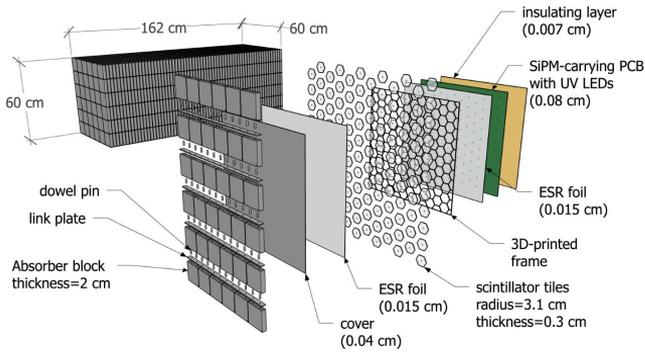
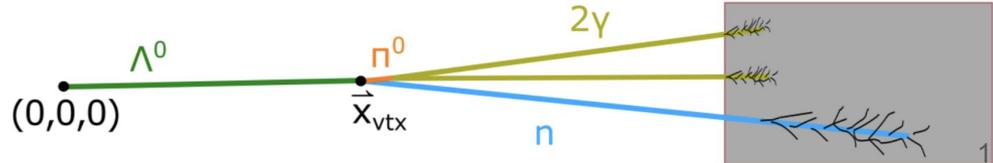


# Updates to Clustering in the Zero-Degree Calorimeter

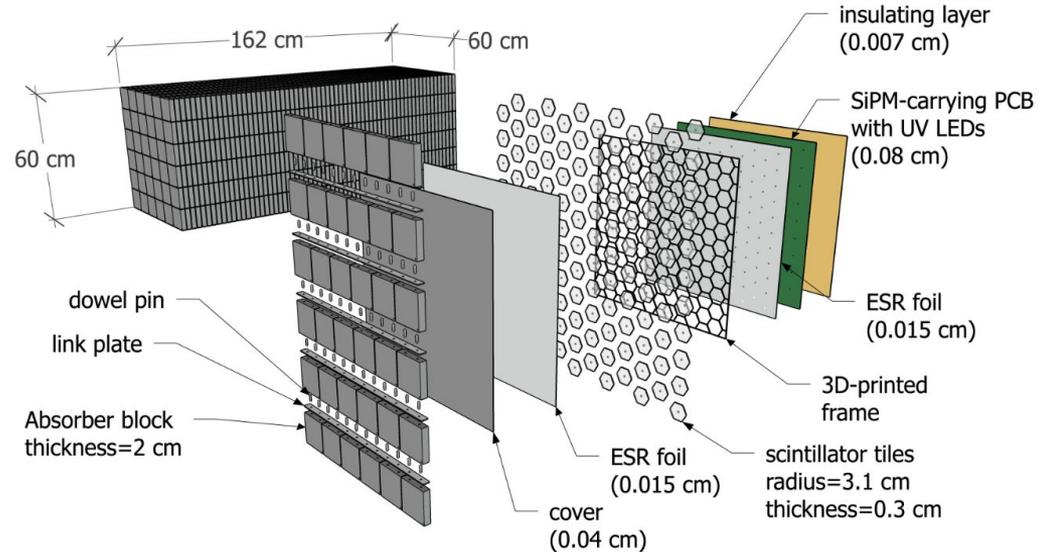


Dr Sebouh Paul  
 UC Riverside  
 1/26/2026



# Zero-Degree Calorimeter

- Located 36 m downstream of interaction point
- Detects photons and neutrons
- Sampling calorimeter with alternating Fe absorbers and scintillator tiles read-out with SiPMs
  - Used as both an ECAL and an HCAL



- Feasibility study for  $\Lambda$  reconstruction published last year in Phys Rev D.
- Lambda reconstruction algorithm added to the EICRecon\* package
- Detector benchmark\*\* incorporated into continuous integration for EIC software

\*<https://github.com/eic/EICrecon/blob/main/src/algorithm/reco/FarForwardLambdaReconstruction.cc>

\*\*[https://github.com/eic/detector\\_benchmarks/tree/master/benchmarks/zdc\\_lambda](https://github.com/eic/detector_benchmarks/tree/master/benchmarks/zdc_lambda)

### Feasibility study of measuring $\Lambda^0 \rightarrow n\pi^0$ using a high-granularity zero-degree calorimeter at the future electron-ion collider

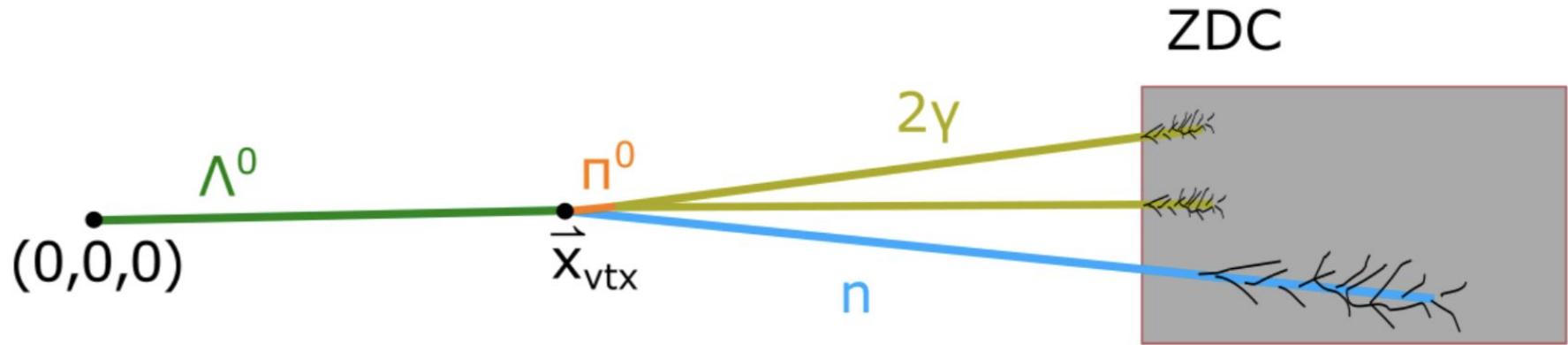
Sebouh J. Paul<sup>✉</sup>, Ryan Milton<sup>✉</sup>, Sebastián Morán, Barak Schmookler<sup>✉</sup>, and Miguel Arratia<sup>✉\*</sup>  
*Department of Physics and Astronomy, University of California, Riverside, California 92521, USA*

 (Received 26 March 2025; accepted 13 May 2025; published 27 May 2025)

Key measurements at the future electron-ion collider (EIC), including first-of-their-kind studies of kaon structure, require the detection of  $\Lambda^0$  at forward angles. We present a feasibility study of  $\Lambda^0 \rightarrow n\pi^0$  measurements using a high-granularity zero-degree calorimeter to be located about 35 m from the interaction point. We introduce a method to address the unprecedented challenge of identifying  $\Lambda^0$ s with energy  $O(100)$  GeV that produce displaced vertices of  $O(10)$  m. In addition, we present a reconstruction approach using graph neural networks. We find that the energy and angle resolution for  $\Lambda^0$  is similar to that for neutrons, both of which meet the requirements outlined in the EIC Yellow Report. Furthermore, we estimate performance for measuring the neutron's direction in the  $\Lambda^0$  rest frame, which reflects the  $\Lambda^0$  spin polarization. We estimate that the neutral-decay channel  $\Lambda^0 \rightarrow n\pi^0$  will greatly extend the measurable energy range for the charged-decay channel  $\Lambda^0 \rightarrow p\pi^-$ , which is limited by the location of small-angle trackers and the accelerator magnets. This work paves the way for EIC studies of kaon structure and spin phenomena.

DOI: 10.1103/q7w9-sbsc

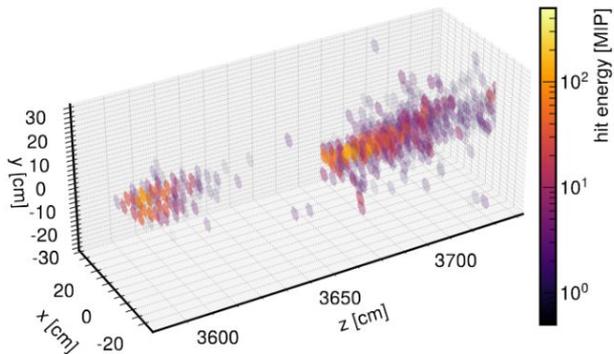
# Event topology



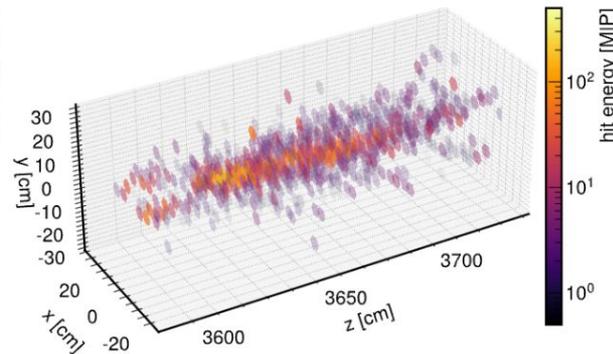
36 m downstream of IP

# Example events

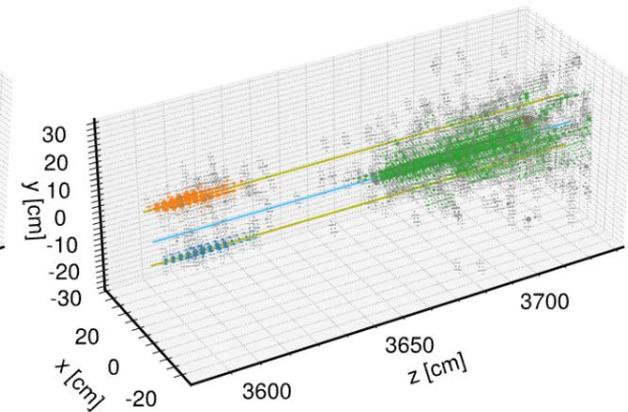
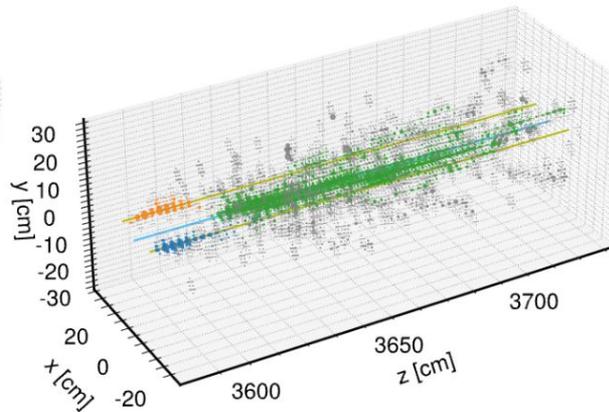
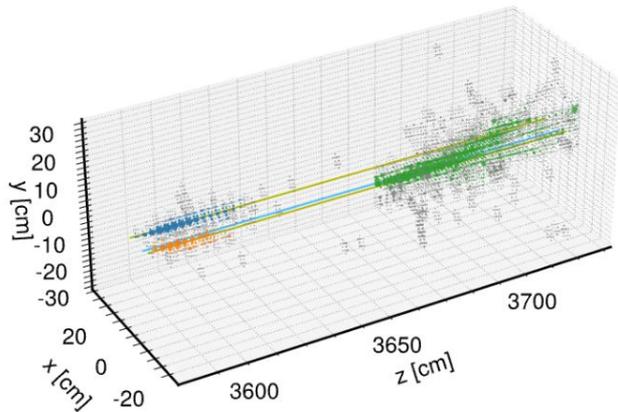
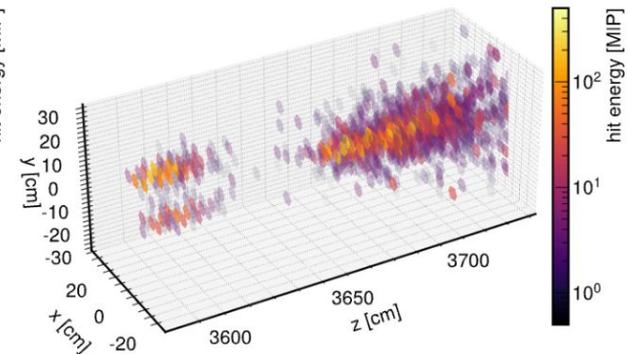
$E_{\Lambda^0} = 103 \text{ GeV}$ ,  $\theta_{\Lambda^0} = 0.6 \text{ mrad}$ ,  $z_{\text{vtx}} = 25.5 \text{ m}$



$E_{\Lambda^0} = 152 \text{ GeV}$ ,  $\theta_{\Lambda^0} = 1.1 \text{ mrad}$ ,  $z_{\text{vtx}} = 27.1 \text{ m}$



$E_{\Lambda^0} = 248 \text{ GeV}$ ,  $\theta_{\Lambda^0} = 1.1 \text{ mrad}$ ,  $z_{\text{vtx}} = 12.4 \text{ m}$



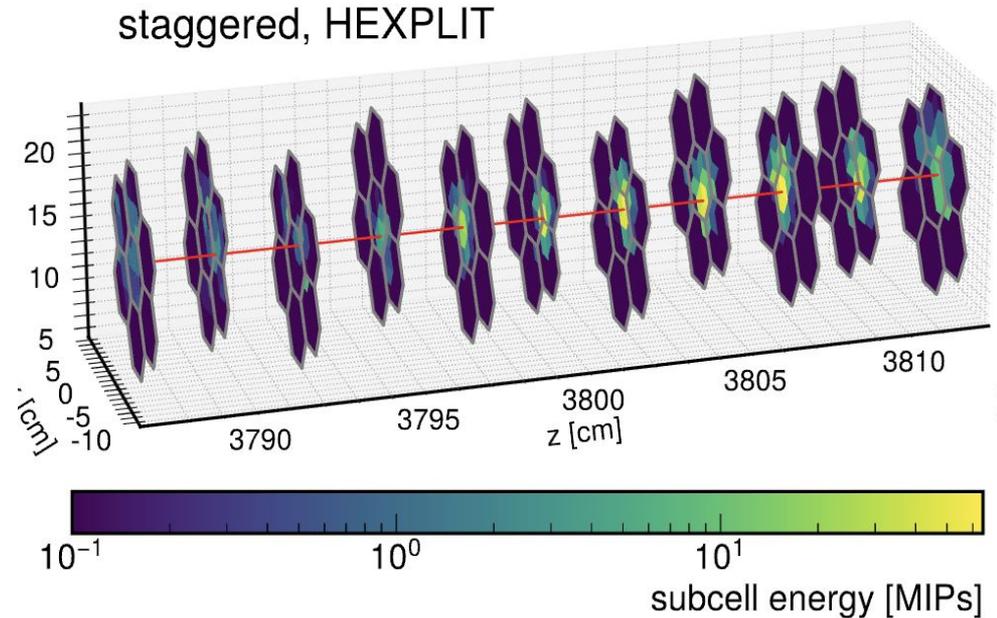
# HEXPLIT algorithm\*

- Takes advantage of overlapping cells\*\*
- Redistributes energy within a given hit into “subcell hits” in regions defined by overlap between cells.
- Feeds into the clustering algorithm

<https://github.com/eic/EICrecon/blob/main/src/algorithms/calorimetry/HEXPLIT.cc>

<https://github.com/AIDASoft/DD4hep/blob/master/DDCore/src/segmentations/HexGrid.cpp>

<https://doi.org/10.1016/j.nima.2023.169044>



# Topological clustering

Using pre-existing ImagingTopoClustering algorithm implemented by Chao Peng.

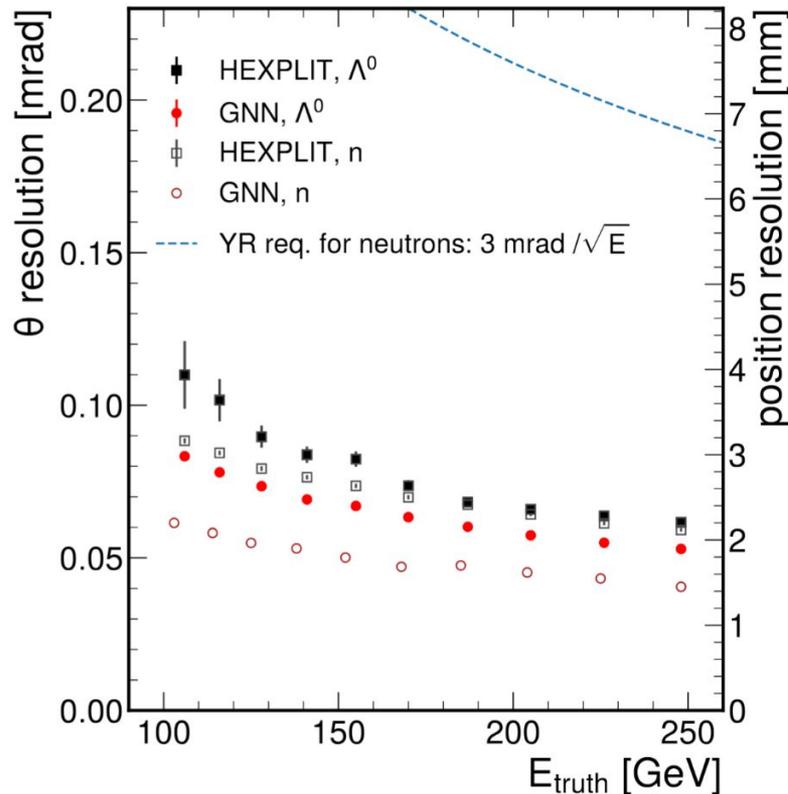
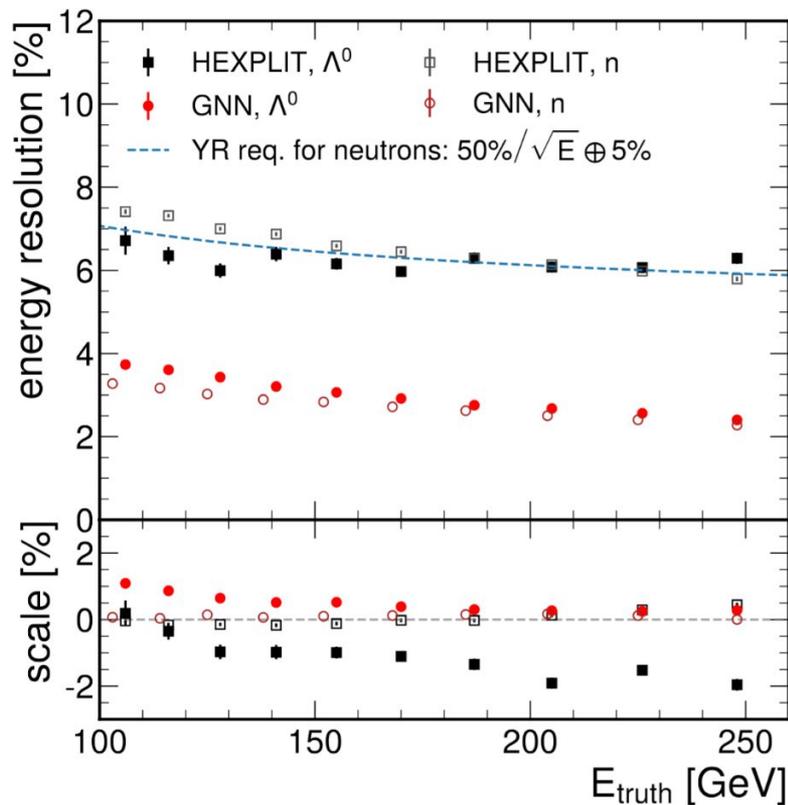
Starts with a definition of a neighbor:

- Same or adjacent layer,  $\Delta x$  and  $\Delta y$  cuts

Algorithm:

- 3 thresholds are defined for cell energy:  $S$  for seeding proto-clusters,  $N$  for growth of proto-clusters, and  $P$  for the minimum energy of any hit included
  - Currently in the ePIC code,  $S=N$  (though a case can be made to change this)
- Define seed hits for proto-clusters as those above threshold  $S$ , and include their neighboring hits in the proto-clusters that are above threshold  $P$
- For any hit with energy greater than  $N$ , include all of that hit's neighbors above  $P$ . (and merge if it has neighbors in more than one proto-cluster)

# Energy and polar angles reconstructed for $\Lambda$ better than YR requirements for neutrons

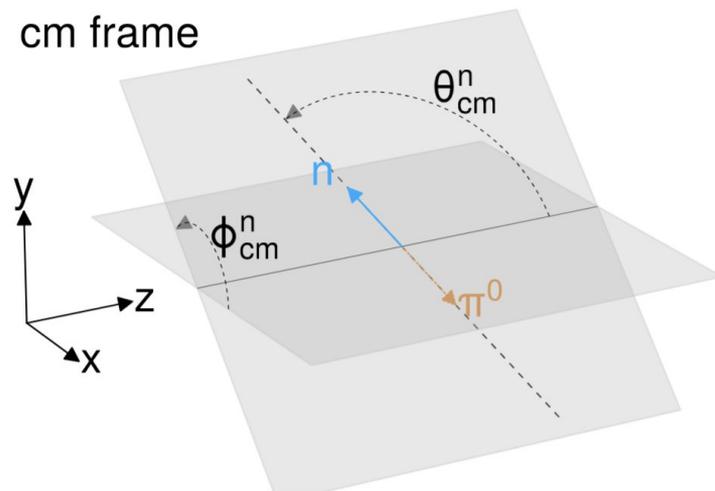
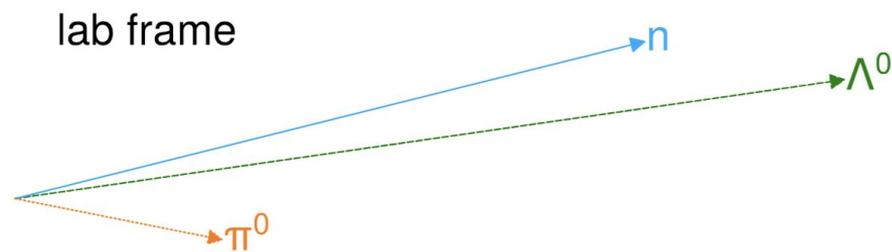


# Polarization measurements

Polarization is related to the direction of the neutron in the CM frame

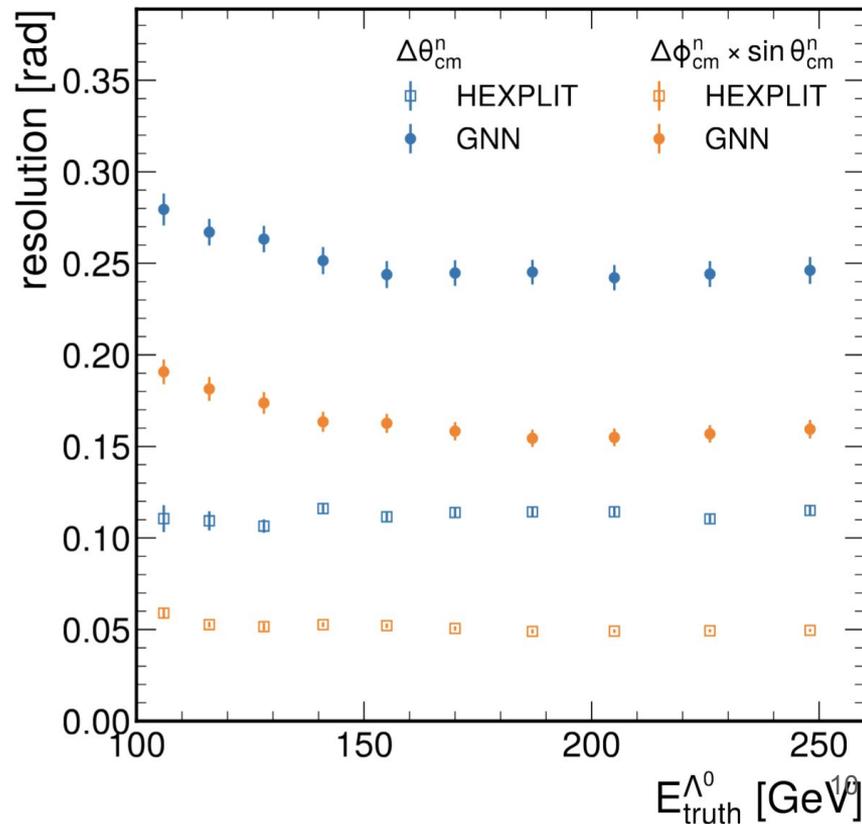
$$\frac{dP}{d\Omega_n} = 1 + \alpha \vec{\mathcal{P}}_{\text{cm}}^{\Lambda^0} \cdot \hat{p}_{\text{cm}}^n$$

$\alpha=0.74\pm 0.05$  from PDG



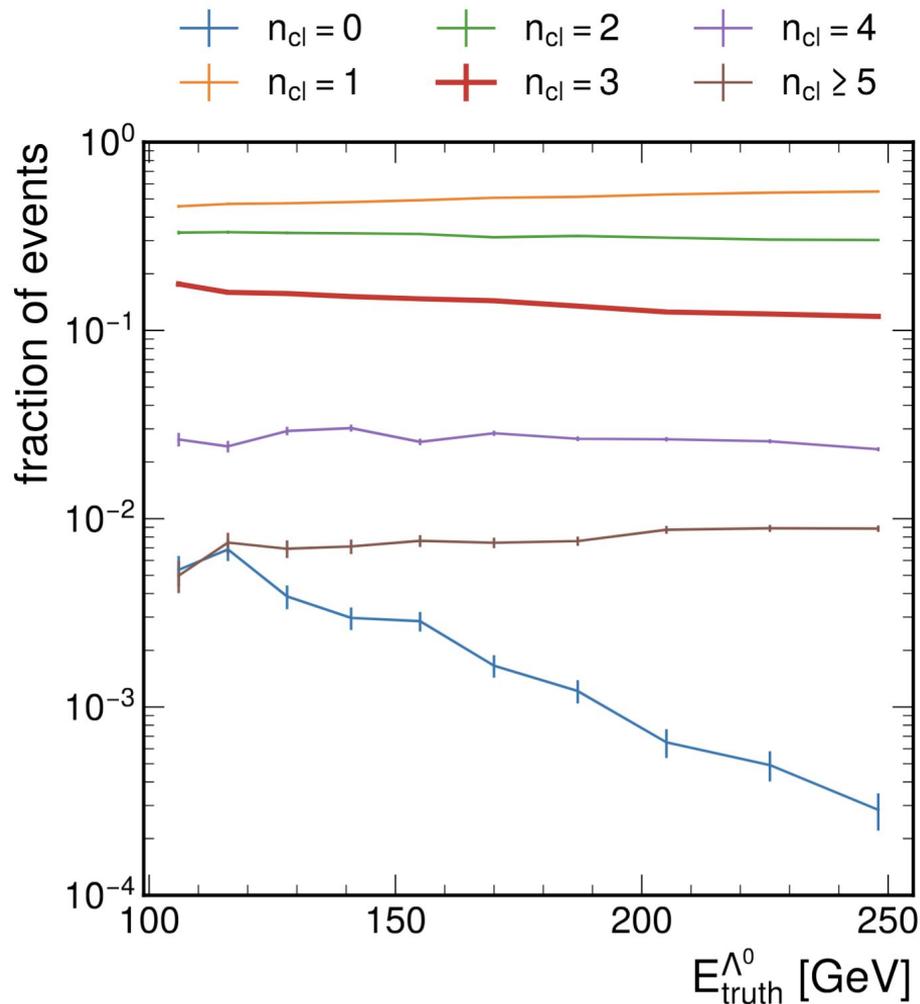
# Neutron-axis resolution

- Determined using Gaussian fits to  $\Delta\theta_{\text{cm}}^n$  and  $\Delta\phi_{\text{cm}}^n \times \sin\theta_{\text{cm}}^n$  distributions
- Conventional method (HEXPLIT combined with IDOLA) outperforms the AI/ML (GNN) method:
  - This could be due to the conventional method requiring a more picky selection of events in which the showers are well-separated, which the AI/ML doesn't do.



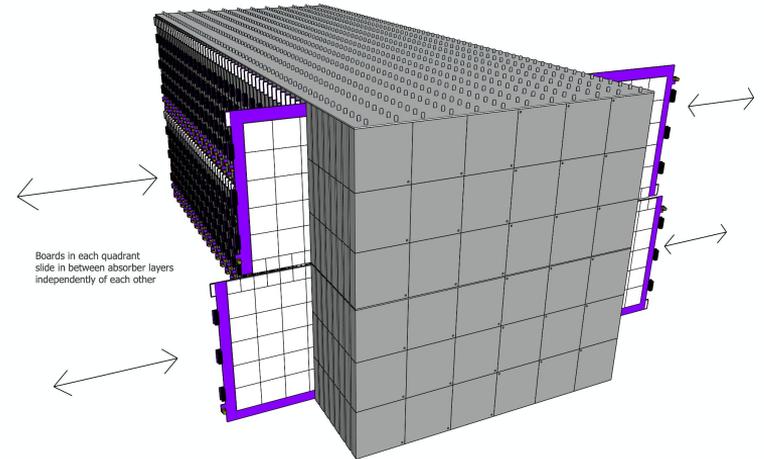
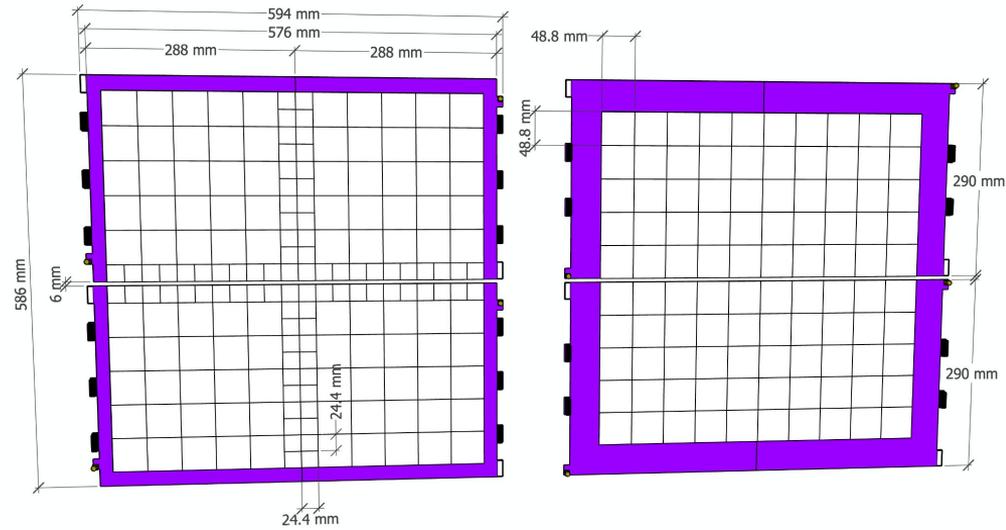
# What is the problem?

- Conventional recon has low efficiency for multi-particle events
  - Should have 3 clusters per event, usually find one or two.
- Too frequently the showers from different particles were merged together
- This is even worse when trying to reconstruct  $\Sigma^0 \rightarrow \Lambda^0 \gamma \rightarrow n \gamma \gamma \gamma$  (four clusters expected)



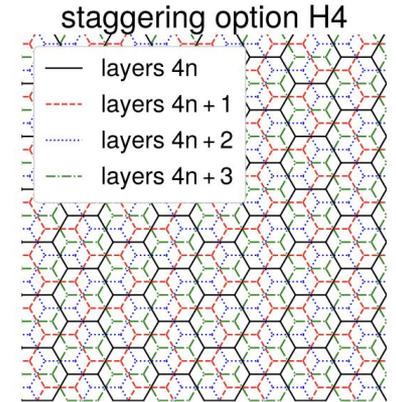
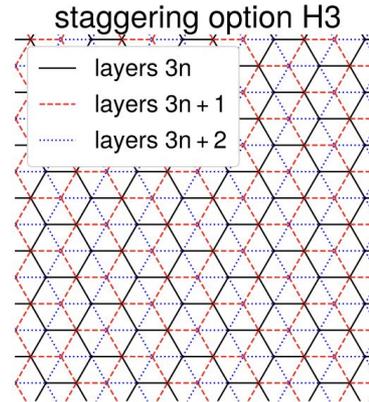
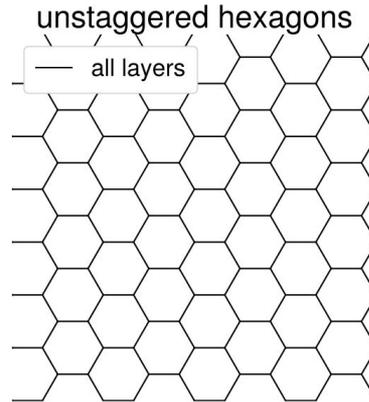
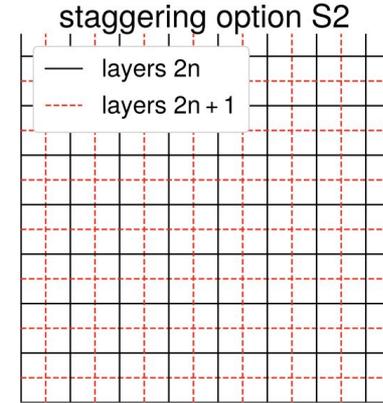
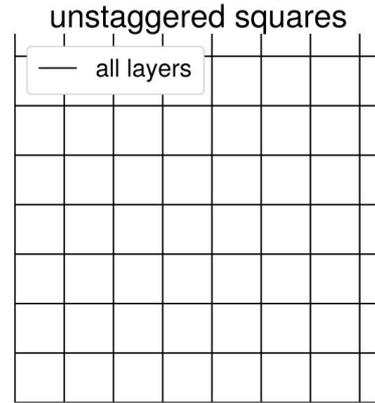
# Additional factor to consider

- Cell layout with squares instead of hexagons
  - Allows the detector to be designed in quadrants without deadspace between them
- Adapted HEXPLIT algorithm to use staggered squares (S2) instead of staggered hexagons (H4)



# Hexagons versus squares

A smaller effective cell size can be achieved with staggered hexagons than with staggered squares.



# Where do we start?

- First we need to reestablish the baseline with the square cells:
  - Subcell hits are considered neighbors if they are orthogonally adjacent or diagonally adjacent, and on the same or adjacent layers.
  - Keep the same thresholds for hit retention and seeding as before
  - Minimum number of hits should be 10, instead of 30 (since there are 3 fewer subcells)
- Then we establish the following as our metrics for the clustering
  - Reconstruct energy and theta for single- $\gamma$  and single-n MC events using the same conventional methods as before.
    - Check that these produces energy and theta resolution results consistent with published results for the ZDC\*
  - For double- $\gamma$  MC events, we want to see what percent of events have the two clusters merged together, as a function of the separation between the two showers

\*Milton et al, <https://doi.org/10.1016/j.nima.2025.170613>

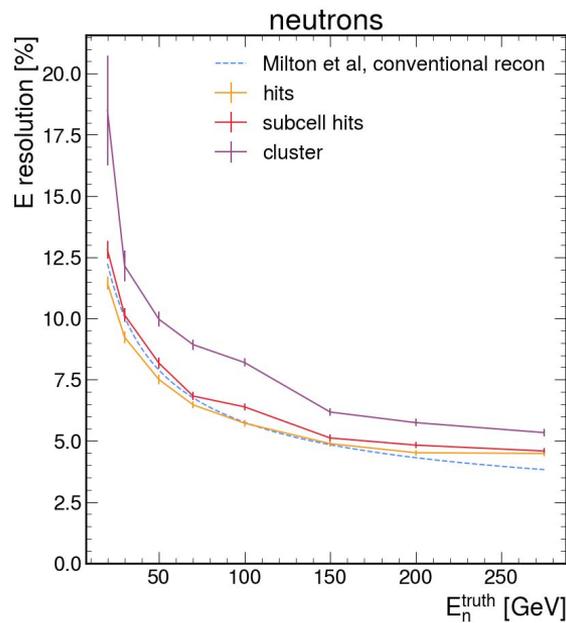
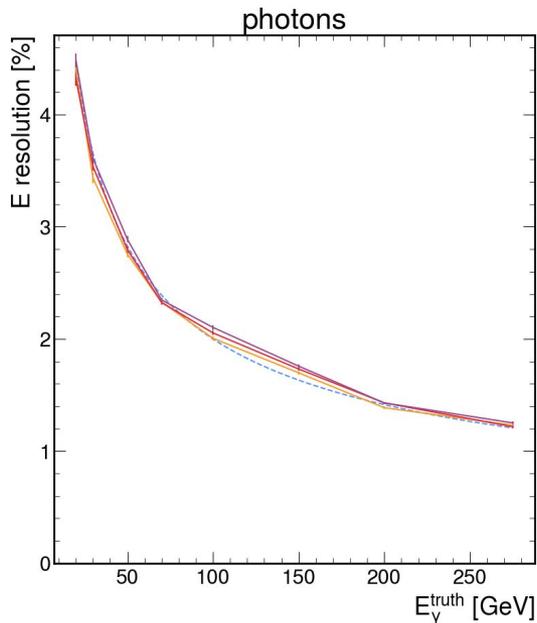
# Energy resolution

3 conventional algorithms are considered to see where energy is being lost:

- sum of hit energies /SF
- Sum of subcell hit energies/SF
- Sum of cluster energies/SF

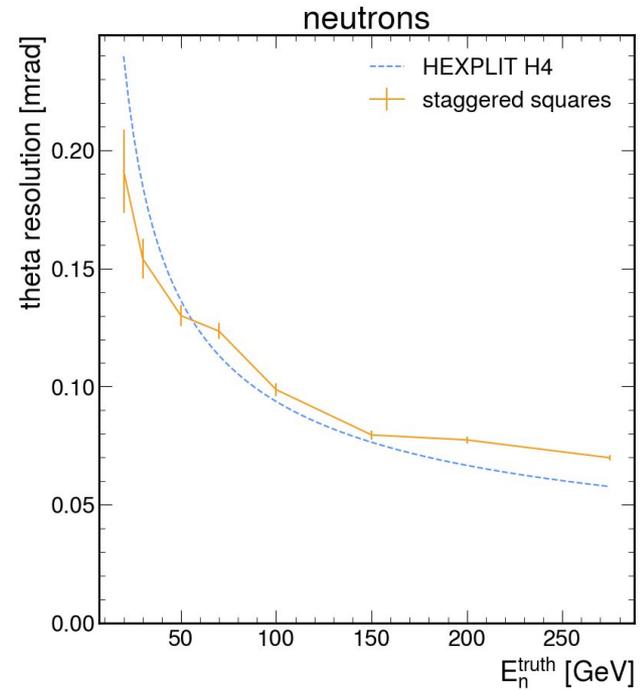
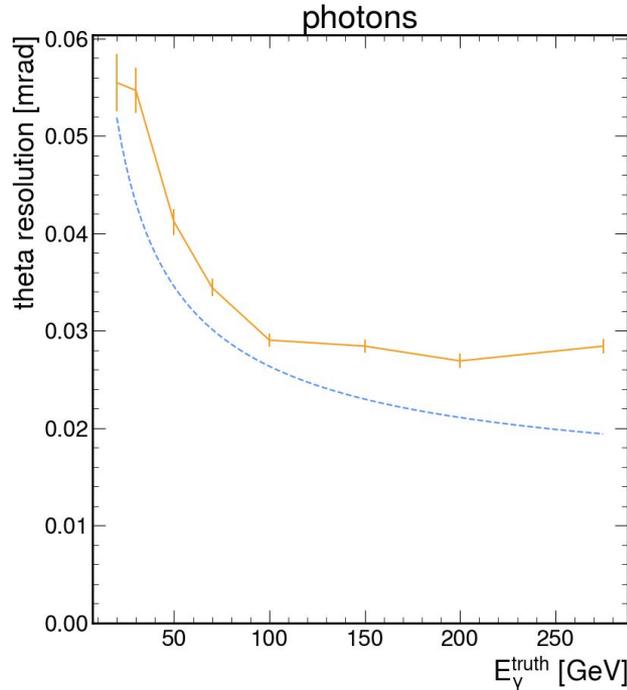
Loss of energy resolution due to not including all hits is negligible for photons

Neutron energy recon is worse due to energy lost by not including all (subcell) hits in the energy reconstruction



# Theta resolution

- Used a log-weighted CoG algorithm for cluster position determination
  - This requires fine-tuning based on further studies
- Shower position is reconstructed as the cluster position of the highest energy cluster in the event
- $\Theta$  resolutions are slightly worse for photons with the square cells than our earlier results with hexagon cells
  - Seems to be reaching a limit to what we can achieve with square tiles (S2 pattern) instead of hexagons (H4 pattern)



# Cluster merging

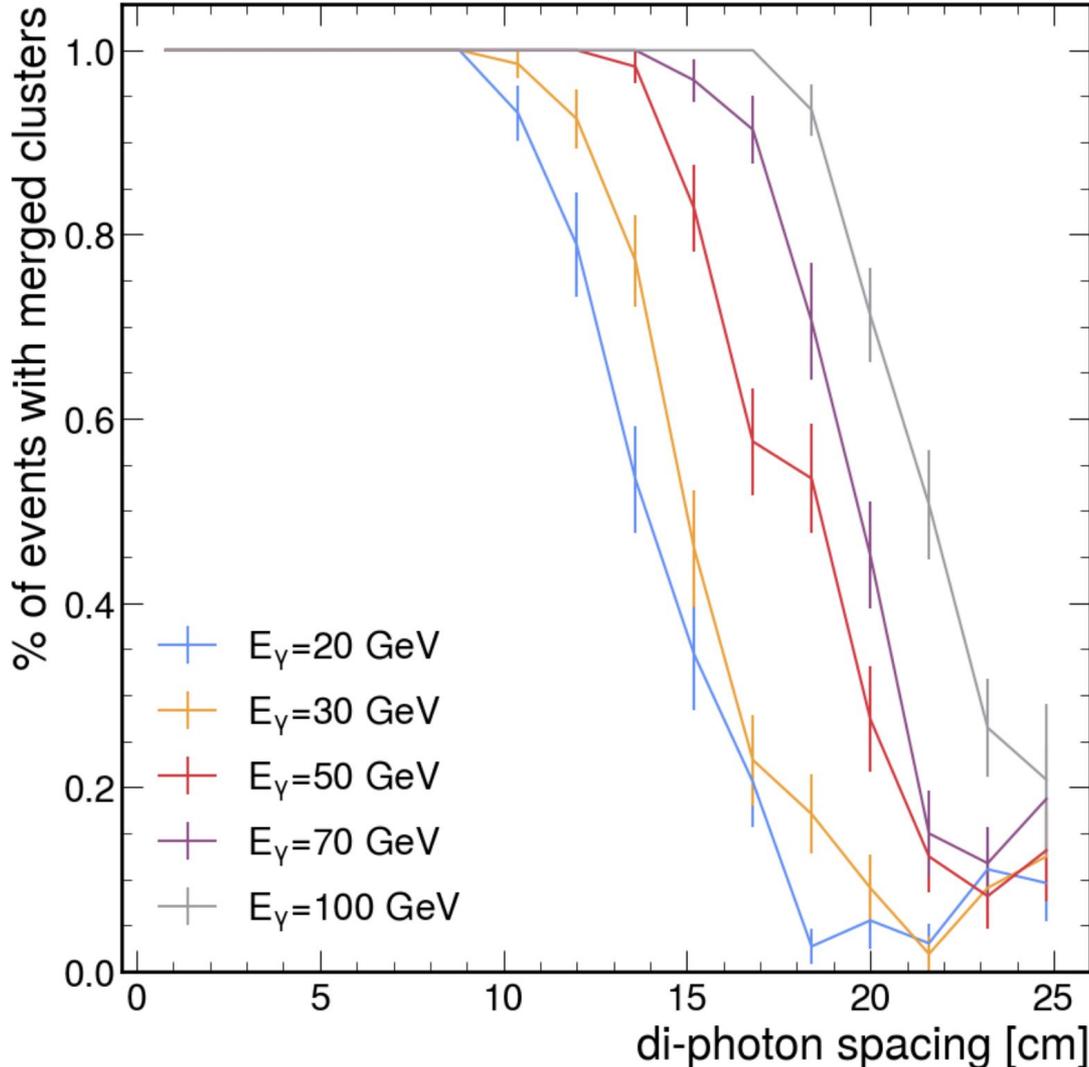
As showers get closer together, merging of clusters gets more frequent

- Can happen if a  $\Lambda^0$  decays close to the ZDC front face and the photons from the  $\pi^0$  are therefore close together

The minimum resolvable spacing increases with larger photon energy.

Possible ways to mitigate this:

- Choose a higher threshold  $N$  for which hits can be used for extending a cluster?
  - Need to decouple  $N$  from seeding threshold  $S$ , otherwise we'd lose some of the clusters due to insufficient seed energy.
- Including a cluster splitting algorithm for bimodally-shaped clusters



# Things to consider when trying to improve this

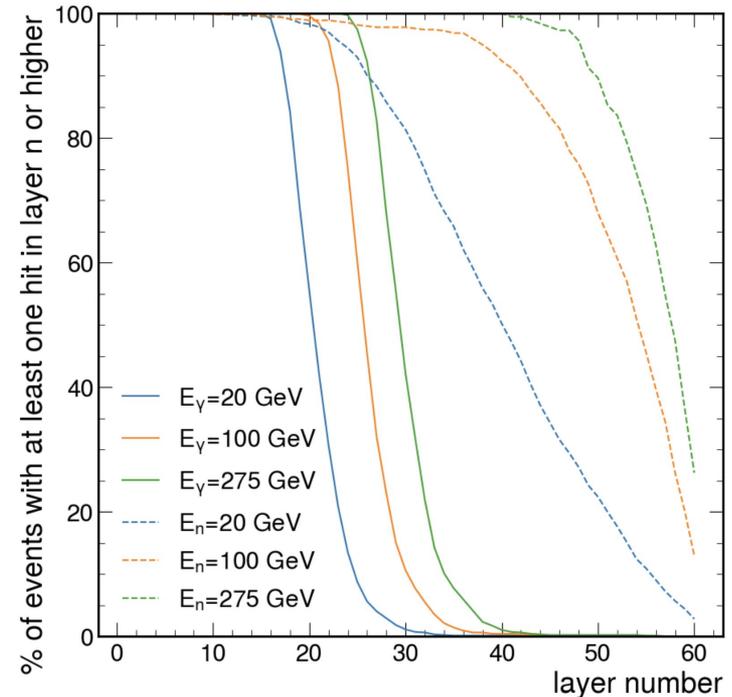
- Recognize that the ZDC is both an ECAL (photon showers) and an HCAL (neutron showers)
- Neutron showers:
  - Typically start deeper in the detector
  - Large transverse size
- Photon showers:
  - Start early in the detector
  - Small transverse size
  - Deposit most of the energy in the first few layers

# Some ideas of how to improve these things (TODO)

- Redefine which clusters are neighbors to one another based on the depth within the detector
  - Near the front of the detector (where both photons and neutrons penetrate):
    - Only the orthogonally or diagonally adjacent subcells are considered neighbors to one another
  - Near the back of the detector (where there are almost exclusively neutron hits)
    - Consider hits on subcells “neighbors” if they are within XXX subcell positions from one another
- Decouple the S and N clustering parameters from one another
  - Have their values vary in a gradient from layer to layer

# How do we define “front” and “back” of the detector?

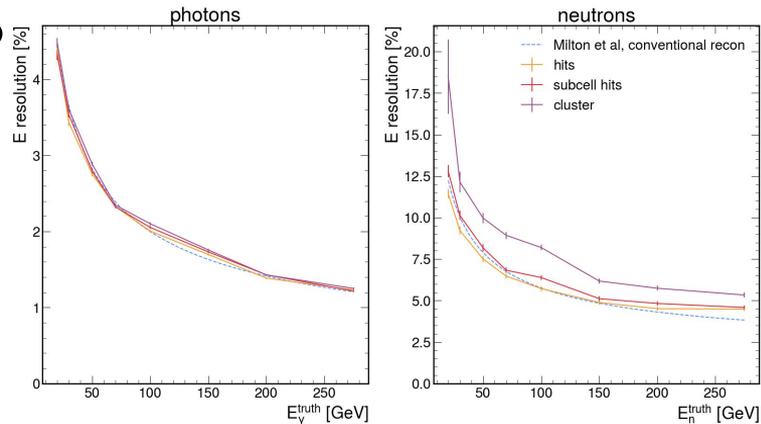
- Simulated single-photon and single-neutron events at various energies
- Looked to see where the last layer with hits on it was in these events
- Even at the highest energy, less than 50% of the  $\gamma$  events have hits in layer  $> 30$ .
  - So, the cutoff should be at around layer 20-30



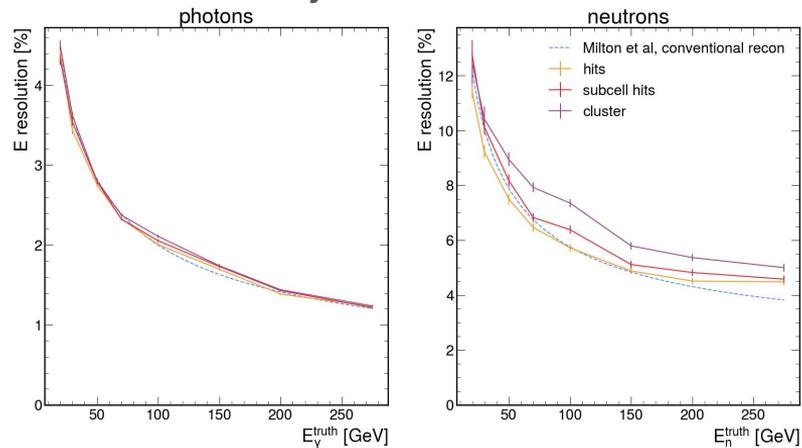
# What happens if we consider next-to-adjacent hits as neighbors?

- Improvement in neutron energy recon (photons remain the same)

adjacent



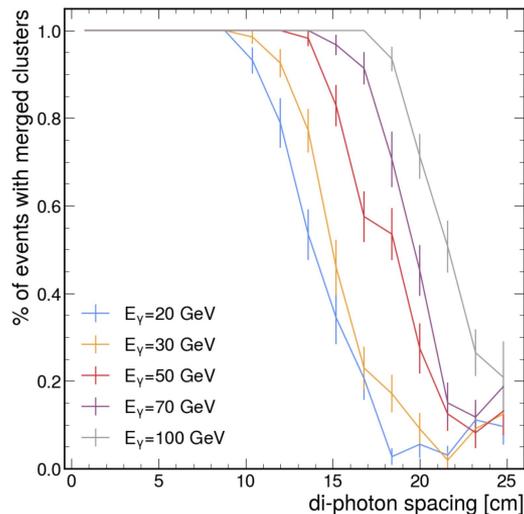
next-to-adjacent



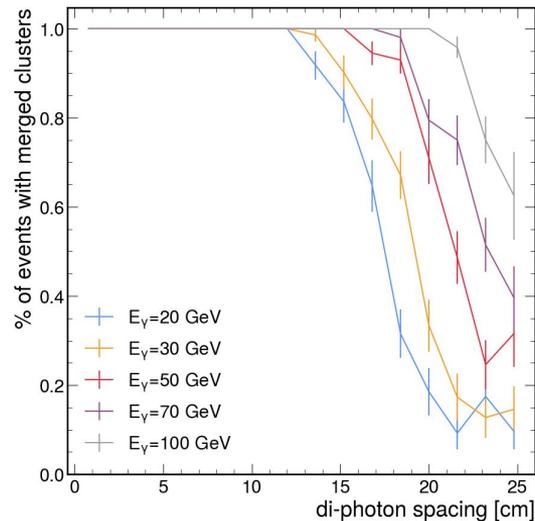
# What happens if we consider next-to-adjacent hits as neighbors?

- Improvement in neutron energy recon (photons remain the same)
- Degrades the photon-shower separation

adjacent

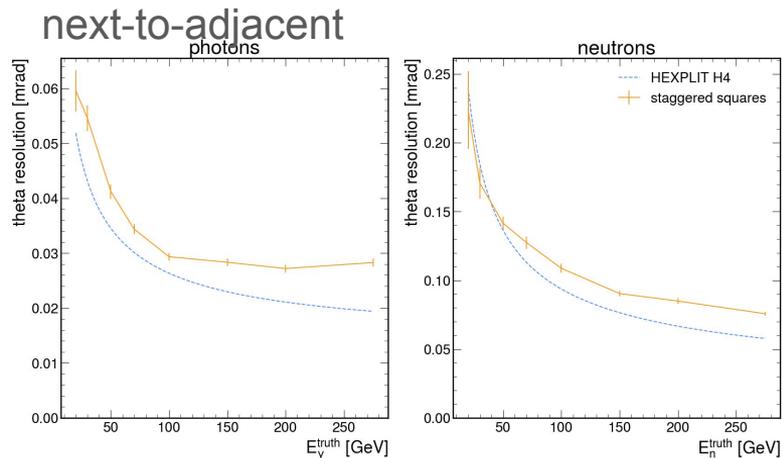
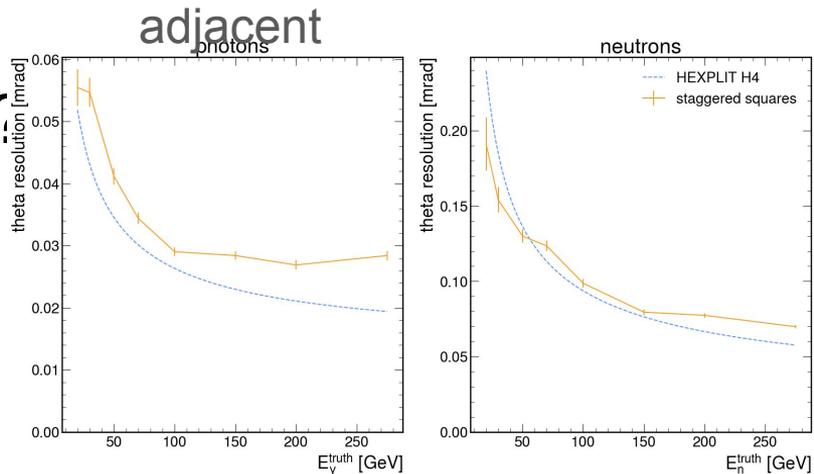


next-to-adjacent



# What happens if we consider next-to-adjacent hits as neighbors?

- Improvement in neutron energy recon (photons remain the same)
- Degrades the photon-shower separation
- Similar theta recon
  - slightly worse for neutrons, but this could be compensated for by adjusting the parameters of the log-weighting
- TODO:
  - Check if considering next-to-adjacent or even next-to-next-to-adjacent hits as neighbors improves results for neutron-energy recon without harming photon-shower separation
  - Readjust log-weighting for position determination



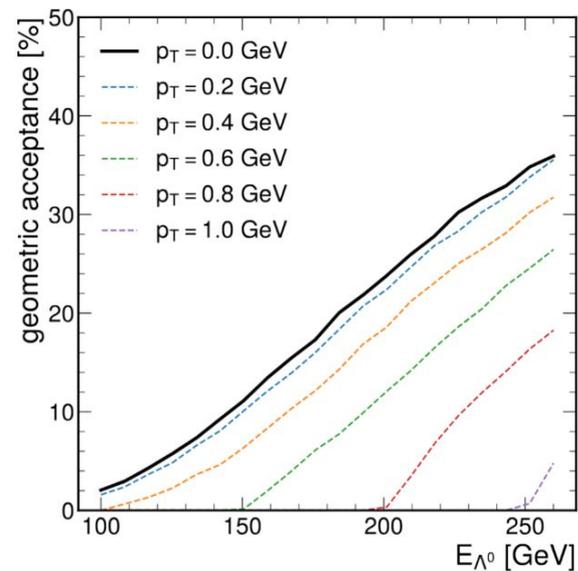
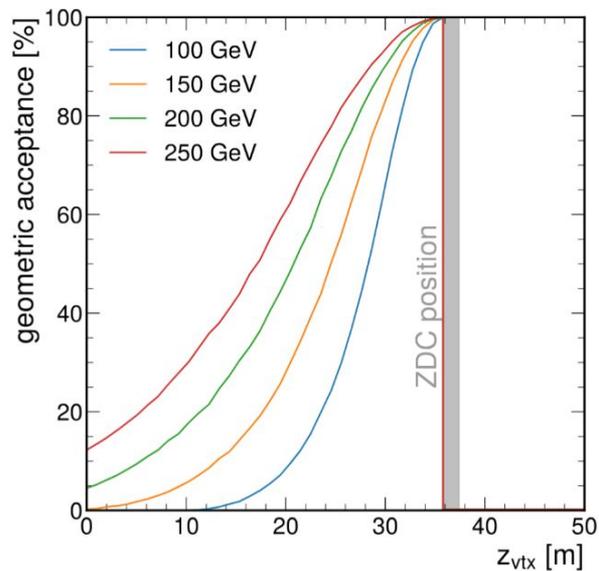
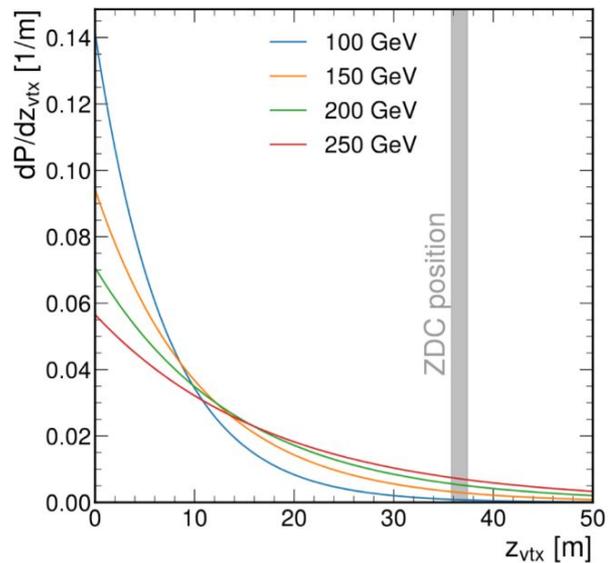
# Summary

- Efficiency of reconstructing  $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$  was found to be limited by merging of nearby photon clusters (from the  $\pi^0$ )
- Before further fine-tuning the algorithms, I had to adapt them to work with staggered square patterns
- Established some metrics for how to test the finetuning:
  - Resolutions in energy and theta for single photon and neutron events
  - Merging probability for double photon events in MC
- Showed that simply increasing the allowed distance between “neighbors” improves some things but makes others worse.
- TODO:
  - Decouple seeding threshold (S) from expansion threshold (N)
  - update clustering algorithm to allow for depth-dependent clustering parameters



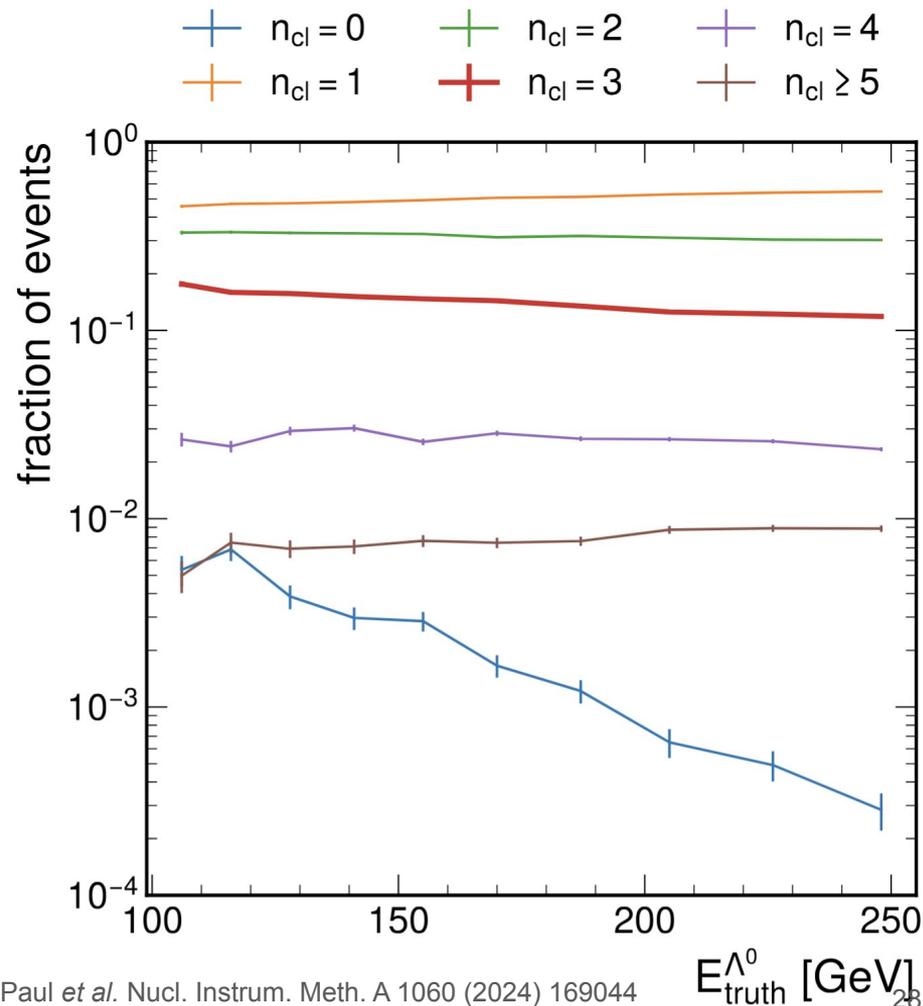
# Backup slides

# Geometric Acceptance



# Clustering in conventional reconstruction

- We used the HEXPLIT\* algorithm followed by topoclustering\*\* algorithm to get the clusters
- Ideally we want to have 3 or more clusters (2 of which are from the photons, and the rest from the neutron).
- About O(10%) of events within acceptance have 3 or more clusters
- This may improve with further modifications and fine-tuning of the topoclustering algorithms outside the scope of this paper



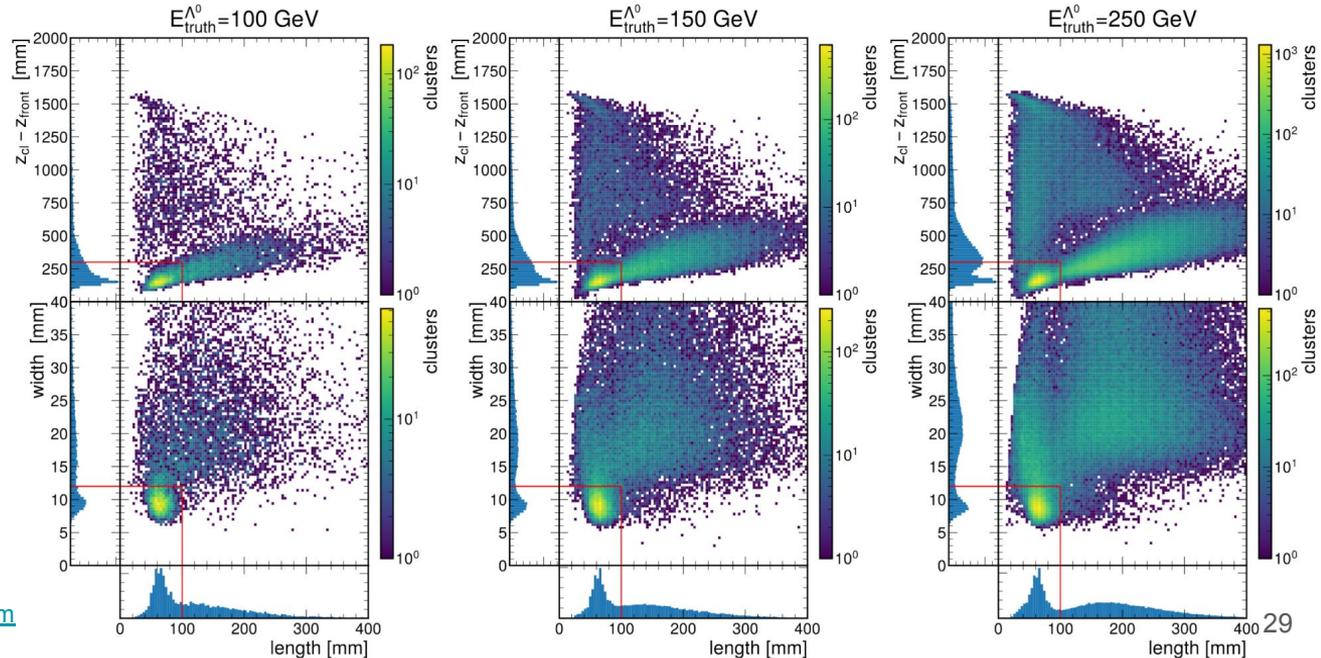
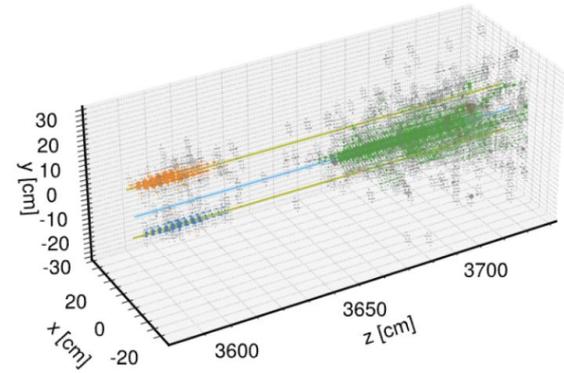
\*S.J. Paul *et al.* Nucl. Instrum. Meth. A 1060 (2024) 169044

\*\*ATLAS Collaboration, G. Aad *et al.* Eur. Phys. J. C 77 (2017) 490

# Photon-cluster identification

Clusters from photon showers:

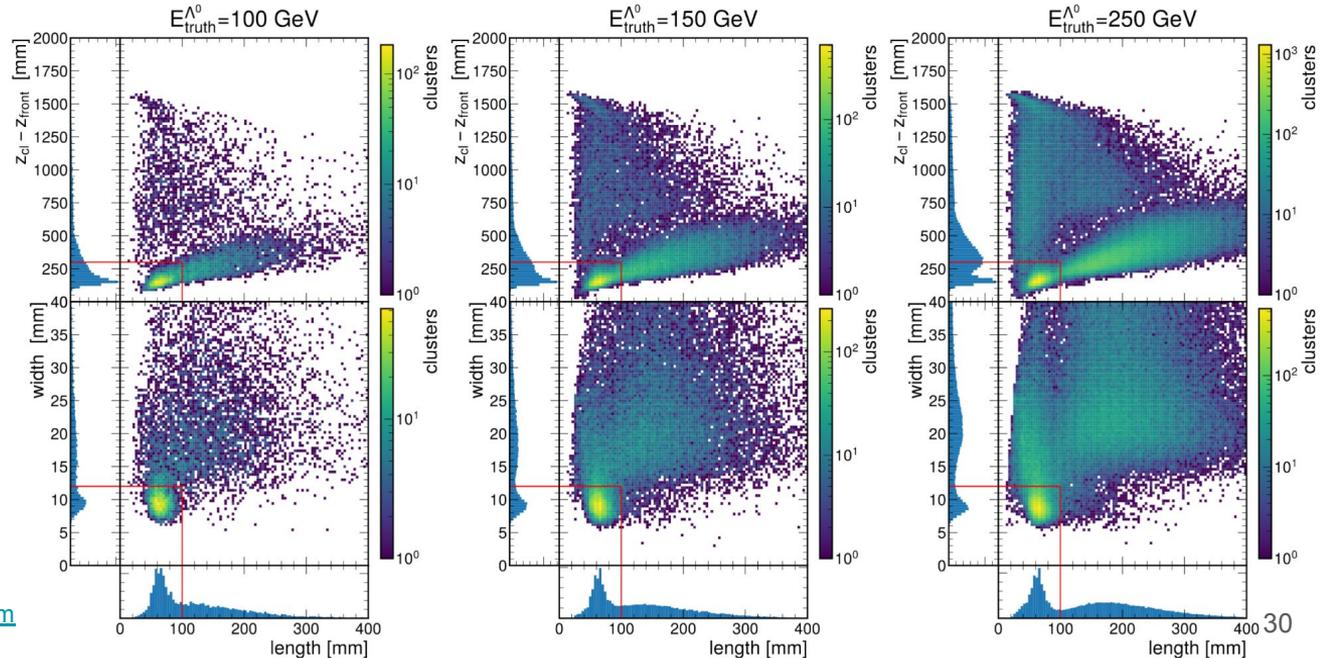
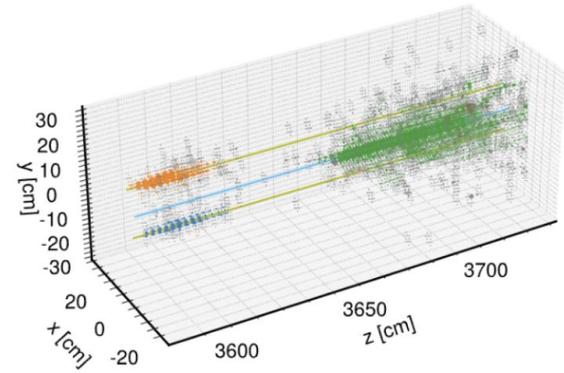
- Start near the face of the detector
  - Cut on the longitudinal position of the log-weighted CoG of the cluster)



# Photon-cluster identification

Clusters from photon showers:

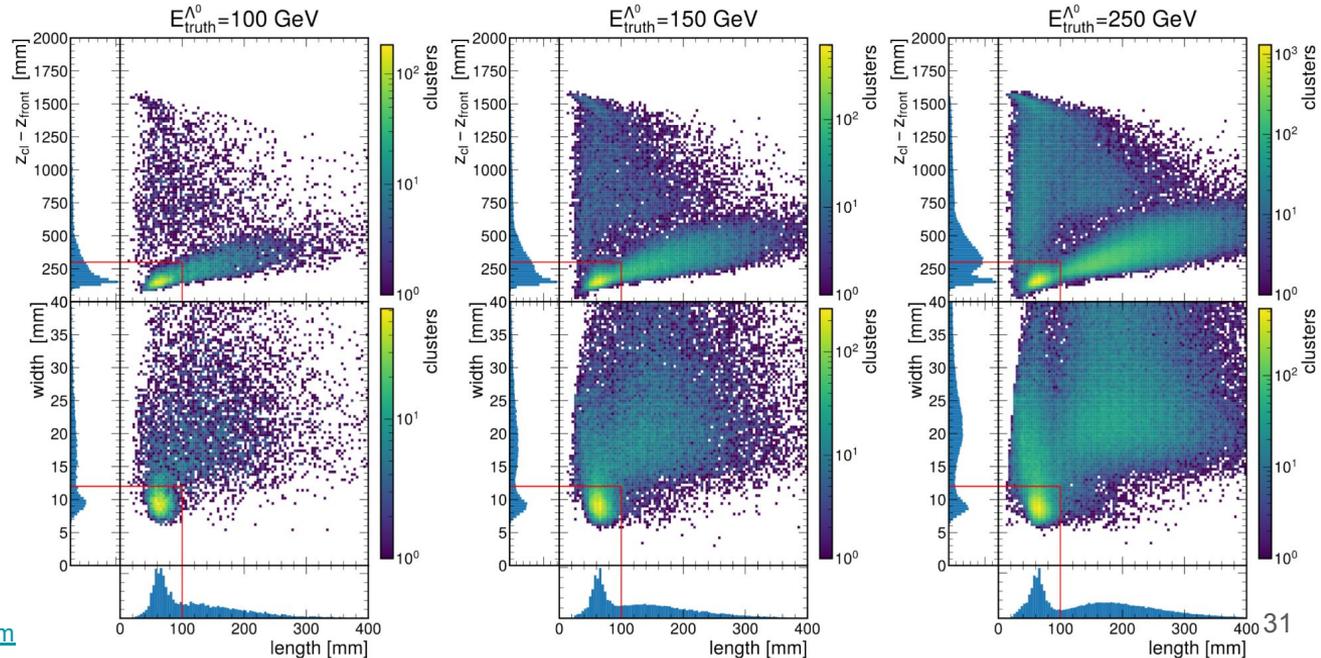
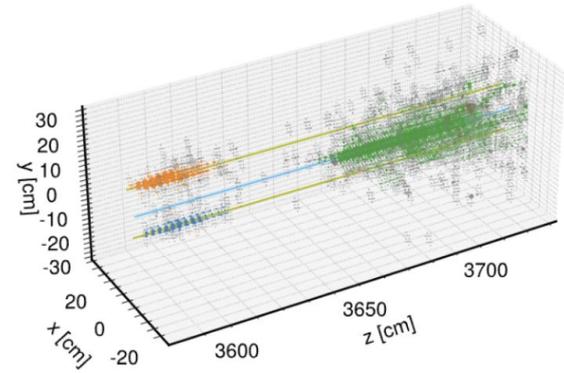
- Start near the face of the detector
- Small longitudinal extent
  - Cut on the largest eigenvalue of the moment matrix (“length”) of the cluster



# Photon-cluster identification

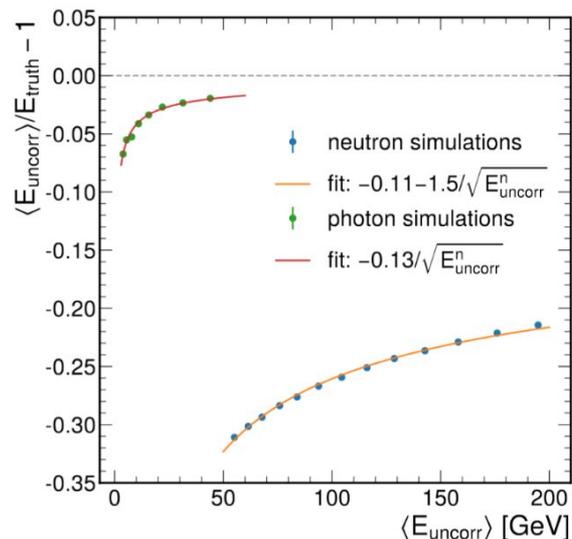
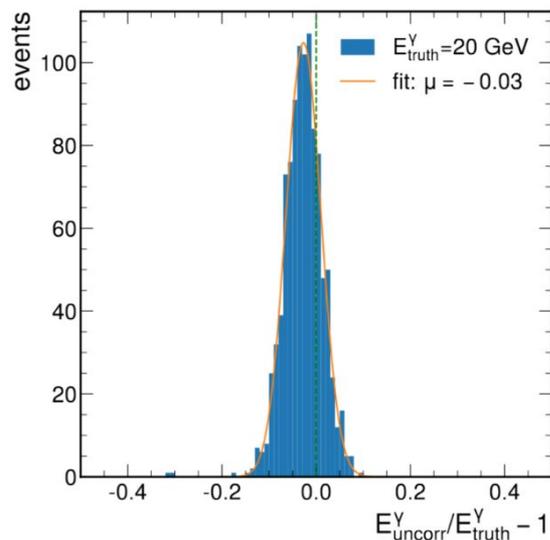
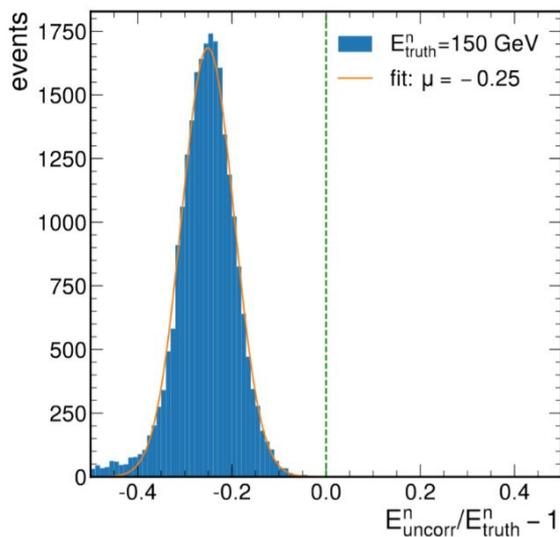
Clusters from photon showers:

- Start near the face of the detector
- Small longitudinal extent
- Small transverse size:
  - Cut on the second-largest eigenvalue (“width”).



# Energy corrections

- Start with sum of energies of hits in cluster(s) associated with particle
- Divide by EM sampling fraction (determined with single-electron simulations)
- Apply energy correction (determined by a fit):
  - Hadronic vs EM scale (neutrons only)
  - not all energy of shower included in cluster (photons and neutrons)

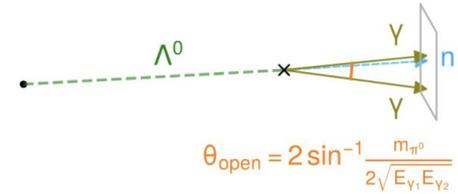


# IDOLA algorithm

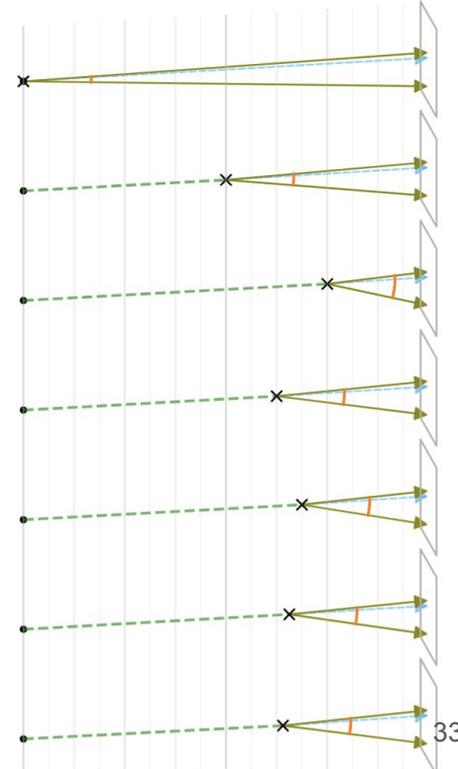
- “Iterative Determination of Origin in Lambda Analyses”
- Applies a binary search to find the longitudinal position of the lambda decay vertex such that the reconstructed  $\pi^0$  mass matches the PDG value.
- Inspired in “kinematic fitting” but has aim to get displaced vertex, not improve energy or position resolution.
- To our knowledge, no previous attempt to reconstruct O(10) m displaced vertex was ever done, in any experiment.

<https://doi.org/10.5281/zenodo.14518550>

Truth event:  
 $f \equiv \frac{z_{vtx}}{z_{ZDC}} = 0.64$

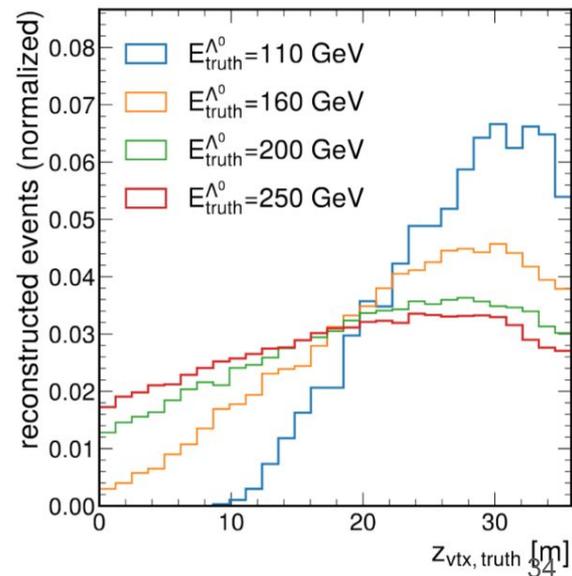
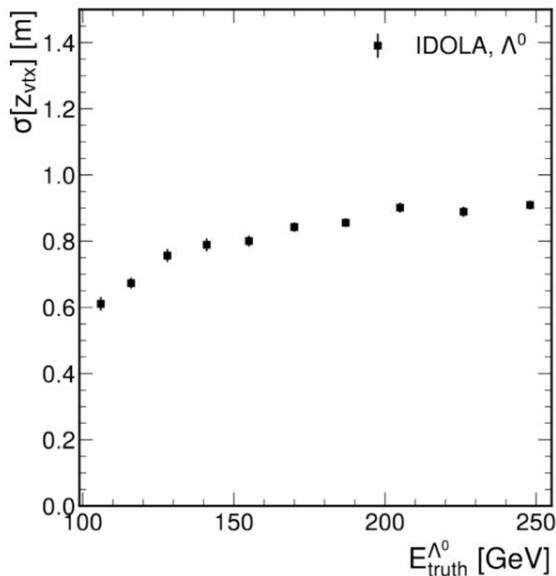
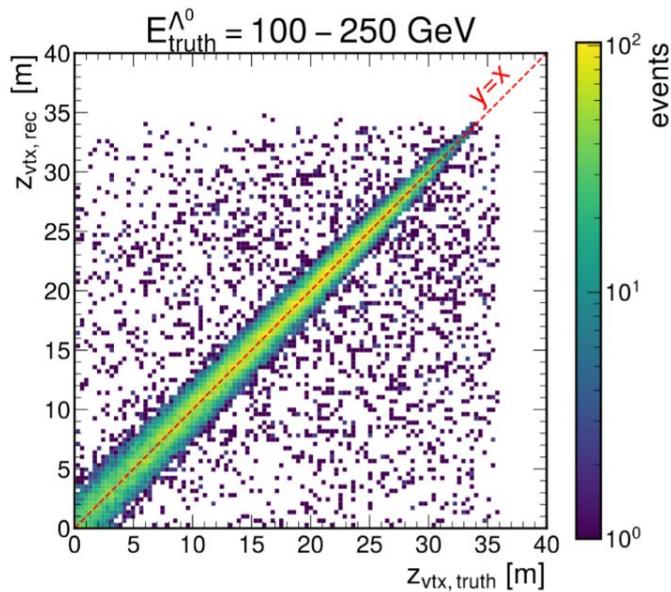


Iter.	f
1	0.00
2	0.50
3	0.75
4	0.62
5	0.69
6	0.66
7	0.64



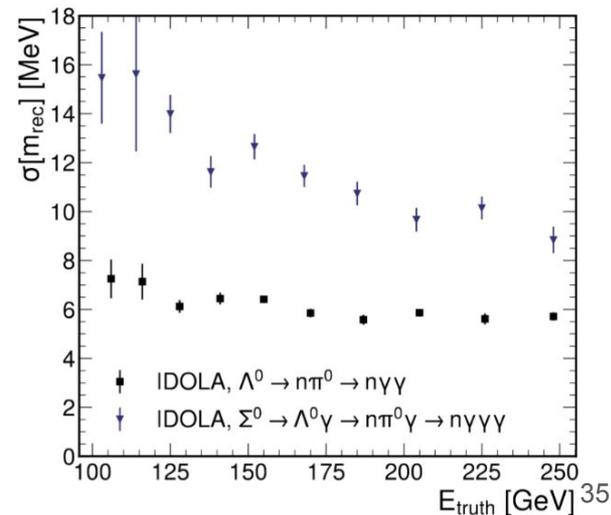
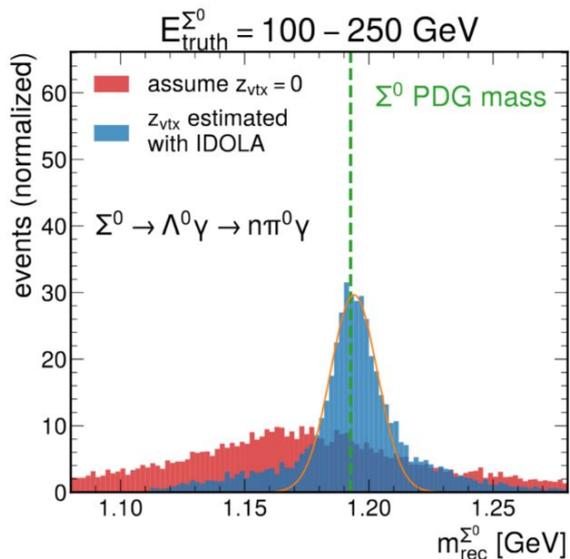
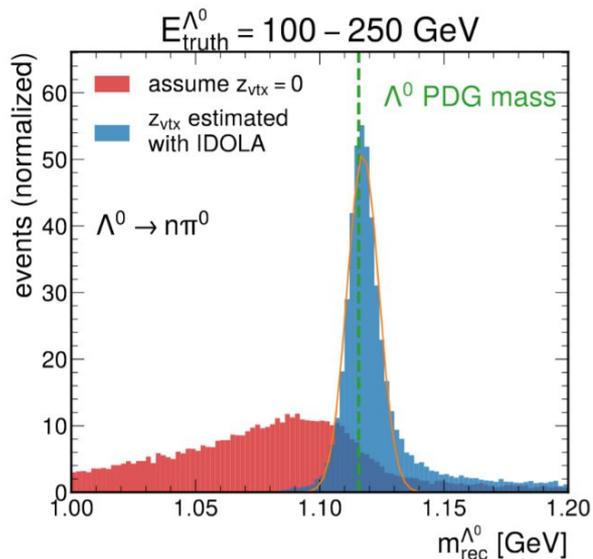
# Results for the IDOLA algorithm

Resolution  $O(1 \text{ m})$



# Results for the IDOLA algorithm (continued)

- Reconstructs mass of  $\Lambda^0$  to within about 6-8 MeV
- Somewhat worse resolution for  $\Sigma^0$  (9-16 MeV), but not bad either
  - Future studies may improve reconstruction efficiency/resolution for  $\Sigma^0$



# $p_T$ resolution

Dominated by beam effects

$$\frac{\Delta p_T}{p_T} \approx \frac{\Delta E}{E} \oplus \frac{E \Delta\theta}{p_T} \oplus \frac{E \sigma_{\text{beam}}}{p_T}.$$

