ZDC Analysis Work Summary

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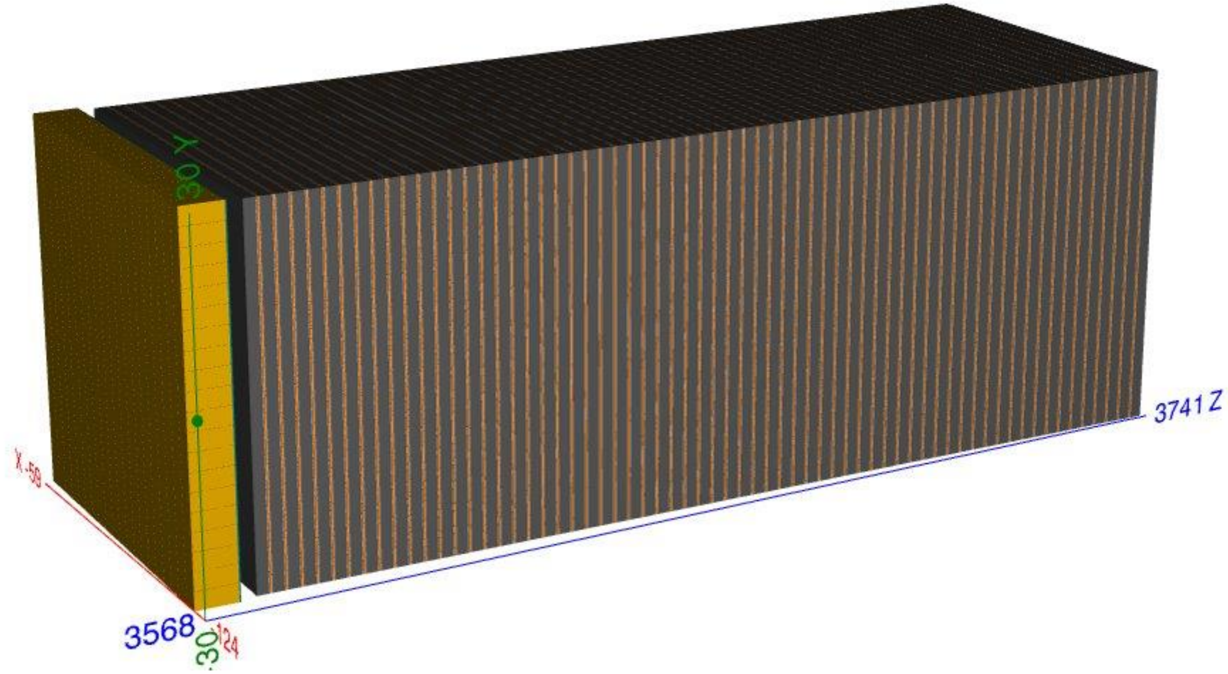
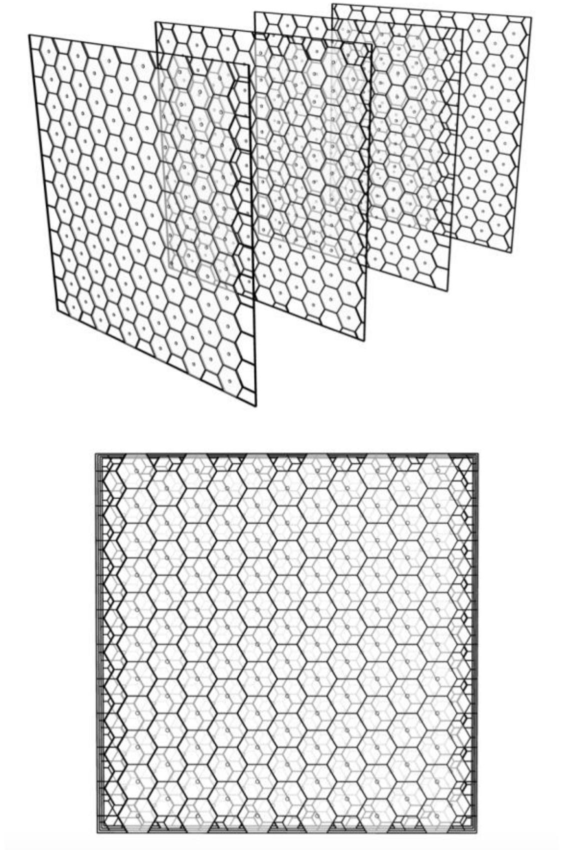
What is the ZDC

- The ZDC is the far forward zero degree calorimeter for EIC ePIC
- The goal is to reconstruct the energy and vertex of neutral particles that go in the far forward direction (low t regime)
- Our specific goals are to study the energy, vertex, angular resolution and efficiency of the ZDC for the lambda decay to pi0 and neutron
- We are interested in this as it is essential to studying the structure of K via the Sullivan Process at EIC
- For this we have to determine what events are likely to make it to the ZDC and what events are likely to be reconstructed

ZDC 3D Geometry



ZDC Geometry (ECal is yellow and HCal is brown)



3D rendering of SiPM tiles (top: offset, bottom: head on)

https://arxiv.org/pdf/2406.12877

ZDC Geometry

- The ZDC sits 35.5m away along the -25mrad line from the e beam
- This correspond to the proton beam's angle (the proton beam line bends away from the 25mrad line in the forward direction)
- The ZDC is 60cm by 60cm and ~2m long
- ZDC is composed of two calorimeters: a thin (7cm) LYSO crystal ECal in front and a SiPM HCal behind
- The ECal is a single layer of crystal cells (3cm by 3cm), primarily designed for low energy photons from nuclear breakups
- The HCal sits behind the ECal and is composed of 64 layers of hexagonal SiPM tiles with ~130 tiles per layer
- The HCal is a sampling calorimeter, and has different sampling ratios for EM showers and hadronic showers (both have been calculated for relevant energies of photons and neutrons)
- The hexagonal design of the SiPM provides excellent spatial resolution of the showers

ZDC Location

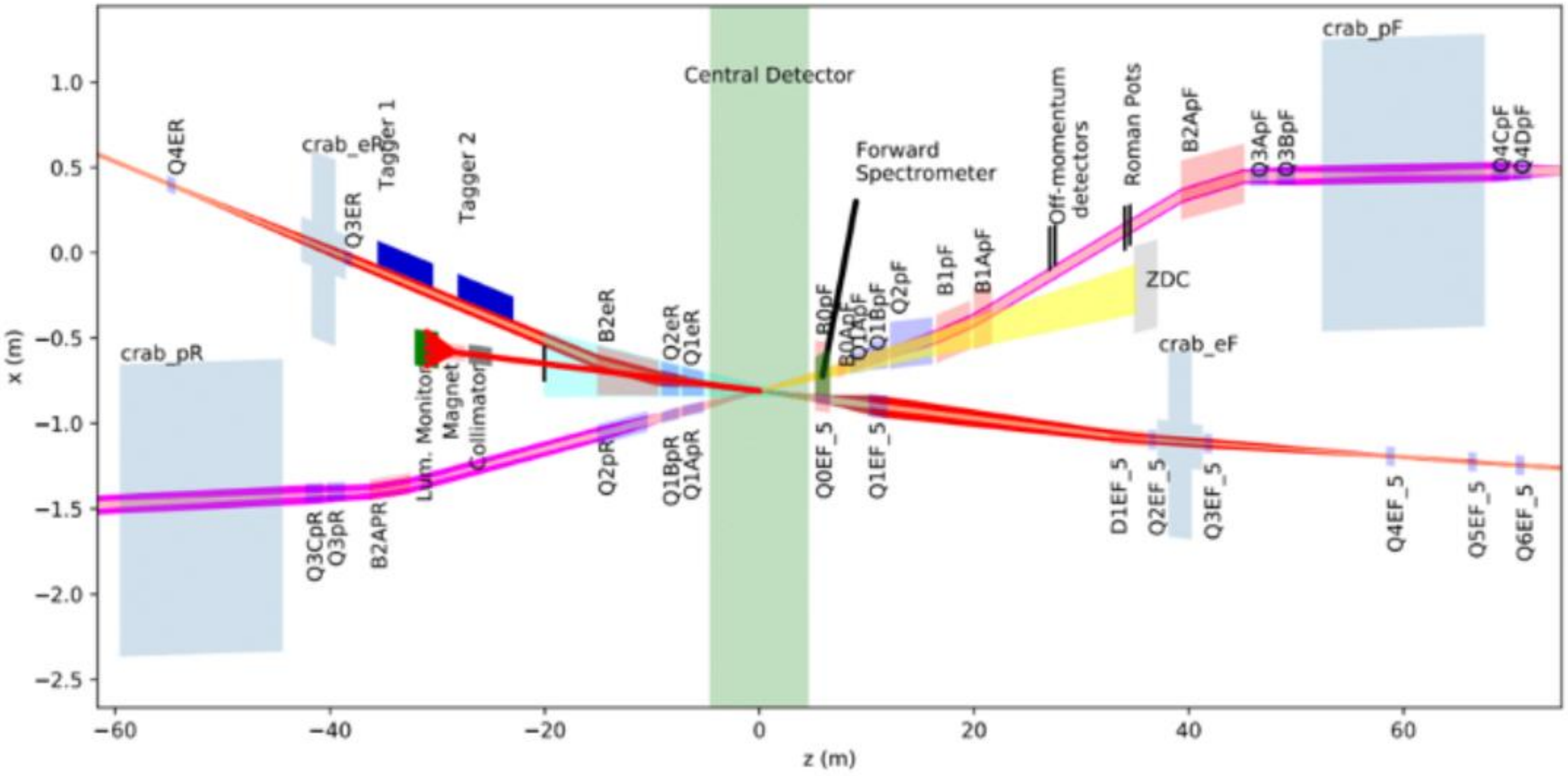


Figure 11.85: Image of the full EIC baseline IR layout.

ZDC Geometry 2

- Because the ZDC is an imaging calorimeter, there are discussion about how its resolution can be improved
- One suggestion is to remove the ECal for certain runs to take advantage of the HCal design
- One suggestion is the addition of WSi layer between the ECal and HCal
- One goal of our study is to determine if the current set up has good enough resolution for proposed physics goals

Our Data

- We have been testing the ZDC using various particle gun simulations
- Because there is no generator for the Sullivan process yet, we don't have access to physics variables like W^2, Q^2 or t (we spoke to the meson structure group)
- Our data is the raw detector hits before it goes through reconstruction software
  - o We do not use the reconstruction software as we want to examine the best case scenario of reconstruction from the ZDC
- We have simulated single photon, pion, neutron, (unpolarized) lambda both directly at the ZDC and with some angular variation

Our Current Status 1

- We examined lambda data to determine which events are likely to make it to the ZDC
    - Without realistic simulation, this analysis is stalled
- We are working on clustering ZDC hits with the goal of reconstructing the lambda and determining resolutions
- Due to the differences between the ZDC and other calorimeters, we have been working on our own clustering algorithms
- Two approaches: Density based scan and peak finding
- Density based scan groups together nearby hits into clusters
- Peak finding finds peaks energy deposits and expands clusters out from them

Our Current Status 2

- Most lambda events cannot be reconstructed due to overlap between neutron and photon showers, making them impossible to separate
- We have developed several cuts to remove most overlap events, but some remain
- On good events (clear separation between photon showers and neutron showers), clustering algorithms are successful
- We are unable to quantify the accuracy of clustering without truth information

Next Steps

- We need to determine a robust system of determining if clustering succeeded or failed using MC truth
- We do not know the accuracy of our clustering and, because we do not have truth clusters, need to determine how to verify the accuracy of clusters
- We want to determine the energy resolution of reconstructed photons and neutrons
- We want to reconstruct the pi0 (and by extension the lambda) by both reconstructing the vector and via the missing mass of the pi0

Effeciency of the ZDC based on lambda kinematics

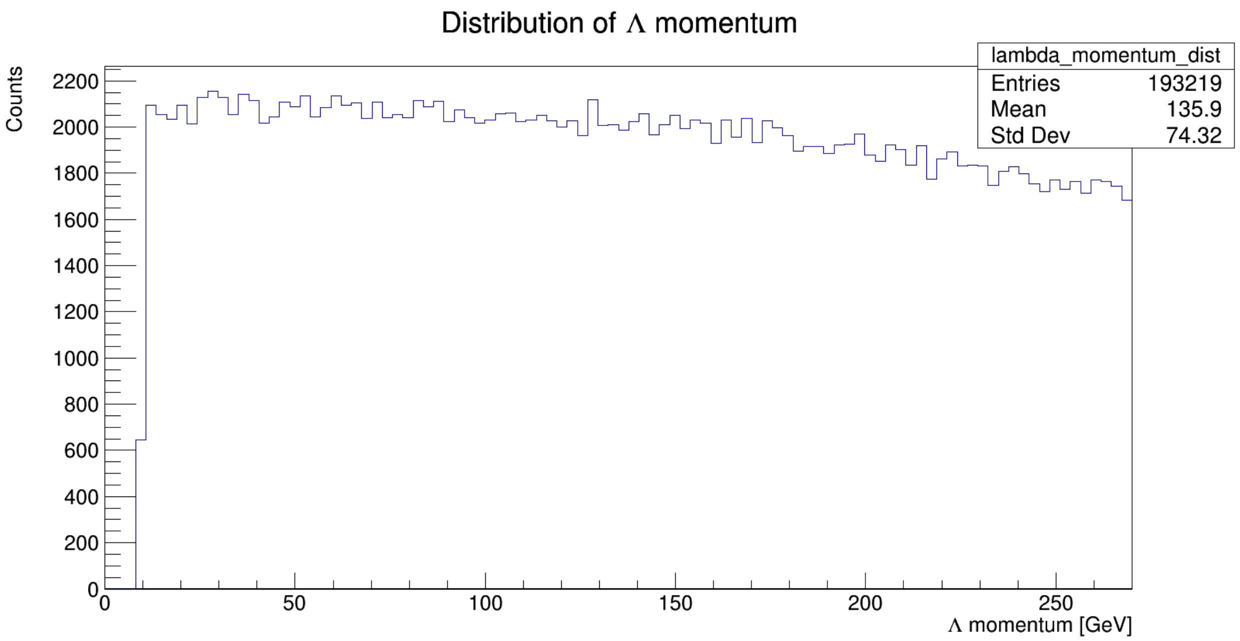
Purpose

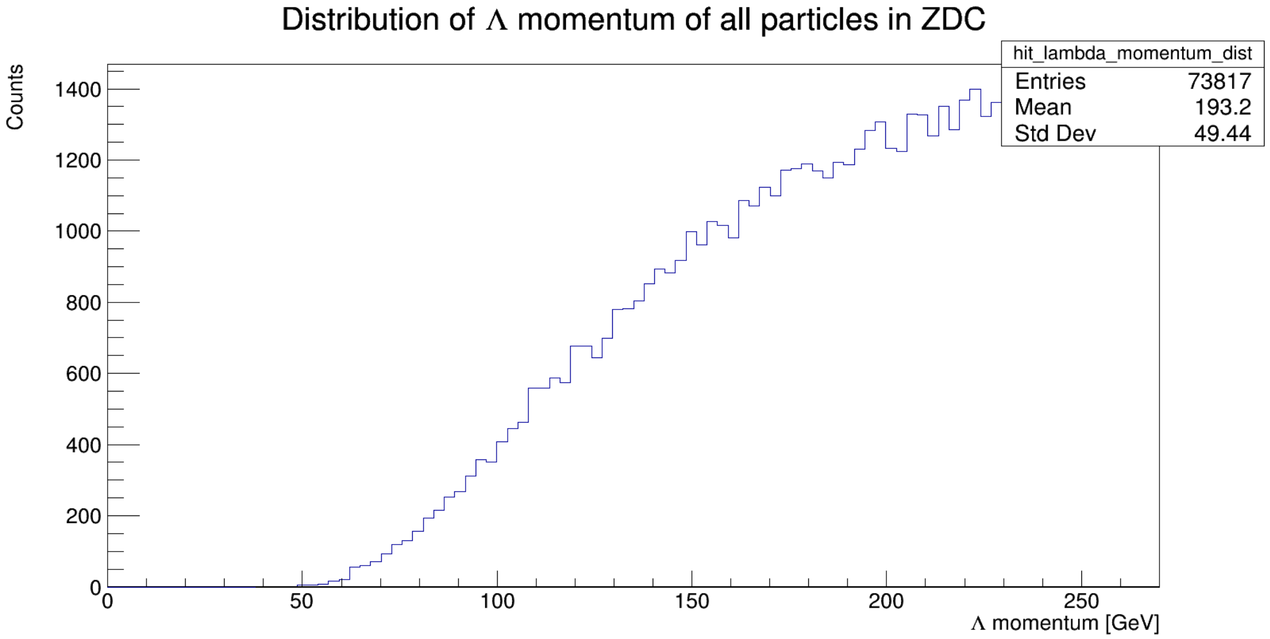
- The goal is to look at lambda particle gun data to determine which events reach the ZDC as a function of lambda momentum, decay distance and (if applicable) angle
- Reaching the ZDC is defined as when the lambda's decay particle (neutron and two photons) all reach the ZDC
- This analysis does not consider if the event can be successfully reconstructed by the ZDC, just that they potentially could be reconstructed

Data and Cuts Info

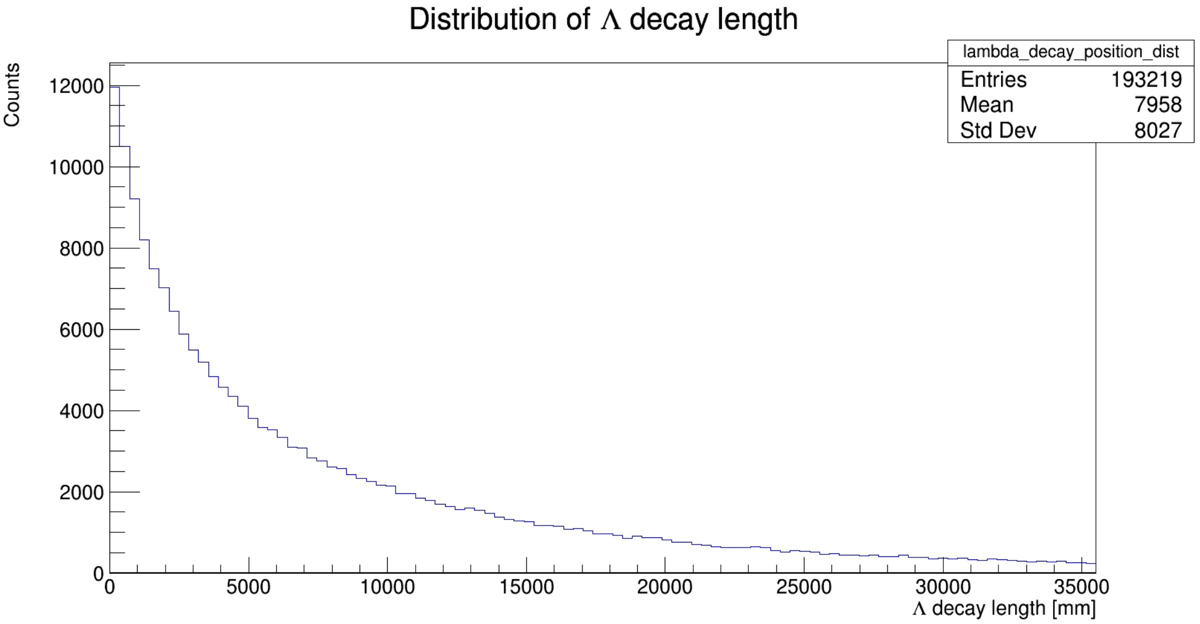
- Data is fixed angle unpolarized lambda particle gun MC
- The fixed direction is (sin(-.025), 0, cos(-.025))
- Energy range from 0 to 270 GeV
- Data is immediately cut to remove beam pipe collision events and events where the lambda reaches the ZDC
- To determine if an event can be clustered:
  - Both photons and neutrons need to land in the ZDC at least 20mm from the edge
  - Both photons need to come from a neutral pion and that neutral pion from a lambda
  - Neutron needs to come from a lambda

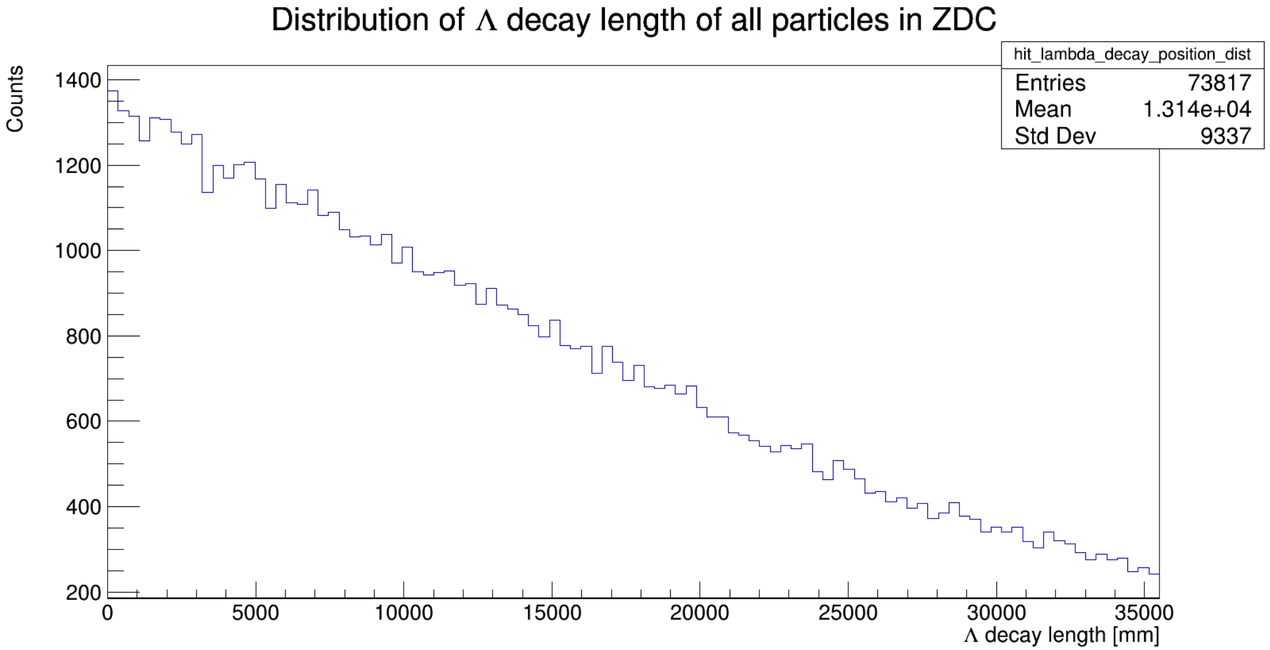
Lambda momentum



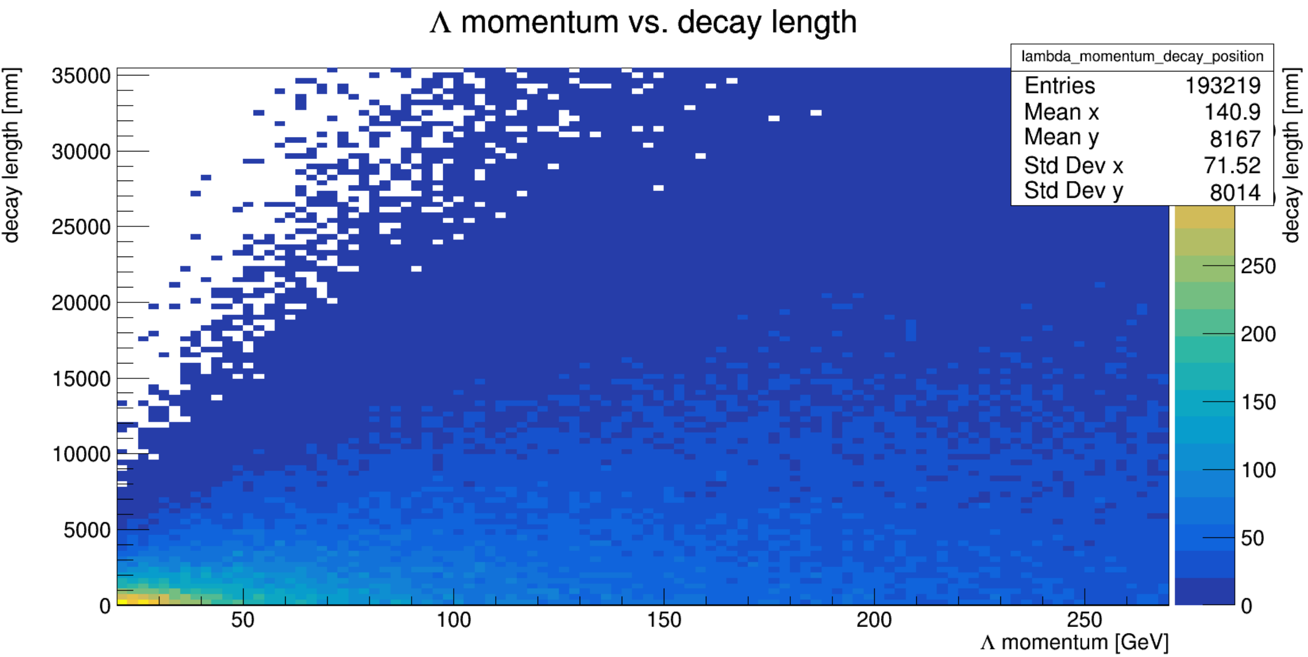


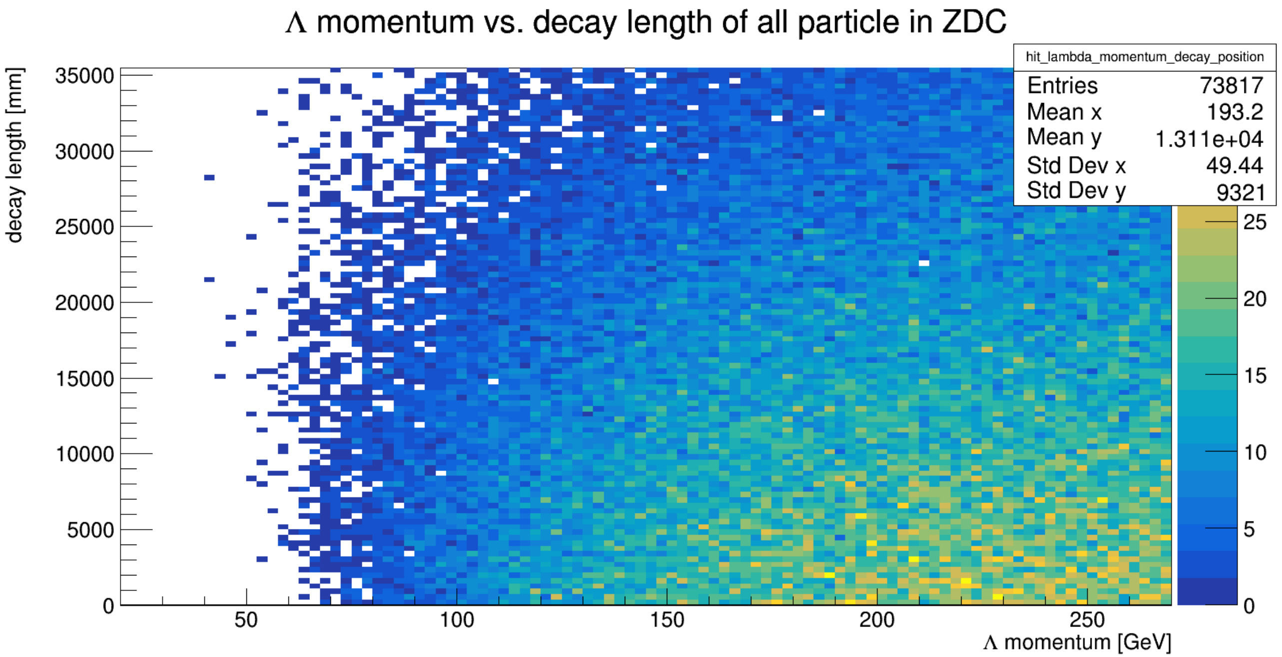
Lambda decay distance



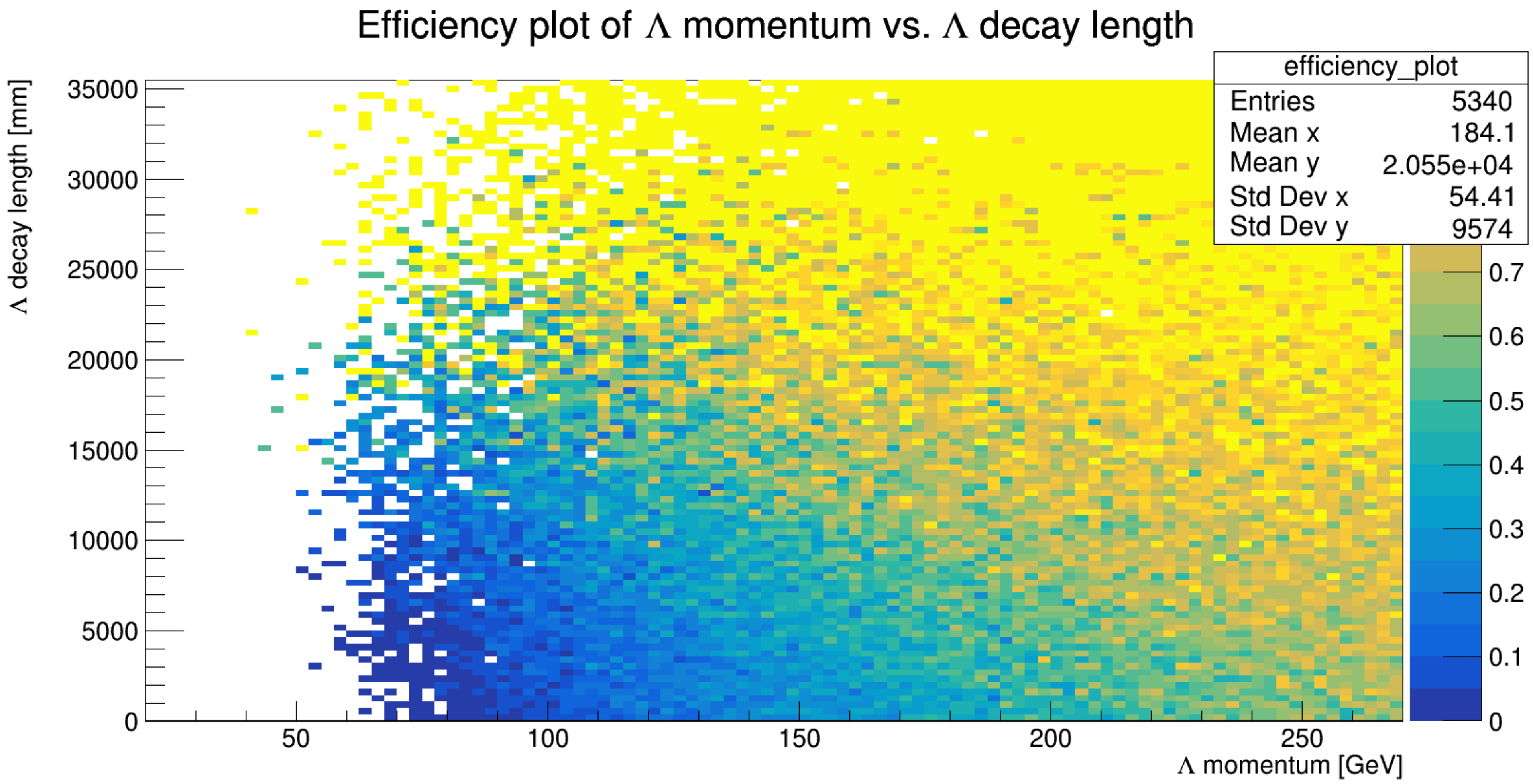


Lambda Momentum vs decay distance



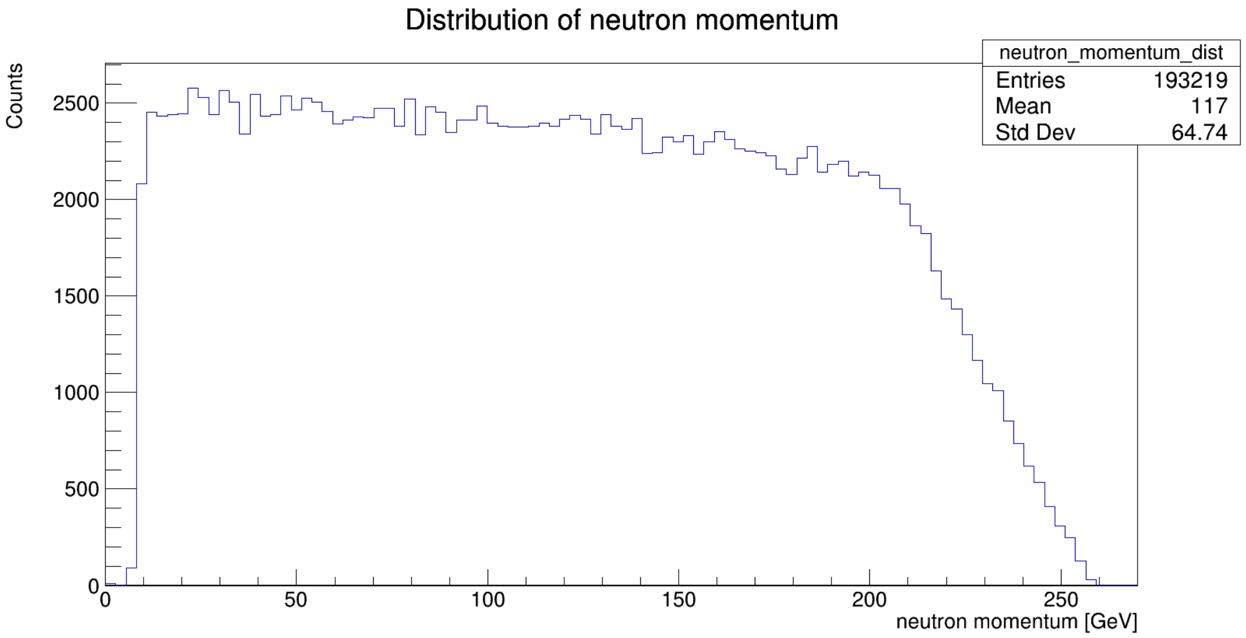


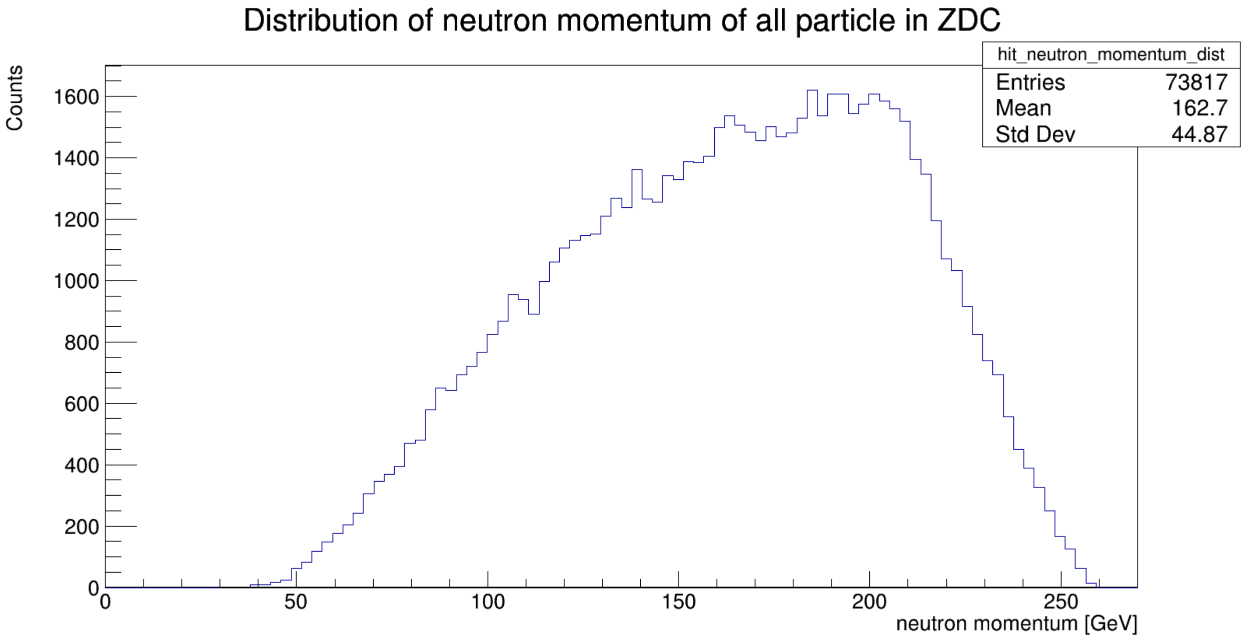
Efficiency



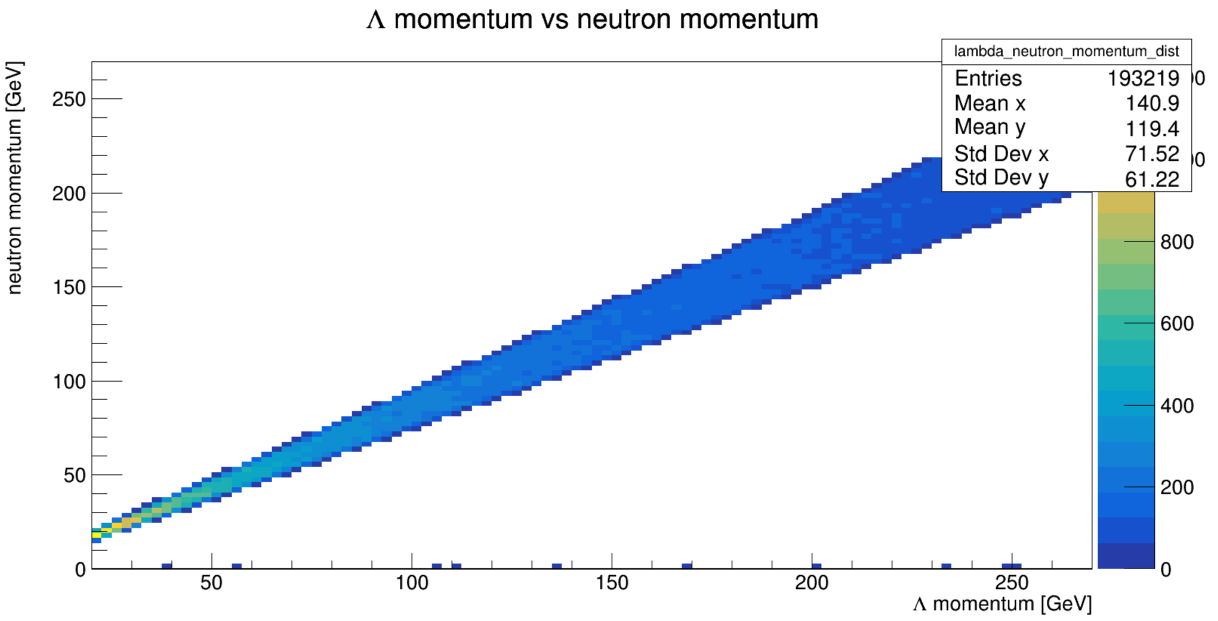
Efficiency plot of Λ momentum vs. Λ decay length
efficiency_plot
Entries 5340
Mean x 184.1
Mean y 2.055e+04
Std Dev x 54.41
Std Dev y 9574
Λ decay length [mm]
Λ momentum [GeV]
35000
30000
25000
20000
15000
10000
5000
0
50
100
150
200
250
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

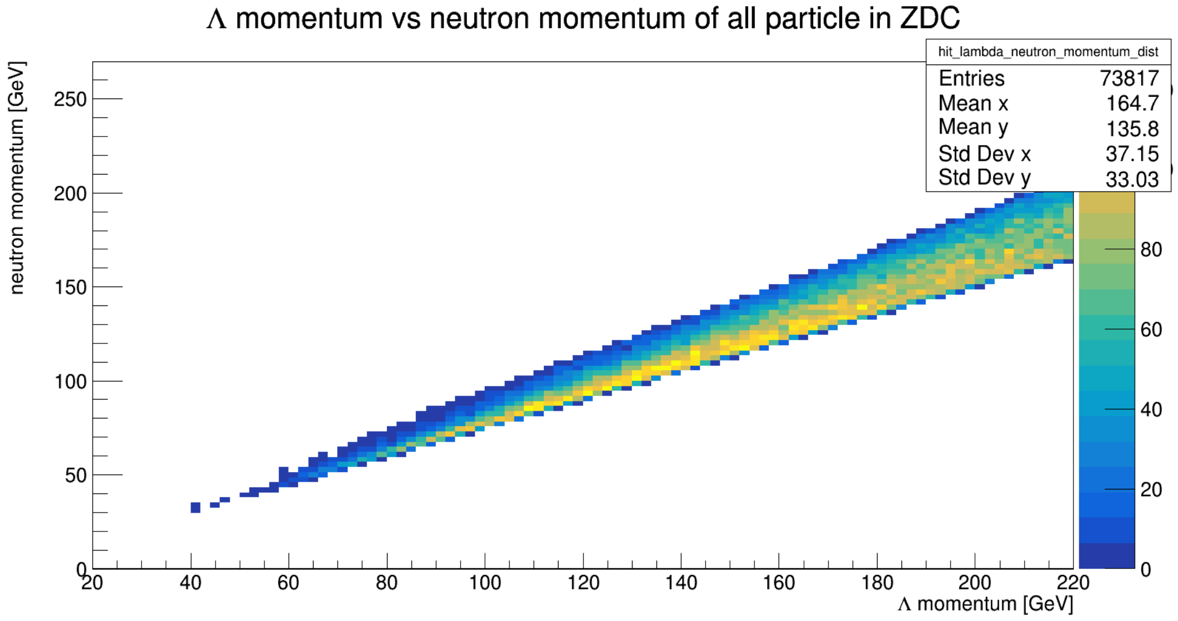
Neutron Momentum



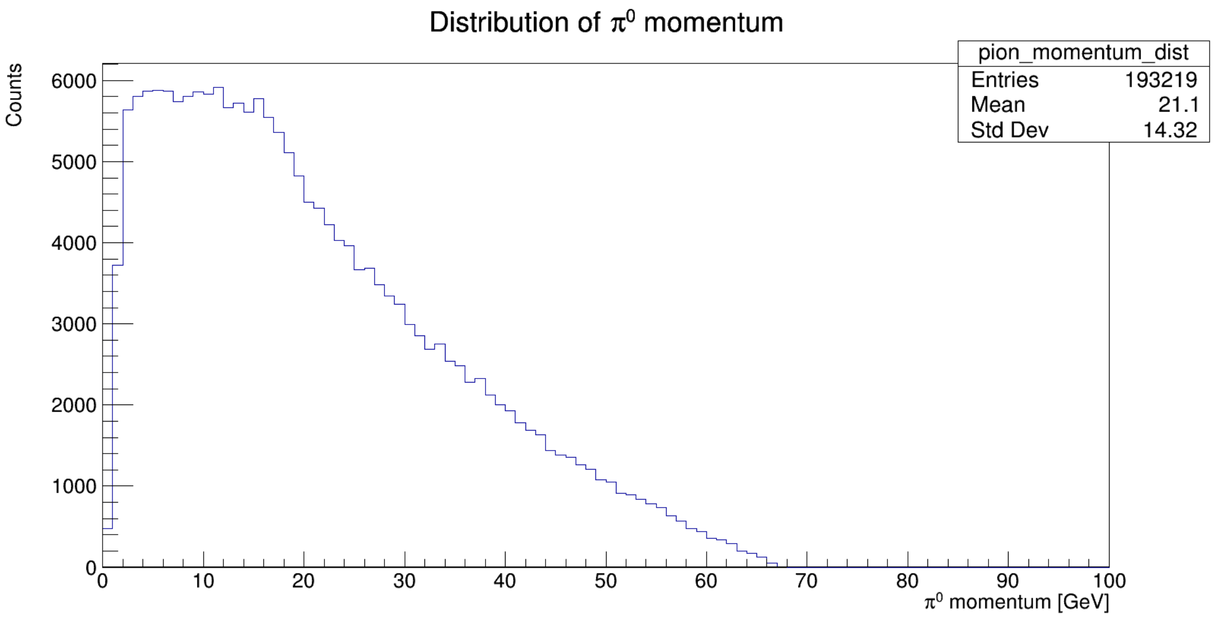


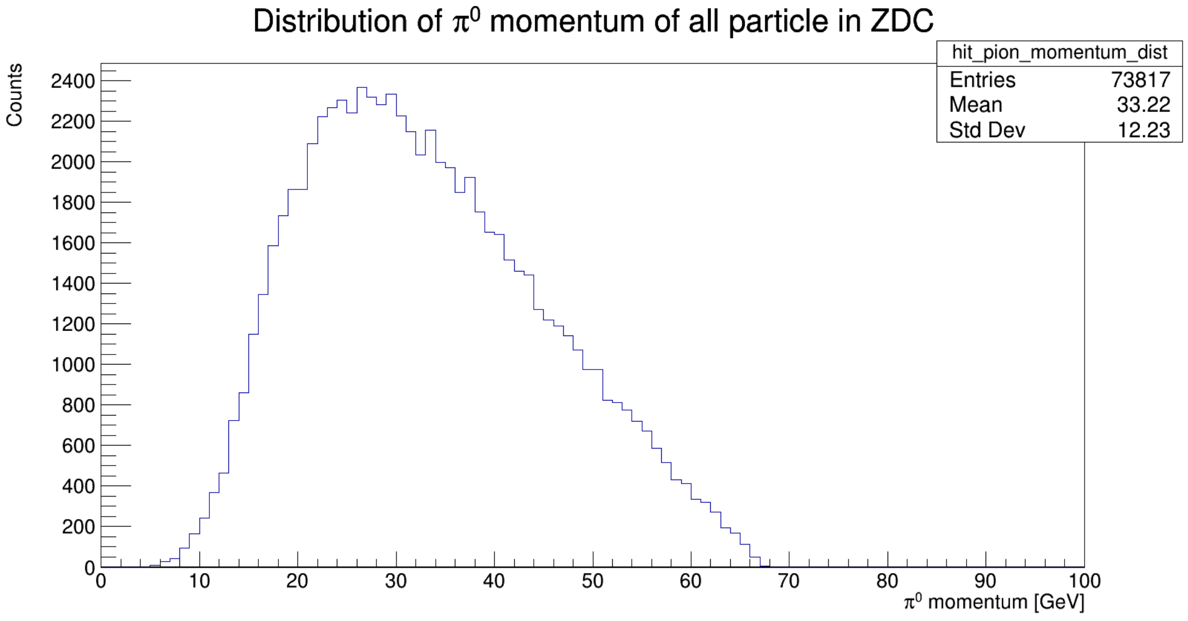
Lambda momentum vs Neutron momentum



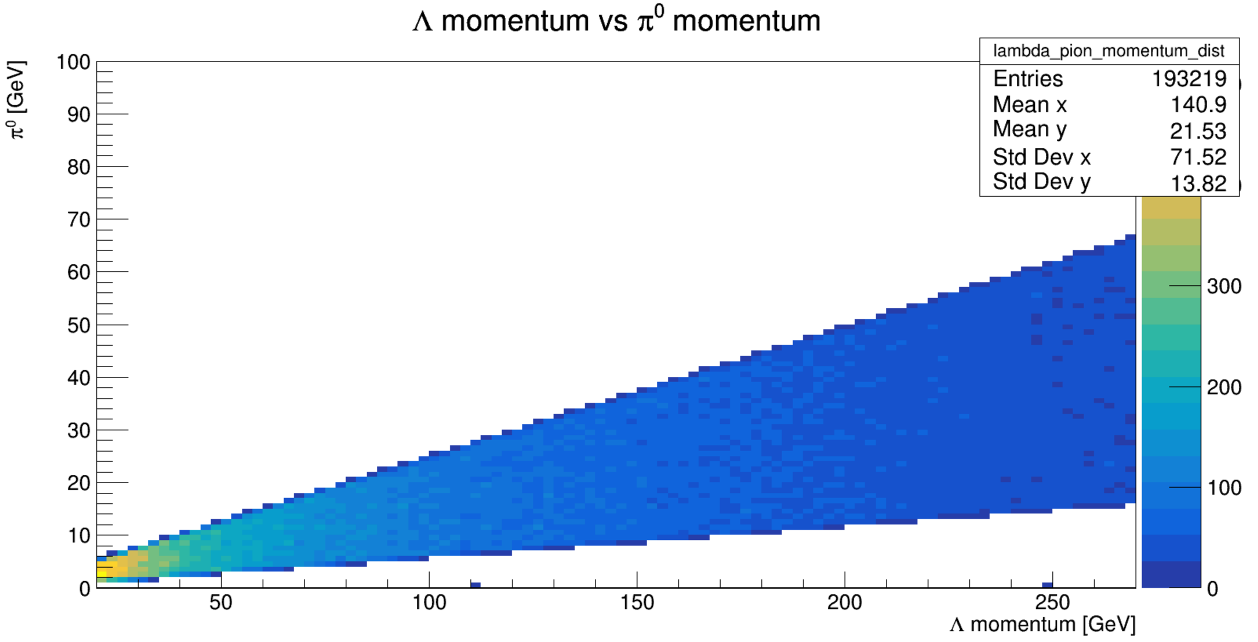


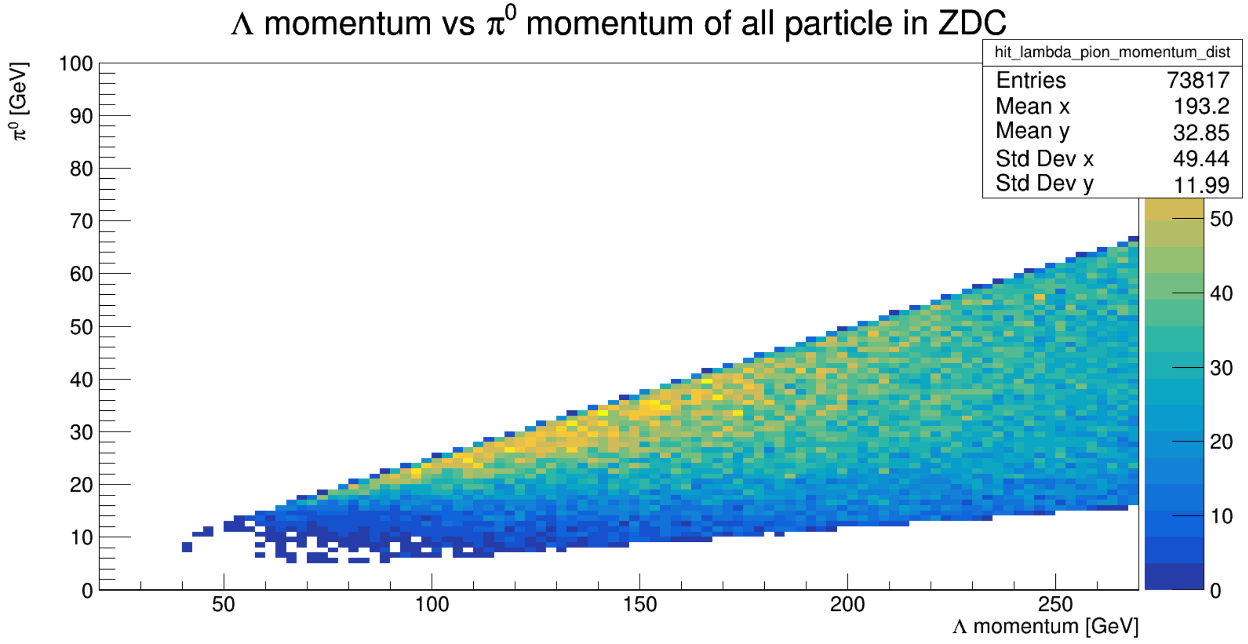
Pion Momentum



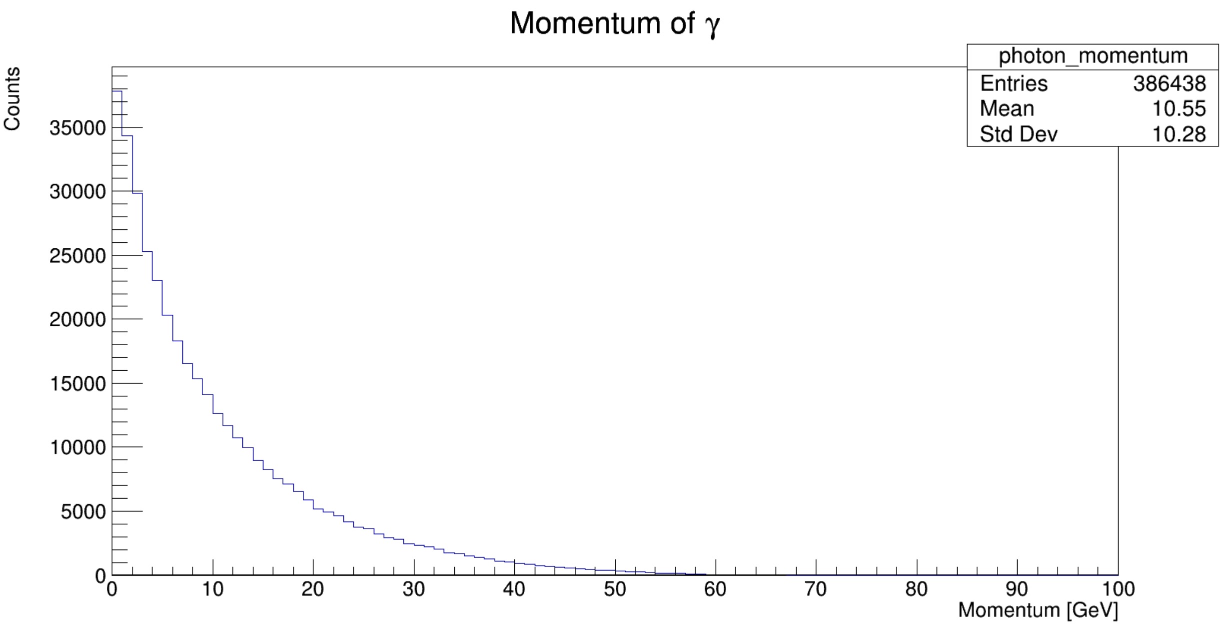


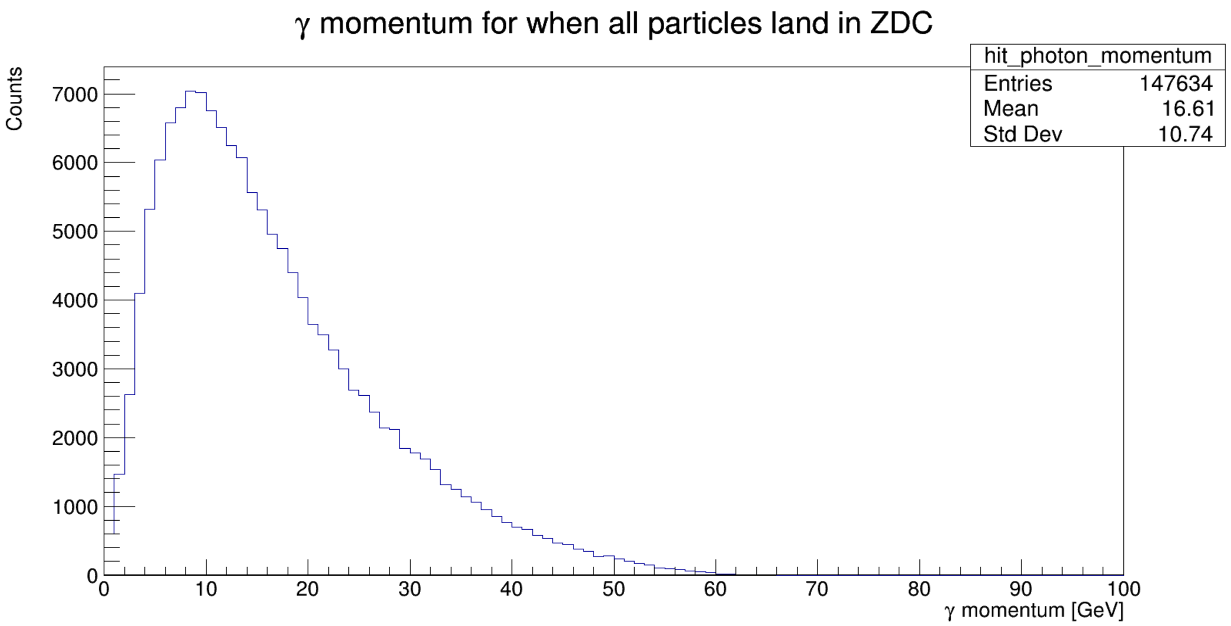
Lambda momentum vs pion momentum



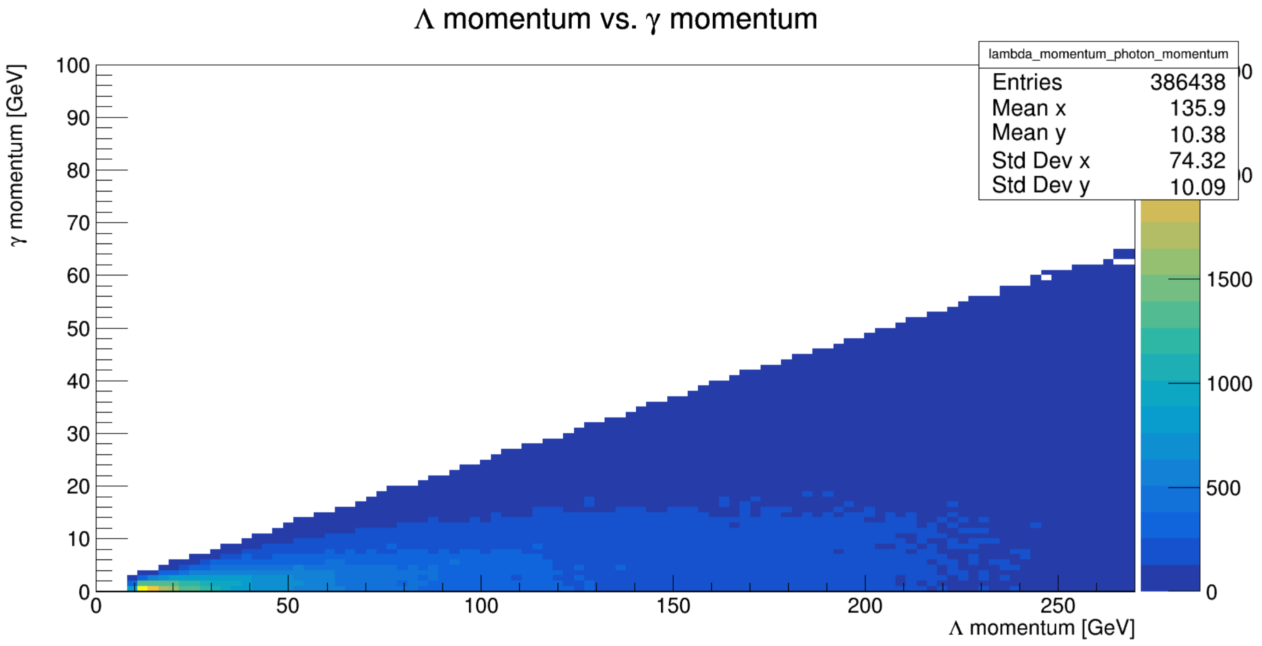


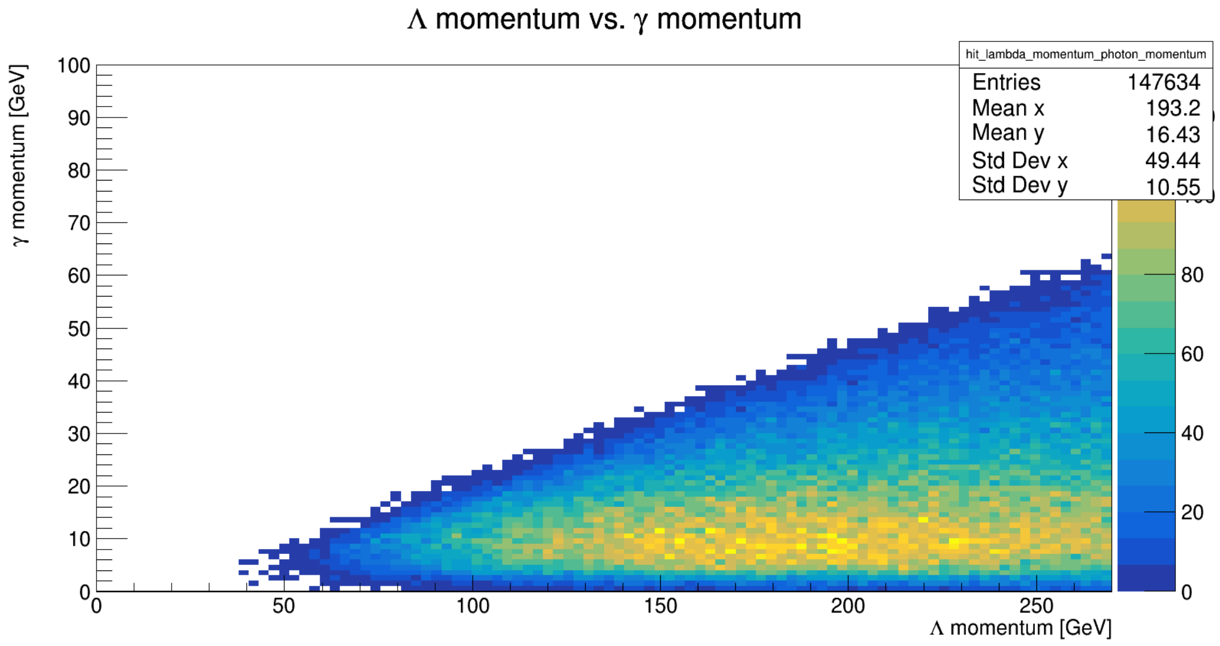
Photon Momentum



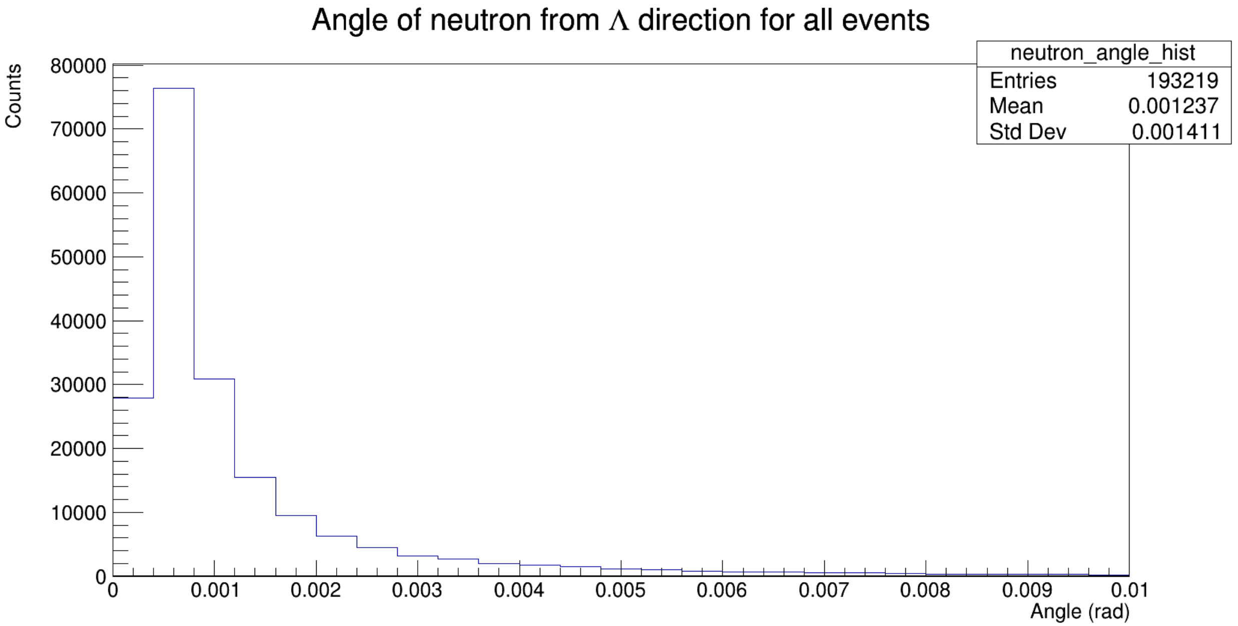


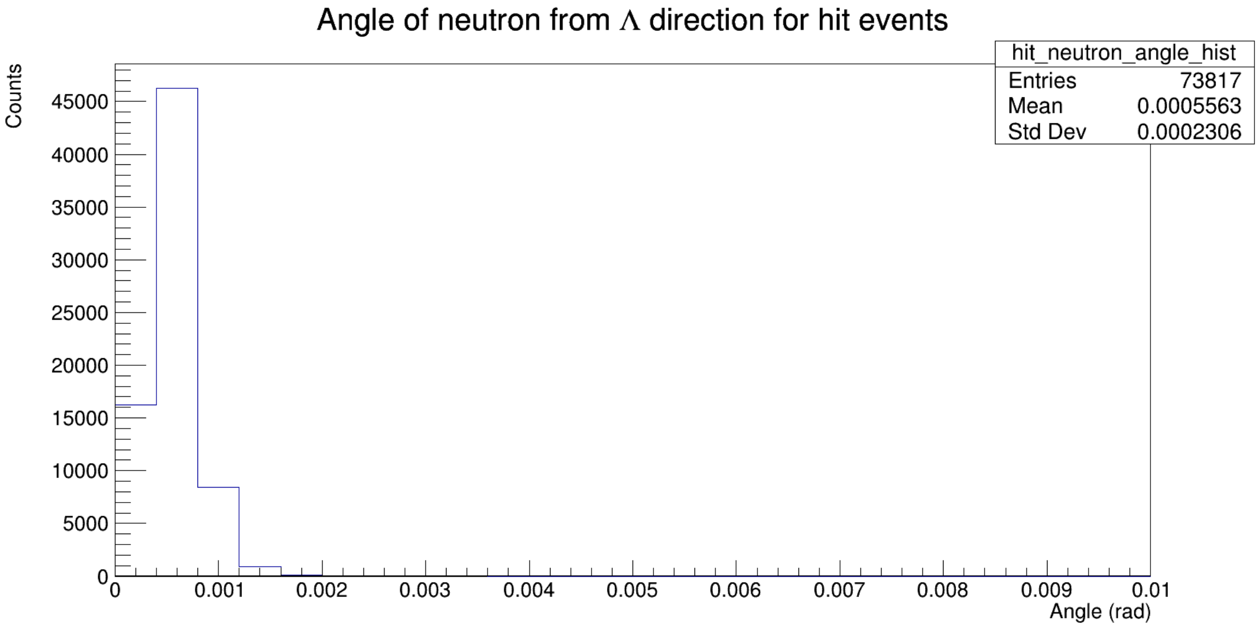
Lambda momentum vs photon momentum



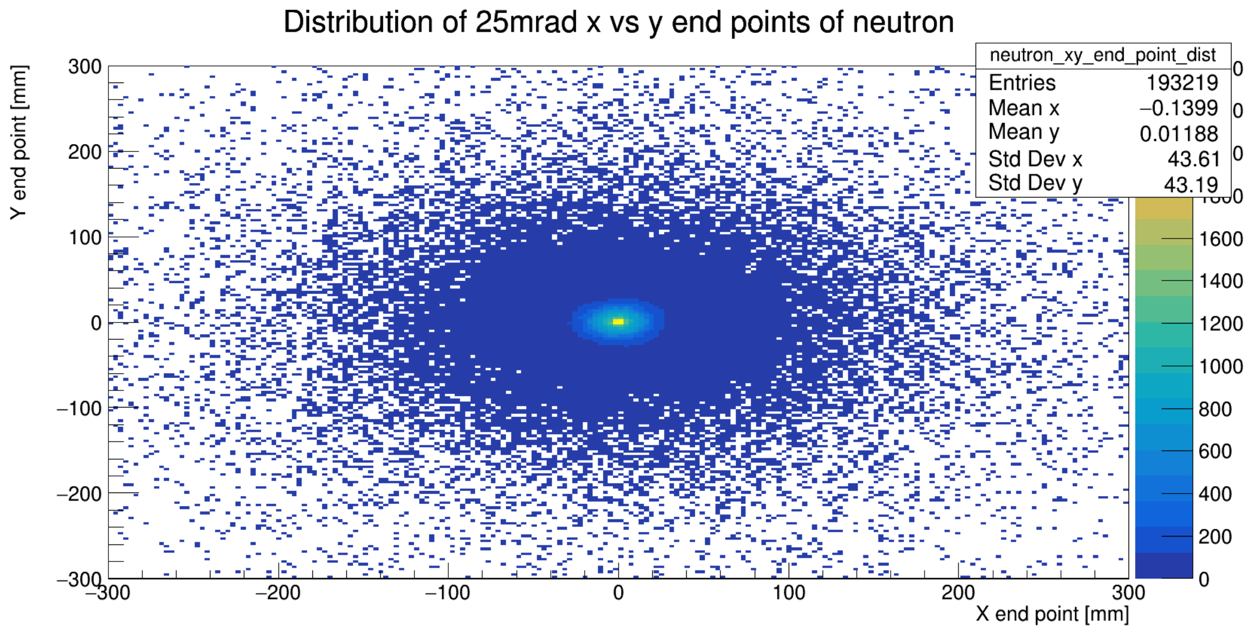


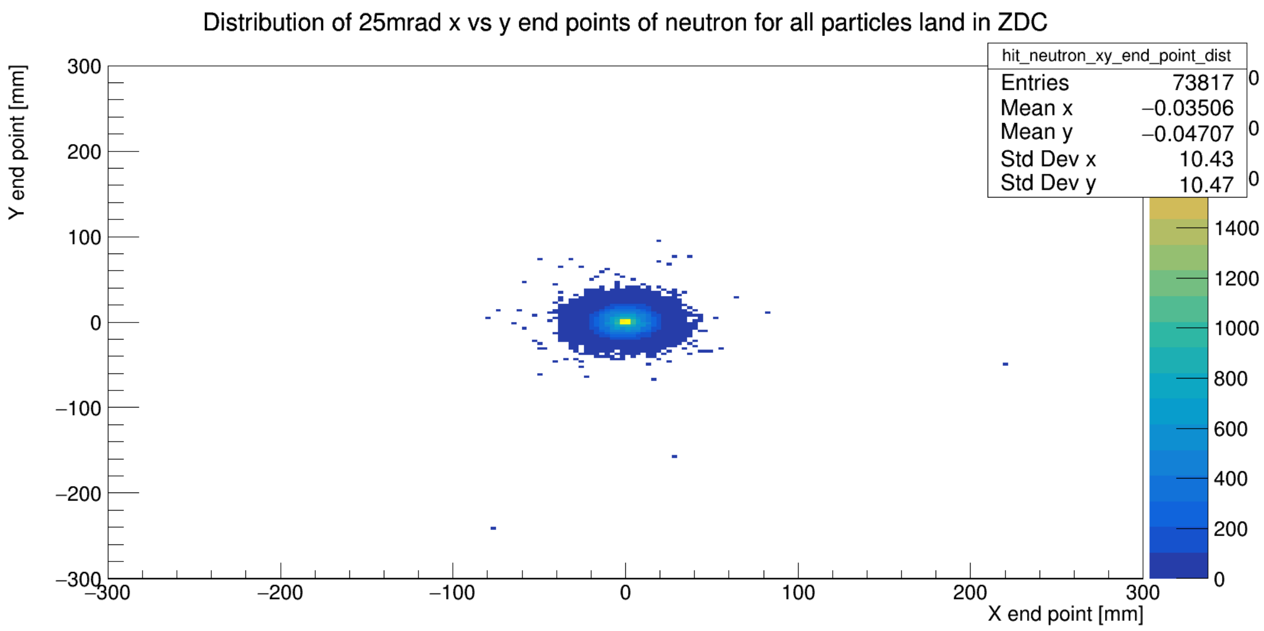
Neutron Angle with lambda



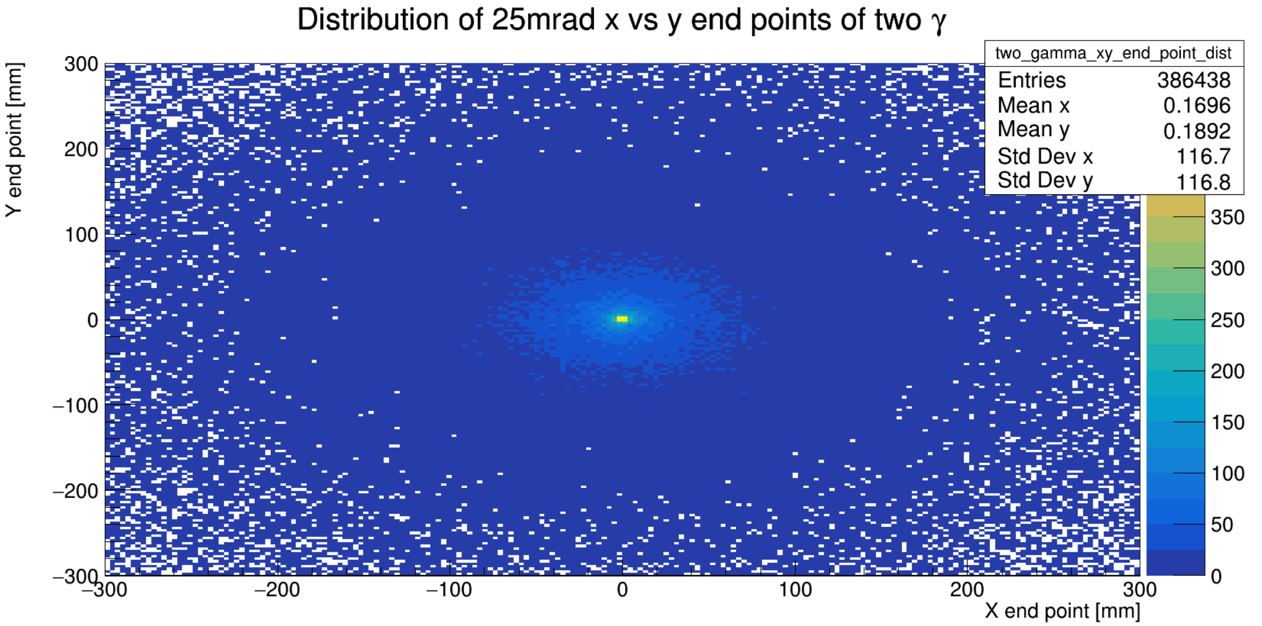


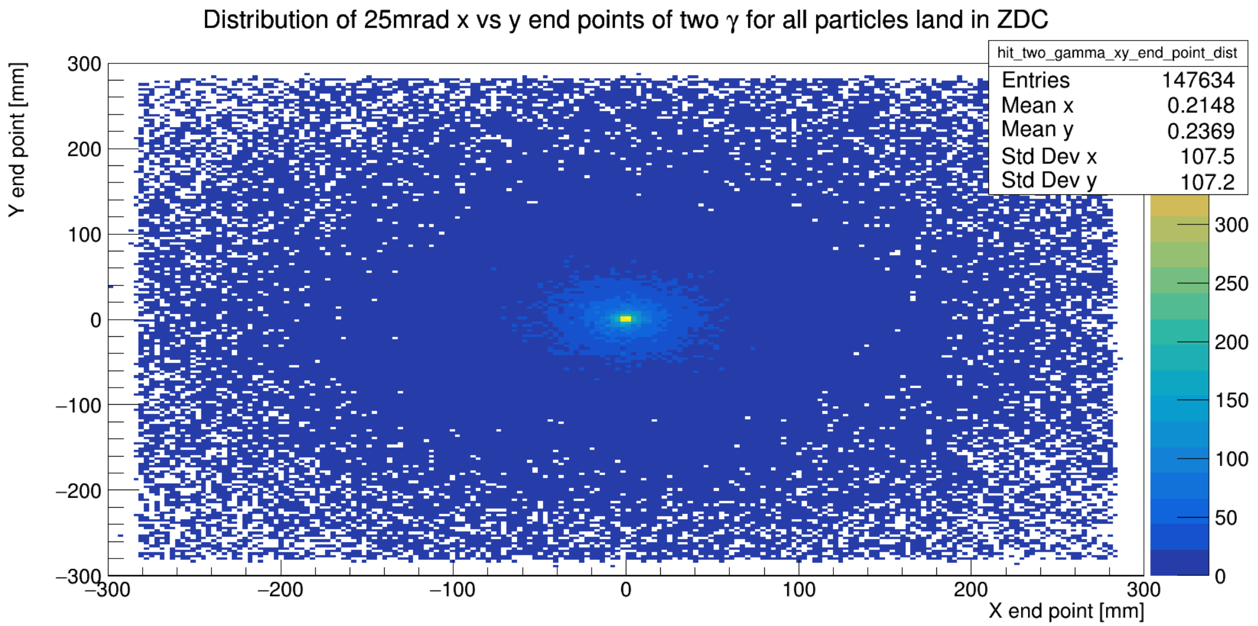
Rotated XY Map of Neutron endpoint



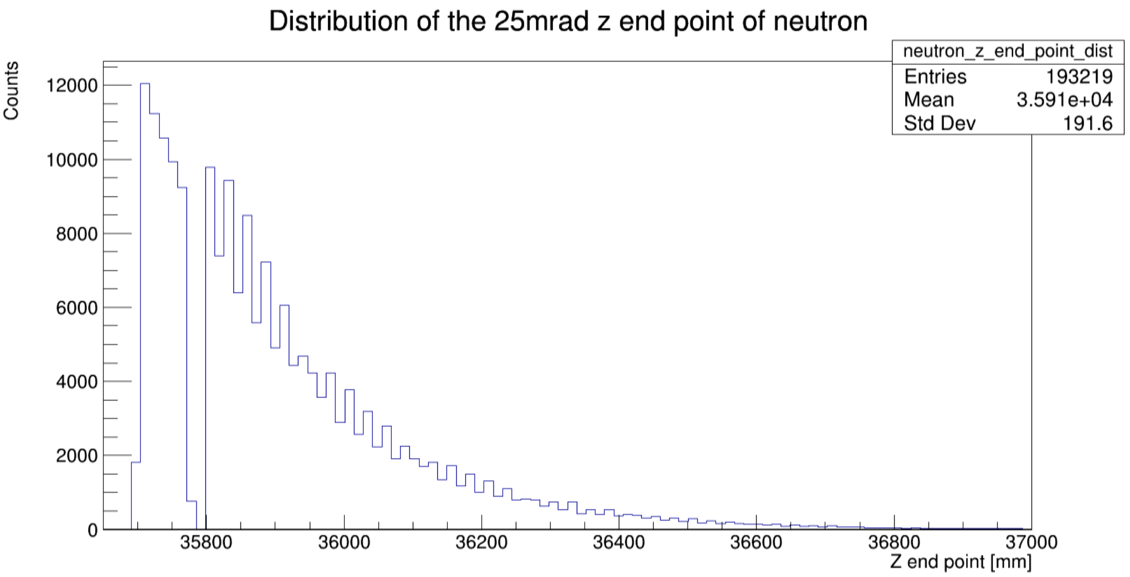


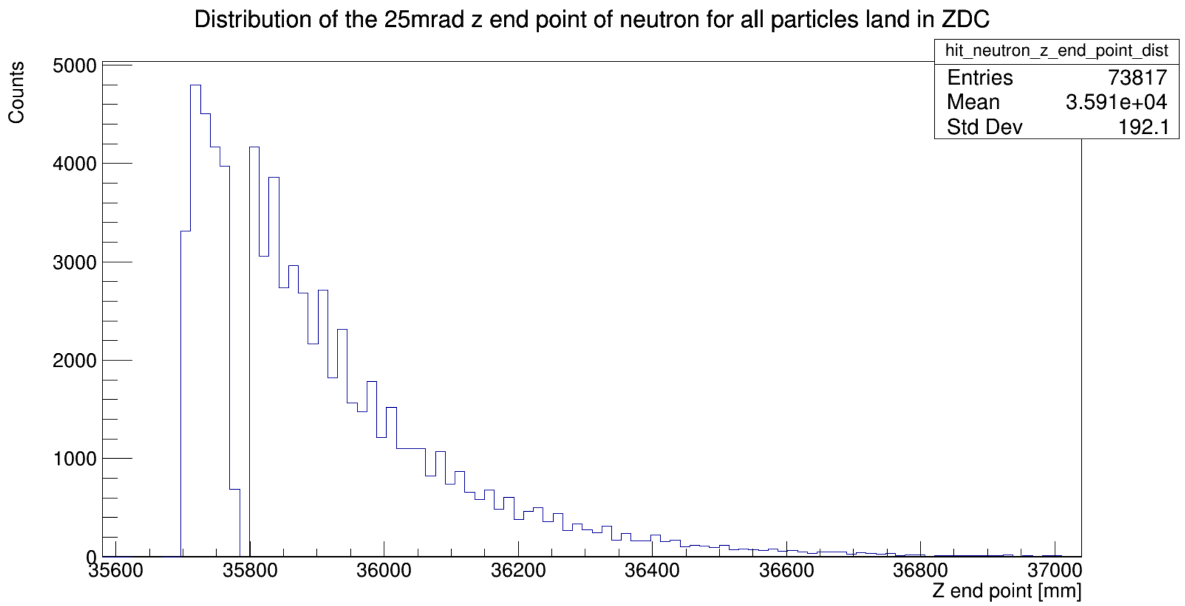
Rotated XY Map of Photon endpoints





Neutron Z Endpoint





Reconstruction in the ZDC

First Step of Reconstruction

- The first step to reconstructing is determining the particle tracks through the ZDC
- We have chosen to do this via clustering the hits
- This means grouping the hits together based on distance, energy and context to associate hits into showers

Clustering Algorithms

- Clustering refers to grouping hits based on the likeliood they belong to a single particle's shower
- We work directly with the data in 3D space + energy
- We have developed two separate clustering algorithms
  - One is based off of the density and energy density of hits to determine clusters
  - One is based upon finding energy peaks and creating clusters by adding neighboring hits
- These clustering algorithms takes in the data and returns groups of hits

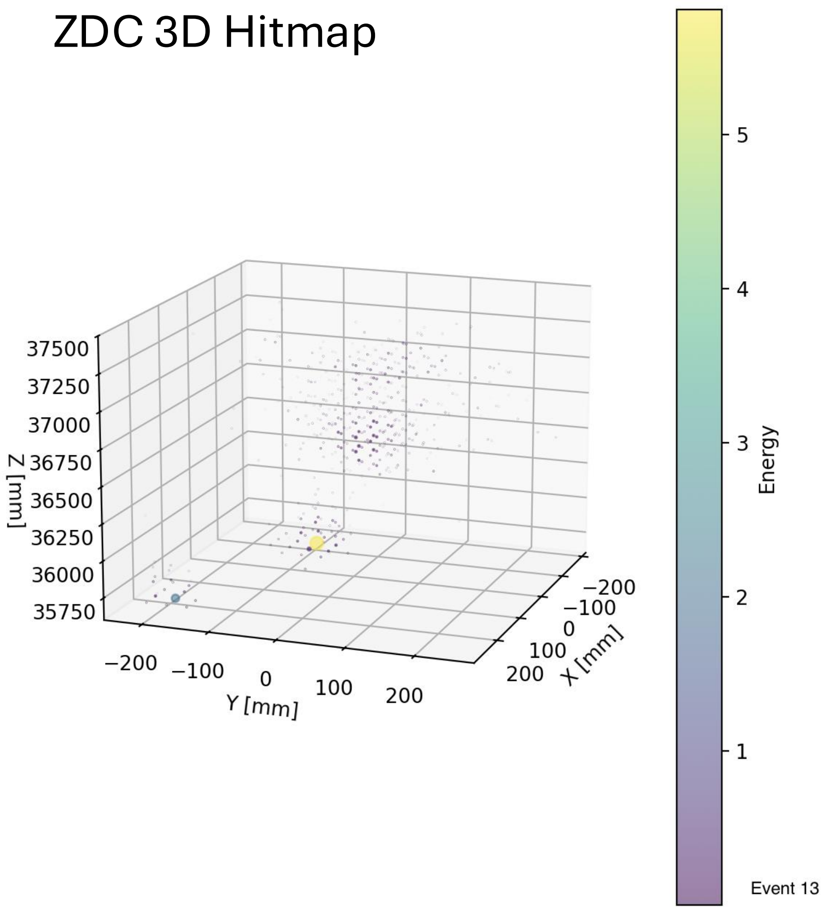
DBSCAN

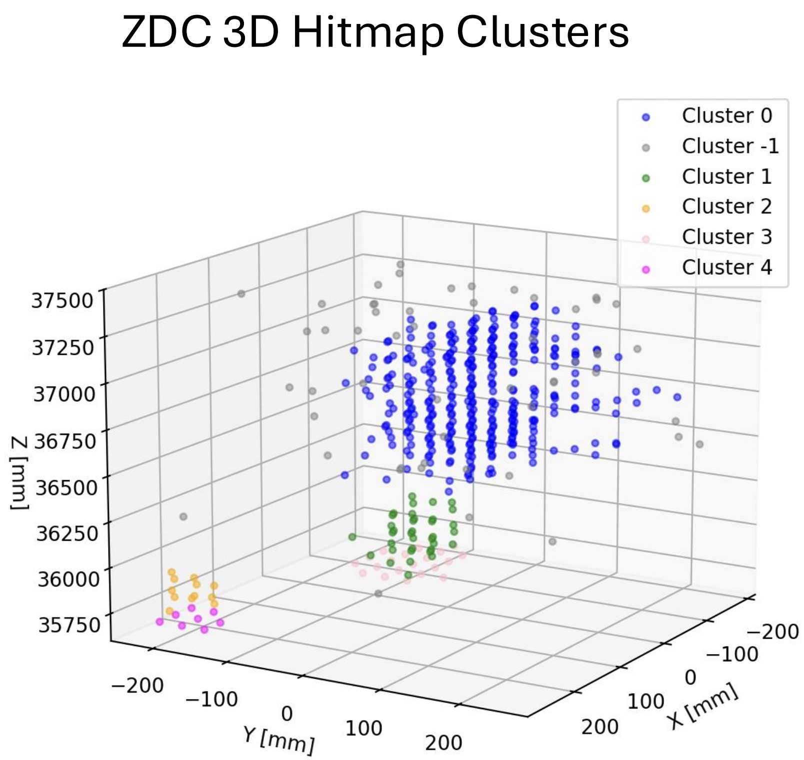
- Method of clustering the data based off the energy density and distribution of hits
- Starts with high energy hits and constructs clusters based off a combination of the density of hits and the density of energy
- Hits with few energy/few neighbors are considered edge hits and the cluster stops expanding from them
- Excells at identifying well separated showers
- Struggles when there is a hit connecting possible clusters and the energy density at the edge of the neutron cluster is not significantly different from that of a photon cluster

DBSCAN

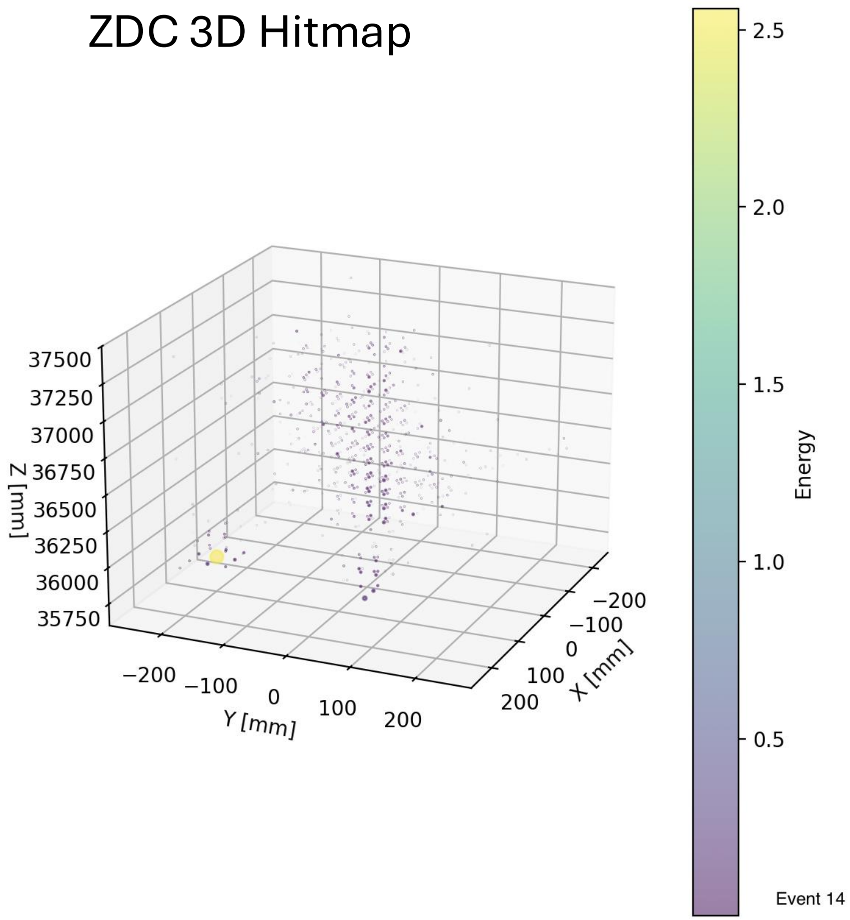
- Clustering is currently a two-step process and results in 3D clusters for the full ZDC.
- Step 1 performs clustering based on an energy threshold (0.01GeV) for determining core points.
    - Step 1 paramters: epsilon, minPts , energy_threshold
- Step 2 is more aggressive and performs clustering based on the change in energy density as we move away from the core of the largest cluster from step 1. This step is implemented if the neutron and photon clusters are not seperated after step 1.
    - Step 2 paramters: epsilon, minPts and distance_threshold

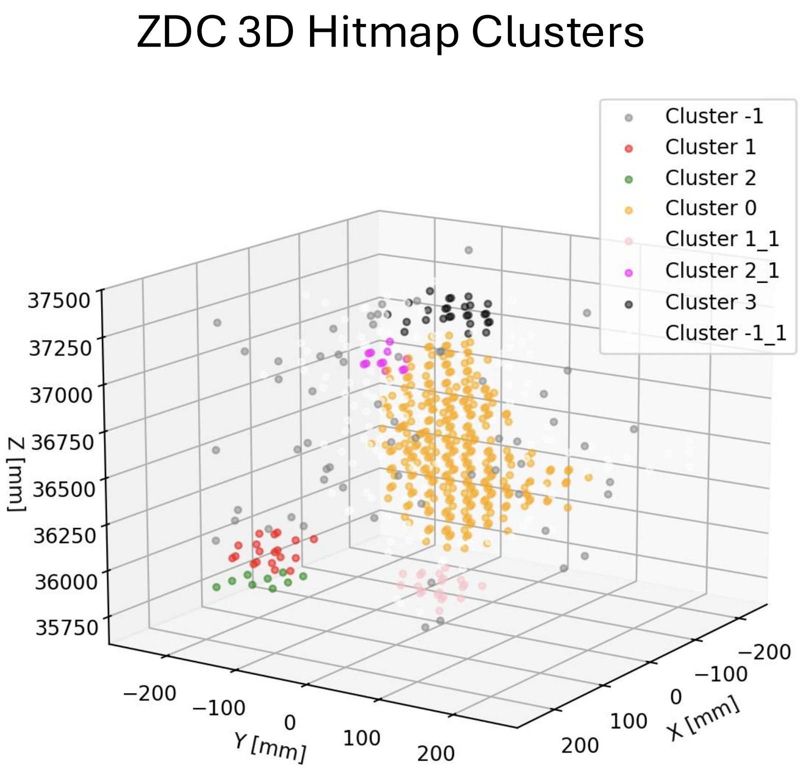
DBSCAN Plots 1



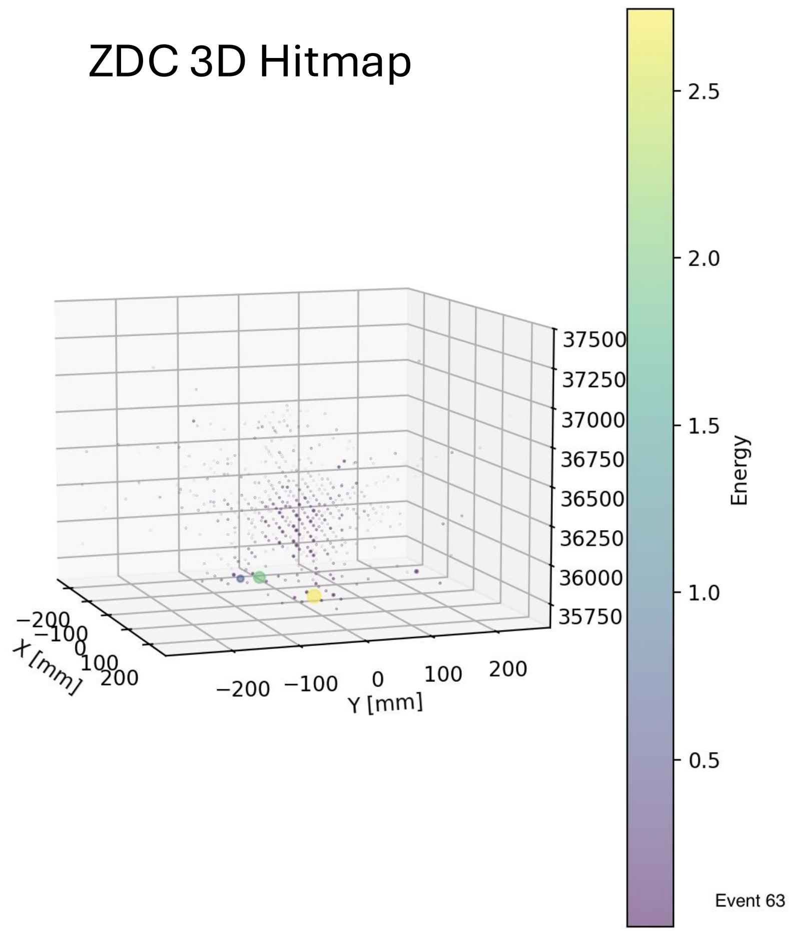


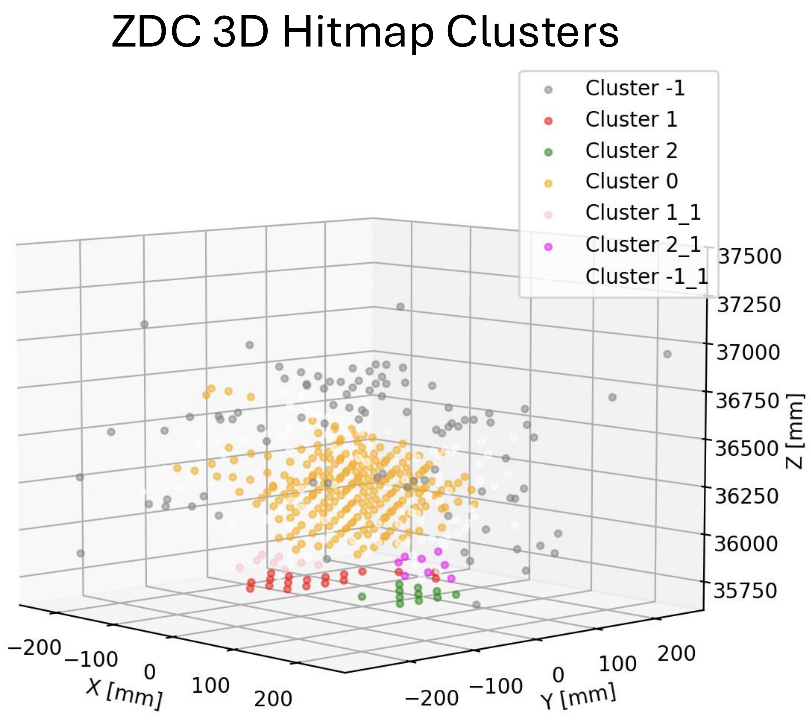
DBSCAN Plots 2





DBSCAN Plots 3





Peak Finding

- Second method of clustering/event identification
- By establishing nieghborhoods based on distance of hits, we can find local maximums of energy deposited
- Examining these peaks in the ECal and HCal can tell us approximately what has happened in an event
- The number of peaks in the ECal tells if we can distinguish two photon clusters, if the neutron started shower in the ECal
- The early peaks in the HCal tell us if the photons can be distinguished from the neutron shower
- Matching peaks between the ECal and HCal allows us to be confident about photon clusters

Peak Finding

- Once we can be confident that a set of peaks belong to a photon, we can expand the HCal peak to include neighboring hits of similar and lower energies
- Expand inside the predetermined region which covers the typical shape of the photon
- Expand only if the neighboring hits are of similar or lower energy than the peak hit and if external neighbors do not have higher energy
- Showers have a high energy core which fades as you move far away, high energy hits away from the center indicate another shower

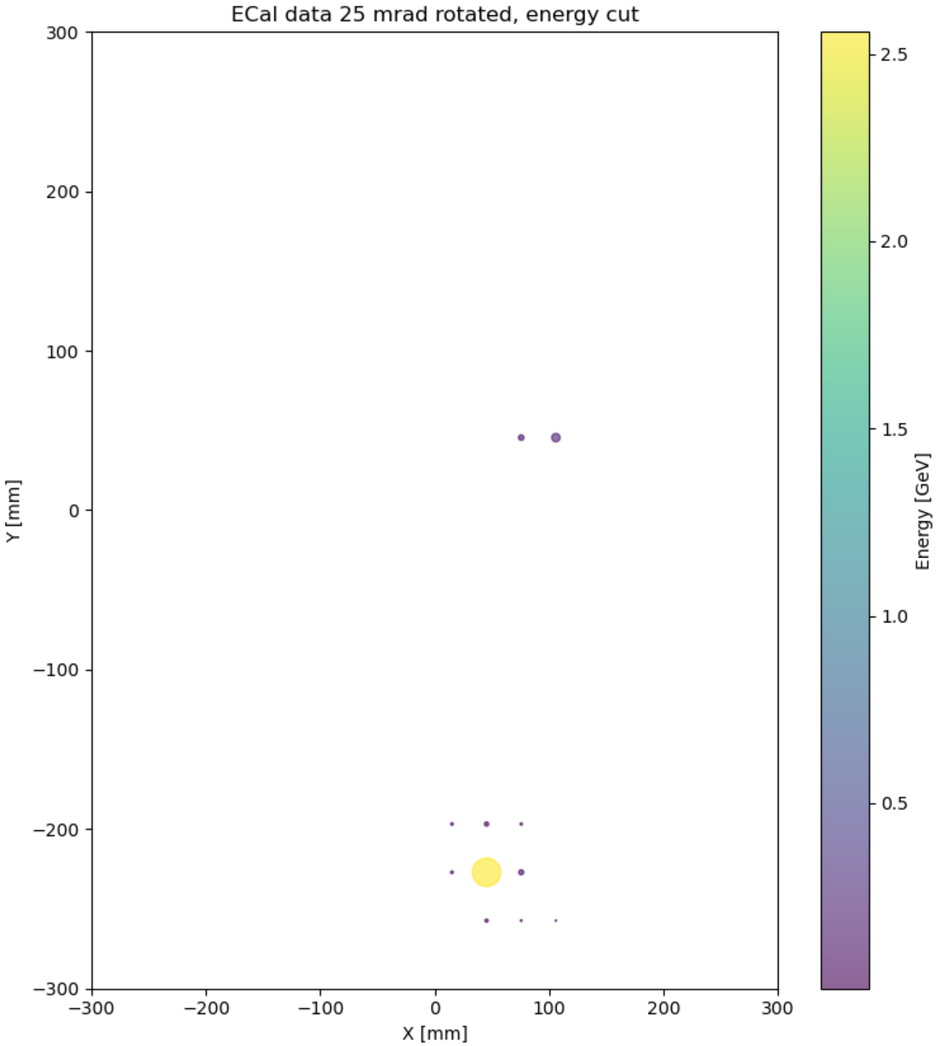
Difficult Events in Reconstruction

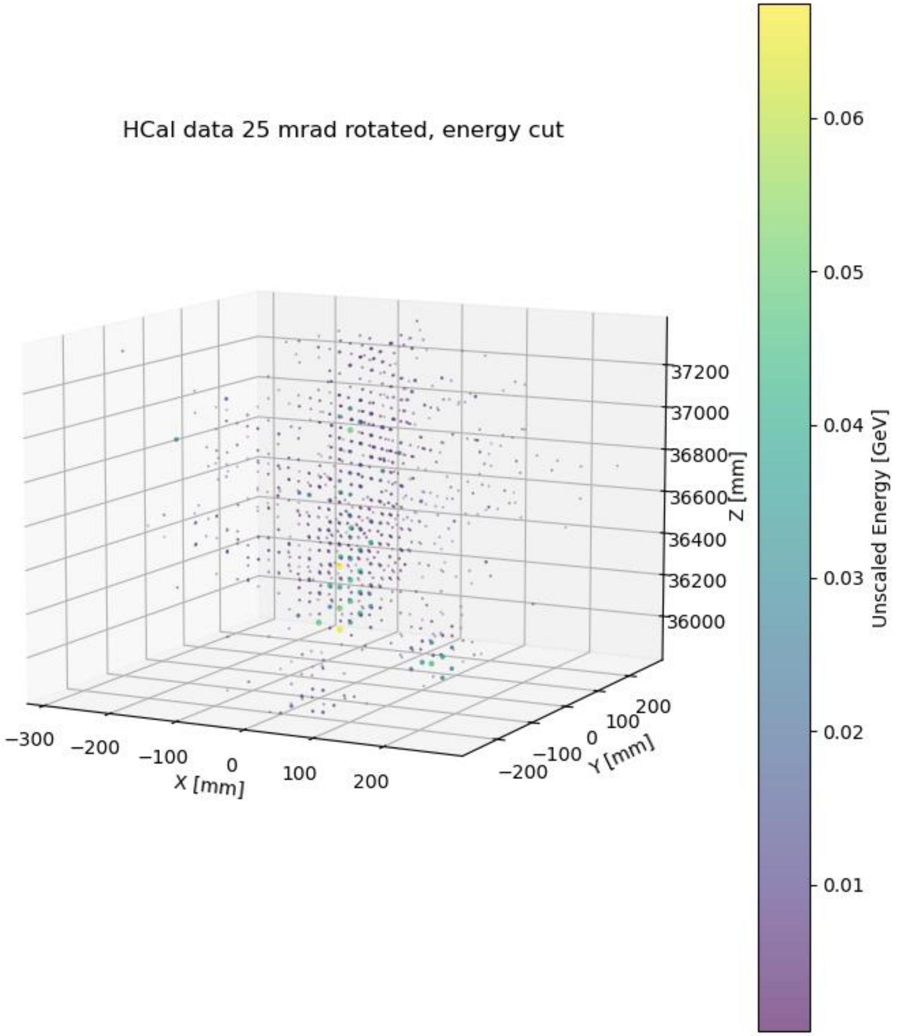
- We have found that there are many events we can't reconstruct and they fall into a few categories
- Due to our kinematics, often one higher energy photons is close to the neutron and one low energy photon is far away
- The neutron energy range is usally from 60 GeV to 250 GeV, the photon is 1 GeV to 30 GeV
- When they do overlap, can't distinguish photon shower from neutron shower unless with additional context (high energy hit marks in the ECal, location in ZDC)
    - It simply blends in with the other hits from the neutron shower

Difficult Events Continued

- Early neutron shower
  - If the neutron starts showering in the ECal, it is difficult to identify low energy photon marks in the ECal and impossible to confidently distinguish photon showers
- Overlapping photons
  - Low energy pion and late lambda decays often produce close photons
  - If they are too close, they will land in adjacent cells in the ECal
- Missing ECal marks/Deep photons
  - Sometimes photons (more often low energy photons) do not interact with the ECal or leave minimal marks
  - Sometimes the photons travel further into the HCal than typical, difficult to tell if they are actually photons if close to the neutron
- Missing Photons
  - Photon showers might be contained entirely within the ECal, leaving few marks in the HCal
- Shower overflow
  - In variable angle data, neutron showers can often leave the ZDC

An Ideal event





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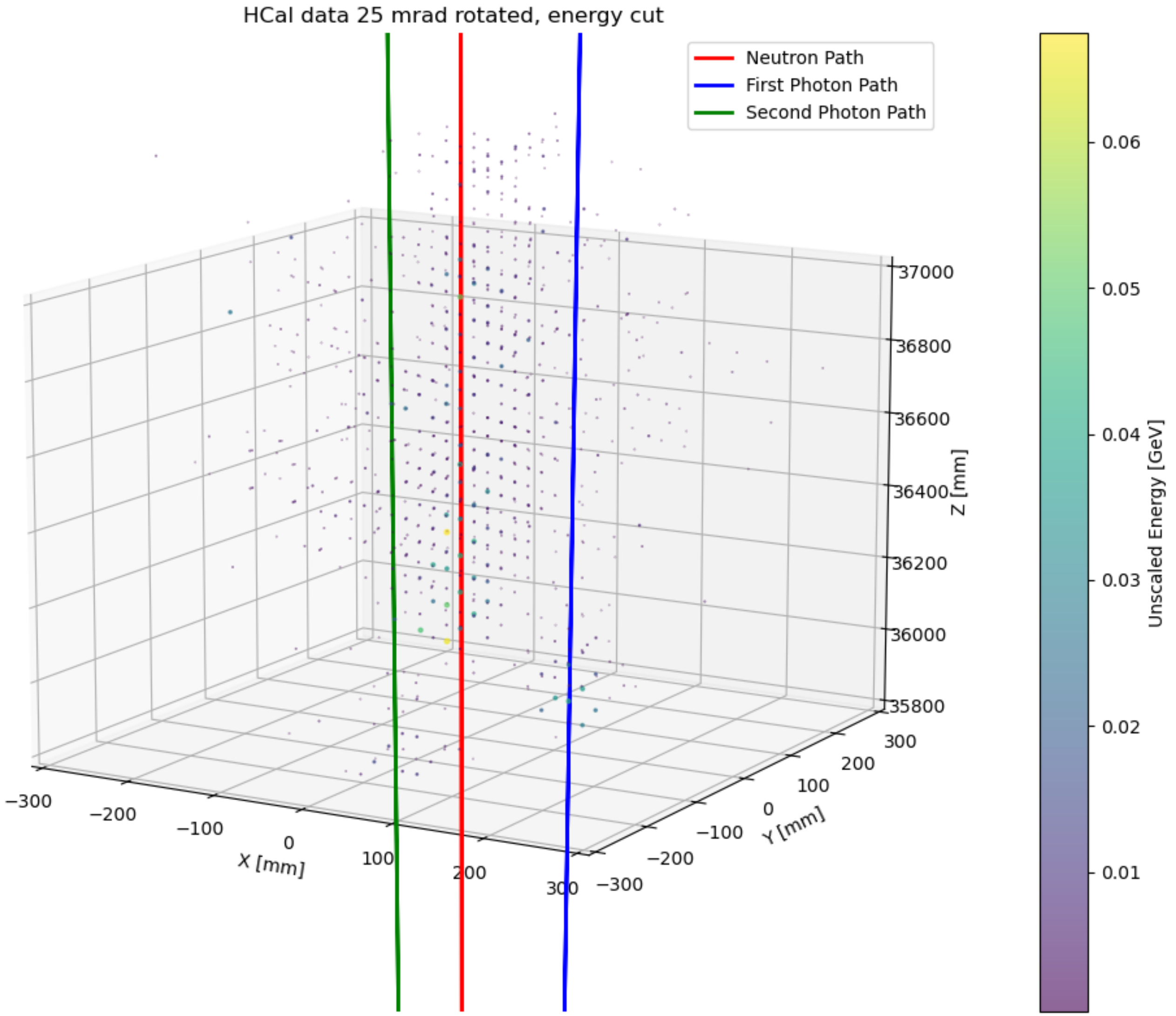
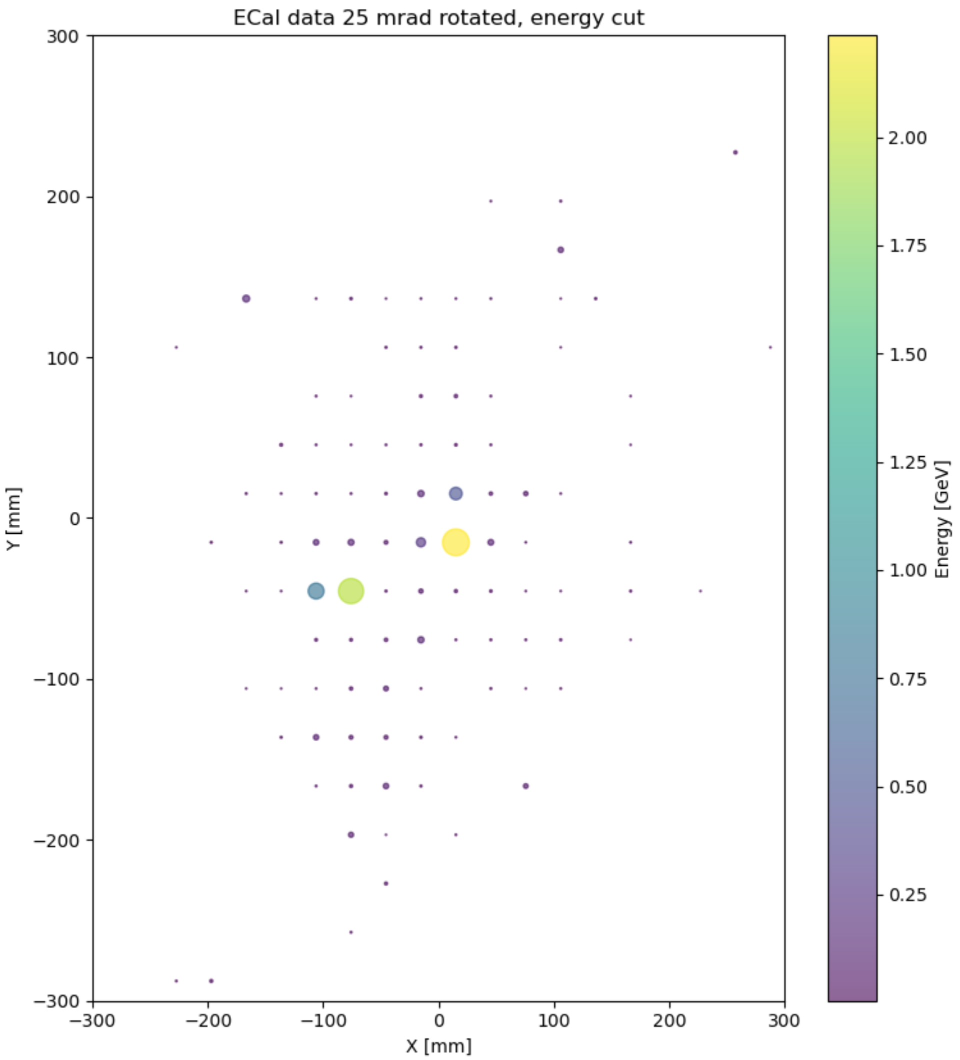
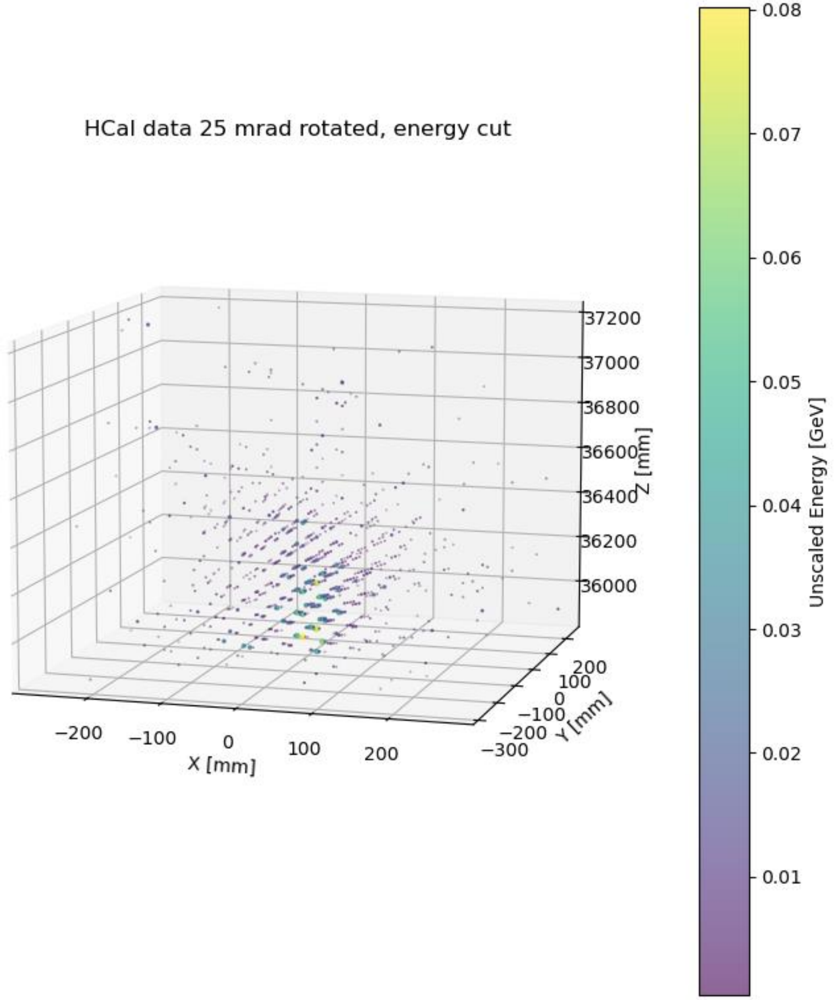


HCal data 25 mrad rotated, energy cut
Neutron Path
First Photon Path
Second Photon Path
X [mm]
Y [mm]
Z [mm]
−300
−200
−100
0
100
200
300
35800
36000
36200
36400
36600
36800
37000
Unscaled Energy [GeV]
0.01
0.02
0.03
0.04
0.05
0.06

Early Neutron Showers





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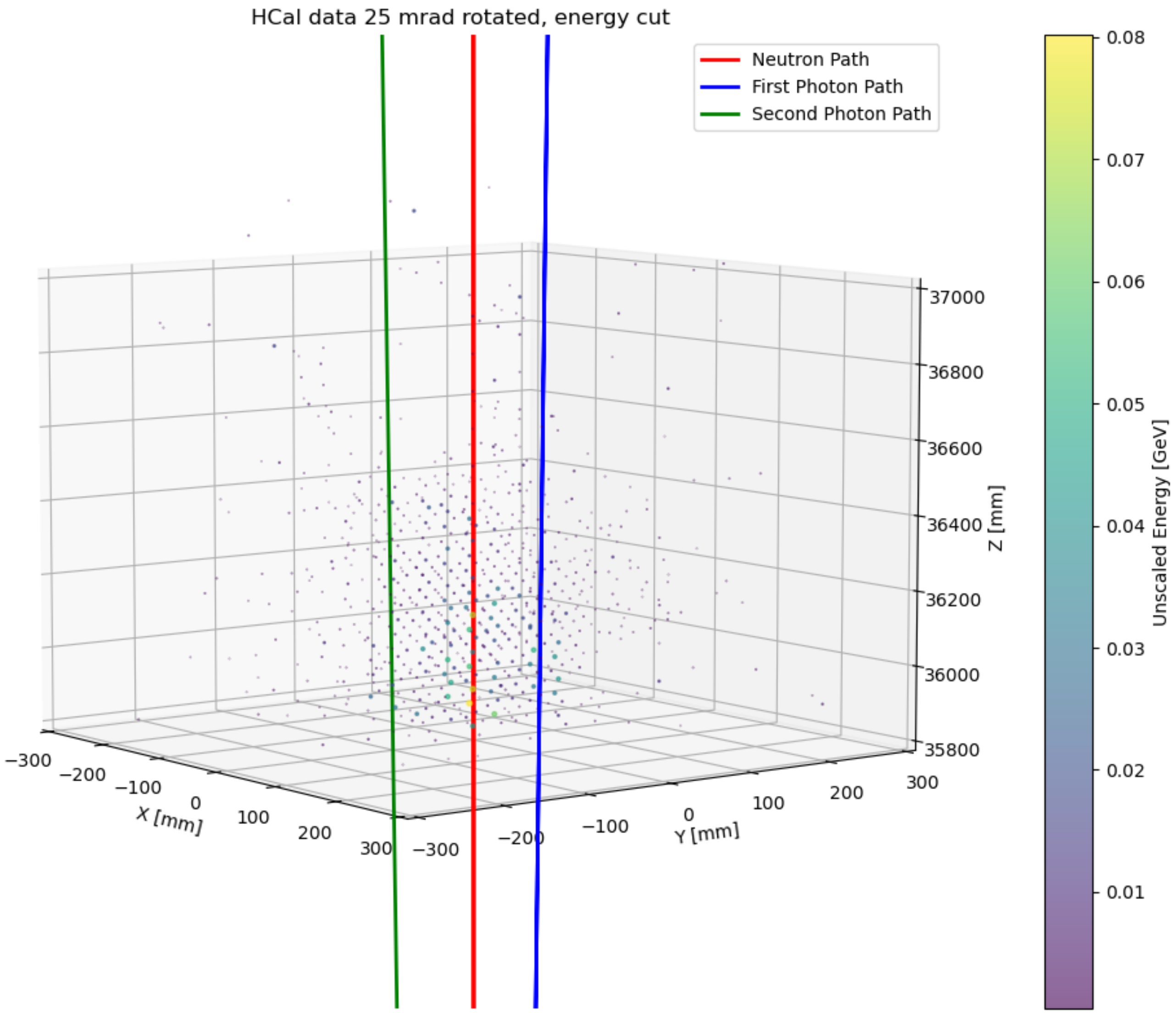
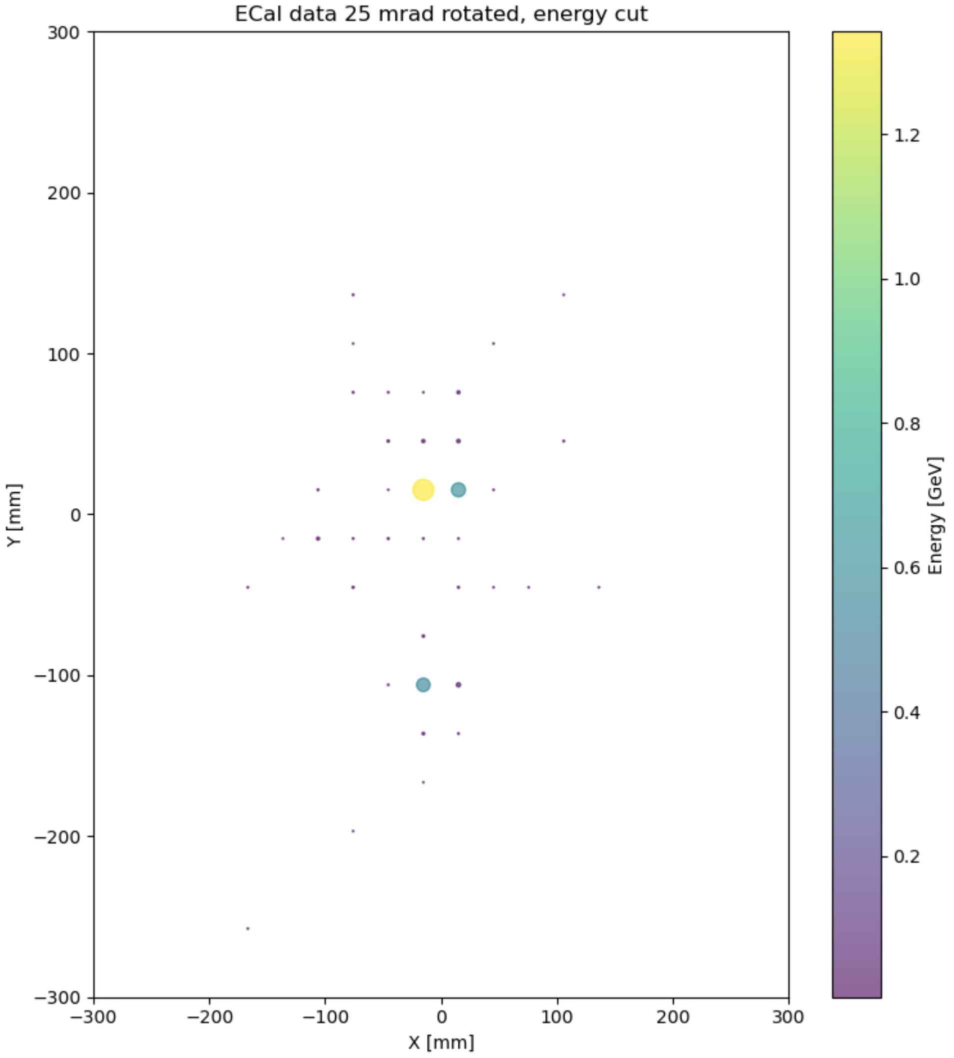
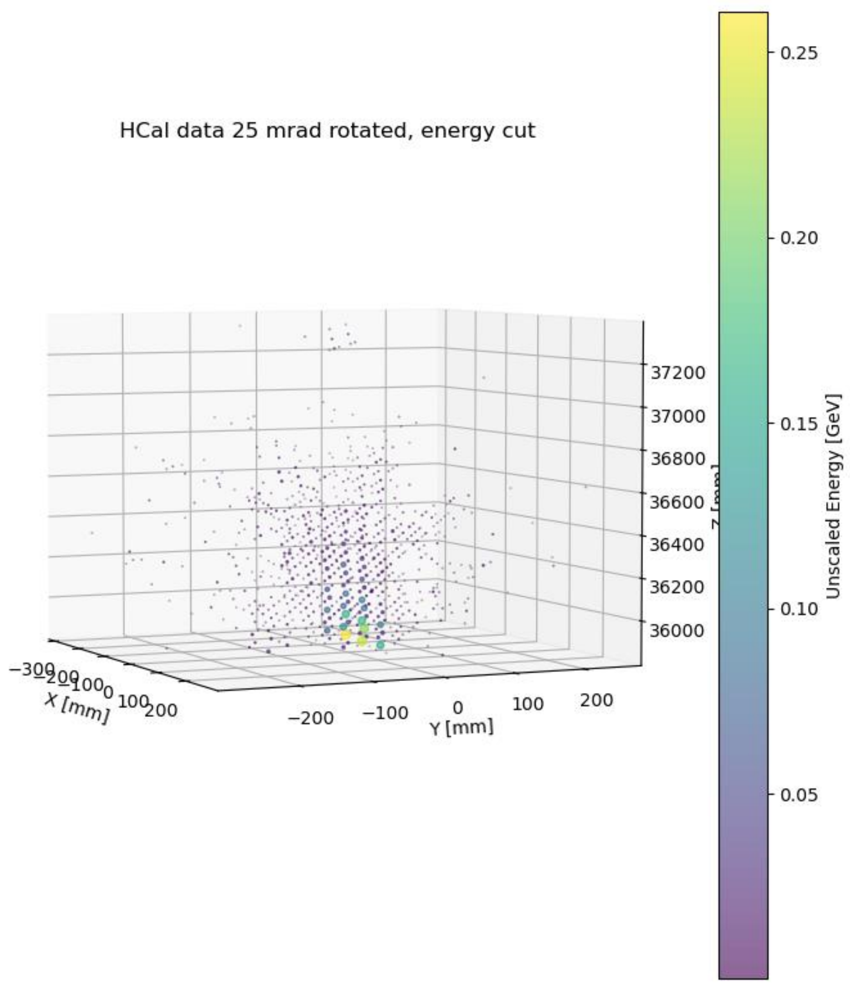


HCal data 25 mrad rotated, energy cut
Neutron Path
First Photon Path
Second Photon Path
X [mm]
Y [mm]
Z [mm]
Unscaled Energy [GeV]

2nd Early Neutron Shower





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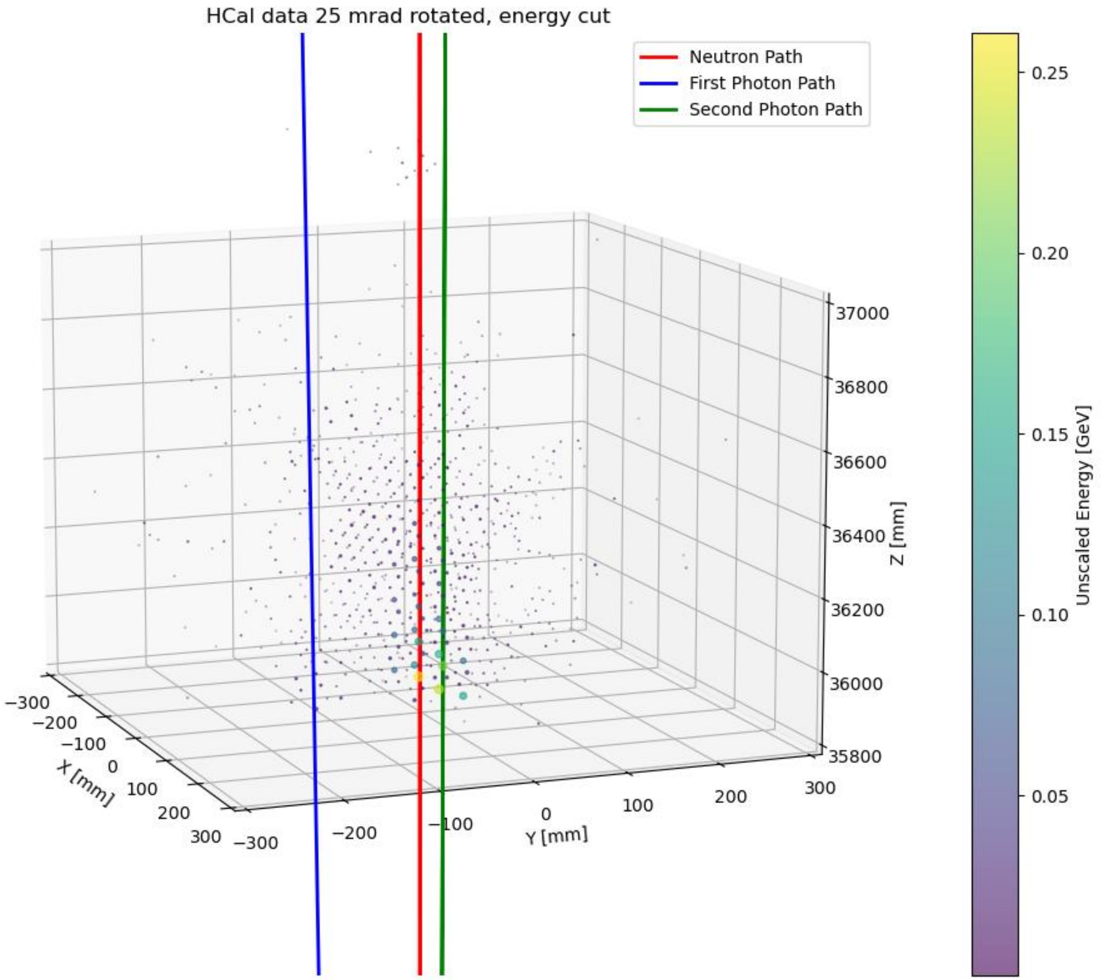
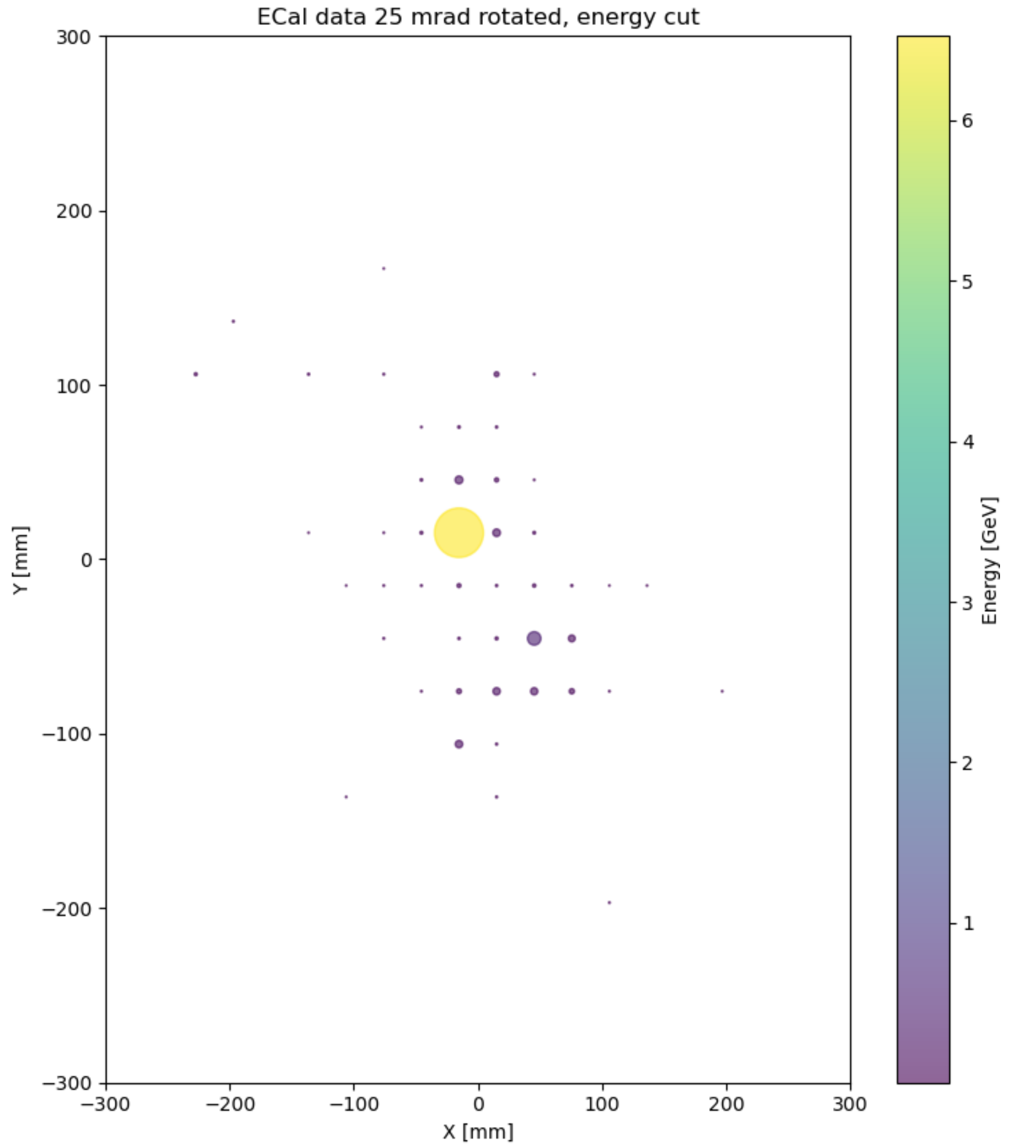
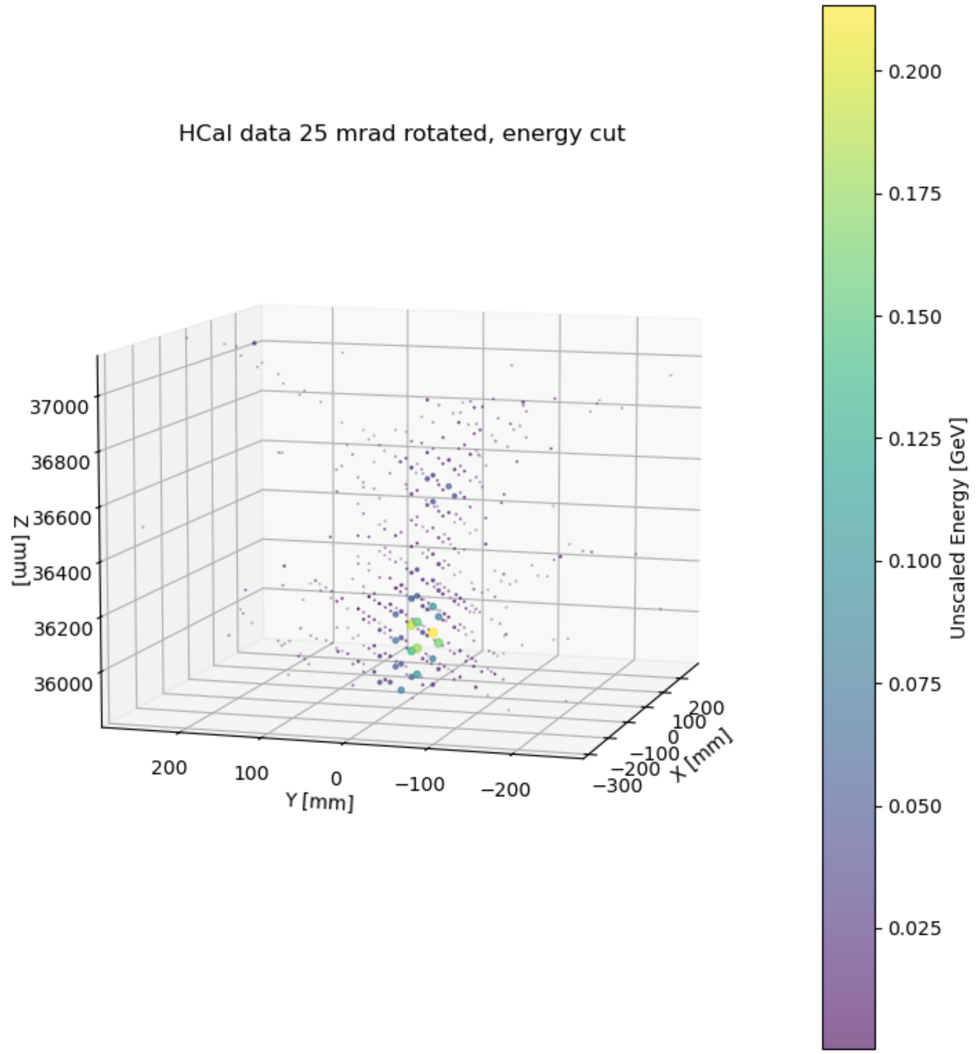


HCal data 25 mrad rotated, energy cut
Neutron Path
First Photon Path
Second Photon Path
X [mm]
Y [mm]
Z [mm]
−300
−200
−100
0
100
200
300
35800
36000
36200
36400
36600
36800
37000
Unscaled Energy [GeV]
0.05
0.10
0.15
0.20
0.25

Missing Photon





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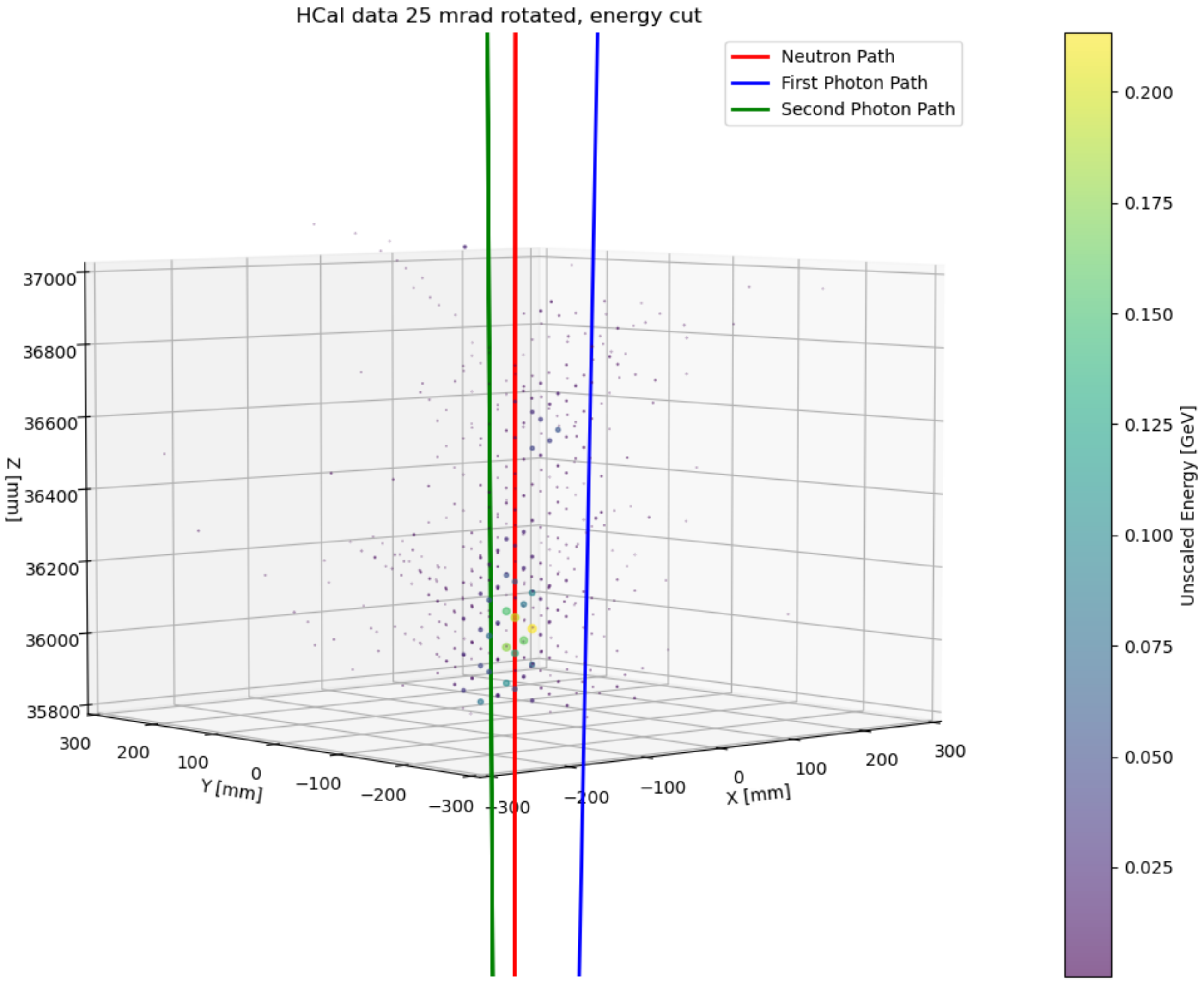
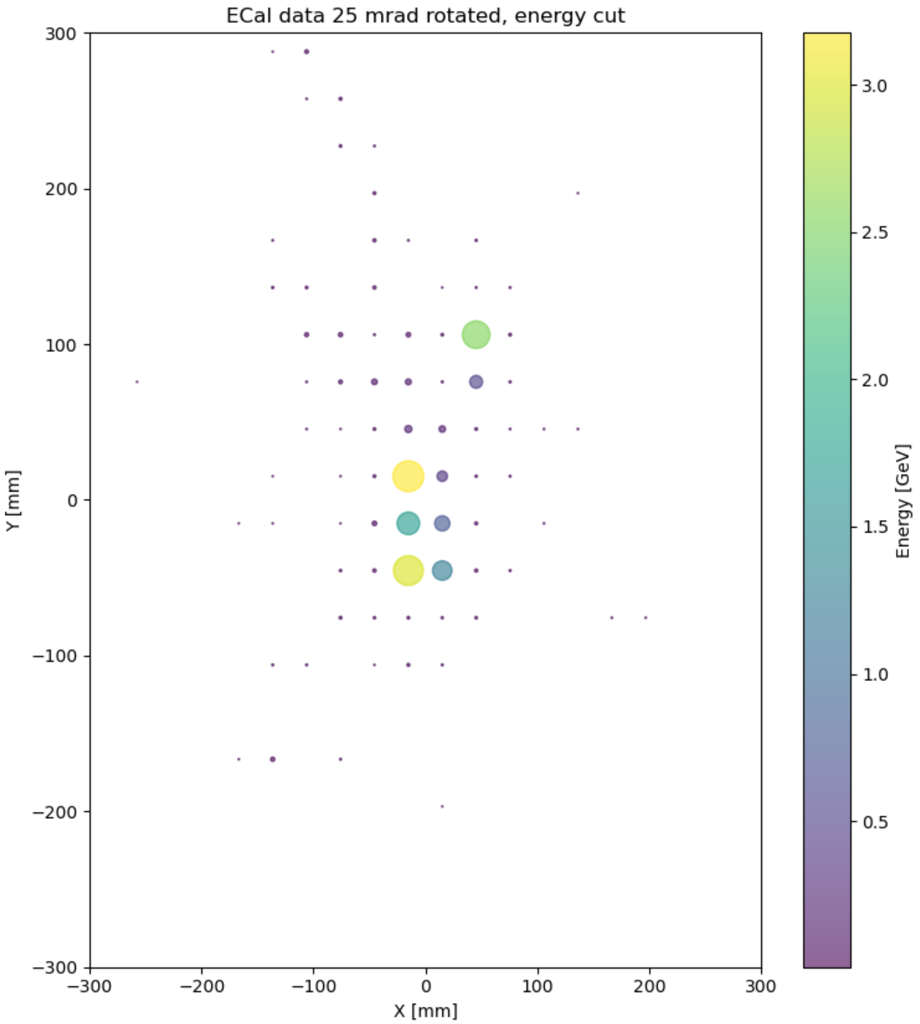
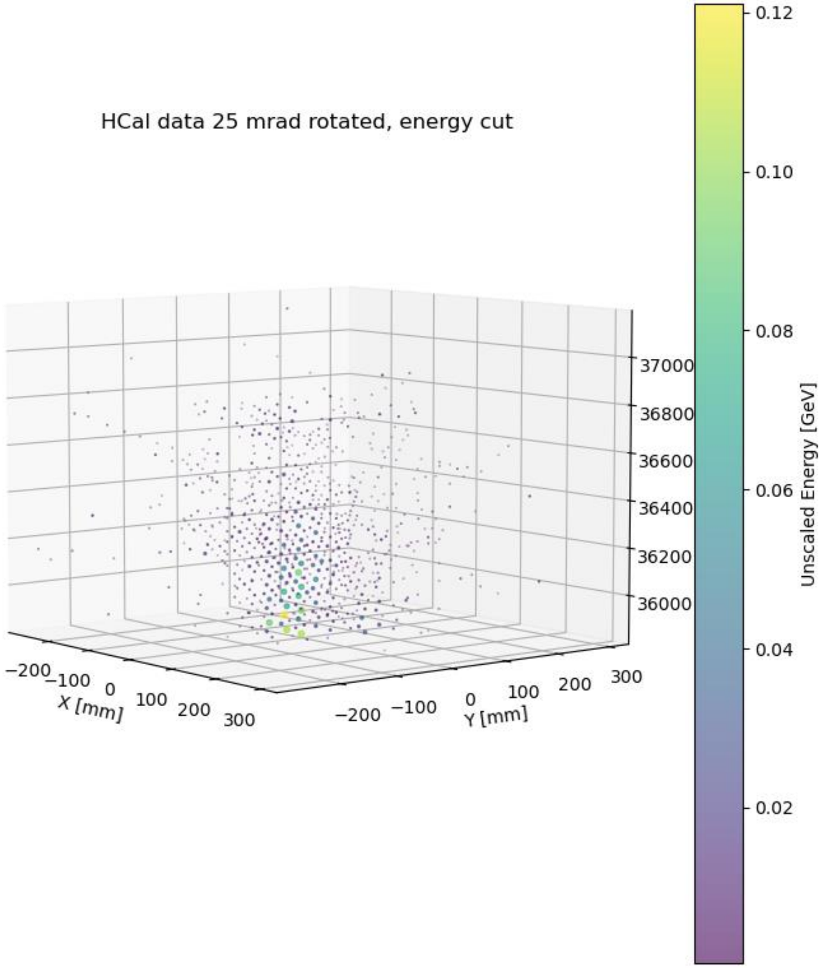


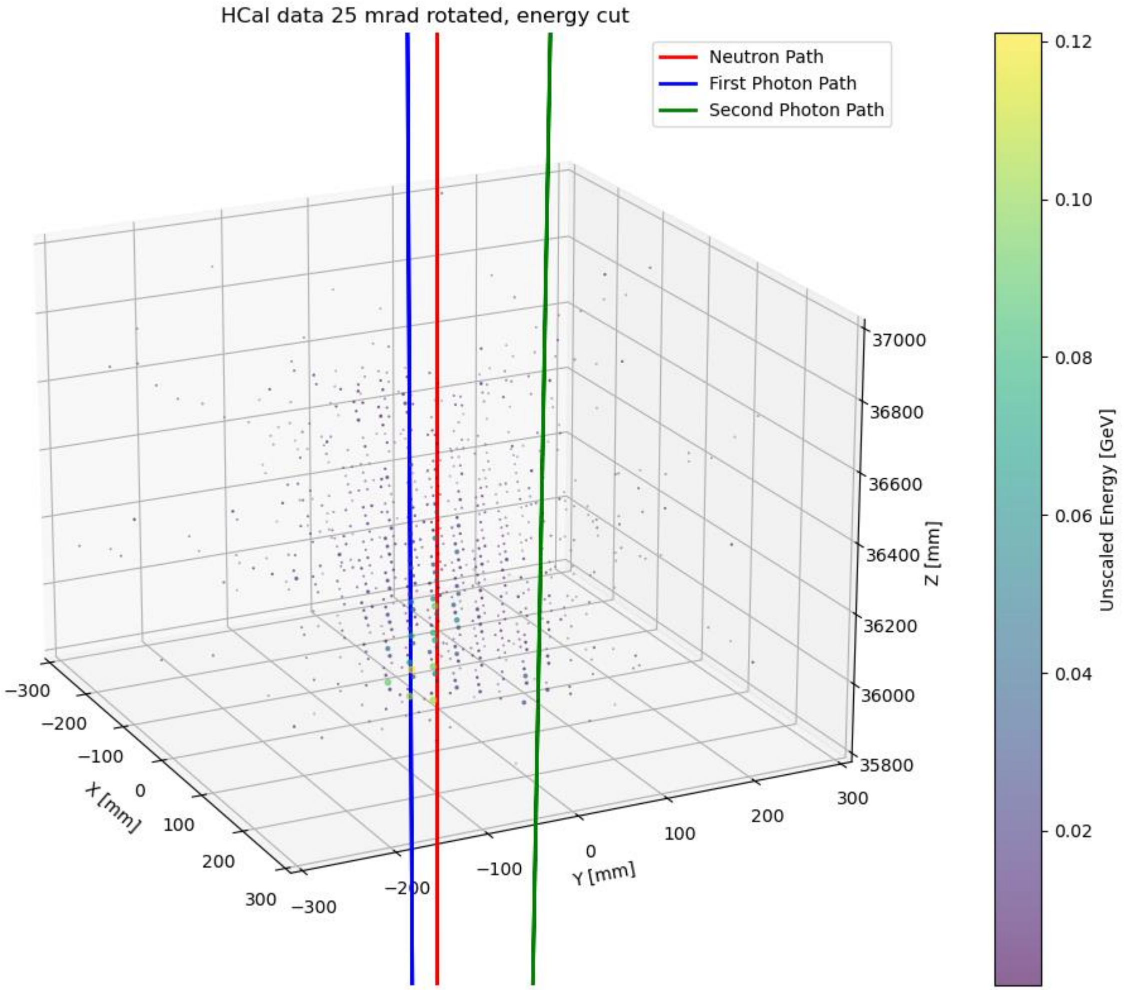
HCal data 25 mrad rotated, energy cut
Neutron Path
First Photon Path
Second Photon Path
37000
36800
36600
36400
36200
36000
35800
Z [mm]
300
200
100
0
−100
−200
−300
Y [mm]
−300
−200
−100
0
100
200
300
X [mm]
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
Unscaled Energy [GeV]

High Energy Overlap





Cont.

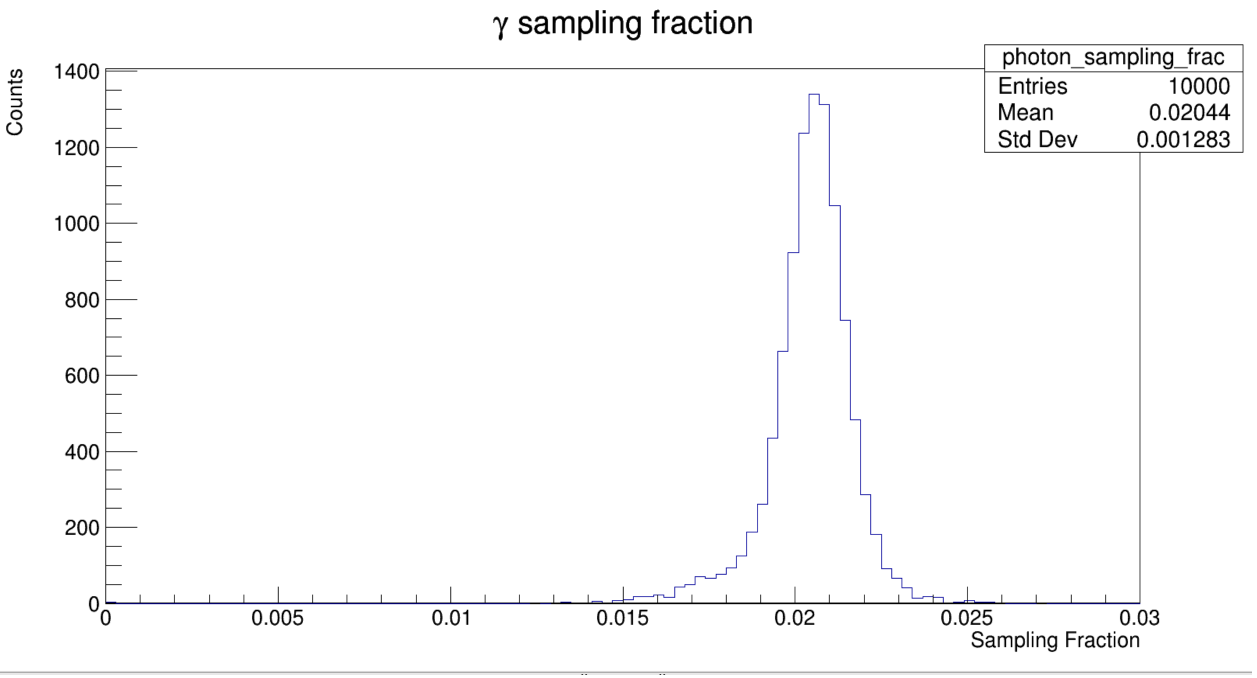

HCal data 25 mrad rotated, energy cut
Neutron Path
First Photon Path
Second Photon Path
X [mm]
Y [mm]
Z [mm]
Unscaled Energy [GeV]
−300
−200
−100
0
100
200
300
35800
36000
36200
36400
36600
36800
37000
0.02
0.04
0.06
0.08
0.10
0.12

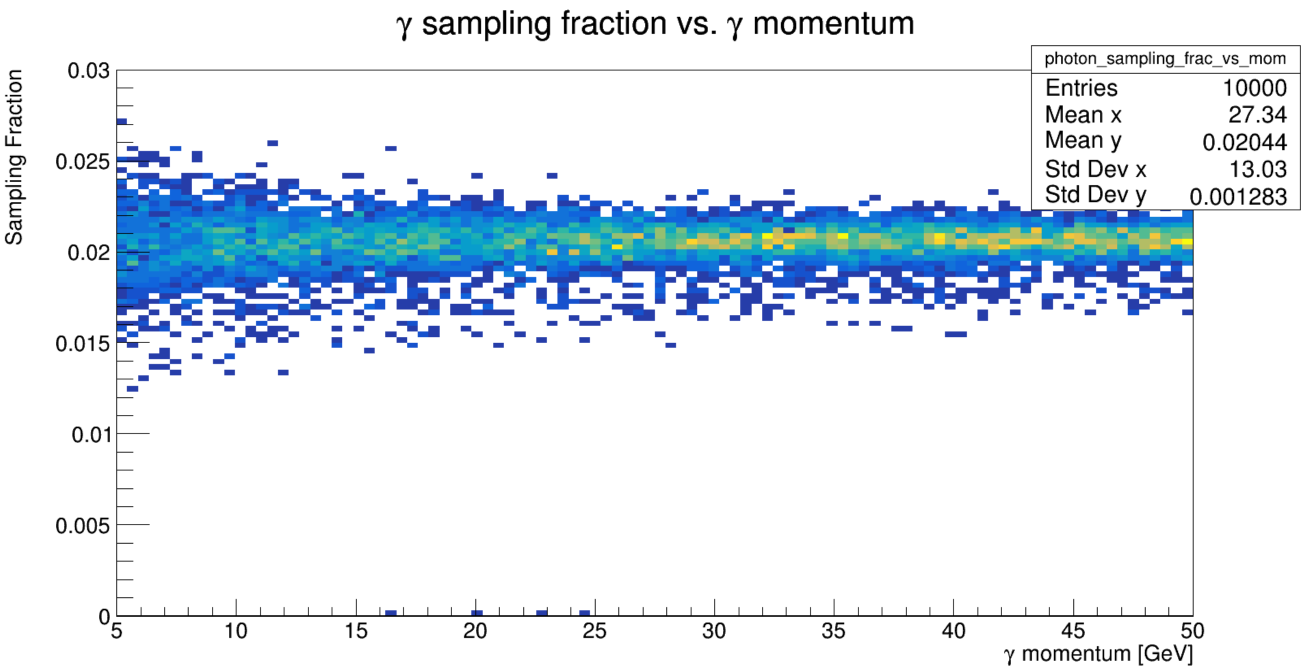
Extra

Sampling Fraction of HCal

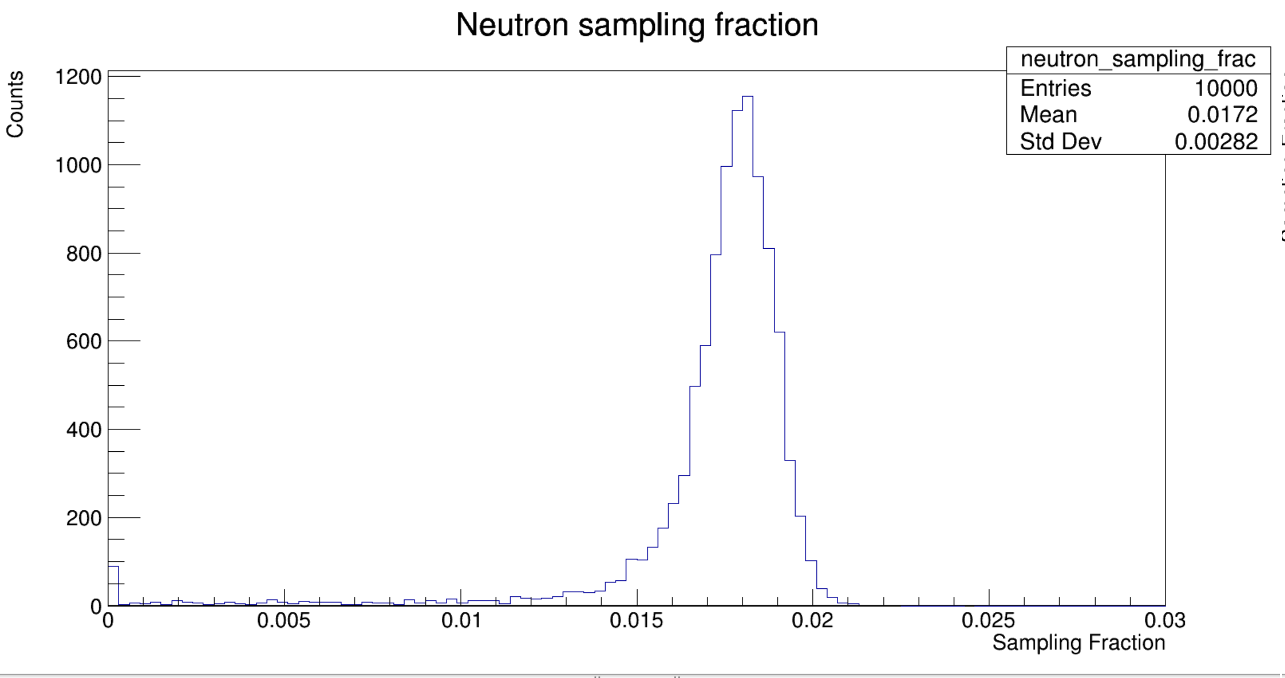
- Determined by firing single photons and single neutrons at ZDC with fixed angle with energy ranges reflecting lambda data
  - For photon, 0 to 50 GeV
  - For neutron, 0 to 250 GeV
- The sampling fraction is calculated by taking (sum of energy in HCal)/(true energy – sum of energy in ECal)
- EM showers have a higher sampling fraction than hadron showers

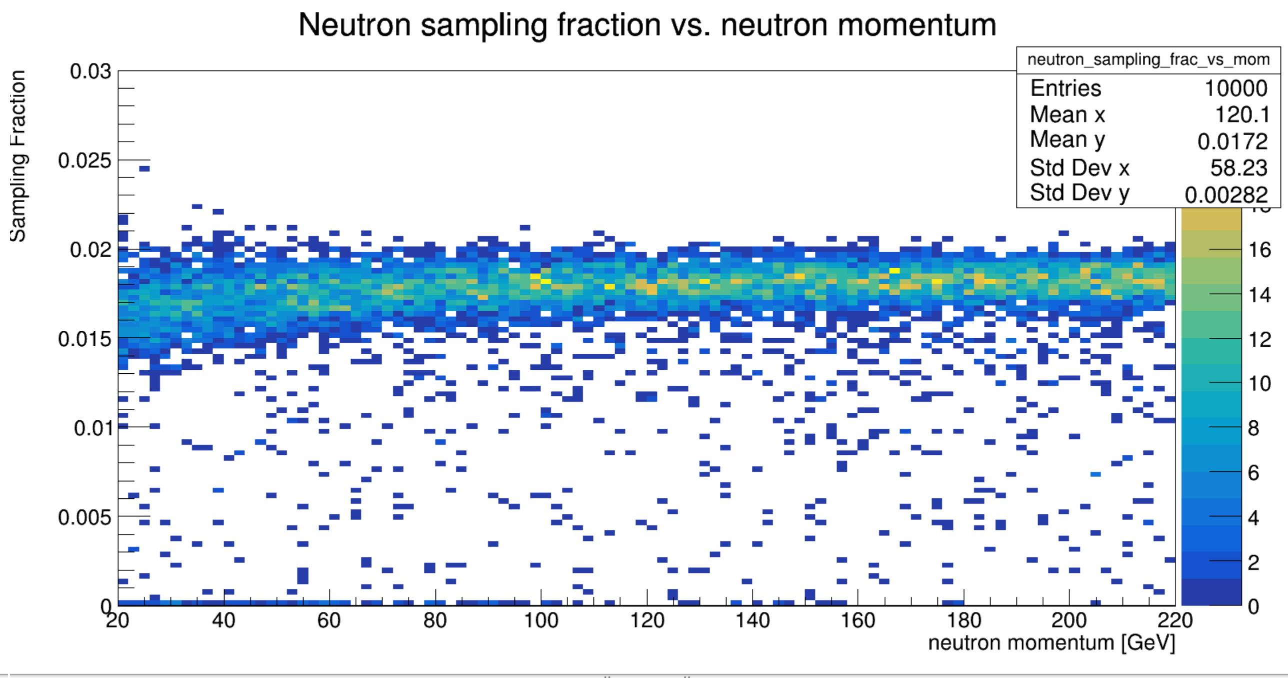
EM Sampling Fraction



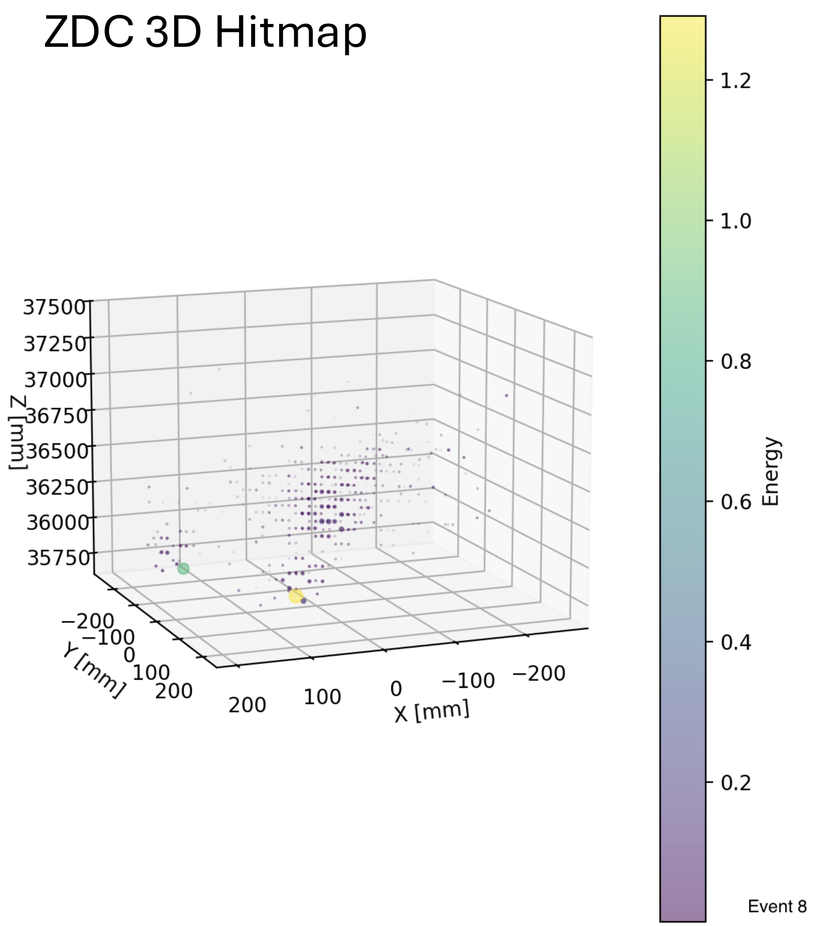


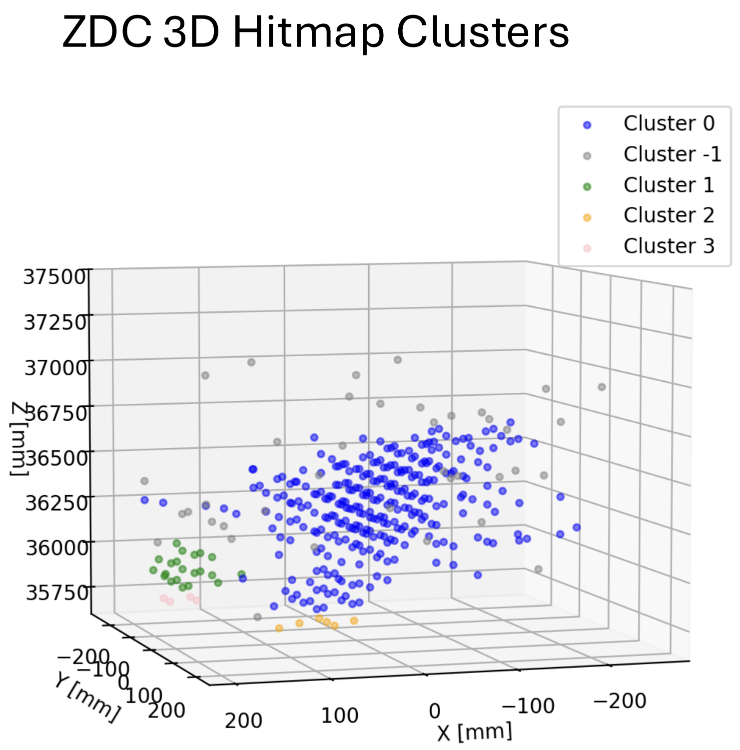
Neutron Sampling Fraction





DBSCAN Plots 4





DBSCAN Plots 5