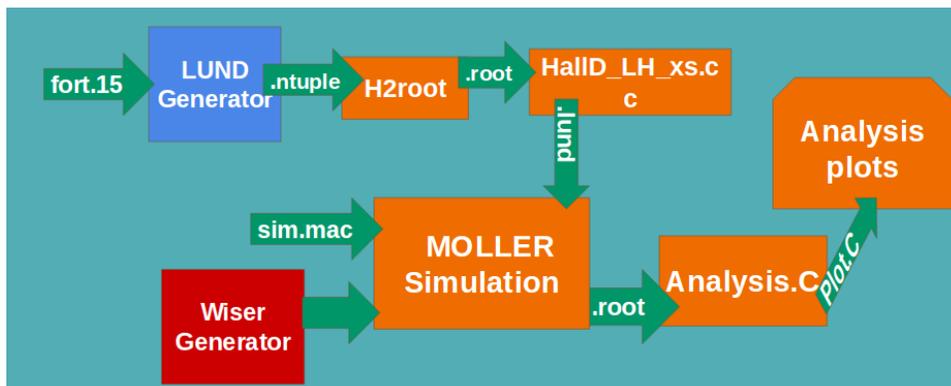


Figure 1: MOLLER simulation code flow

The orange boxes stand for different programs or simulations, the arrows stand for input and output files, and the blue and red boxes stand for the pion generators. As seen, the LUND generator adds quite a bit of complexity, while the Wiser generator doesn't require any file transfers. The LUND generator is written in FORTRAN and can only be run on 32 bit computers while the Wiser generator is built in C++ and can be run within the MOLLER simulation. Therefore it is much easier to use the Wiser generator.

At the beginning of the project the connection between the .lund files and the MOLLER simulation was not complete. I built in commands which allowed the simulation to accept the .lund files as input. After trouble shooting that connection and ensuring that it was working, I worked my way back toward the LUND generator. I edited the `HallD_LH_xs.cc` code to allow it to run on the William and Mary computers. After doing that I was able to run the LUND generator, take the output and convert it to .root, convert those to .lund files, and then use those as input for the MOLLER simulation. I was the first person to complete this entire connection. Next, I built shell scripts which automate those 3 parts of the code flow so that I can run the simulation quickly and more simply.

During my project I determined that the rate was not being calculated for the LUND generator. I tracked how it was calculated within the LUND generator and studied how it was calculated for the Wiser generator. I discovered that the LUND generator creates particles that are already cross section weighted while the Wiser generator makes particles that are not cross section weighted but calculates cross section on the side. Then, the Wiser generator takes that cross section and calculates rate from the cross section. I also discovered that the LUND generator calculates a total rate for the entire simulation. I built in a new way to calculate rate which uses the total rate for the LUND generator.

During the simulation it also became evident that it was necessary to only produce pions from 0 to 2 degrees. The Wiser generator allows this edit easily. The LUND generator creates particles from 0 to 180 degrees and allows a cut to 0 to 2 degrees to be done later in the code flow. It takes 400 times the number of events in the LUND generator to create 1 event in the MOLLER simulation. Towards the end of the project I needed 1,000,000 event simulations for MOLLER in order to get

good statistics. Therefore, I needed to create 400,000,000 events in LUND. This took 1,300 files to achieve. The amount of tedious work the LUND generator requires makes it less desirable if both generators produce similar results.

2.2 Analysis

The other section of my project was to analyze the differences between the two generators. I began by looking at the amounts of positive, negative, and neutral pions hitting the main detector from the Wiser detector. I quickly switched neutral pions to photons because neutral pions immediately decay to photons. Then I added electrons, positrons, and a pie chart showing the distribution between the different particle types. Next I split the plots by each of the three detector planes in the simulation.

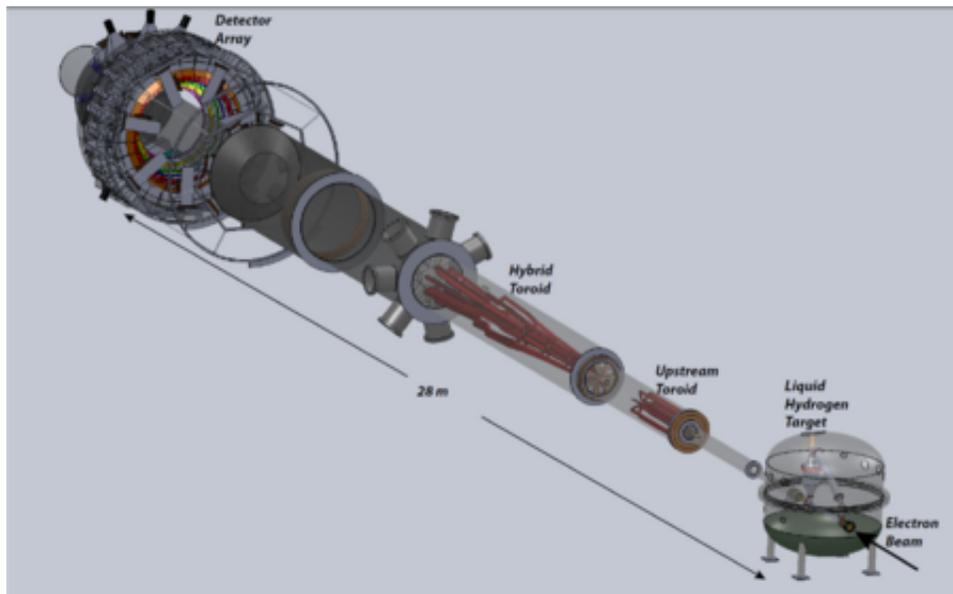


Figure 2: Proposal for the MOLLER Apparatus

There are 3 virtual detectors in our simulation which record all of the particles that pass through them. The first one is located at 5 meters away from the target the second at 10 meters and the final at 28 meters. Finally, once the LUND generator was working, I was able to overlay the two generators and start examining differences.

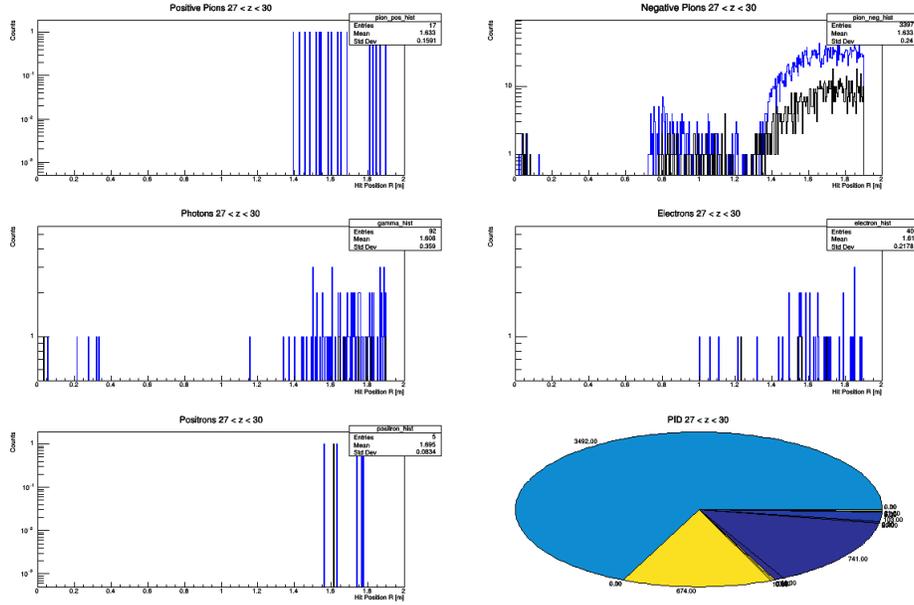


Figure 3: Radial Hits vs Counts in the Main Detector Plane with Negative Pion generation. Black stands for LUND and Blue stands for Wiser.

In these plots we observed that it seemed that equal amounts of positive pions were reaching the main detector as negative pions. As seen in Figure 2 and 3 there is a large amount of pions in radii larger than 1.4 meters. This led us to believe that the magnetic field was not working and that the negative pions were not being bent. In order to determine if the field was working I examined the source code and then started observing the peak of the electrons as I changed the strength of the magnetic field. I used Electron production and changed the magnetic field while observing how the peak amount of electrons moved.

As seen in Figure 4 the peak of electrons moves slightly as the magnetic field is increased. Therefore we concluded that the the magnetic field was working.

We still didn't understand why the positive pions were ending up in the main detector. We observed that both the negative and positive pions were tending towards the outer edge of the detector. So we thought that possibly pions were missing the magnetic fields and directly hitting the detectors. In my version of the simulation the concrete walls that would block these pions were not built in so that my simulation time was manageable. To test this I plotted initial production angle verses

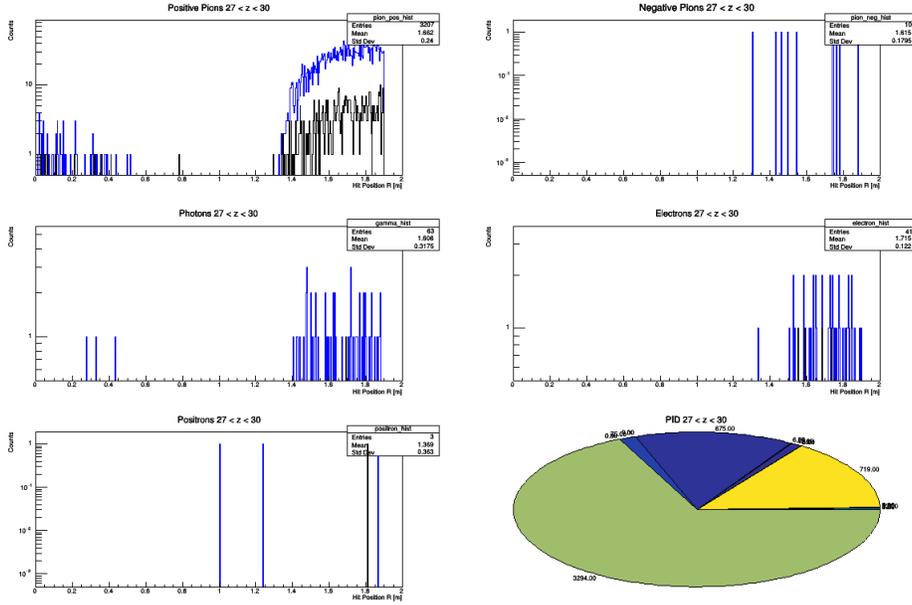


Figure 4: Radial Hits vs Counts in the Main Detector Plane with Positive Pion generation. Black stands for LUND and Blue stands for Wisur.

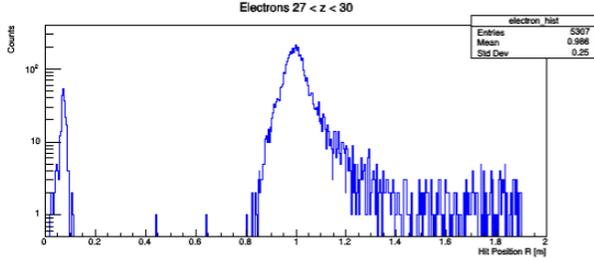
detector hits in the radial direction.

I was then able to see that above 2 degrees the pions were missing the magnetic field completely and running into the main detector in both pion generators. That prompted me to run the rest of the simulations with the parameter that pions would only be allowed to be produced between 0 and 2 degrees.

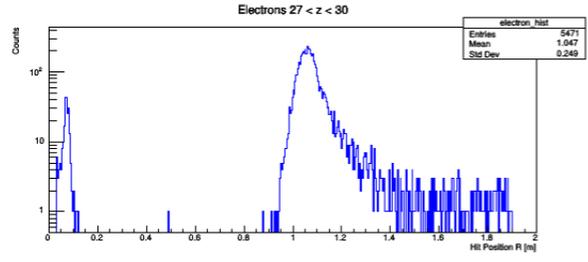
I also started looking at 6 different rings in the radial direction. These were generated in order to more closely examine the difference between the Wisur and LUND generators. The radial cut plots Figures 9-17 can be found in the Appendix and showed that the Wisur and the LUND generator produced similar results radially.

Finally I looked at splitting the results by momentum into 6 sections. This was done so that I could more closely examine the differences for higher and lower energy values.

In figures 6 and 7 it can be seen that both generators track closely. The LUND generator underestimates for lower momentum values while the Wisur generator underestimates for higher momentum values. However, because these models will be used mainly for the purpose of designing



(a) Magnetic field scaled to 1



(b) Magnetic field scaled to 1.2

Figure 5: Electron simulations to confirm that the magnetic field is working. The mean when scaled to 1 is 0.966 meters while the mean when scaled to 1.2 is 1.047 meters.

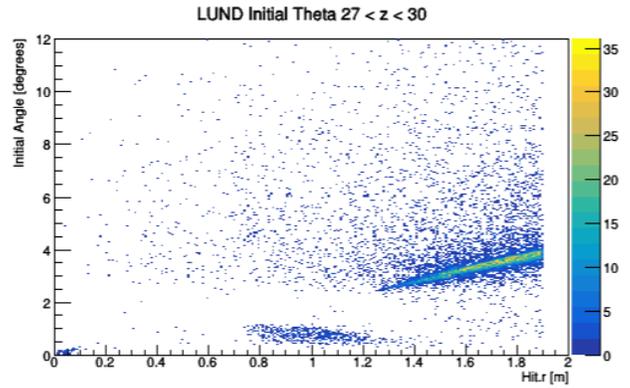
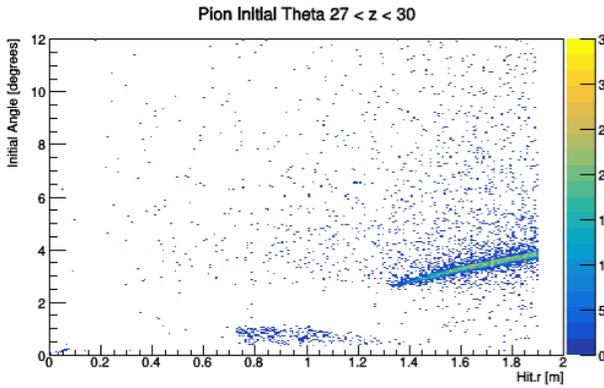


Figure 6: Initial production angle vs Radial Hits with Negative Pion production. The left is the Wiser Model and the right is the LUND model.

the pion background detector, a factor of 3 difference would be acceptable and these fall within that constriction. We will also be able to determine which model is more accurate after the experiment is run and the background is measured.

3 Results

This project was requested because the Wiser model was found to be inaccurate in other experiments. I determined two things through my project. First, the Wiser model is the simpler model to

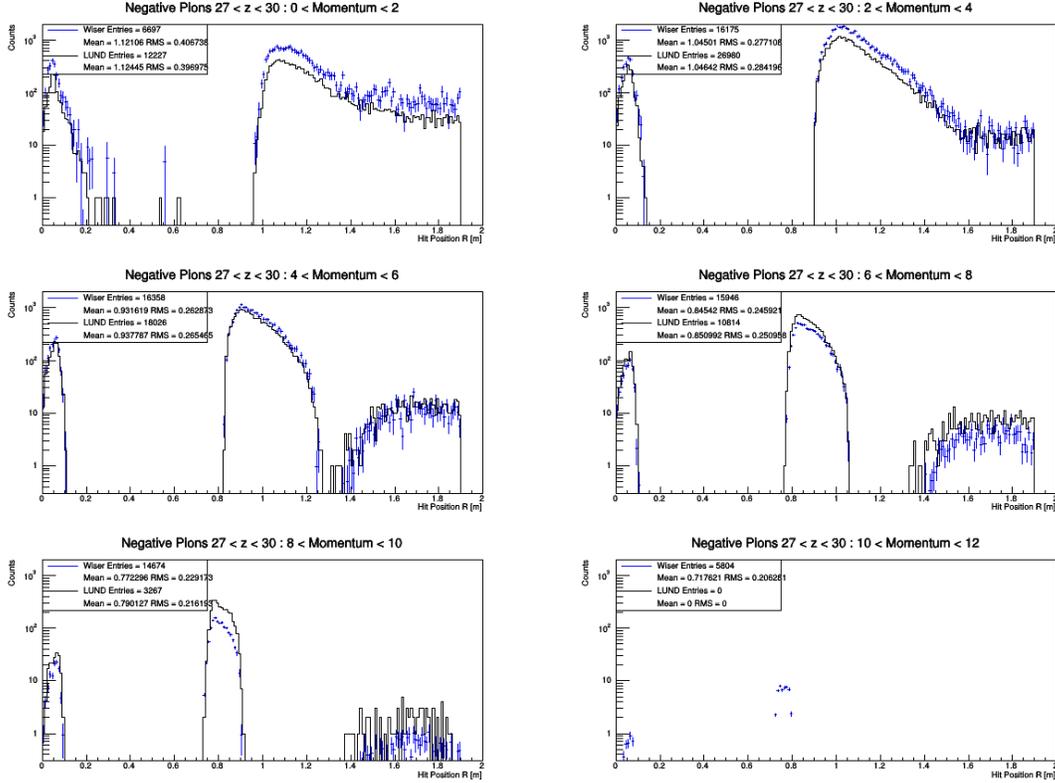


Figure 7: Momentum Cut Negative Pions at the Main Detector

be used for the MOLLER simulation. While the LUND generator requires FORTRAN compilers and many more files and simulation data, the Wisener model is already built into the MOLLER simulation and requires a lot less work. As seen in the radial cuts and momentum cuts we see that the differences between the generators is minimal. Simply using these results we can say that both generators would be accurate for the MOLLER simulation.

4 Conclusion

Through analyzing both generators within the MOLLER simulation I determined that both generators produce similar results. Therefore, on account of the ease of use of the Wisener generator, I recommend to the collaboration of the MOLLER experiment that the Wisener generator should be used and will be accurate within the parameters of this experiment.

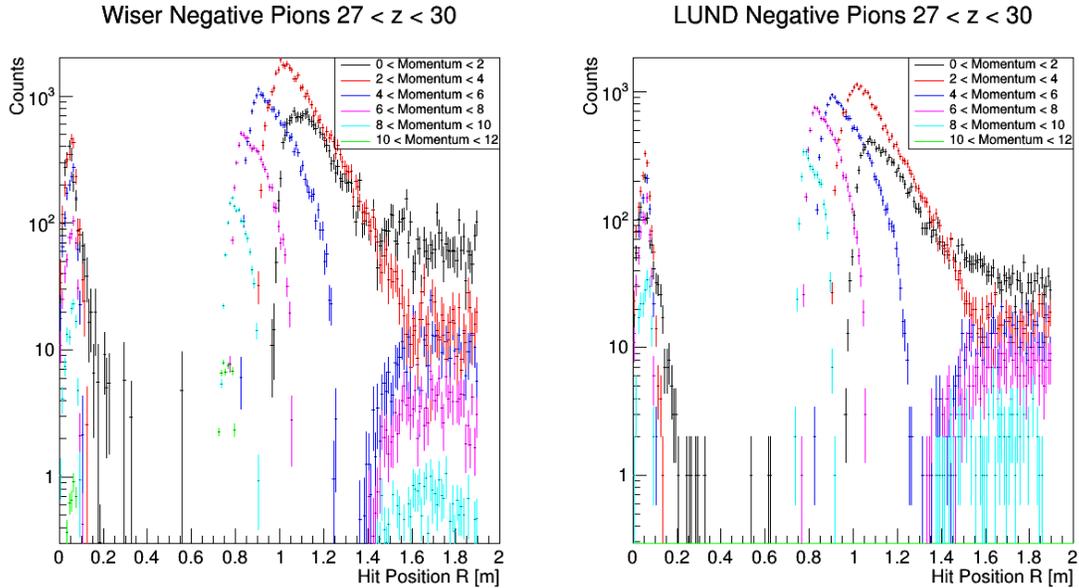


Figure 8: Overlaid Momentum Cut Negative Pions at the Main Detector

5 Future Work

There is no more future work for this project specifically except for verification of results. However, my coworker has been working on a Straw man detector for pions in the MOLLER simulation. The best design for this detector is still being evaluated. Future work for the MOLLER simulation is to build in the pion detector and look at full simulations of the entire apparatus to ensure accuracy. The MOLLER experiment will take data within 5 years at Jefferson Lab. It will take data for 5 years. The data will then be processed and published with a new measurement for the parity-violating asymmetry of Møller scattering.

References

- [1] T. Sjstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026, Comput. Phys. Comm. 178 (2008) 852 [PYTHIA Event Generator].
- [2] SLAC 158 <https://www-project.slac.stanford.edu/e158/experiment.html>

[3] MOLLER MOLLER Experiment Homepage: <http://http://hallaweb.jlab.org/12GeV/Moller/>

[4] B. Anderson, W. Hofmann: Phys. Lett. B 169 (1986) 364

[5] D. E. Wiser, UMI-77-19743. Ph.D. thesis, University of Wisconsin (1977). [Wiser Model]

Appendix

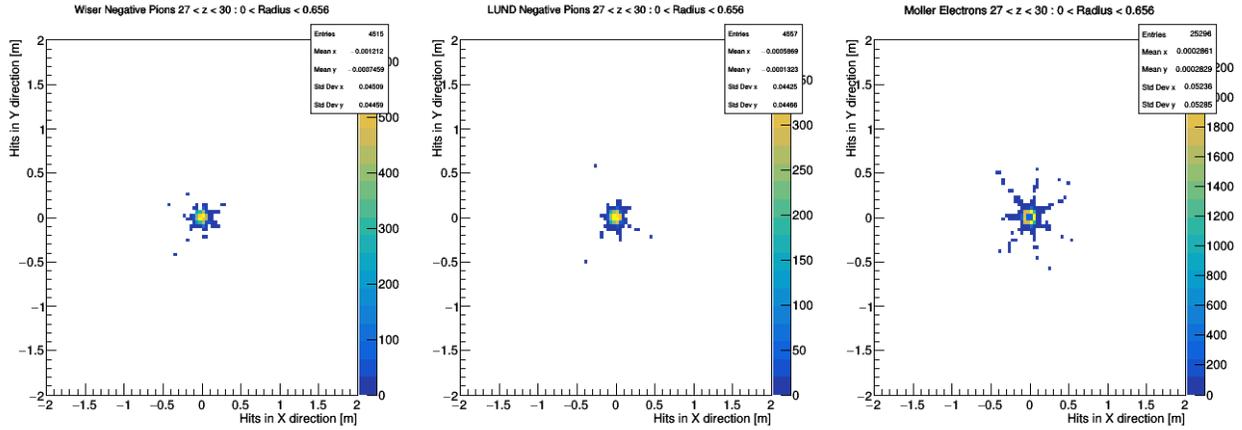


Figure 9: Y position vs X position hits with Negative Pion production

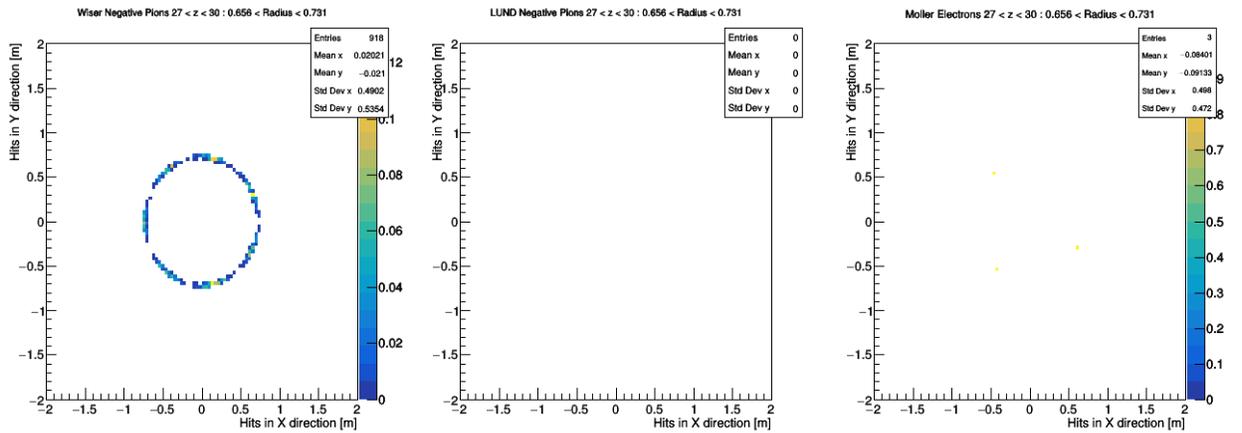


Figure 10: Y position vs X position hits with Negative Pion production

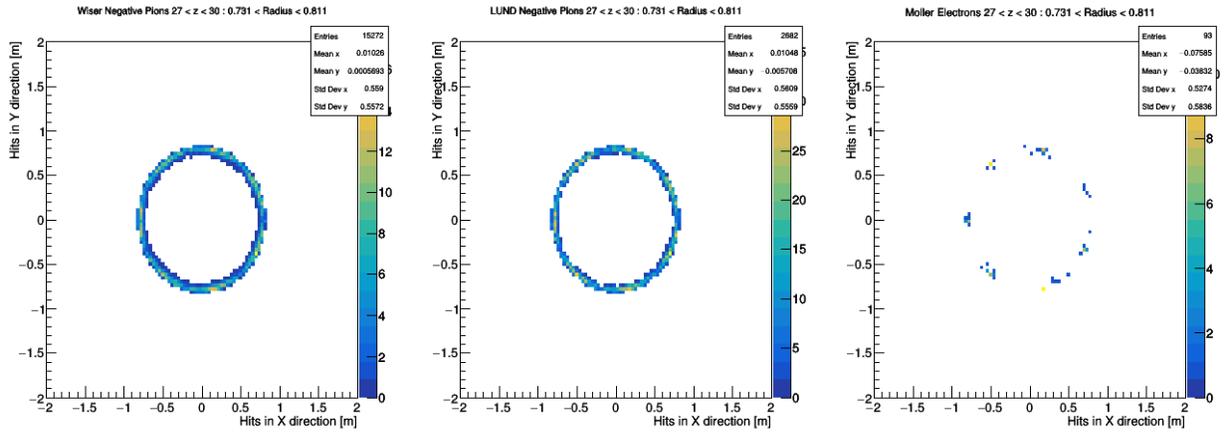


Figure 11: Y position vs X position hits with Negative Pion production

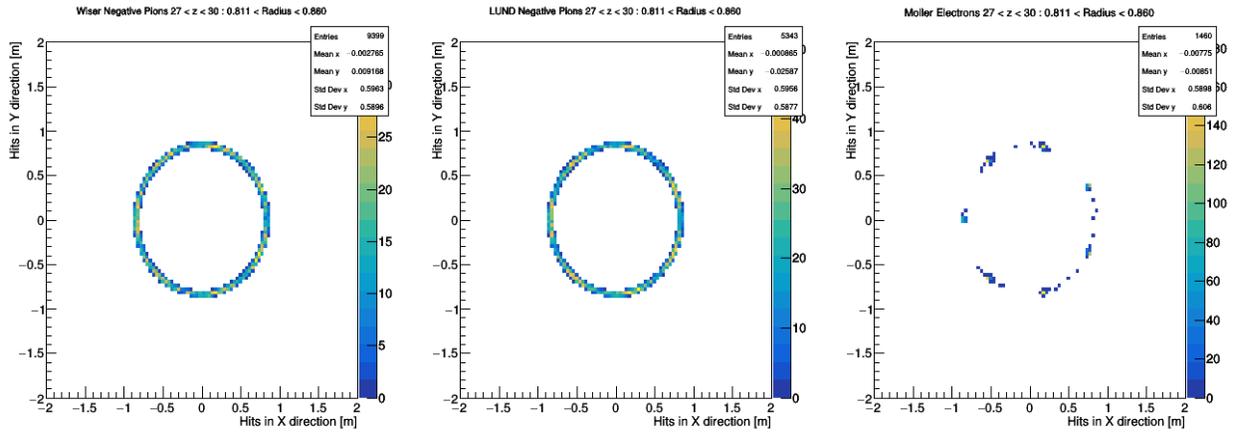


Figure 12: Y position vs X position hits with Negative Pion production

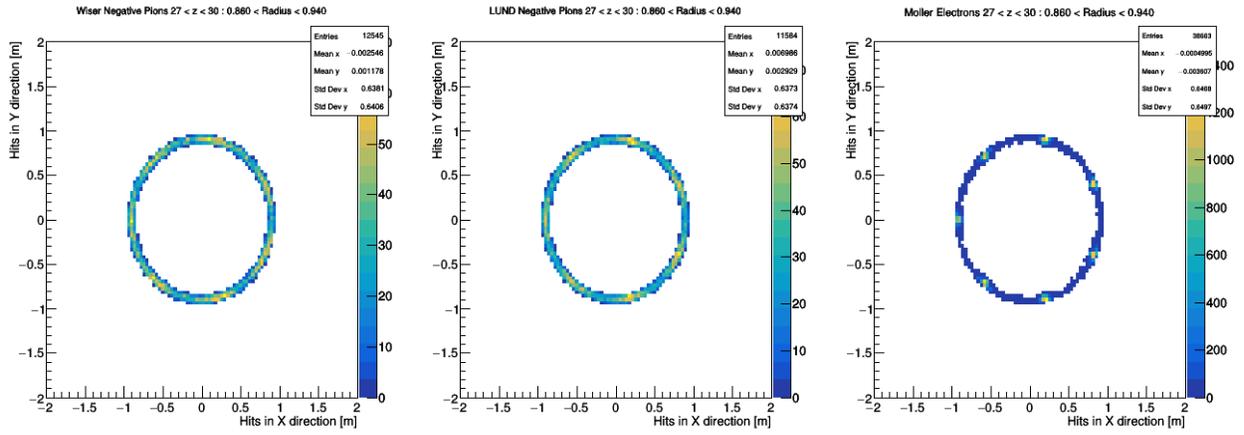


Figure 13: Y position vs X position hits with Negative Pion production

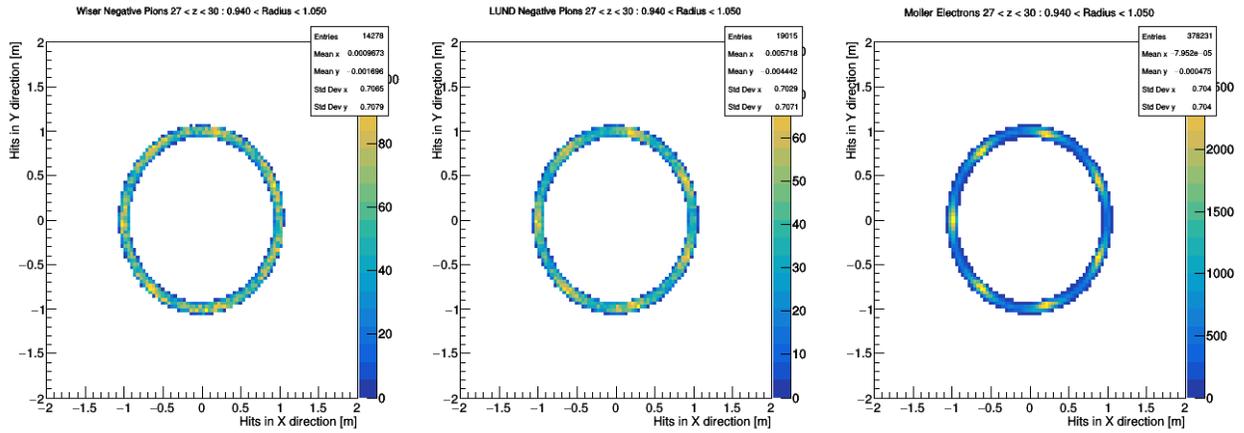


Figure 14: Y position vs X position hits with Negative Pion production

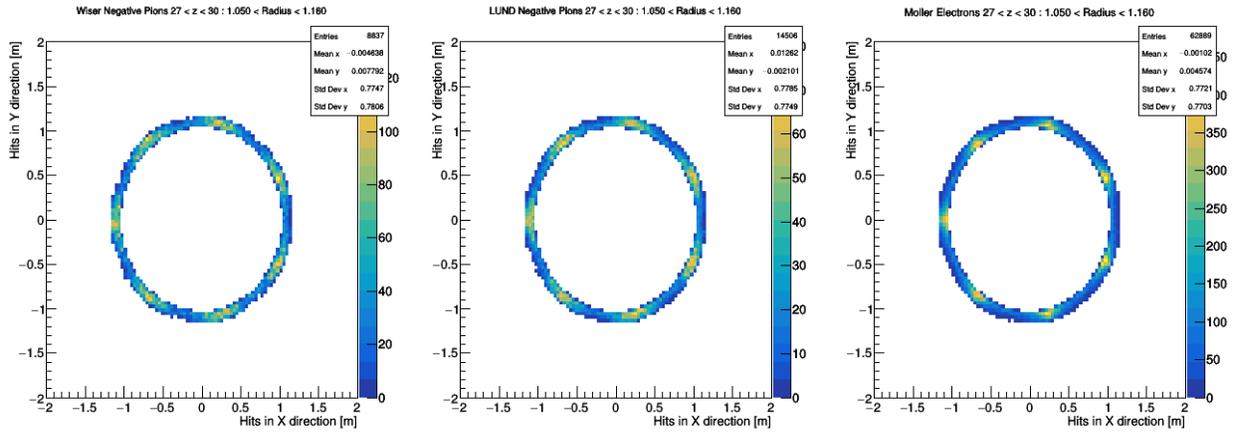


Figure 15: Y position vs X position hits with Negative Pion production

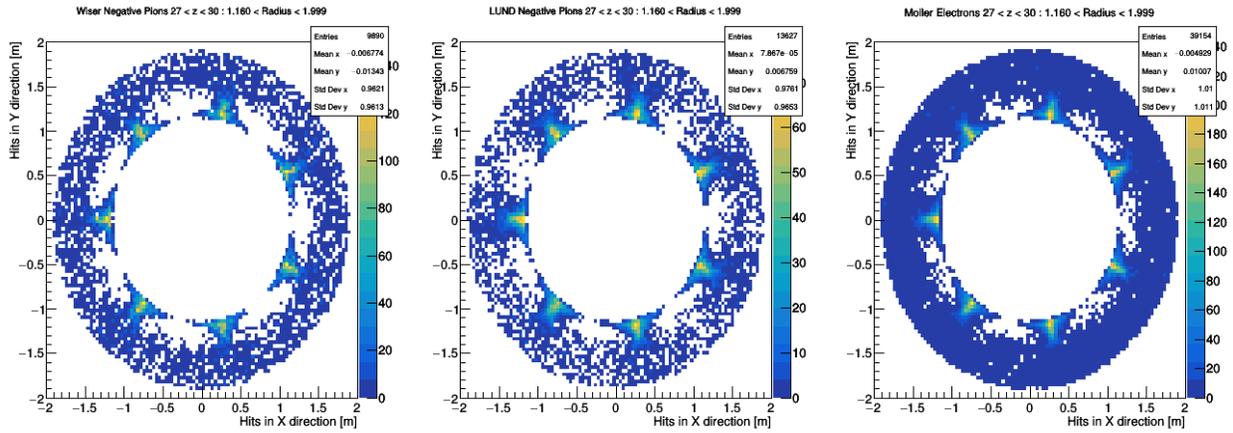


Figure 16: Y position vs X position hits with Negative Pion production

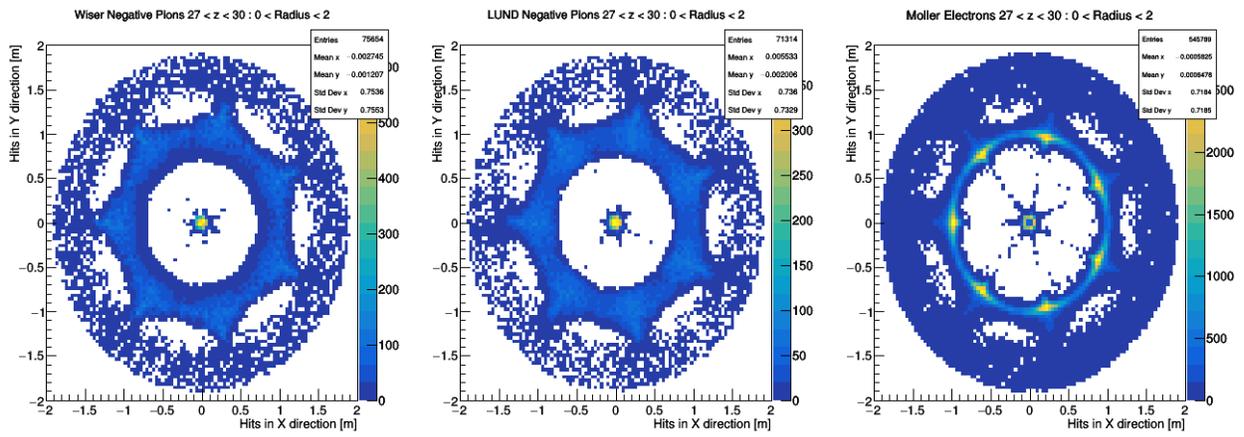


Figure 17: Y position vs X position hits with Negative Pion production