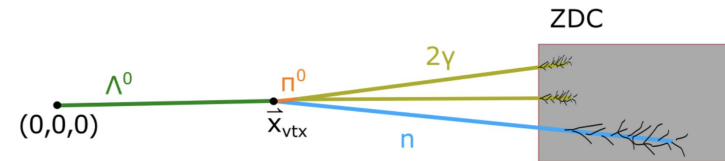
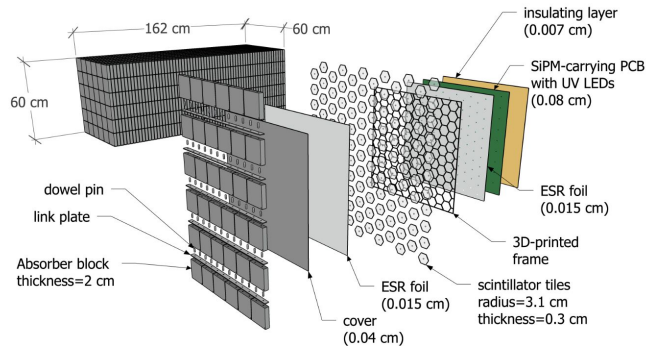


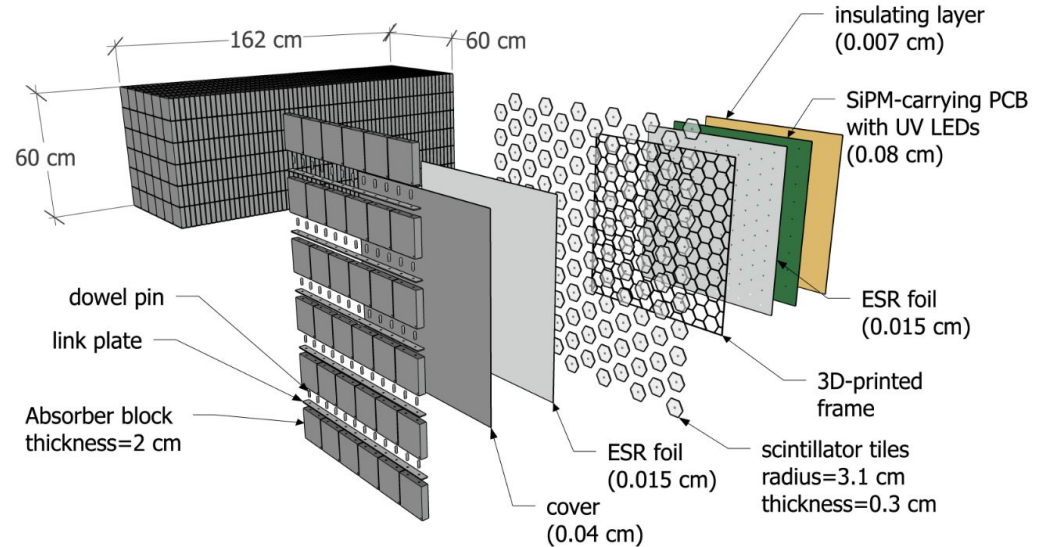
Reconstruction of Λ Baryons in the Zero-Degree Calorimeter

Dr Sebouh Paul
UC Riverside
7/12/2025

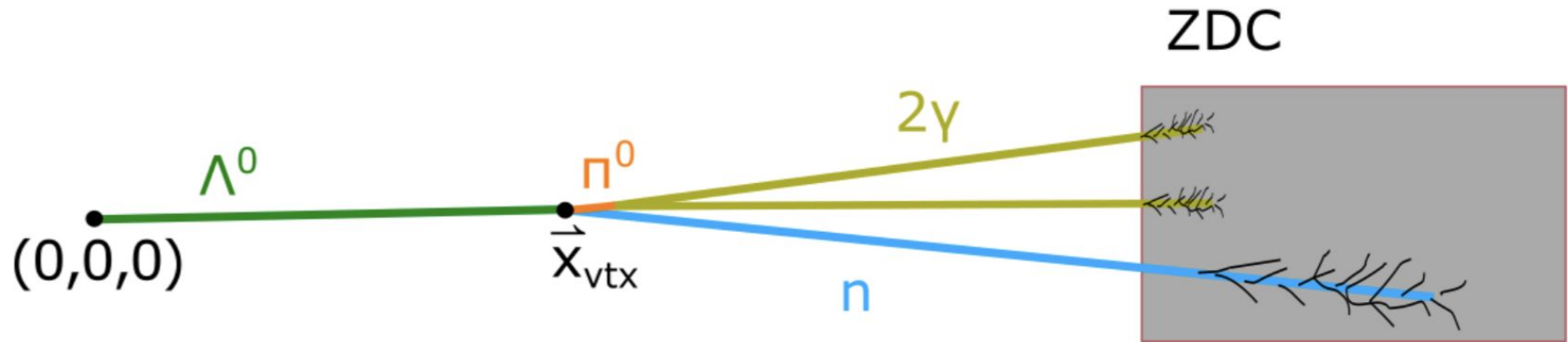


Zero-Degree Calorimeter

- 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



Event topology



36 m downstream of IP

- Details of our studies recently published 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/algorithms/reco/FarForwardLambdaReconstruction.cc>

**https://github.com/eic/detector_benchmarks/tree/master/benchmarks/zdc_lambda

PHYSICAL REVIEW D **111**, 092013 (2025)

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

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Department of Physics and Astronomy, University of California, Riverside, California 92521, USA



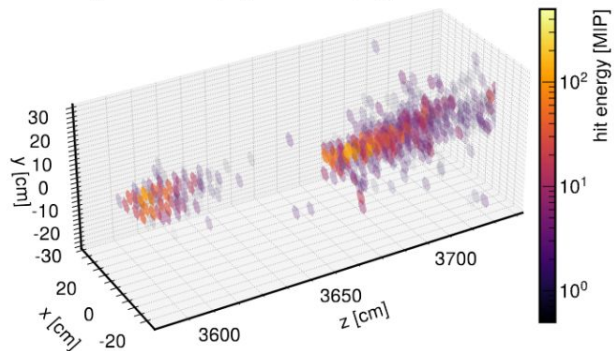
(Received 26 March 2025; accepted 13 May 2025; published 27 May 2025)

Key measurements at the future electron-ion collider (EIC), including first-of-their-kind studies of kaon structure, require the detection of Λ^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 Λ^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 Λ^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 Λ^0 rest frame, which reflects the Λ^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.

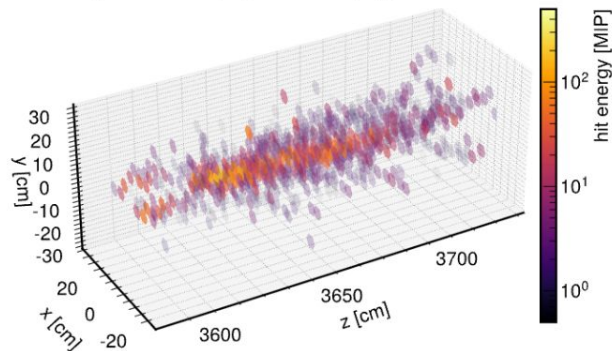
DOI: 10.1103/q7w9-sbsc

Example events

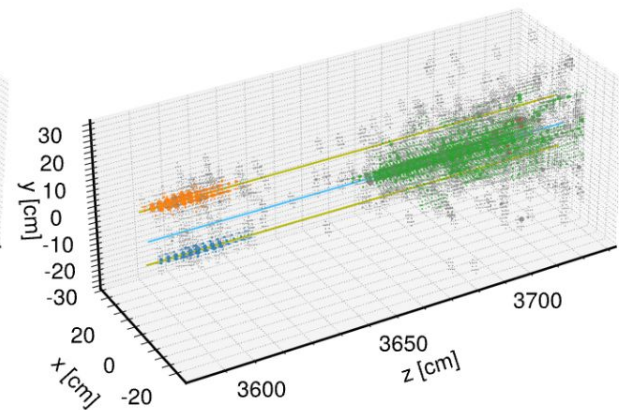
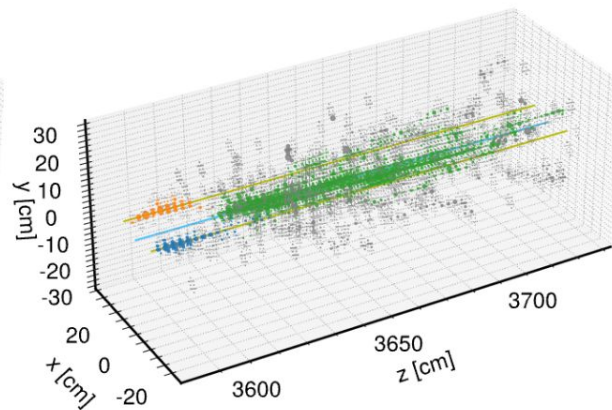
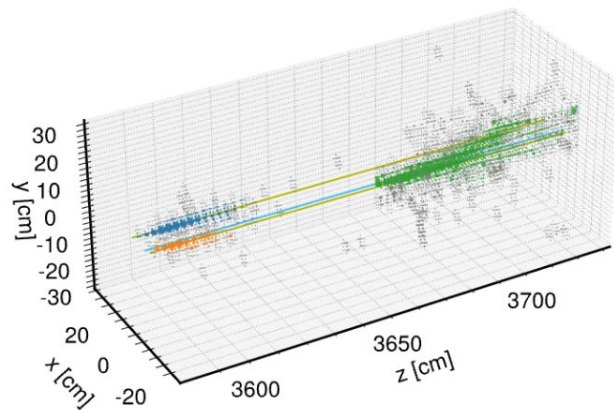
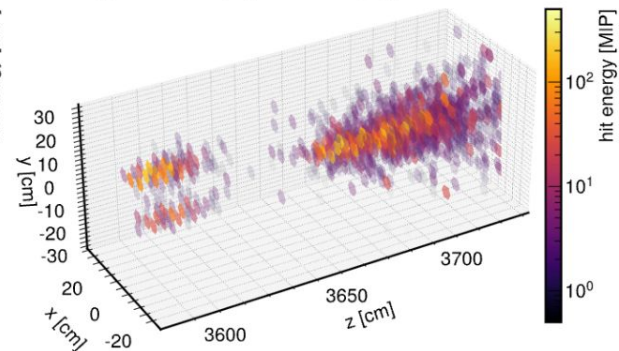
$E_{\Lambda^0} = 103 \text{ GeV}$, $\theta_{\Lambda^0} = 0.6 \text{ mrad}$, $z_{\text{vtx}} = 25.5 \text{ m}$



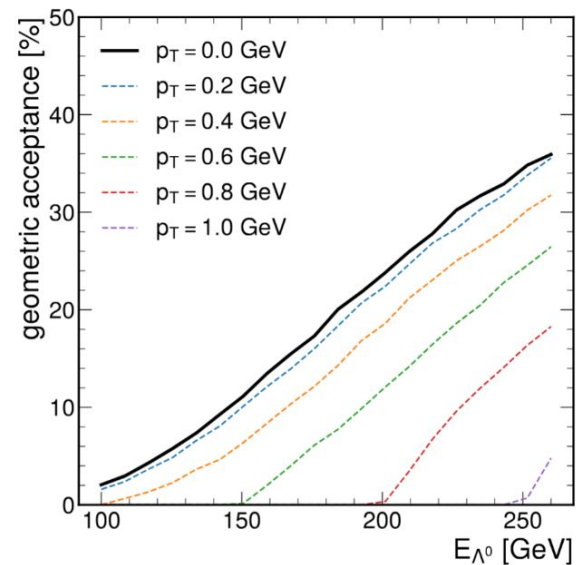
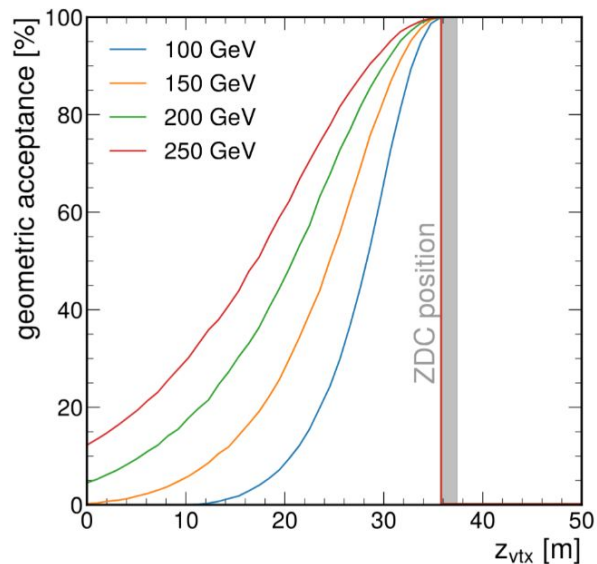
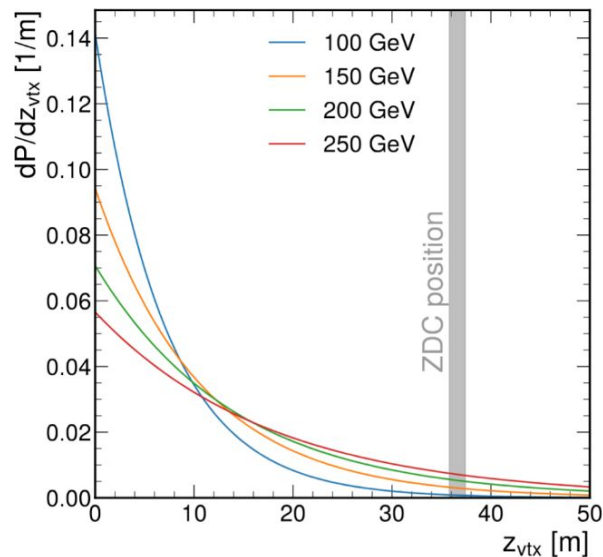
$E_{\Lambda^0} = 152 \text{ GeV}$, $\theta_{\Lambda^0} = 1.1 \text{ mrad}$, $z_{\text{vtx}} = 27.1 \text{ m}$



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

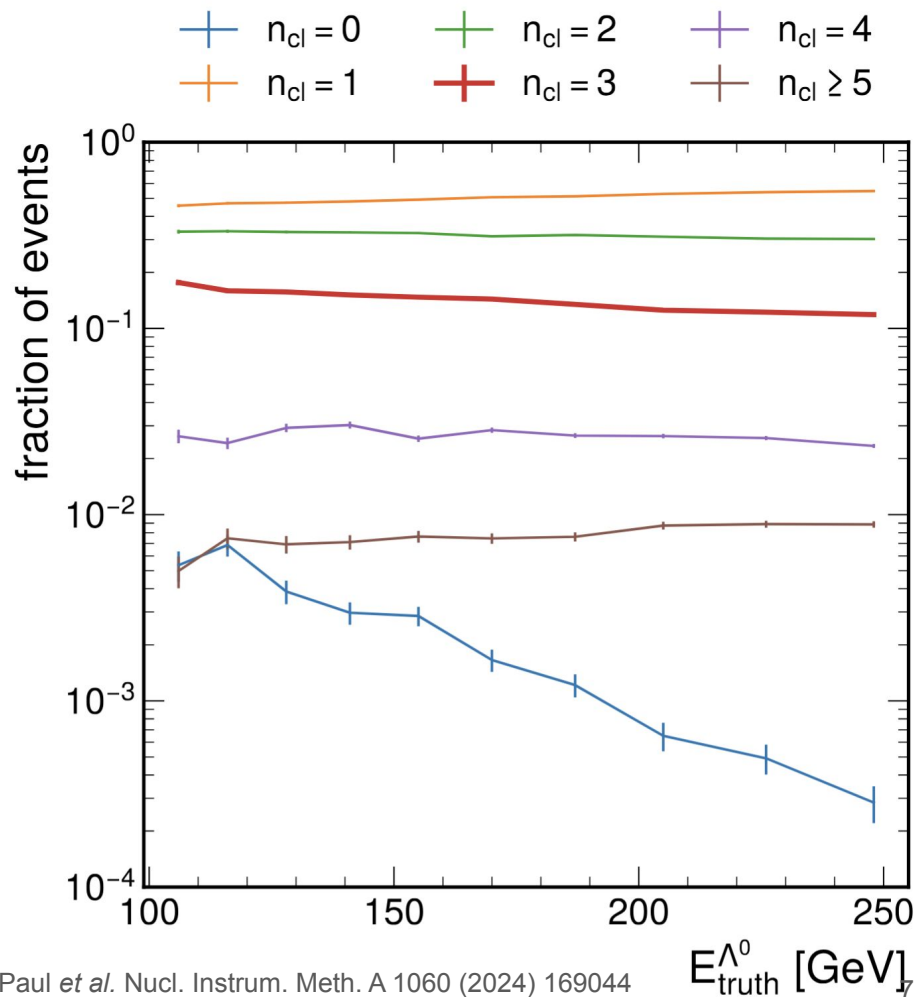


Geometric Acceptance



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



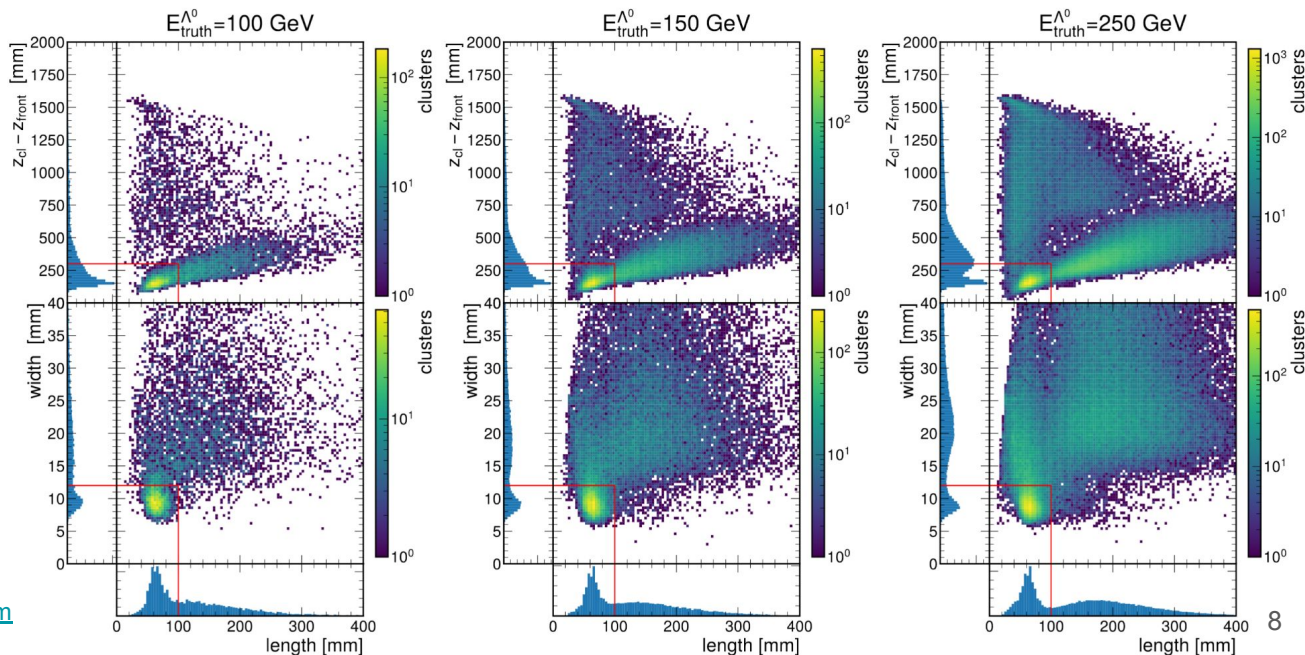
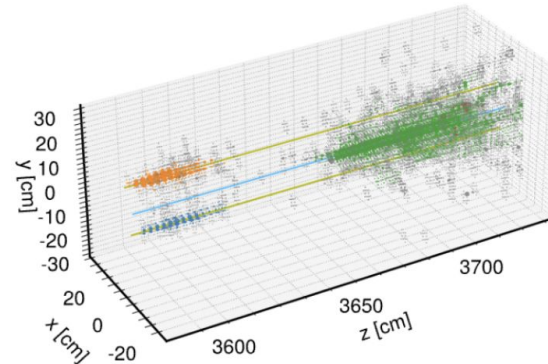
*S.J. Paul *et al.* Nucl. Instrum. Meth. A 1060 (2024) 169044

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

Photon-cluster identification

Clusters from photon showers:

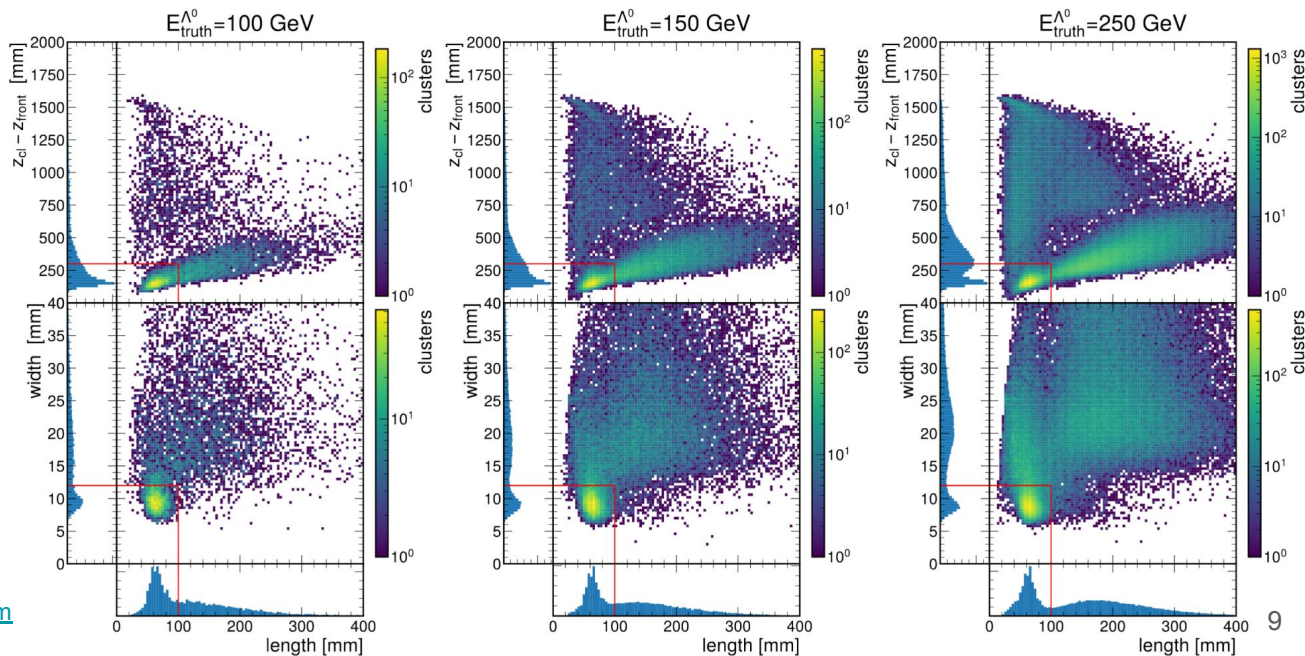
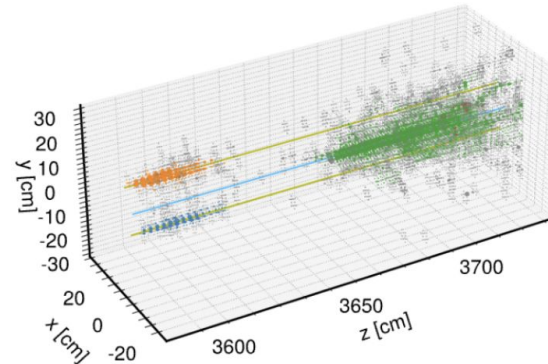
- Start near the face of the detector
 - Cut on the longitudinal position of the log-weighted CoG of the cluster)
-



Photon-cluster identification

Clusters from photon showers:

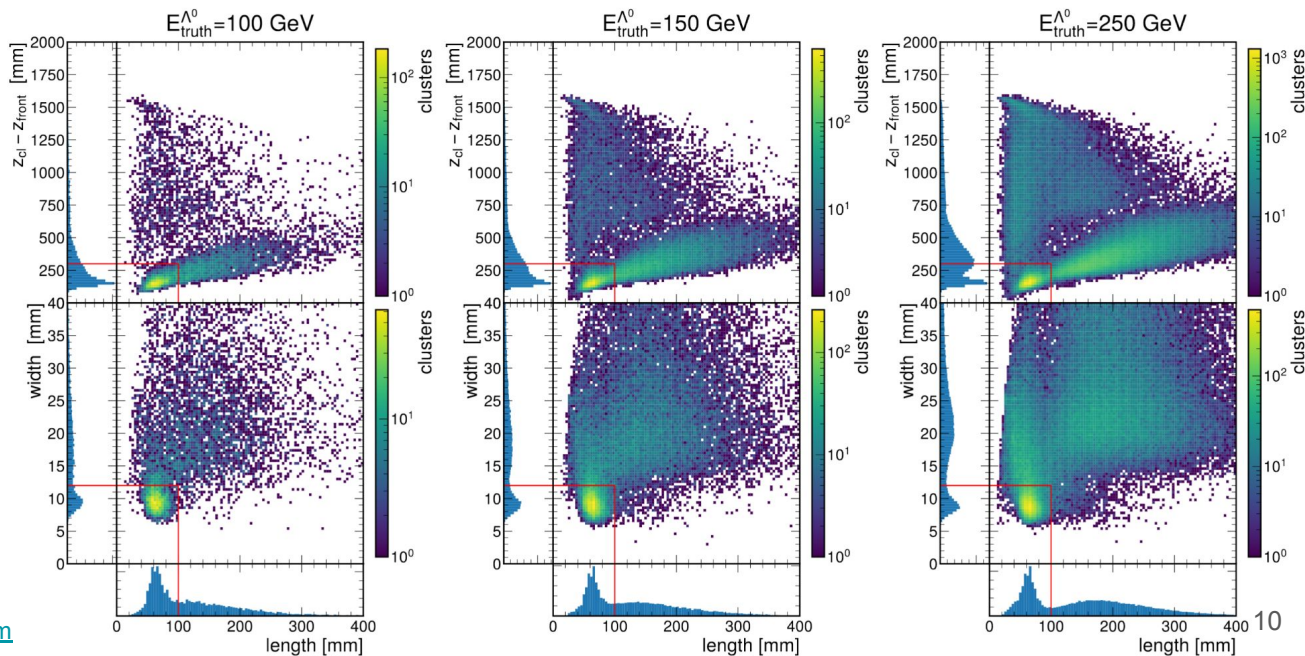
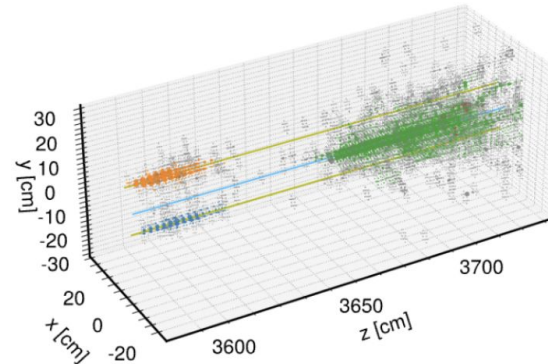
- Start near the face of the detector
- Small longitudinal extent
 - Cut on the largest eigenvalue of the moment matrix (“length”) of the cluster



Photon-cluster identification

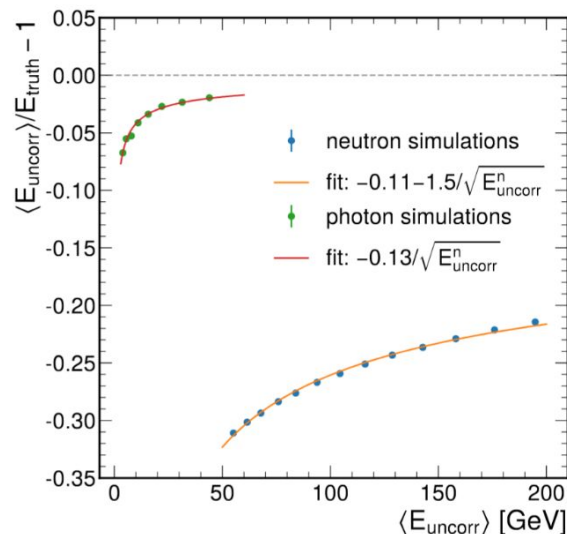
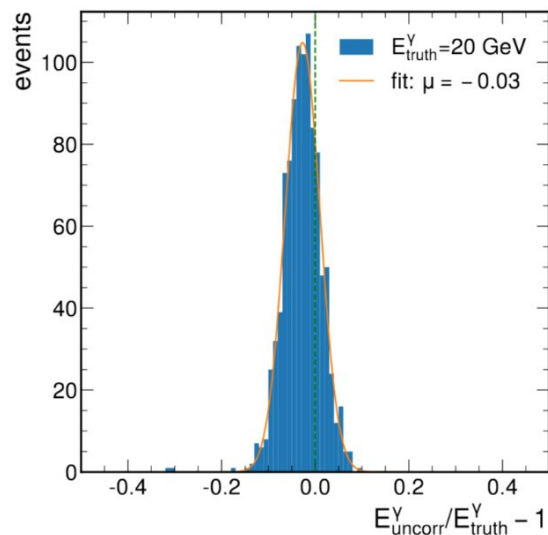
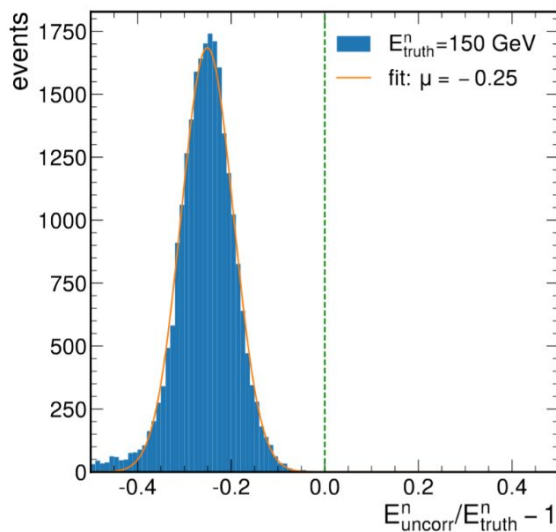
Clusters from photon showers:

- 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)

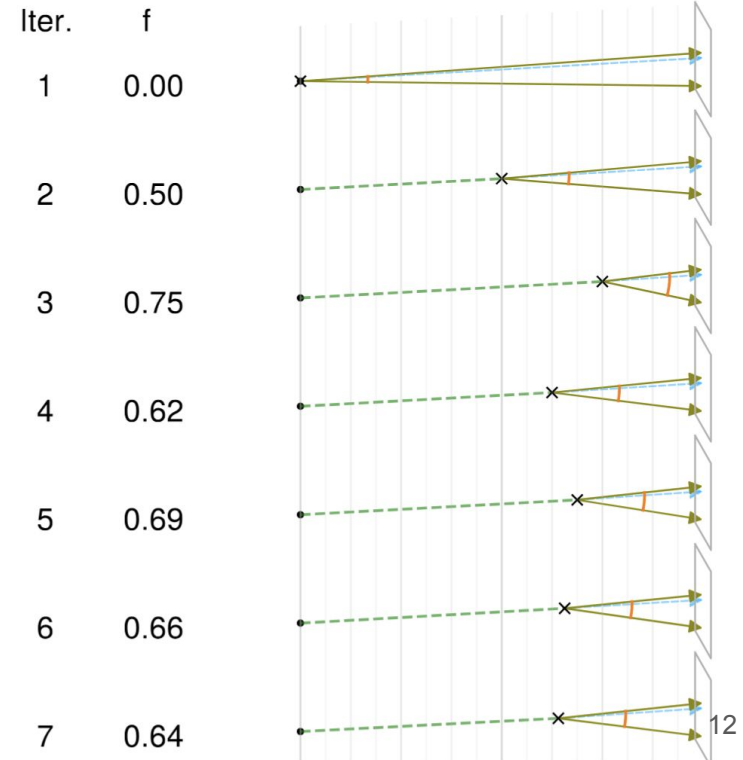
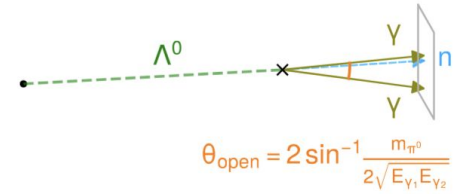


IDOLA algorithm

- “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 π^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.

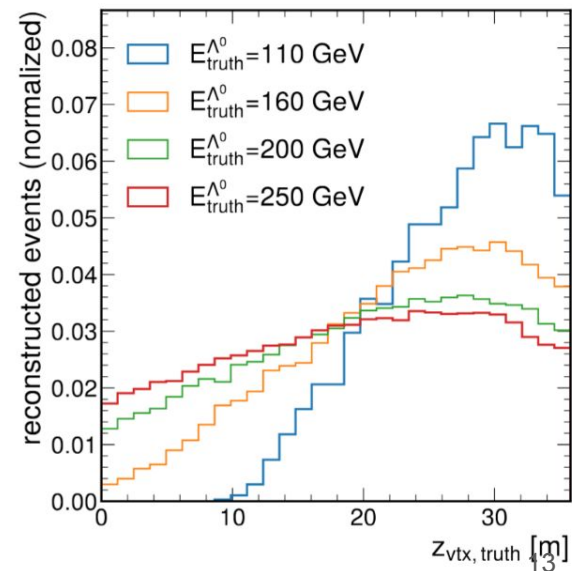
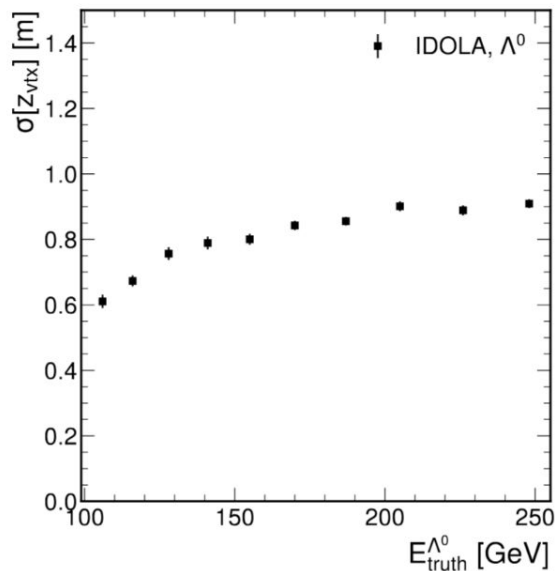
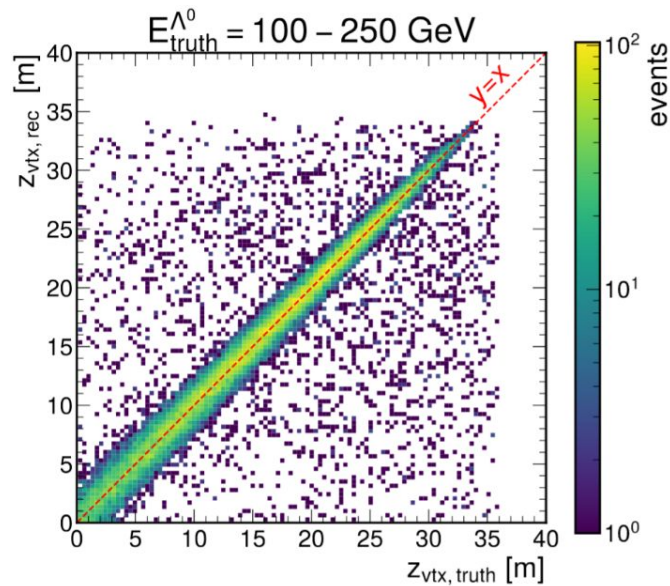
<https://doi.org/10.5281/zenodo.14518550>

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



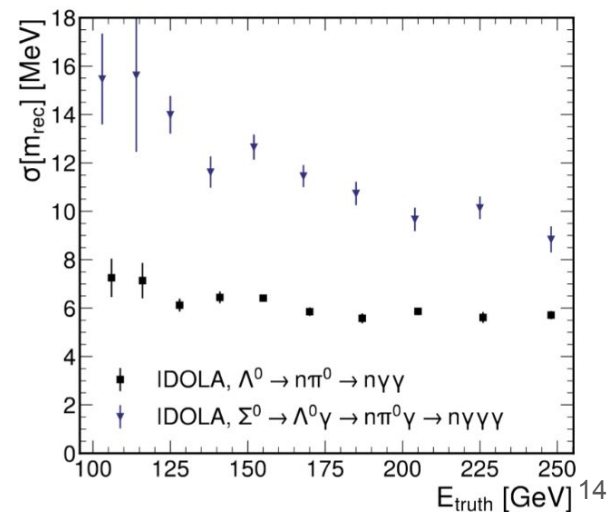
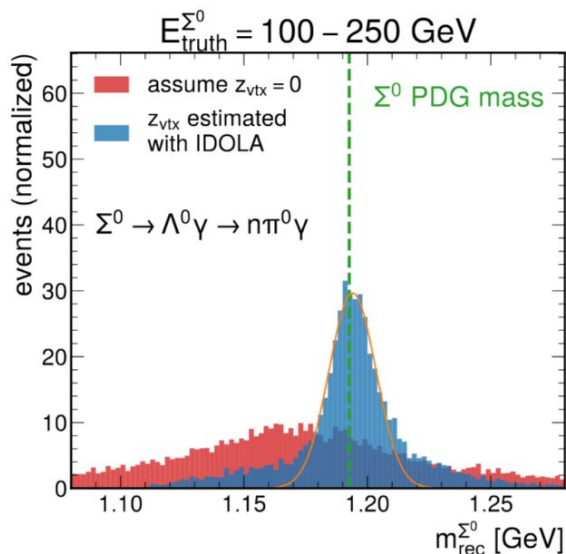
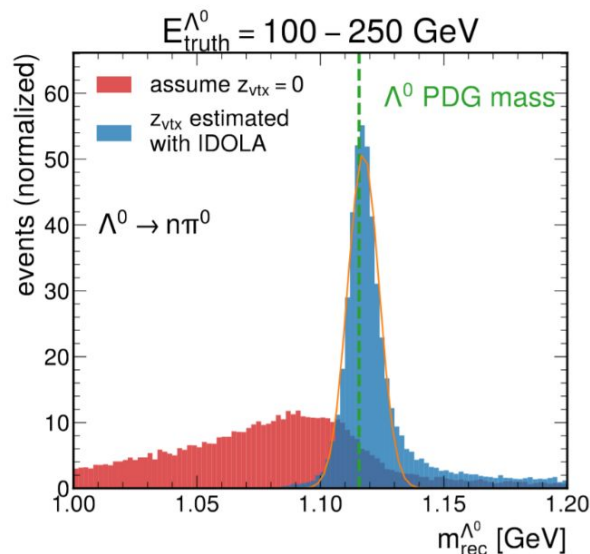
Results for the IDOLA algorithm

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



Results for the IDOLA algorithm (continued)

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



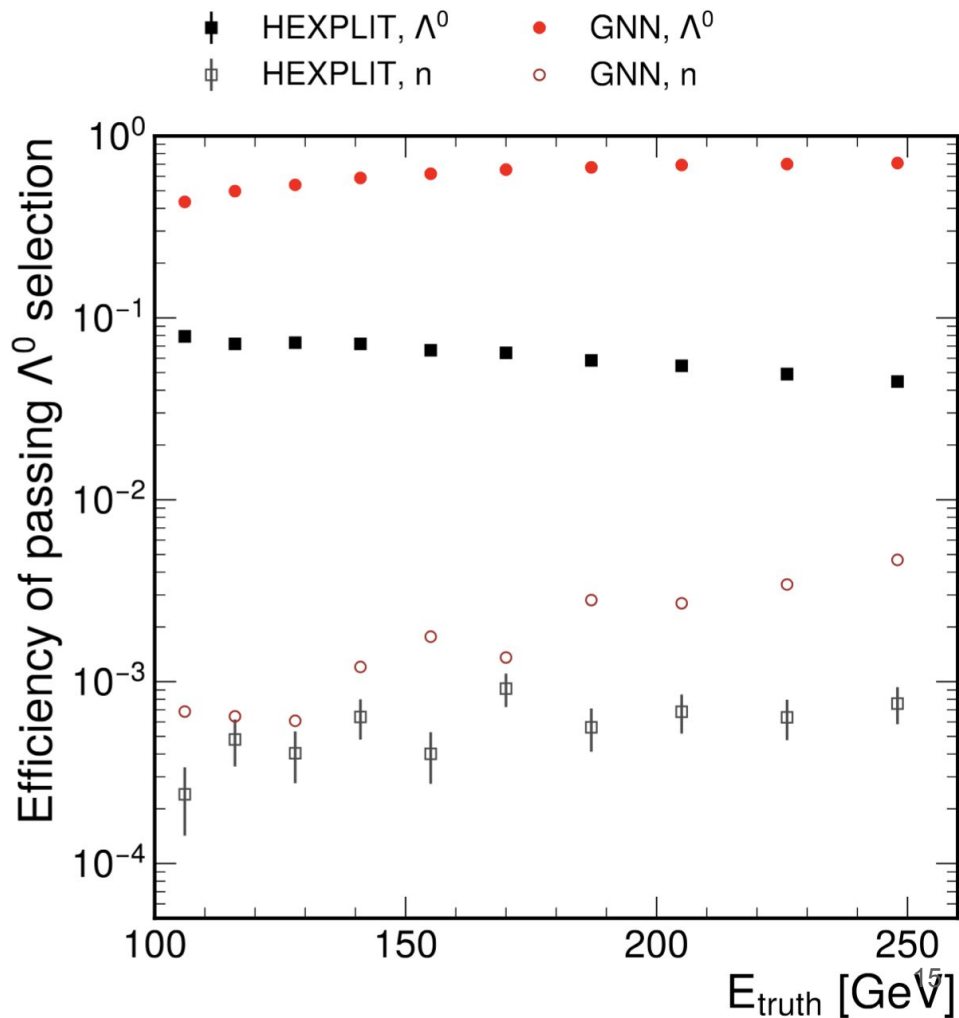
Λ^0 selection efficiency

Conventional recon:

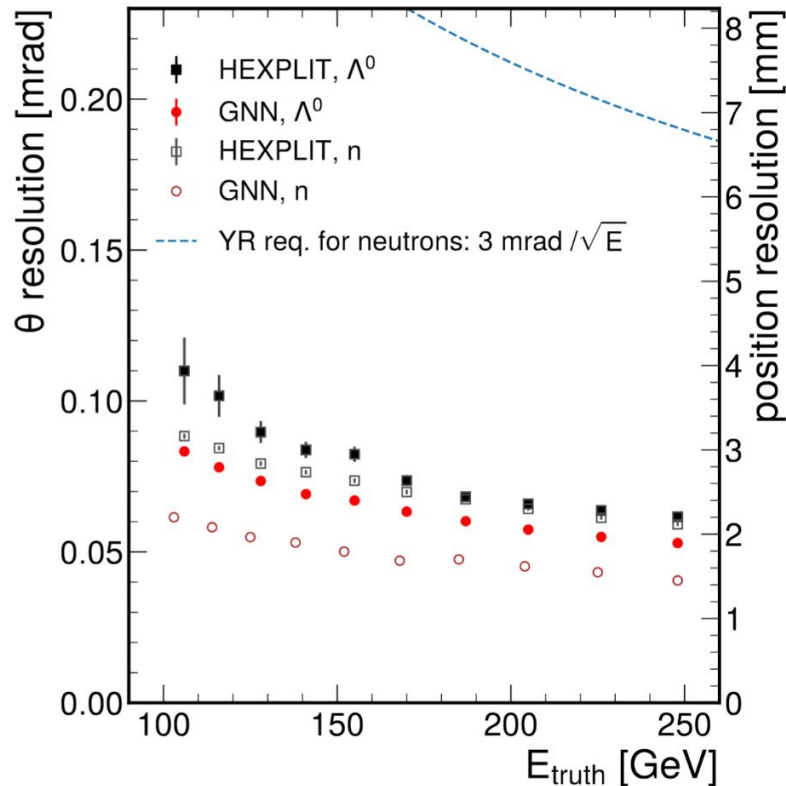
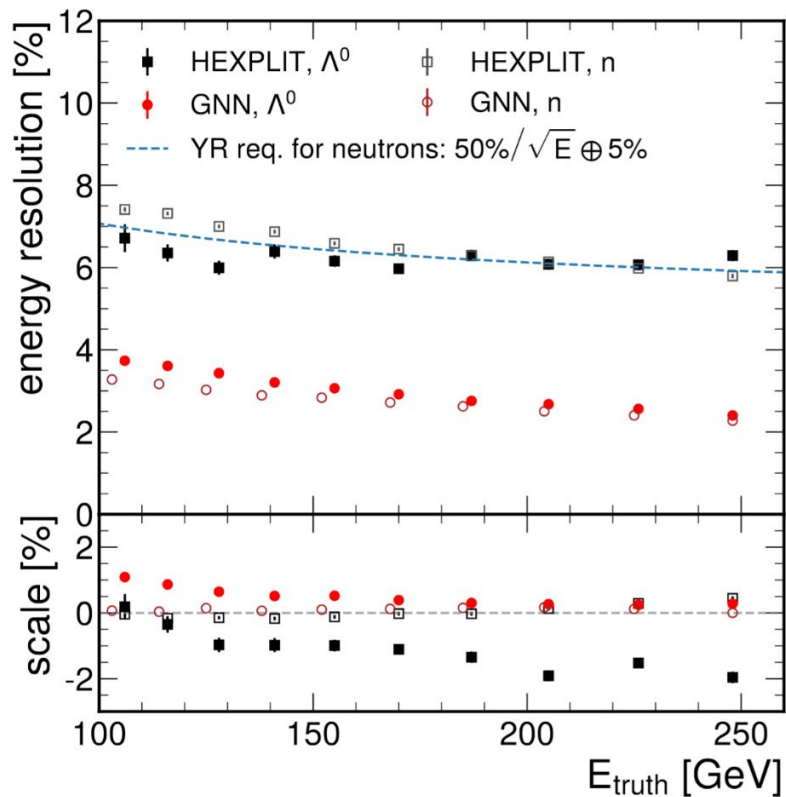
- Require ≥ 3 clusters, exactly 2 of which are photons
- Λ^0 mass should be reconstructed within 30 MeV of PDG value
- Efficiency: $\sim 4\text{-}8\%$

AI/ML recon

- Graph Neural Network
- Uses a classifier trained to distinguish Λ^0 events from single-neutron events
- Efficiency: $\sim 40\text{-}70\%$



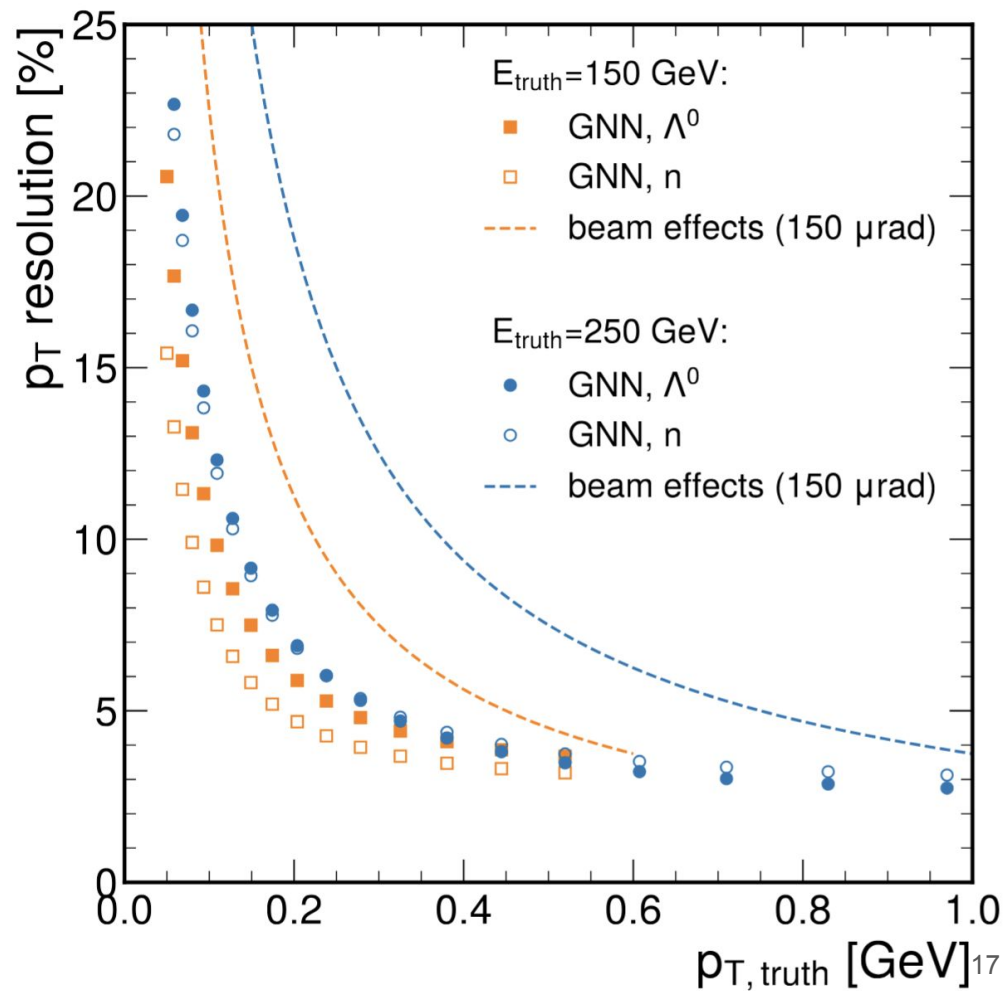
Energy and polar angles reconstructed better than YR requirements for neutrons



p_T resolution

Dominated by beam effects

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



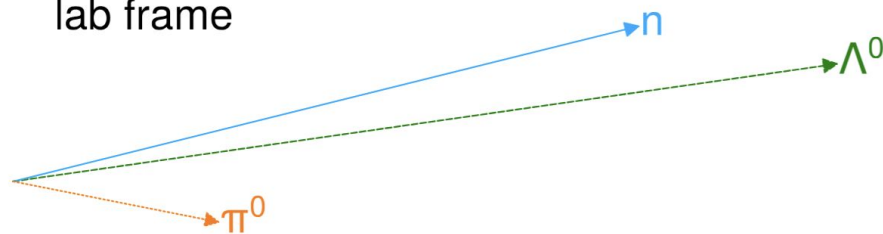
Polarization measurements

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

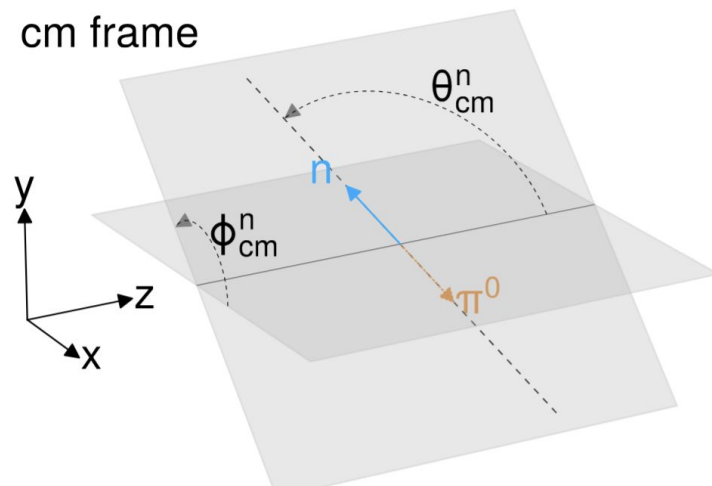
$$\frac{dP}{d\Omega_n} = 1 + \alpha \vec{\mathcal{P}}_{\text{cm}}^{\Lambda^0} \cdot \hat{p}_{\text{cm}}^n$$

$\alpha = 0.74 \pm 0.05$ from PDG

lab frame

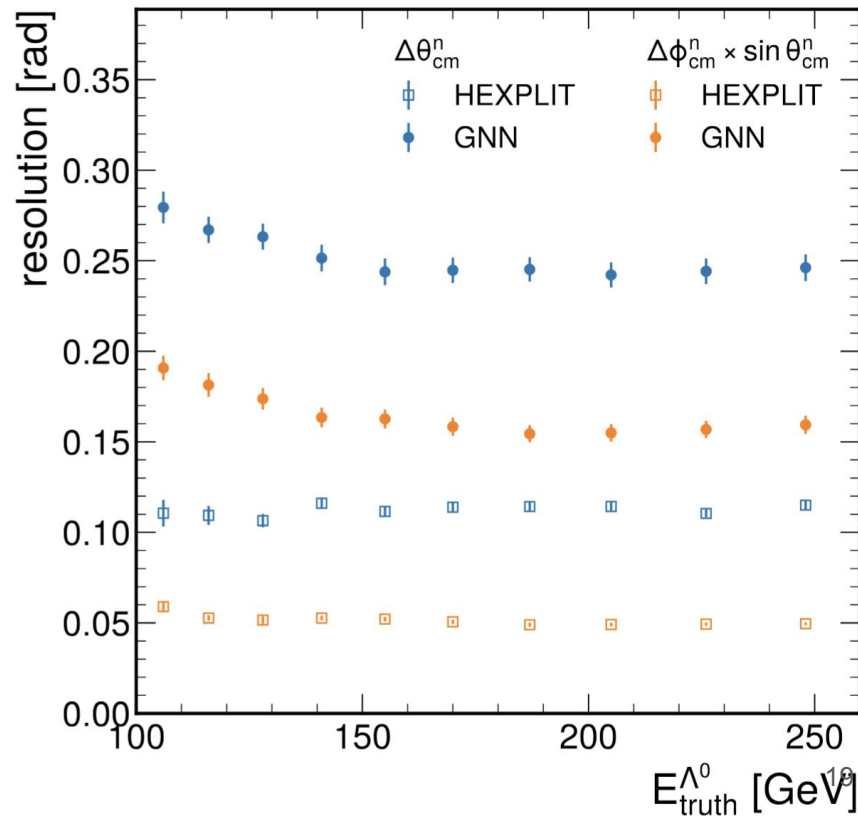


cm frame



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.



Conclusions

- We simulated $\Lambda^0 \rightarrow n \pi^0 \rightarrow n \gamma \gamma$ events, and reconstructed them with conventional and AI-based methods using the SiPM-on-tile ZDC as a stand-alone detector
 - Λ^0 decay position determined using novel IDOLA algorithm
 - Energy and pT resolutions surpass requirements from the YR for neutrons
 - Neutron-axis direction in CM determined within $O(100 \text{ mrad})$.
- Reconstruction of Λ has been implemented in EICrecon* and incorporated into detector benchmarks** for continuous integration of EIC software

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

**https://github.com/eic/detector_benchmarks/tree/master/benchmarks/zdc_lambda

Backup slides

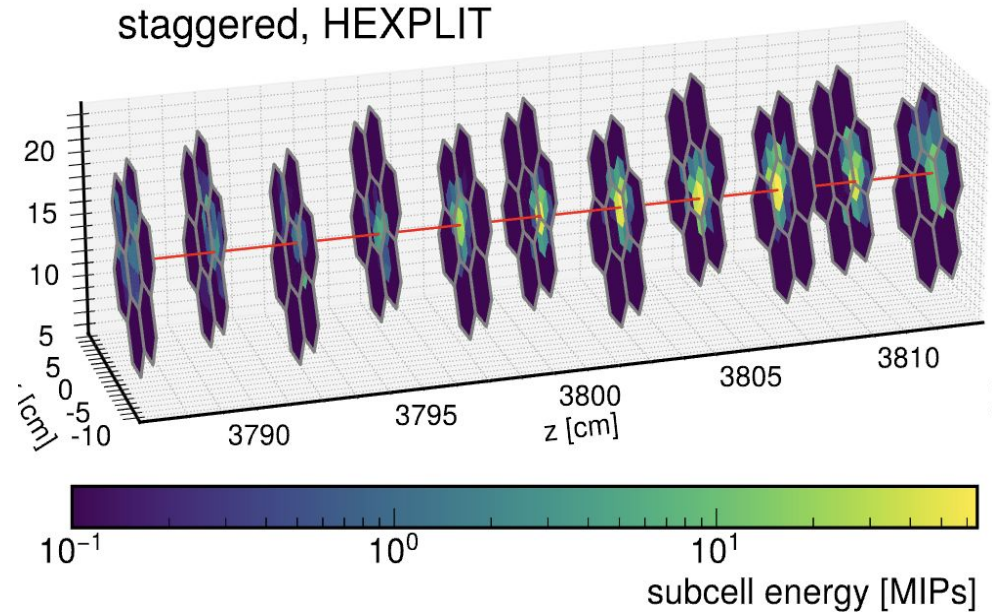
HEXPLIT algorithm*

- 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 layer: Δx and Δy cut
- Adjacent layers: $\Delta \varphi$ and $\Delta \eta$ cut

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
- Define seed hits for proto-clusters as those above threshold S , and include their neighboring hits in the protoclusters 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 protocluster)