Low-Energy Neutron Reconstruction in LDMX

Fermilab SIST Internship Final Report

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ABSTRACT

This project explored low-energy neutron reconstruction in the hadronic calorimeter and electronic calorimeter of the proposed LDMX experiment. The aim was to identify missing hits and find the resolution of these low-energy neutrons.

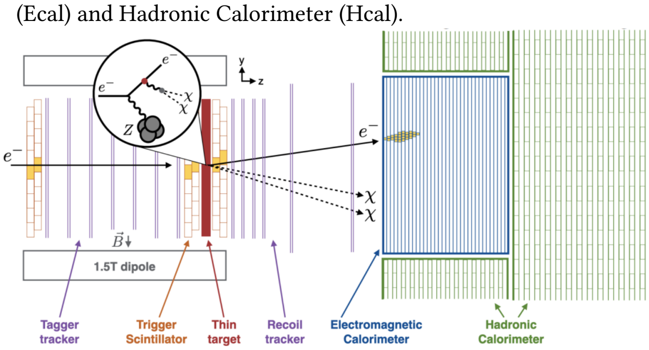
1 INTRODUCTION

1.1 Motivation

The current dark energy search has primarily been focused on higher energy regimes, particularly at energies greater than 1TeV. Colliders such as the LHC have been very effective at filtering out energies at which dark matter could be found, with no positive results yet. There are cosmological bounds placed on possible dark matter energies, and "light" dark matter has not been probed, meaning the region below 1TeV. LDMX, the Light Dark Matter Experiment, seeks to explore the light dark matter energy range with unprecedented sensitivity.

1.2 Background

LDMX aims to indirectly detect dark matter through missing momentum methods. This proposed experiment will be hosted at SLAC, and the experimental setup is as follows: A 4GeV electron beam will be fired into a fixed target, causing a scatter. This scatter will produce particles that will be caught by the Electronic Calorimeter (Ecal) and Hadronic Calorimeter (Hcal).



The Hcal surrounds the Ecal, and particles will pass through the Ecal first. These sensors will attempt to resolve as many detections as possible by classifying the particle and cluster. The electron from the gun will recoil in some direction after being scattered, and it will lose some momentum. This momentum can be carried away by many different background processes, such as photonuclear effects and bremsstrahlung. If we are able to remove all other background processes, we will be able to isolate events where an electron scatters with seemingly no other particles. This can be identified as a dark matter event, as we can infer the energy and momentum of the particles from the deflected electron. Low-energy neutrons are produced in photonuclear processes, and it is vital that all processes are removed. Thus, the goal of this project is to study how effective the detector is at identifying these low-energy neutrons.

2 METHOD

The LDMX-sw software suite, organized with Git, was used in a Ubuntu terminal to generate root files of guns of varying energies, analyze the guns to extract variables, and package the root files into Pickle (pkl) files. Vim was used to modify the analysis program to extract new variables as the studies progressed. The pkl files were then analyzed using custom plotting software written first in Google Colab and then Jupyter Notebook.

2.1 Analysis

Geant4 was used to generate neutron guns with different energies for analysis. The gun configuration file was modified to fire from different locations and create large files with 100,000 events. A General Particle Source (GPS) generation file was also utilized to create root files with a linear distribution of energy.

The analysis software was constantly modified to parse different variables from the root files. These variables were not directly produced in the root files, so they had to be calculated by first looping over hits and then over events, depending on the needed variable. Categories of variables are listed below. Most of the analysis was performed on the Hcal, with some preliminary work performed on the Ecal.

- Maximum and Minimum Layers
- Maximum and Minimum Positions
- Positions of Rechits
- Positions of Rechits with PE Cuts Applied
- Energies of Rechits
- Layers, Sections, and Strips of Rechits
- Percentage of Missed Hits in Hcal
- Theta Angle and Associated Variables for Resolution
- Standard Deviation
- Sum Energies of Events
- Clusters of Events

2.2 Graphing

A graphing program was written in Colab/Jupyter to dissect the pkl files and plot the relevant variables for each plot. Both 1D and 2D plots were generated. Mplhep and Matplotlib were used to format and generate the graphs. The graphing program was able

Supervised by Dr. Cristina Mantilla Suarez.

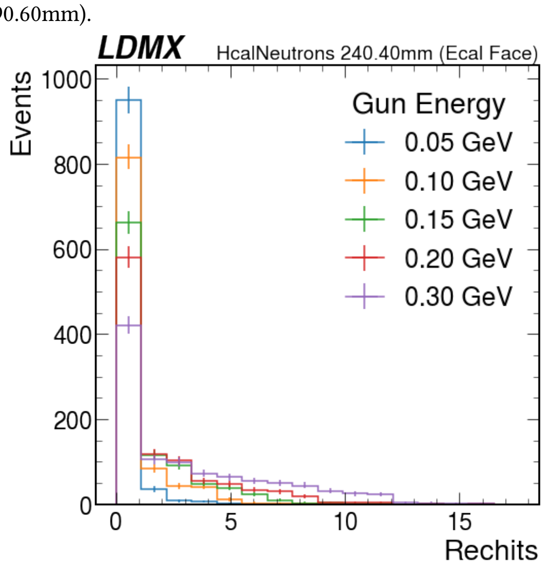
SIST Internship Report, LDMX, Fermilab
2022.

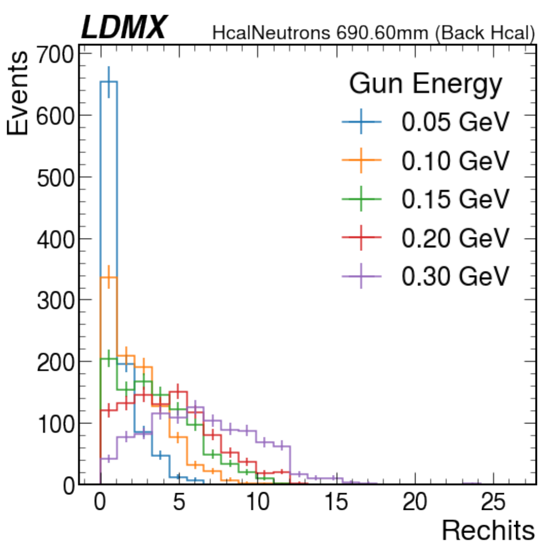
to automatically parse the relevant root files for the energy range being analyzed, and would automatically bin the data from the Root file ranges. If needed, some variables were manually looped over to produce more variables after the pkl had been generated.

3 RESULTS AND ANALYSIS

3.1 Initial Hcal Analysis

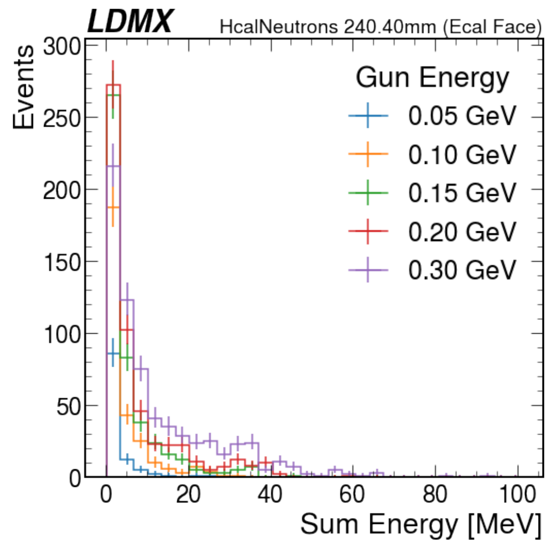
The initial Hcal analysis was performed with 1000 event guns. The key variables to plot were rechits vs events, the sum energy per event, and the maximum and minimum positions with and without PE cuts applied. These were plotted for guns fired both from the front of the Ecal (240.40mm) and the start of the back Hcal (690.60mm).

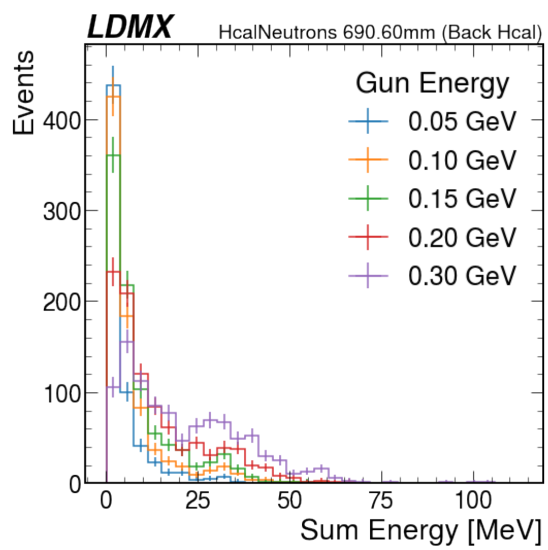


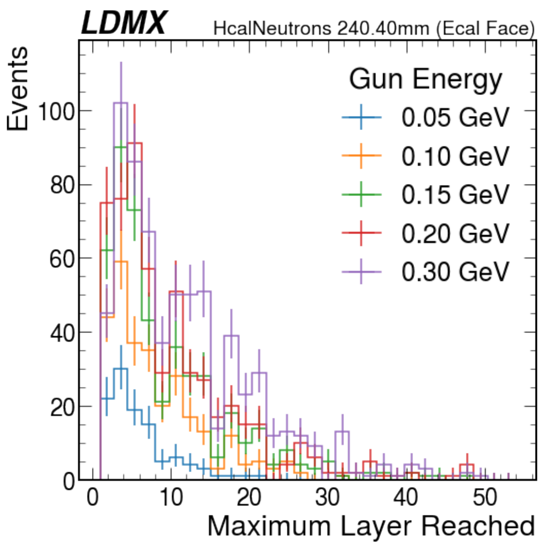


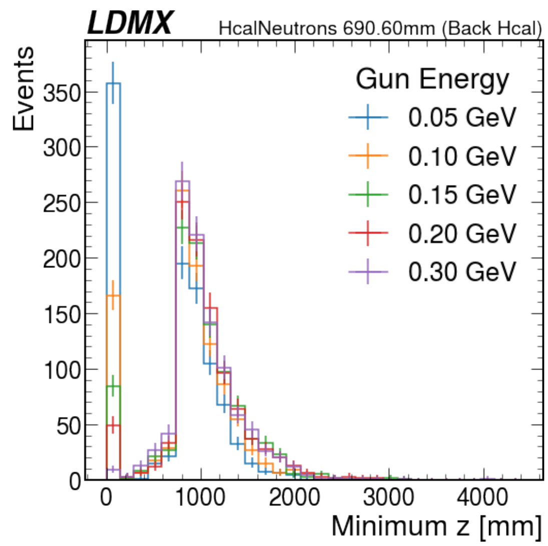
The Rechits vs Events plot shows that events with fewer rechits are more abundant, especially for guns with lower energies. This effect is even more pronounced when the gun is fired from the Ecal, which is a trend that lingers into later plots.

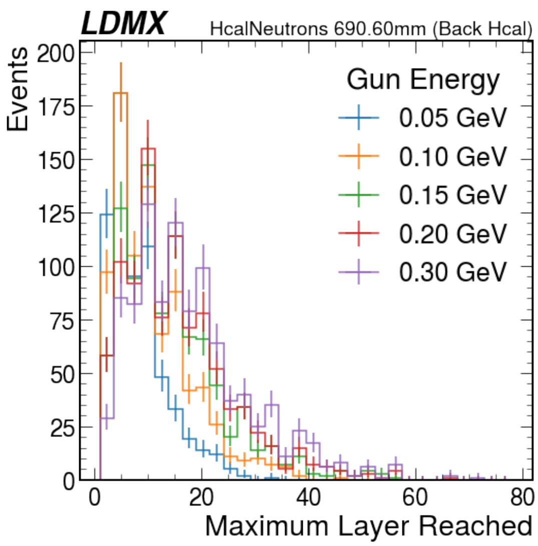
The below plots show that the sum energy readouts are approximately correct for the Ecal. Each neutron deposits around 11% of its energy into a strip, and integrating under each gun gives around 11% of the initial gun energy.

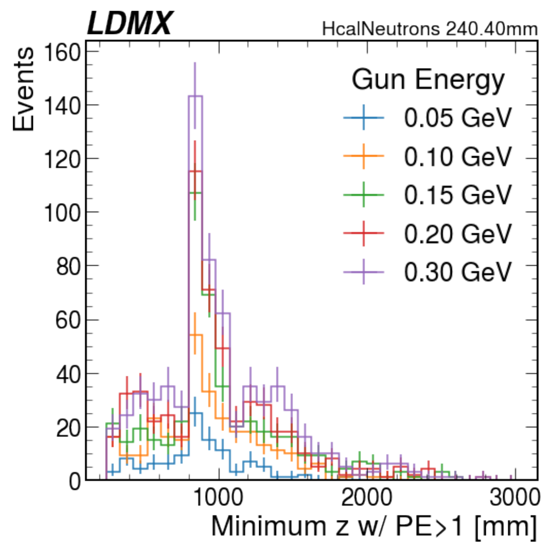


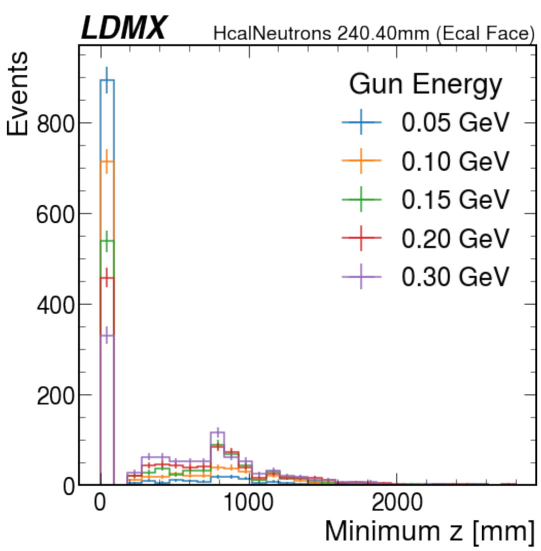


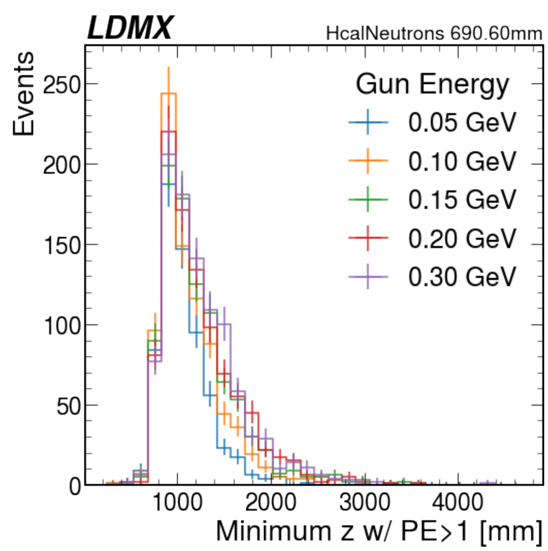

LDMX
HcalNeutrons 240.40mm (Ecal Face)
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Maximum Layer Reached


LDMX
HcalNeutrons 690.60mm (Back Hcal)
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Minimum z [mm]


LDMX
HcalNeutrons 690.60mm (Back Hcal)
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Maximum Layer Reached


LDMX
HcalNeutrons 240.40mm
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Minimum z w/ PE>1 [mm]


LDMX
HcalNeutrons 240.40mm (Ecal Face)
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Minimum z [mm]

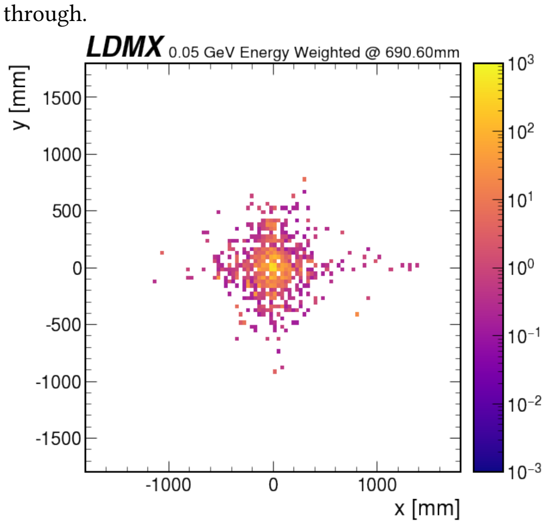

LDMX
HcalNeutrons 690.60mm
Events
Gun Energy
0.05 GeV
0.10 GeV
0.15 GeV
0.20 GeV
0.30 GeV
Minimum z w/ PE>1 [mm]

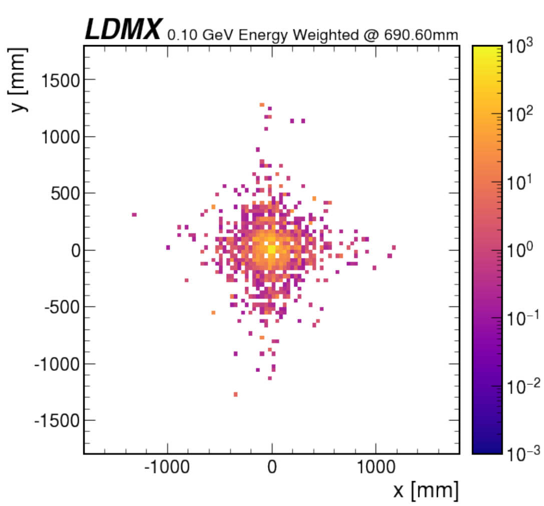
The plots of Max Layer vs Events show that once a low-energy neutron enters the Hcal, it tends to deposit all of its energy and come to a stop inside the Hcal. However, looking at the y-axis shows that many events are missing, especially when fired from the Ecal.

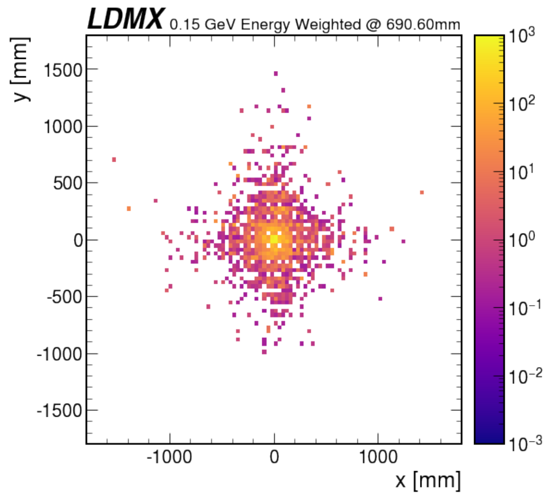
From the Minimum z plots, where empty events are binned to zero, we observe that the majority of low energy events do not make it to the Hcal, meaning that the neutrons are either caught in the Ecal or not detected. Applying the PE cut seems to eliminate the problematic null events, which leads us to believe that the missing hits have very low energies.

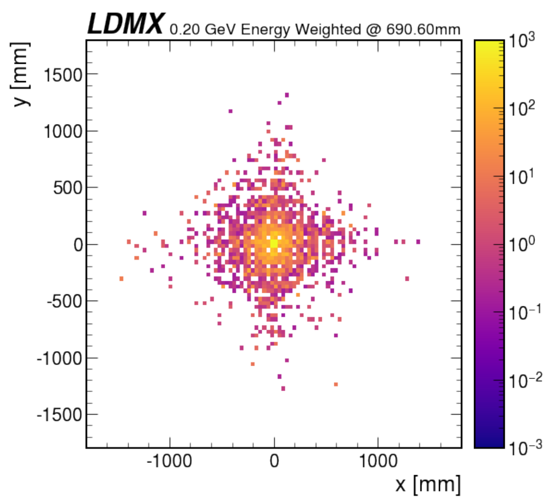
3.2 X vs Y Plots

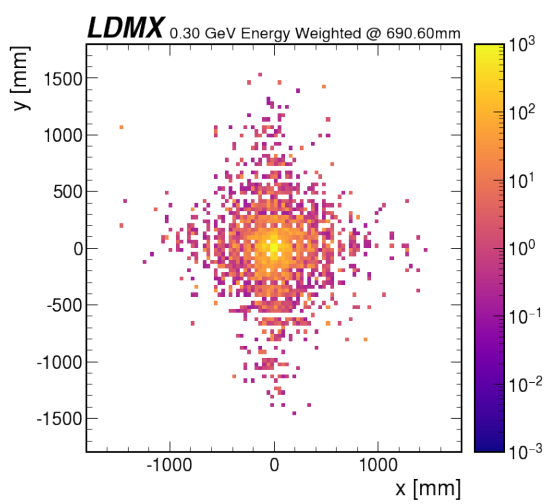
The below plots show that as the energy of the gun increases, the scatter becomes wider. The guns fired from the Ecal have sparser patterns than the ones fired into the Hcal, as fewer events make it through.

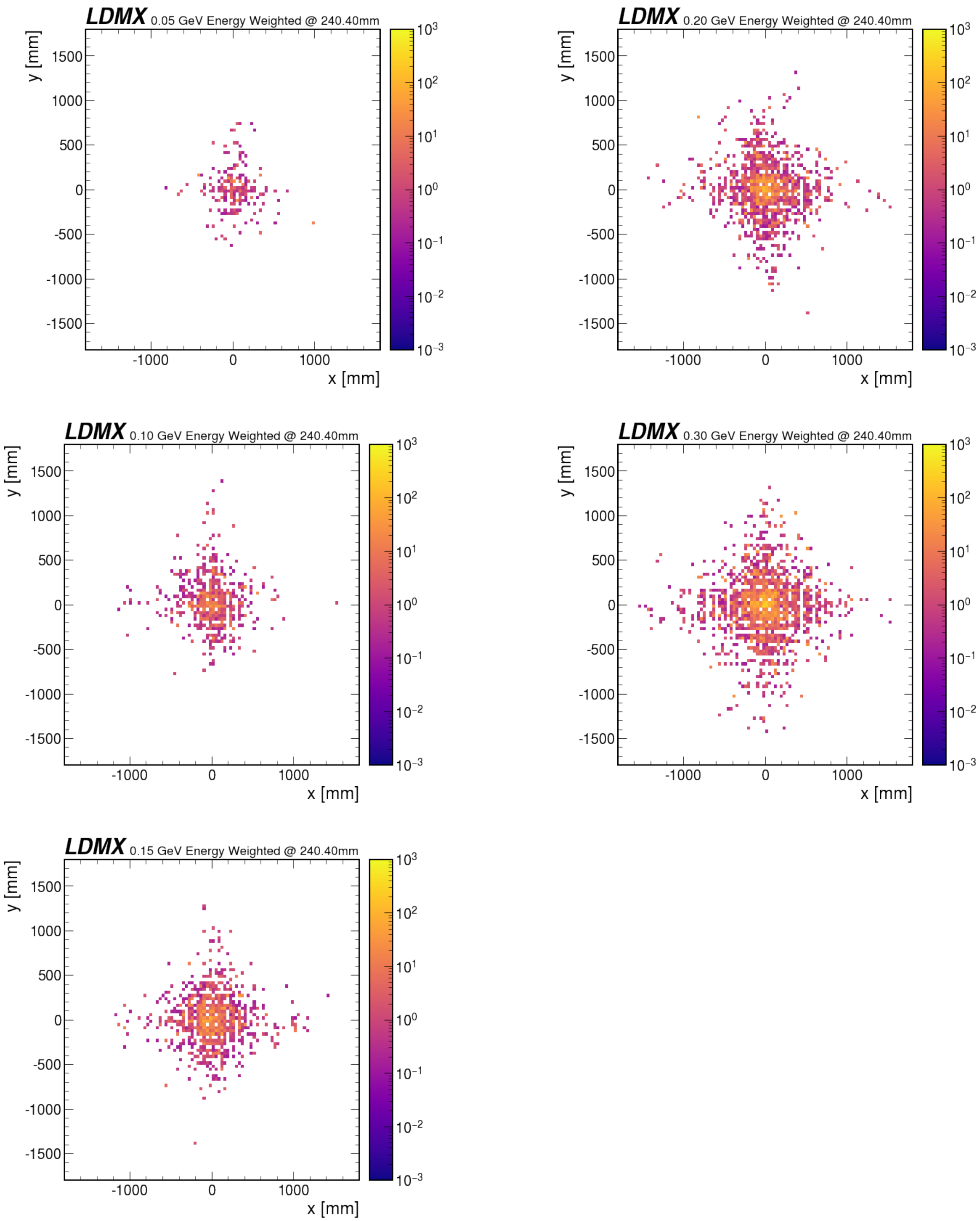






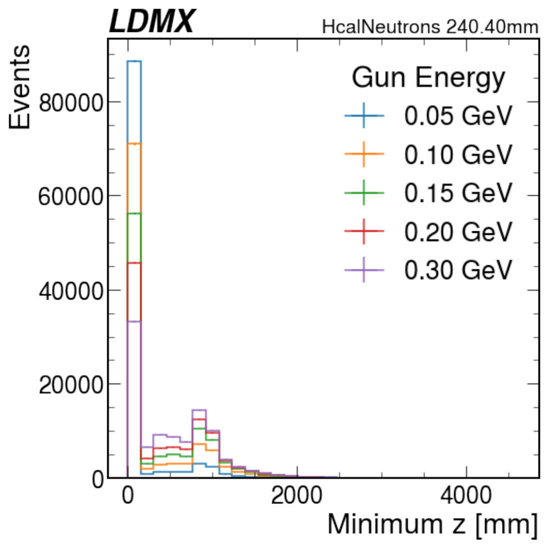


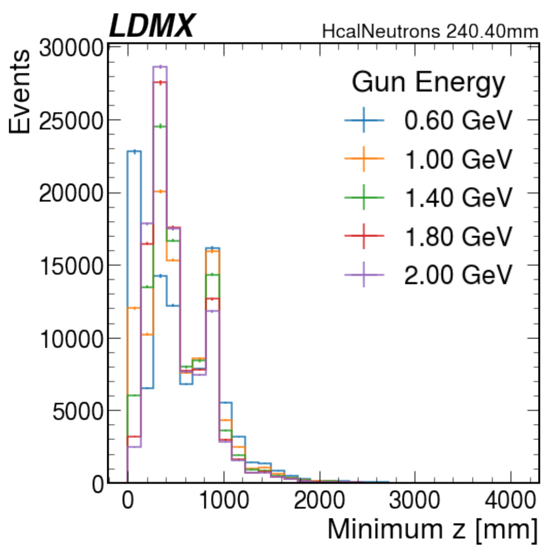


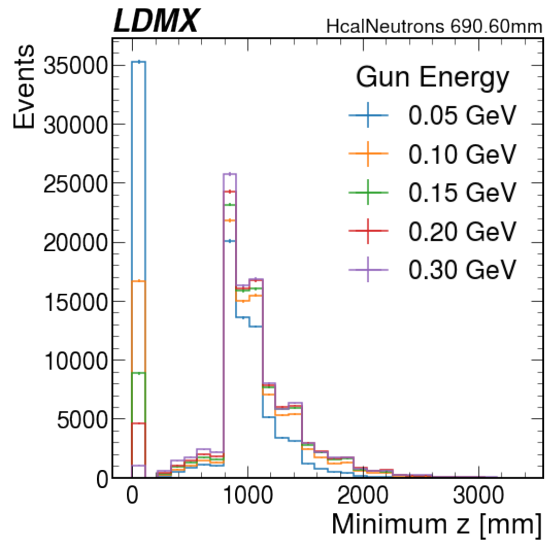

LDMX 0.05 GeV Energy Weighted @ 240.40mm
LDMX 0.20 GeV Energy Weighted @ 240.40mm
LDMX 0.10 GeV Energy Weighted @ 240.40mm
LDMX 0.30 GeV Energy Weighted @ 240.40mm
LDMX 0.15 GeV Energy Weighted @ 240.40mm
y [mm]
x [mm]

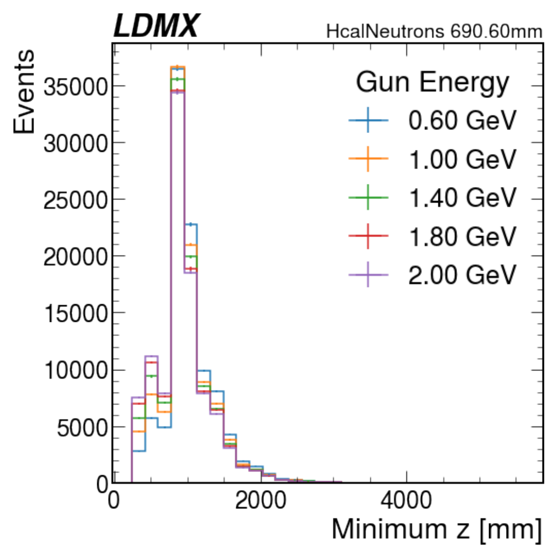
3.3 100,000 Event Gun Plots

3.3.1 Hcal. The minimum z plots were redone with a 100,000 event gun to get better error bars and further examine the behaviour of the neutrons. We found that as the energy of the gun increases, fewer hits are lost. Firing from 690mm, the missing hits are resolved by 0.3GeV, but the problem persists when firing into the Ecal even with a 2.00GeV gun.

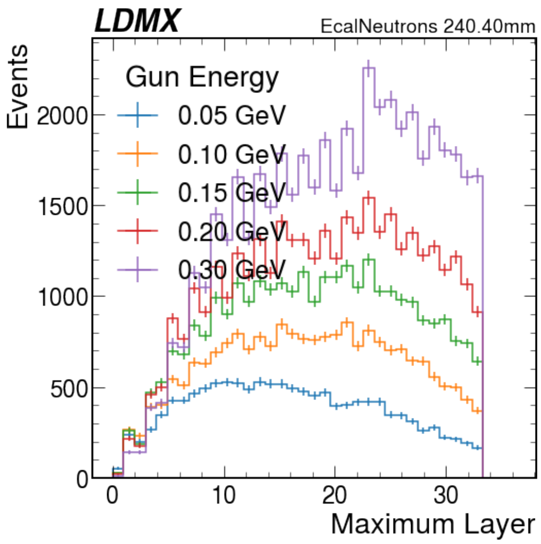


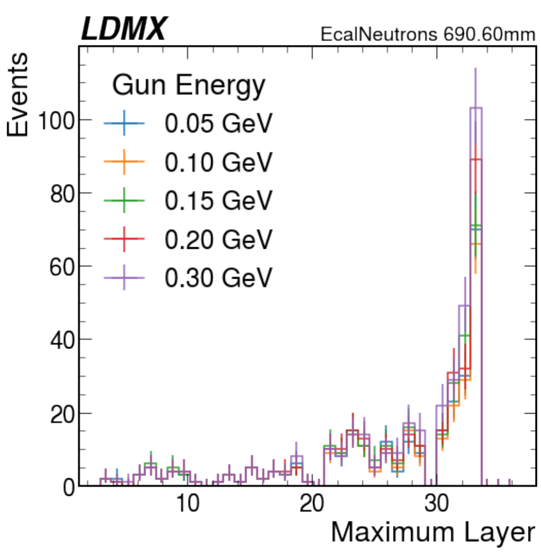




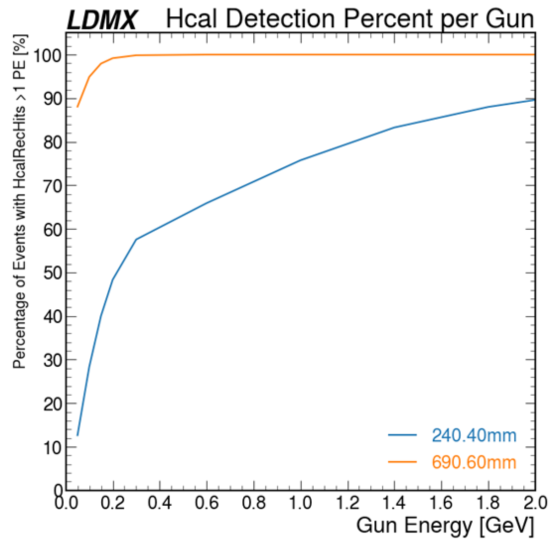


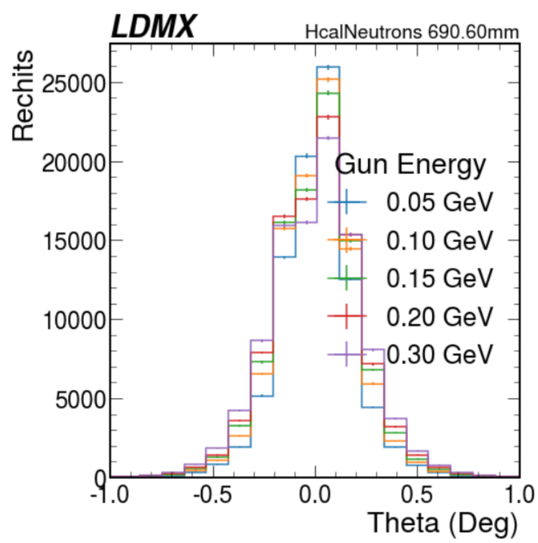
3.3.2 Ecal. The next logical step was to check if the missing Hcal hits were caught in the Ecal. The Ecal energy hits were bugged for the duration of this project, so while we were unable to perform an energy analysis, we inspected the maximum layer in the Ecal per event, which would tell us if neutrons were getting stuck in the Ecal. The graphs show that there are indeed many neutrons that get stuck in the Ecal, as the majority of maximum layers are not occuring at the very last layer in the Ecal. This effect is more pronounced for the lower energies.





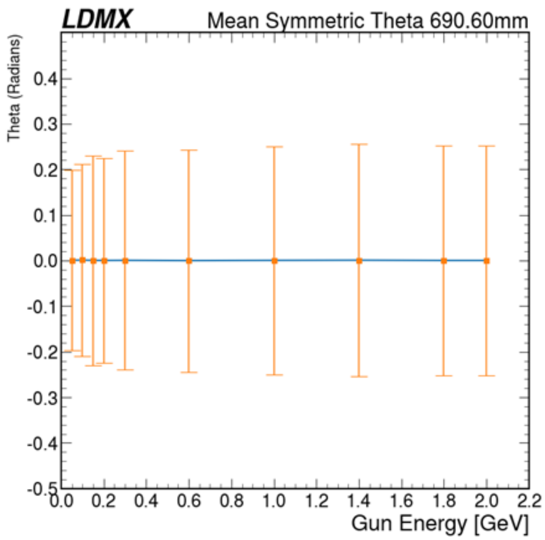
3.4 Results

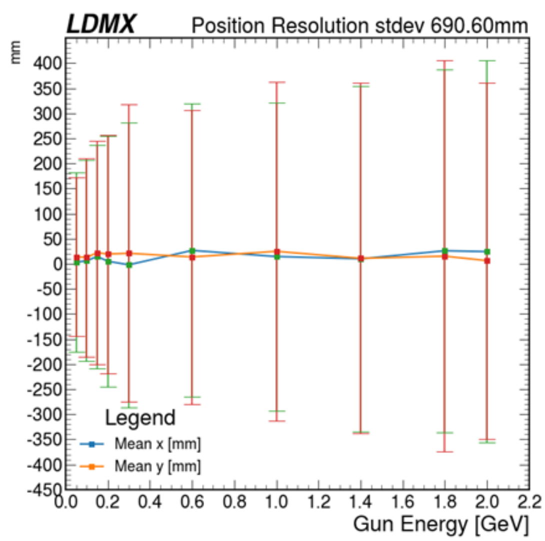




Building upon the Ecal data, we obtained the Hcal Detection Percentage per Gun, which tells us exactly how many events are lost after a 1PE cut is applied. The gun fired from the Ecal has about 12% of its hits detected at 0.05GeV, and this percentage improves as the energy increases. Guns fired from the Hcal have a hit percentage of 100% almost immediately.

The theta vs Rechits plot shows the average shower size. It is still unclear as to why the data skews slightly positive, as we would expect a mean of zero. This is also illustrated in the resolution plots on the next page, where the blue is the mean and the standard deviation is in orange. The gun energy vs theta plot shows that the width of the scatter increases with energy, and the position resolution shows that the standard deviation skews positive as well when energy increases.





4 CONCLUSION

This project was able to determine how neutrons interact with the detector, and we began to explore the resolution of the detector. These contributions will allow the LDMX team to better understand the photonuclear background and will help create cuts for data processing in the future. The code base created, including all the custom variables in the analysis python3 file, can now readily be used again on new files and different guns for further studies. The plots created in this study also leave open questions to be answered about detector behaviour, such as the positive skew of showers.

Next steps would be to fix the Ecal software, which currently is not correctly processing energy simhits, so that we can explore what the energy distribution for the low energy hits looks like inside the Ecal. Clustering studies can also be performed in the Hcal to see how well the detector can cluster low-energy neutrons. Some initial tests show that the seed thresholds have to be lowered a lot for the clustering to work. We can also take a look at the angular resolution of the detector by firing guns at multiple angles, and using a full background sample to determine the percentage of cases in which we see these low-energy neutron backgrounds.

5 ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Cristina Mantilla Suarez, for all of her support and guidance throughout this summer, whether it be late night debugging or providing feedback on a poster. I was very glad to gain experience under such an exceptional scientist. I would also like to thank Dr. Christian Herwig, and my fellow summer students, Jonathan Rositas and Marie Tagliavia for their contributions. Thank you to Charles Orozco and Brian Vaughn for their feedback and mentorship. I also extend my appreciation to Dr. Arden Warner and the rest of the SIST committee for organizing this program and allowing me to contribute to the lab and LDMX.