Reconstructing Lambda Baryon decays with the ePIC Zero Degree Calorimeter (ZDC)

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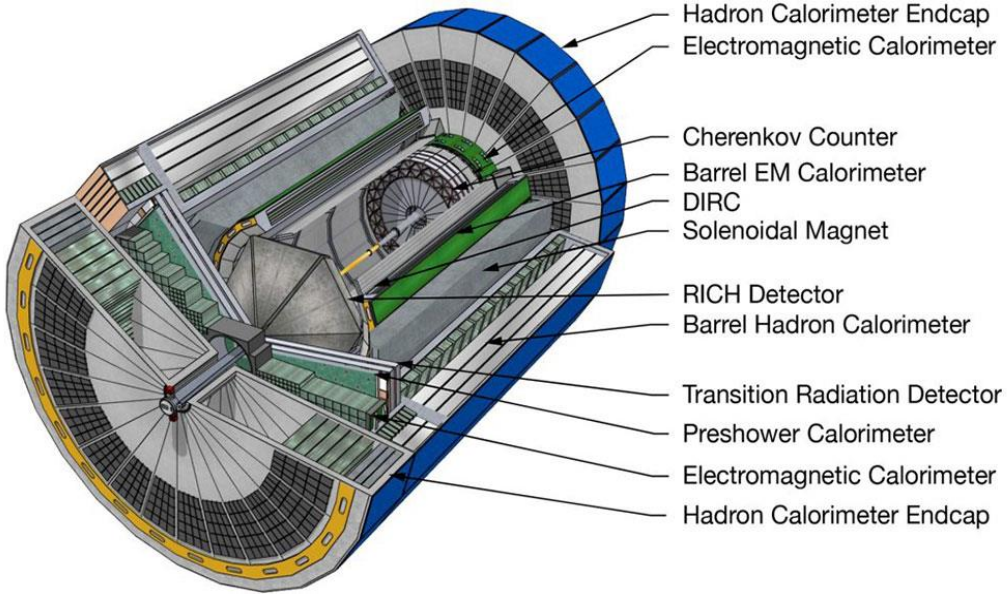
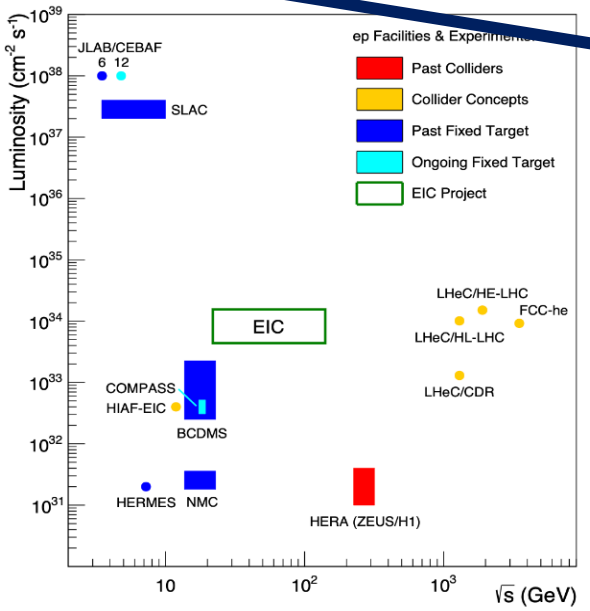
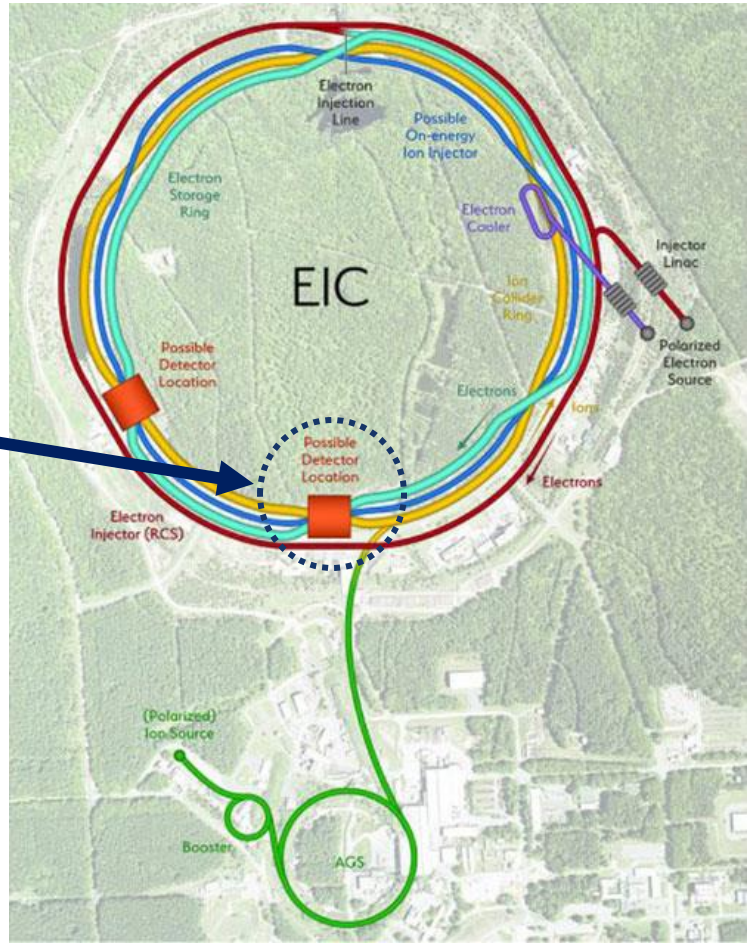
Electron-Proton/Ion Collider (ePIC) experiment at the Electron Ion Collider (EIC)

- Electron Ion Collider (EIC)
  - First high luminosity e-p collider
  - First polarized e-p collider
  - First electron-nucleus collider
- Electron-Proton/Ion Collider (ePIC) experiment will be the first EIC experiment
- ePIC detector will be installed at Interaction Point IP-6



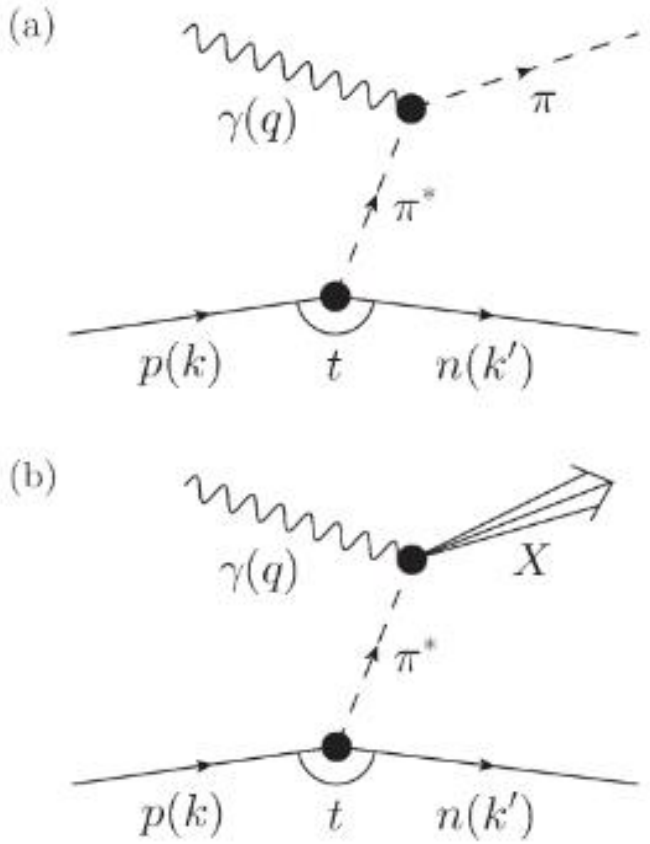




"The Electron-Ion Collider: A Precision Tool for Studying the 'Glue' That Binds Visible Matter." Brookhaven National Laboratory, March 4, 2022.

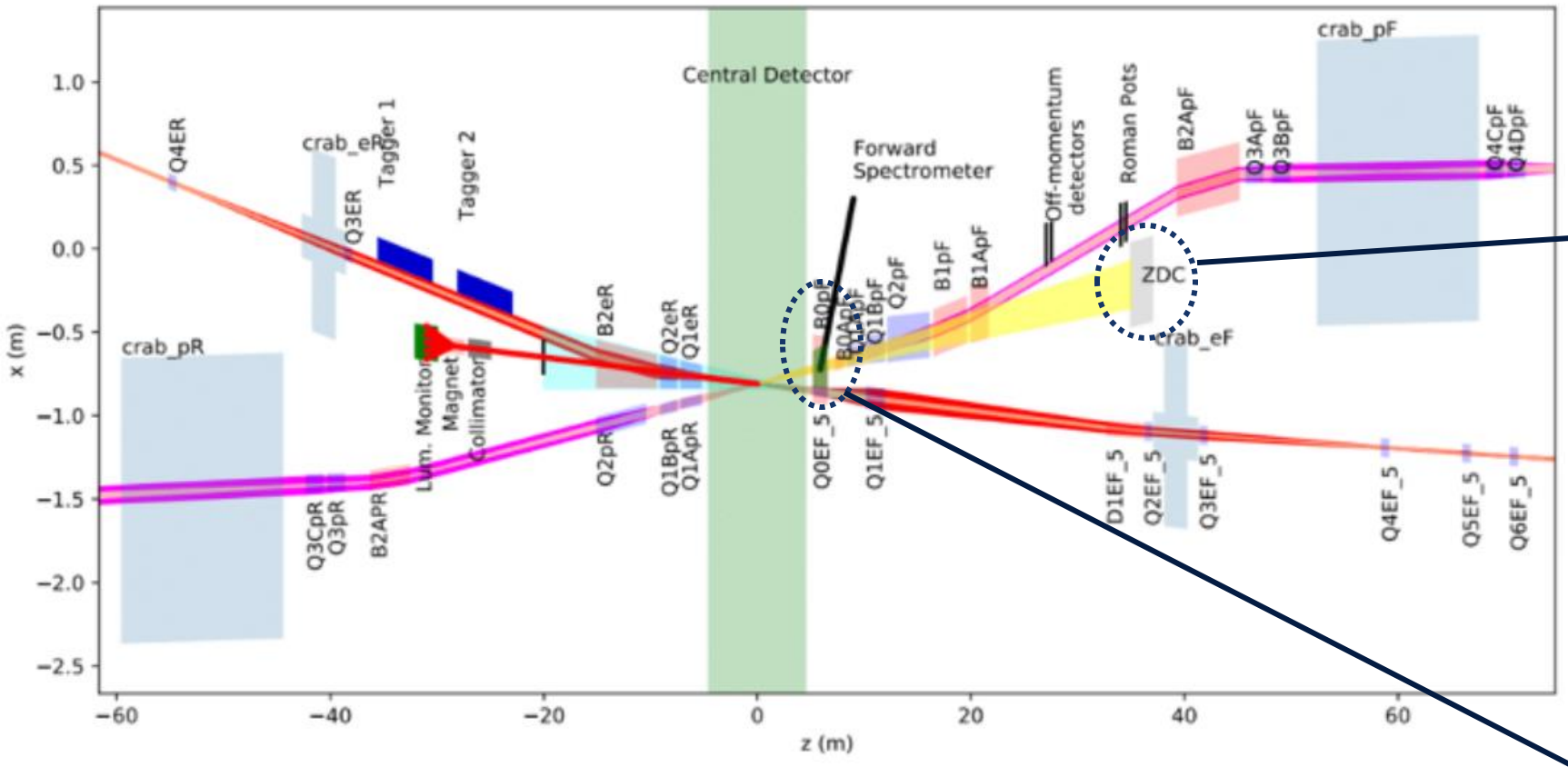
Meson Structure at the EIC: Sullivan Process

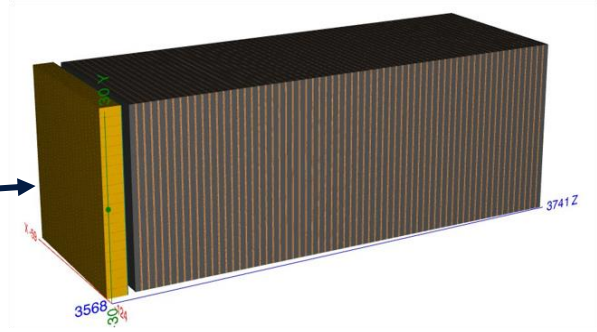
- One goal of the EIC is to study the structure of Pions and Kaons
- The Sullivan Process
  - virtual photon produced by the electron scatters from a virtual meson emitted from the proton
  - allows access to meson elastic form factors and parton distribution functions (PDFs)
  - example: pion form factor can be measured with ratios of positively- and negatively-charged pions in quasi-elastic electron-pion (off-shell) scattering
- When scattering from a virtual kaon, a neutral lambda is sent in the forward direction
- Meson pole dominance in the low t regime



Aguilar, Arlene C., Zafir Ahmed, Christine Aidala, Salina Ali, Vincent Andrieux, John Arrington, Adnan Bashir, et al. 'Pion and Kaon Structure at the Electron-Ion Collider'. *The European Physical Journal A* 55, no. 10 (October 2019).

Far Forward Neutral Particle detection with ePIC





Zero Degree Calorimeter (ZDC)

design source: EIC ePIC Geometry team

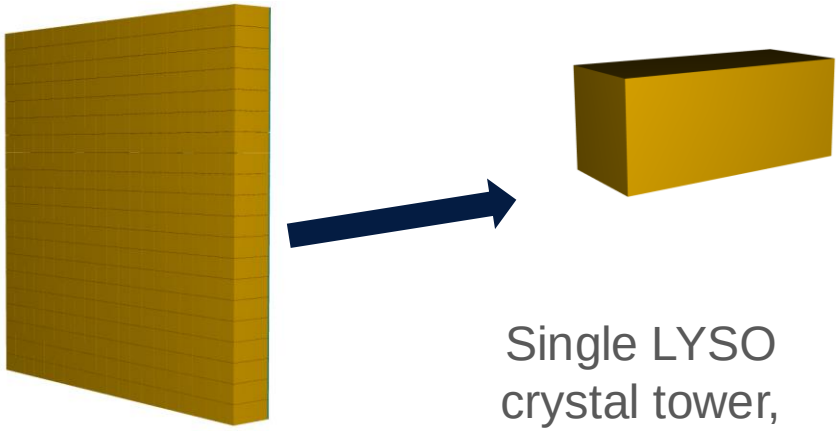
B0 magnet sweeps away charged particles

EIC IR layout

Abdul Khalek, R., A. Accardi, J. Adam, D. Adamiak, W. Akers, M. Albaladejo, A. Al-bataineh, et al. 'Science Requirements and Detector Concepts for the Electron-Ion Collider'. *Nuclear Physics A* 1026 (October 2022)

Zero Degree Calorimeter (ZDC) and Objectives

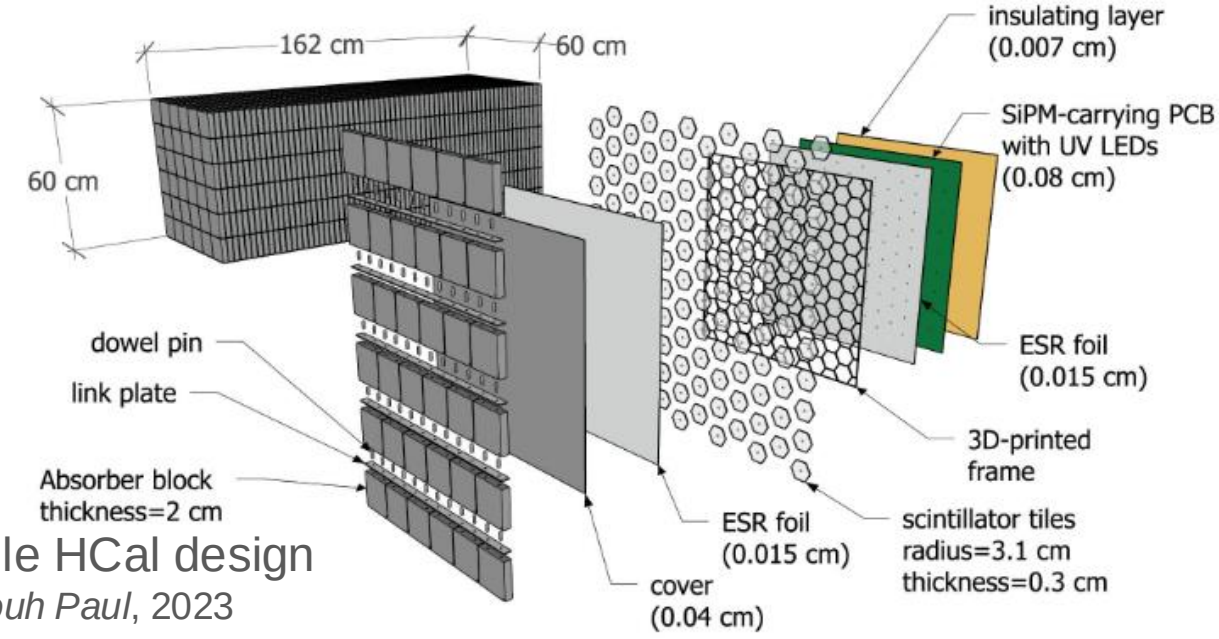
- Far Forward Neutral Particle detector
- Two components:
  - LYSO crystal EM calorimeter [for low energy photons]
  - SiPM on tile hadronic calorimeter [for energy and vertex reconstruction]
- The ZDC will have to reconstruct the lambda baryon's decay vertex from its neutral decay products: π^0 and neutron
- Our goal is to determine if the ZDC will have sufficient resolution in both energy and vertex reconstruction



Single LYSO crystal tower, 3x3x7 cm^3

LYSO crystal and readout

Design source: EIC ePIC Geometry Team



SiPM on tile HCal design

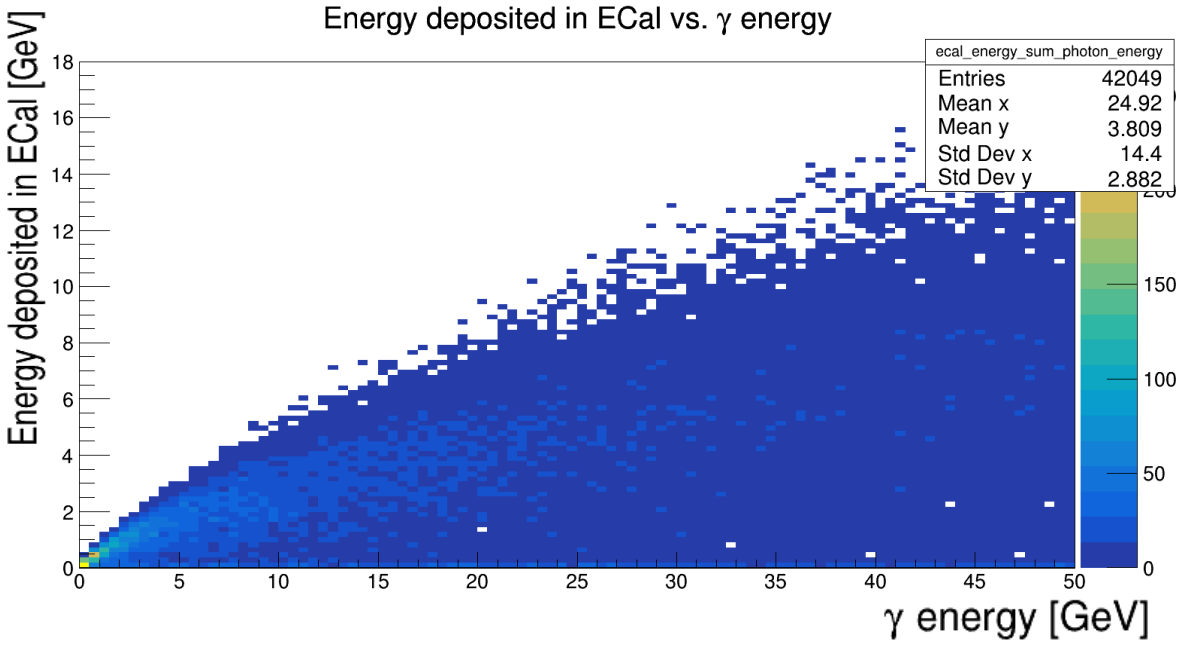
source: *Sebouh Paul*, 2023

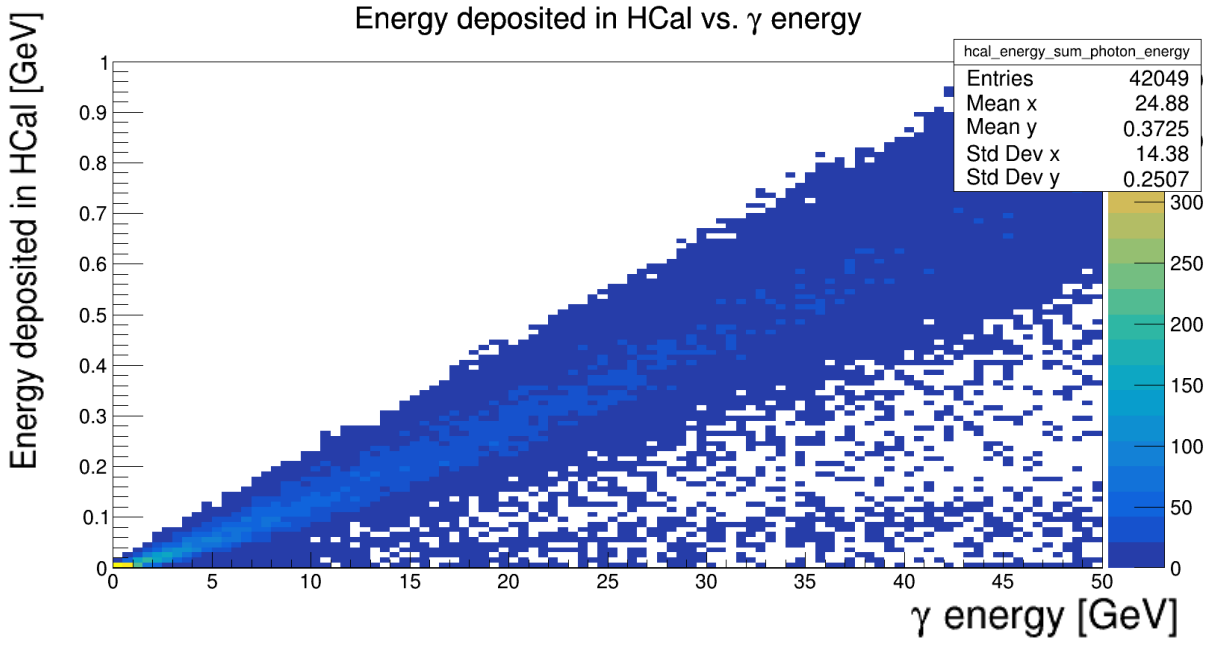
MC Simulation

- **MC Simulations**: Conducted with DD4sim, compiled with Geant4
- **Particle Gun Data**: Generated with variable angles to uniformly cover the ZDC face
- **No Background**: Simulations do not include background
- **Integrated Hits**: The hit data reflects the **integrated energy** deposited in the scintillating pads of the calorimeters, summed over the respective pad and reported at its center
- **ZDC with HCal-Only**: Separate MC data generated for ZDC HCal to study neutron and photon interactions specifically in the hadronic calorimeter
- **ZDC with ECal and HCal**: ZDC geometry in simulations has ECal and HCal
- **Lambda MC**: Energy range 0–270 GeV, with 200k events, decay table restricted to $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$
- **Photon MC**: Energy range 0–50 GeV, with 100k events
- **Neutron MC**: Energy range 50–250 GeV, with 60k events

Single Photon ECal and HCal energy ratio

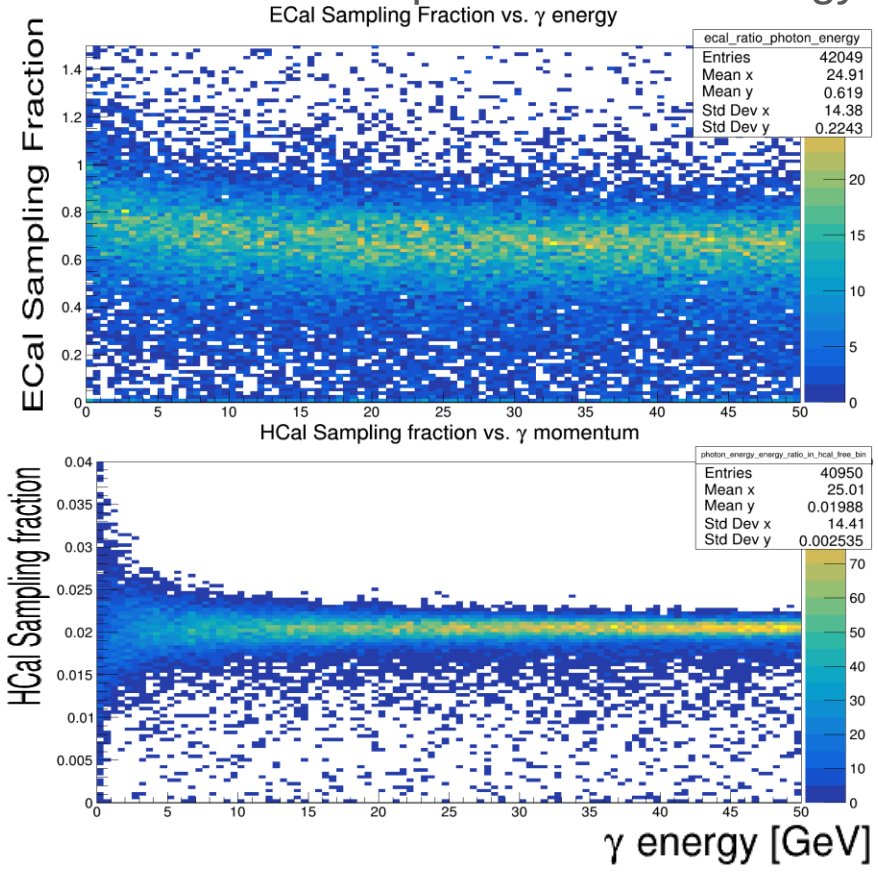
- ECal tiles are short, designed for low energy photons from nuclear breakup
- Most of the photon energy is deposited in ECal, but higher energy showers continue to propagate into the HCal
- Necessary to understand energy resolution for single photon for both calorimeters

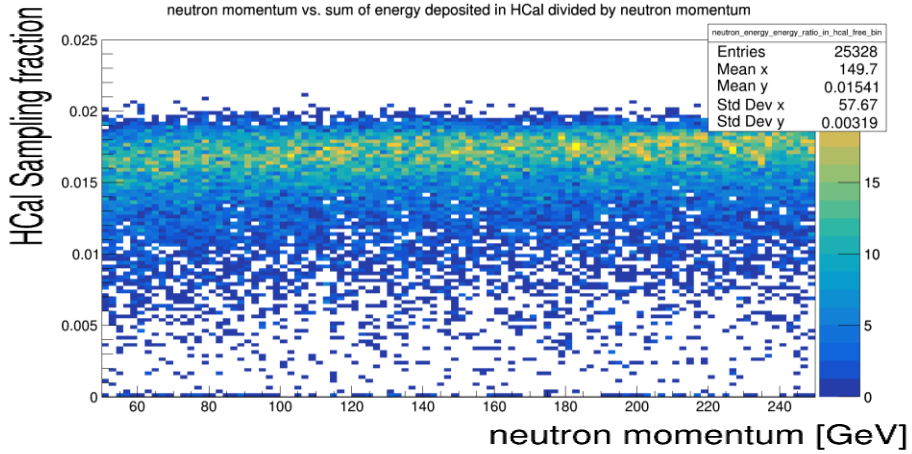




Method for Extracting Sampling Fraction and Energy Resolution

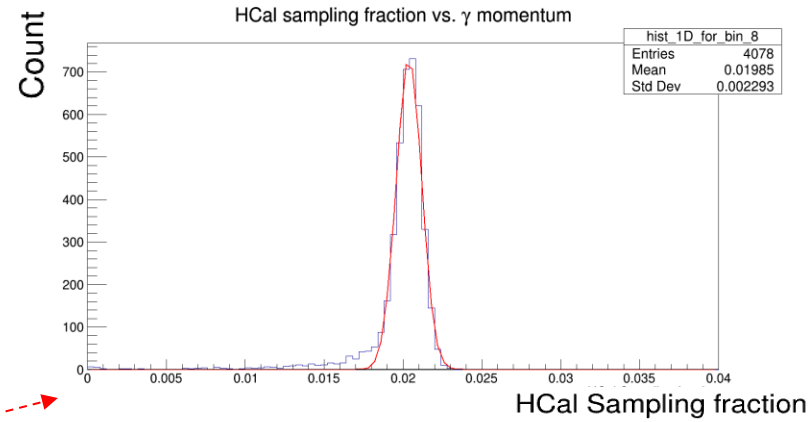
- **HCAL:** Using HCal-only simulation to estimate the HCal sampling fraction and energy resolution
  - fit the ratio of HCal energy deposit to true photon energy as a function of photon energy
- **ECAL:** Using entire ZDC simulation, subtract the HCal-reconstructed photon energy to calculate the photon energy loss in ECAL and compare to ECAL energy deposit

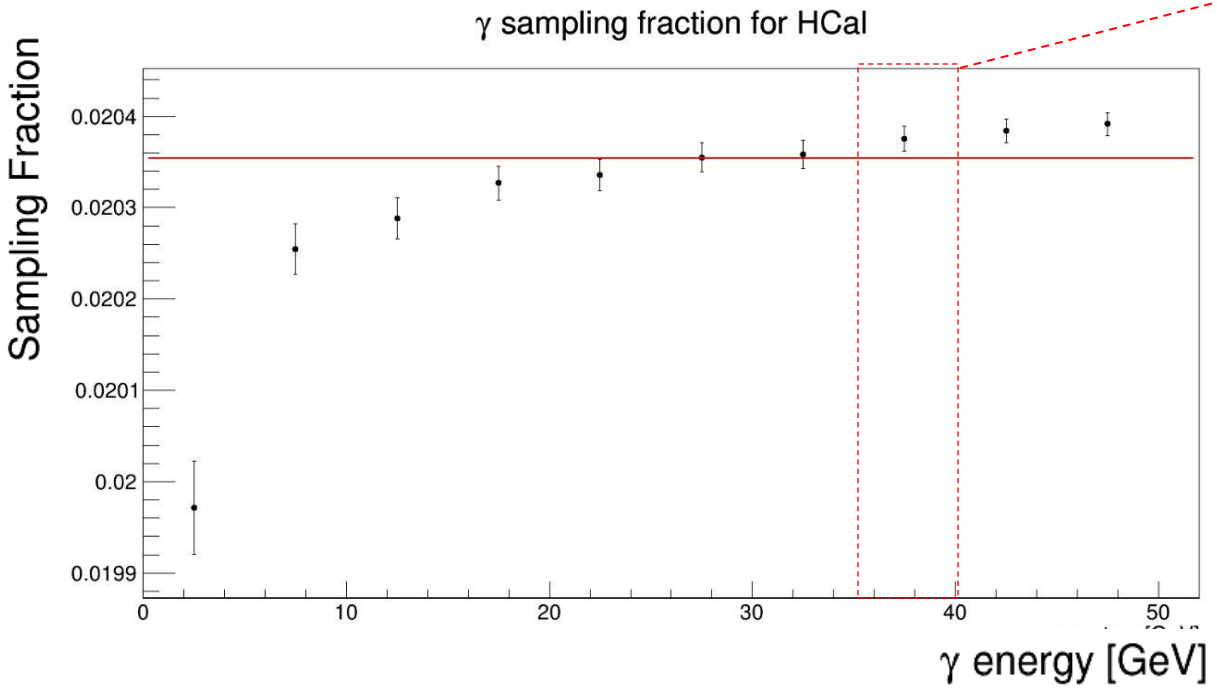


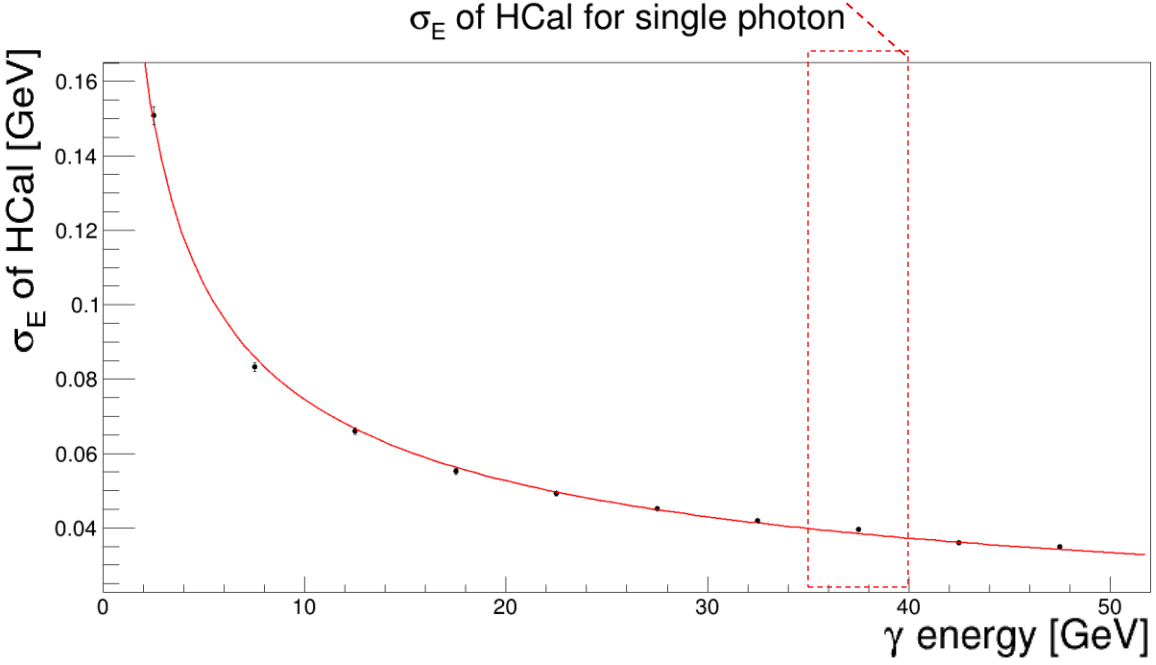


Single Photon Energy Resolution HCal

- HCal-only simulation data
- Sampling fraction is calculated as the ratio of HCal total energy deposit and photon energy
- Measure sampling fraction and energy resolution in 10 bins of photon energy from 0 GeV to 50 GeV
- Preliminary fits: we are still exploring the effect of angles and photon energy on sampling fraction and resolution
- Preliminary fits suggest an energy resolution of 24%/√E

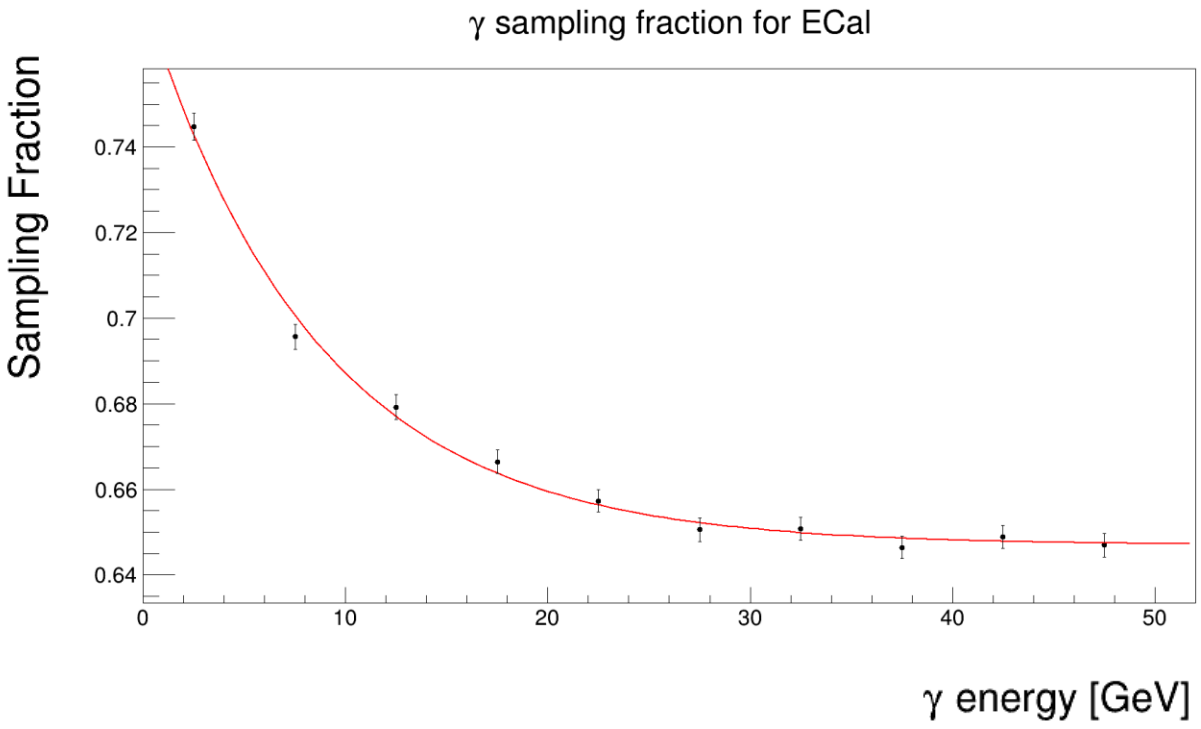


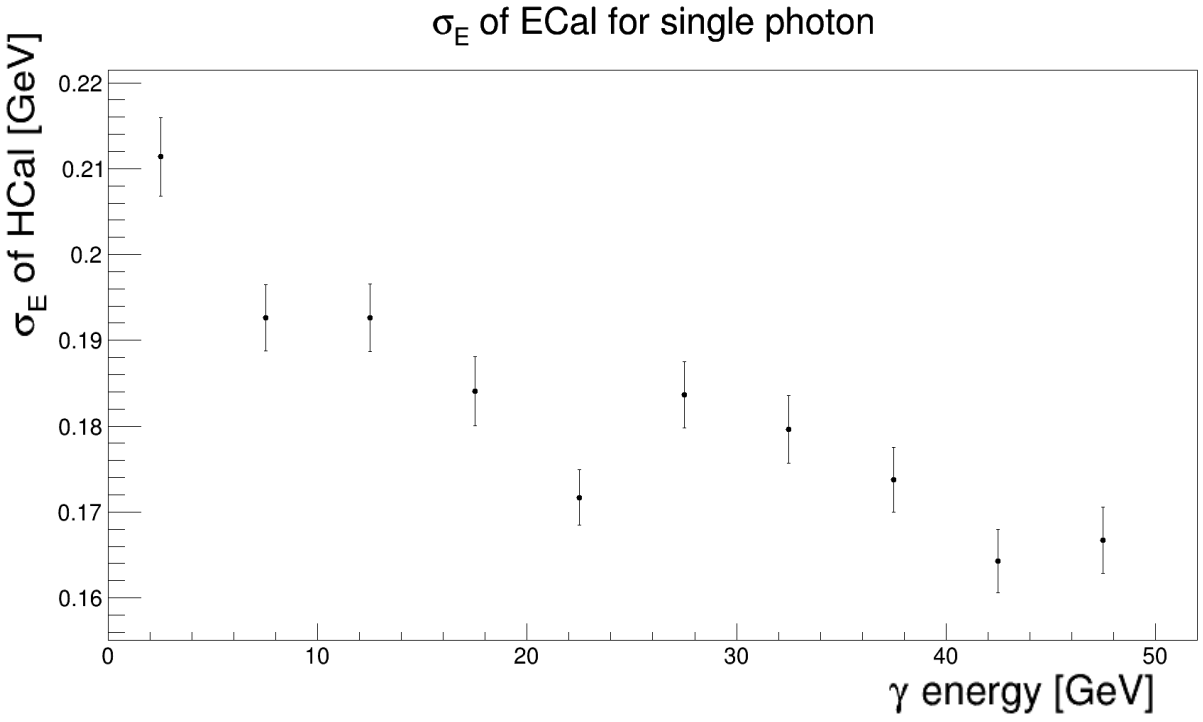




Single Photon Energy Resolution ECal

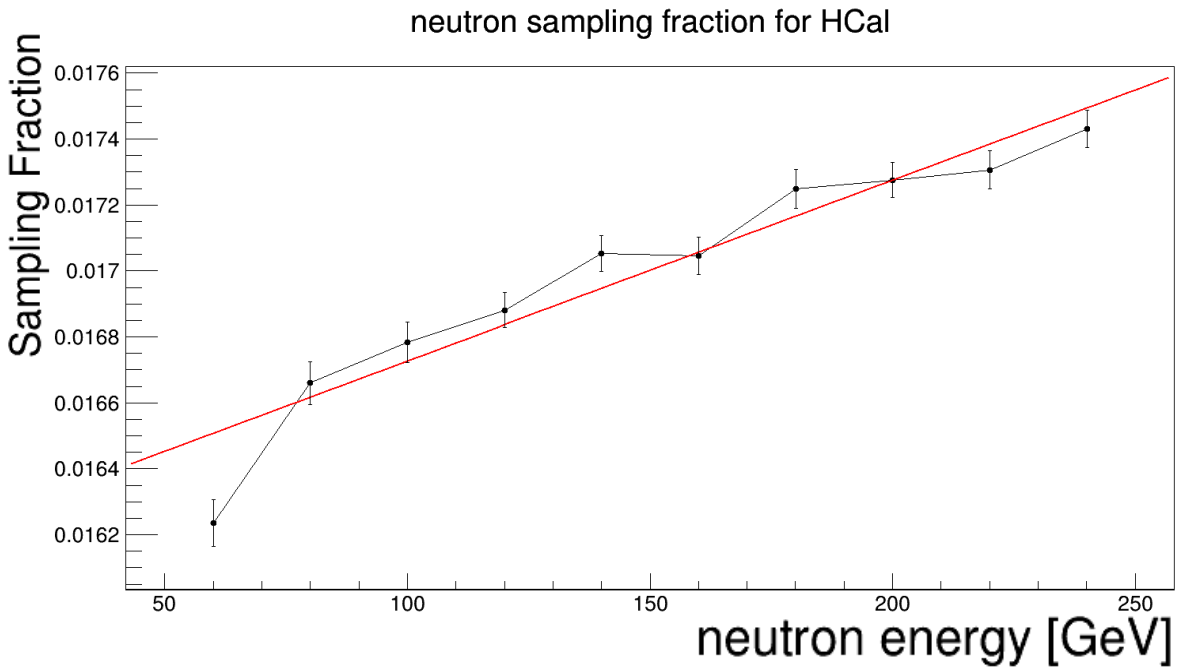
- ECal sampling fraction is calculated as a ratio of ECal energy deposit and photon energy loss in ECal as a function of photon energy
  - Photon energy loss in ECal is estimated by subtracting HCal reconstructed photon energy from true photon energy

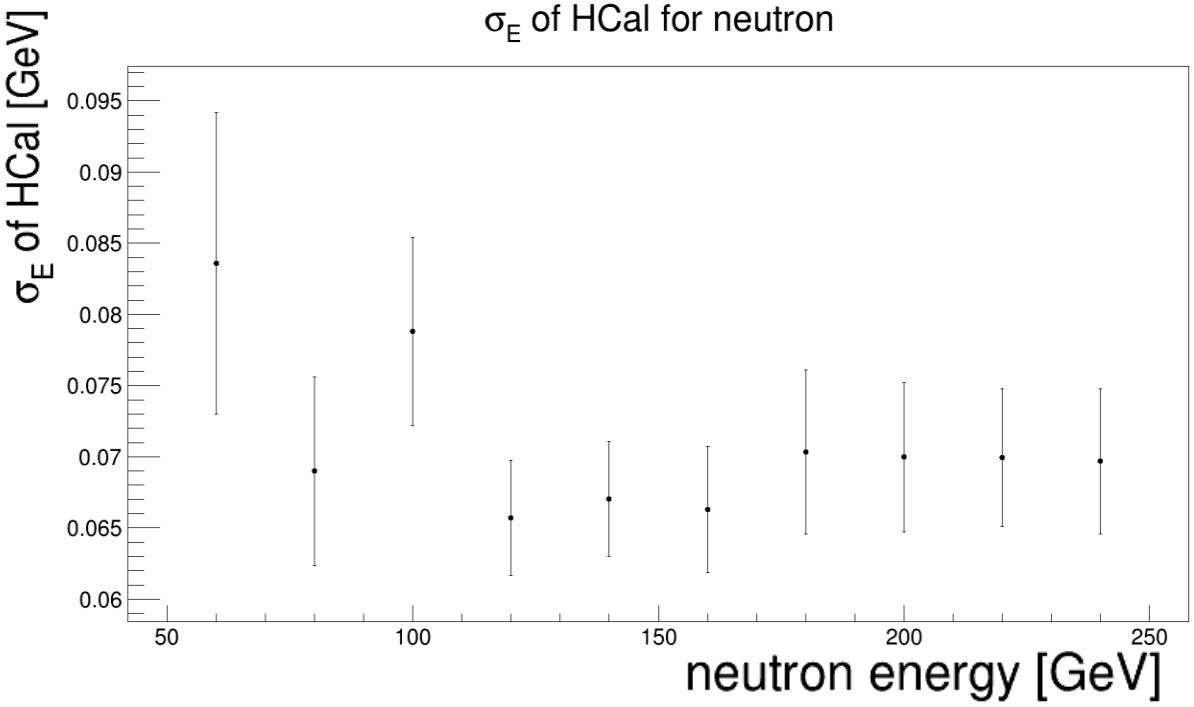




Single Neutron Energy Resolution HCal

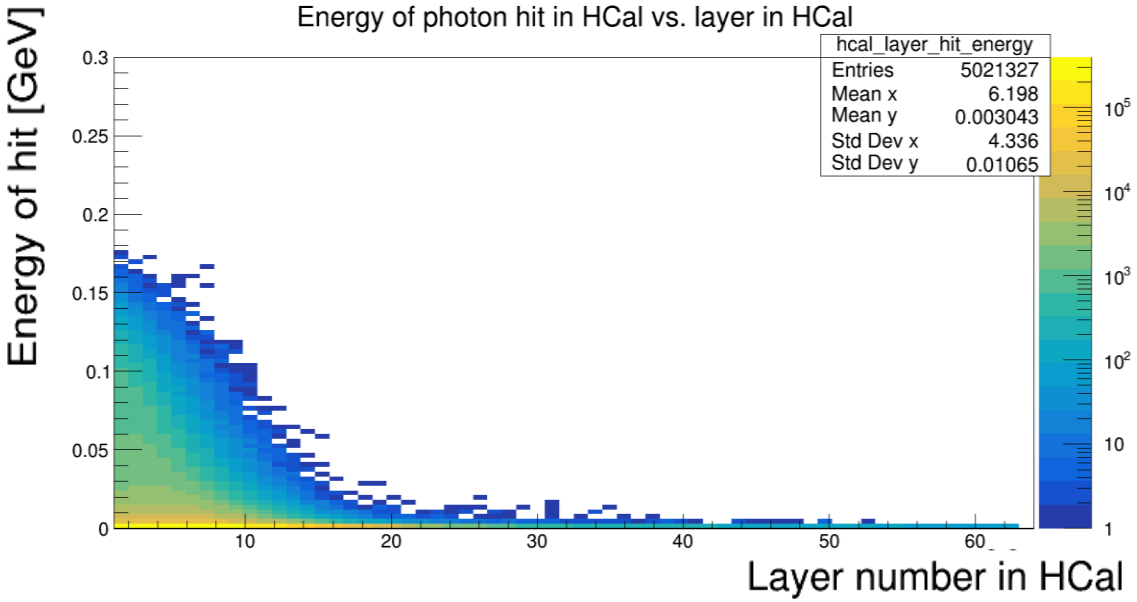
- HCal-only simulation data with single neutrons
- Calculated from ratio of total energy deposited in HCal and true neutron energy
- 10 bins of neutron energy

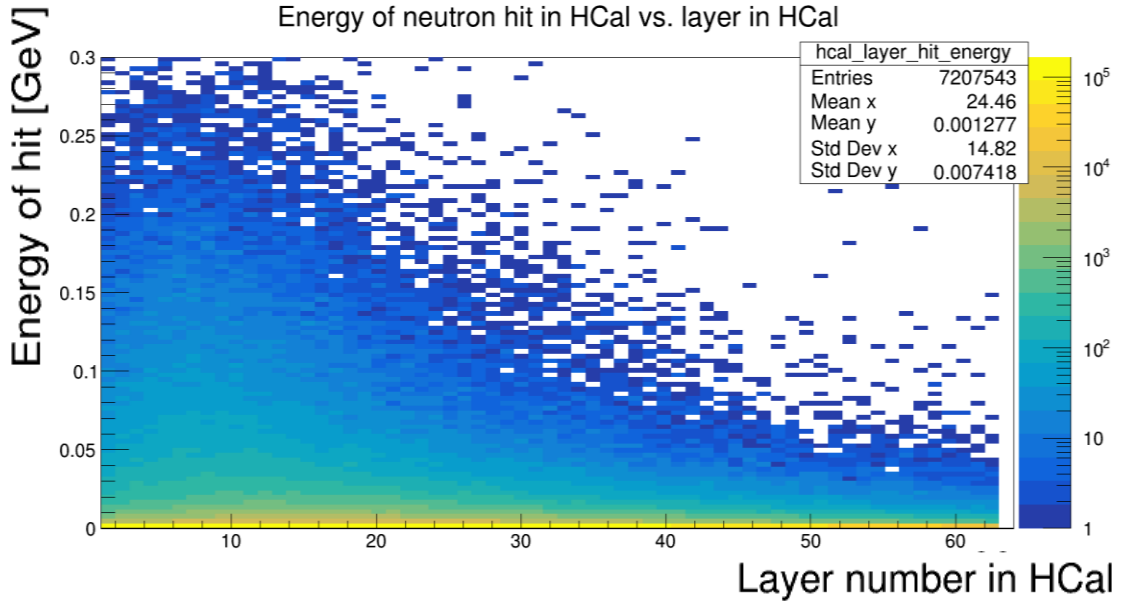




Energy Spread of Single Photon and Neutron in ZDC

- Besides partial energy loss in ECal, photons primarily produce showers in HCal
  - This allows us to reconstruct the photon track in addition to its energy
  - Tracks reconstructions are necessary to reconstruct the lambda vertex with ZDC
  - Photons lose most of their energy in the first 15-20 layers of HCal
- Neutron showers can happen in all HCal layers depending entirely on where it starts showering

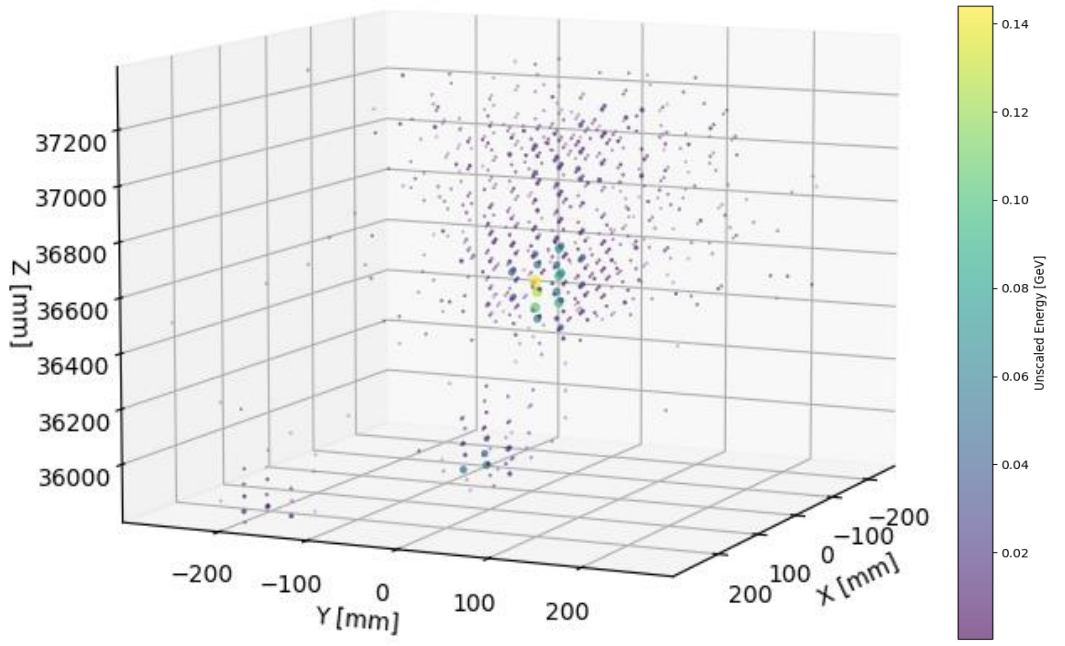




First Steps to extracting 4 momentum

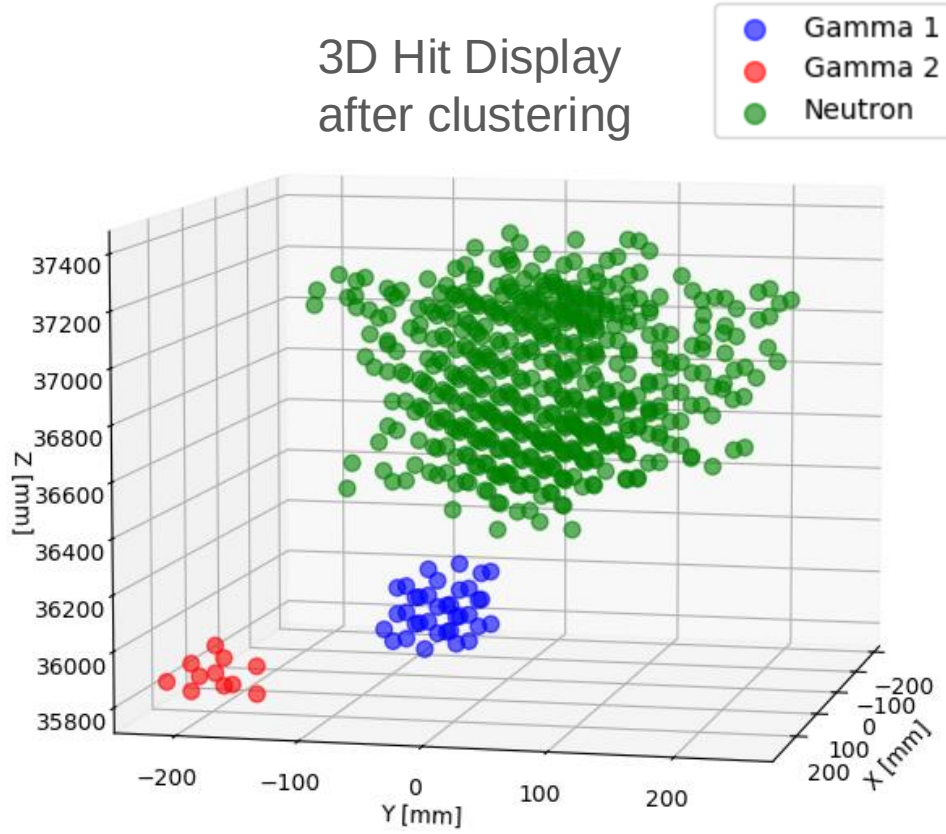
- To extract the 4 momentum, hits must be associated with particle tracks
- One approach is clustering:
  - grouping hits based on proximity and energy
  - resulting in clusters of hits that correspond to particle showers
- π^0 reconstruction begins here

3D Hit Display



Clustering Algorithm

3D Hit Display after clustering



Conclusion and Outlook

- At the Electron Ion Collider, one of the physics goals is studying meson structure
- To study kaon structure at EIC ePIC ZDC can be used to reconstruct the neutral lambda
- Studied single photon and neutron resolution in the ZDC
- Initial steps for clustering algorithm in the ZDC
- Next steps will be looking at the energy and 4 momentum resolutions of photons and neutrons from the lambda

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Extra

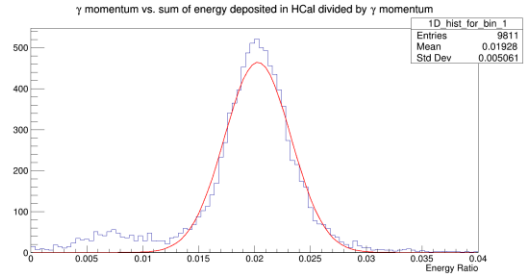
Objectives of this study

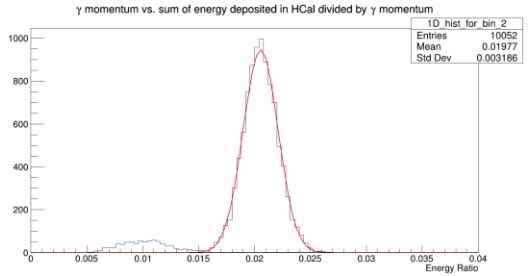
- The ZDC will have to reconstruct the lambda baryon's decay vertex from its neutral decay products: π^0 and neutron
- It is not clear if the current design of the ZDC will be able to do this
- Our study is to determine will the current configuration of the ZDC be able to do this with sufficient resolution
- We further narrow this to the best case scenerio for the ZDC

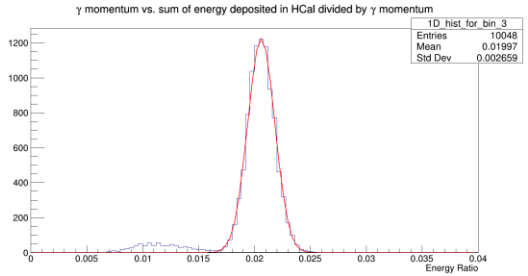
Peak Finding

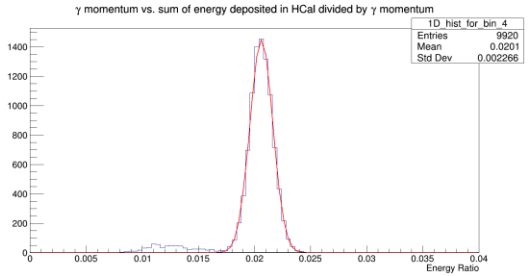
- A method of classifying events based on the distribution of energy in hits
- By establishing neighborhoods in hits, local energy maxima can be identified
- The location and number of energy maxima in ECal and HCal give critical information about the event such as:
  - Depth of neutron shower
  - Number of photons
- Matching peaks between ECal and HCal gives confidence in finding real particles
- Sensitive to energy imbalance between photons

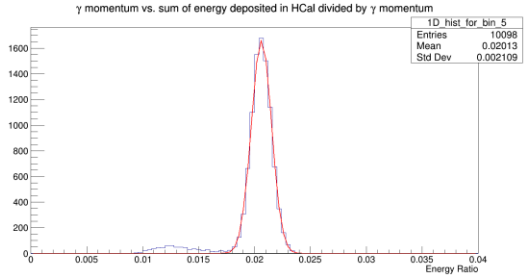
Individual Fits for single photon HCal sampling fraction

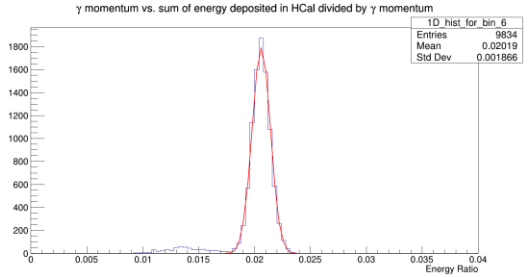


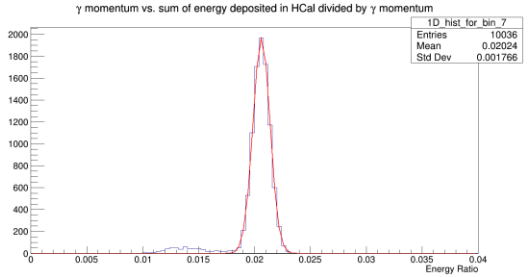


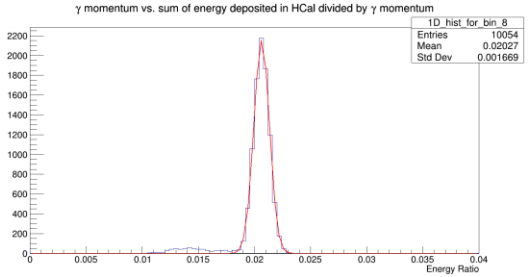


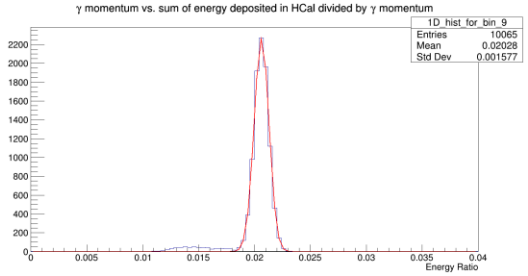


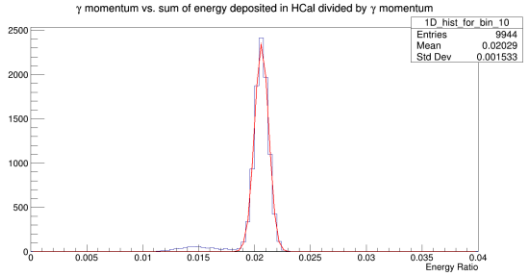




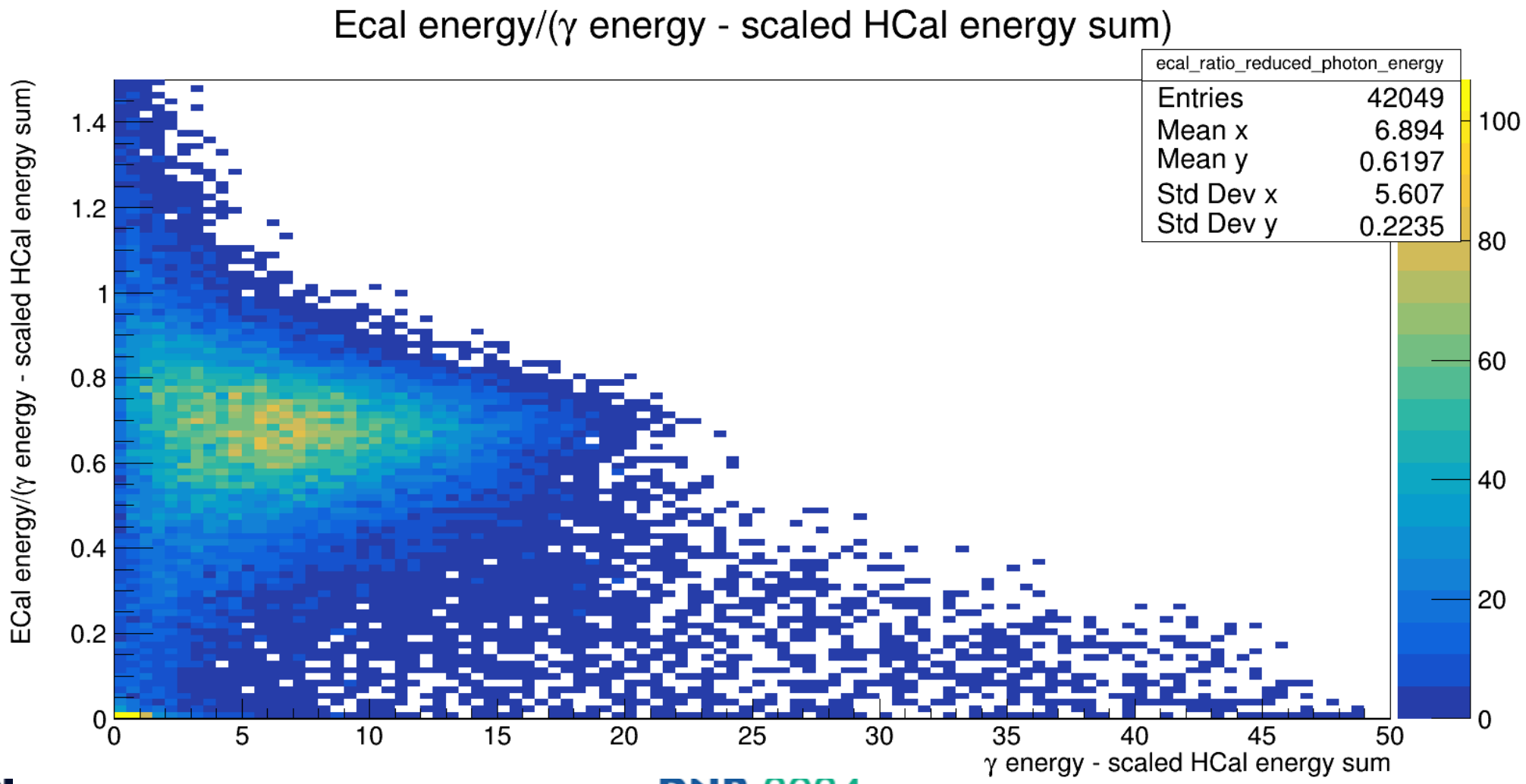








ECal Ratio vs reduced photon energy



Early Neutron Showers