Reconstruction of Λ Baryons in the Zero-Degree Calorimeter

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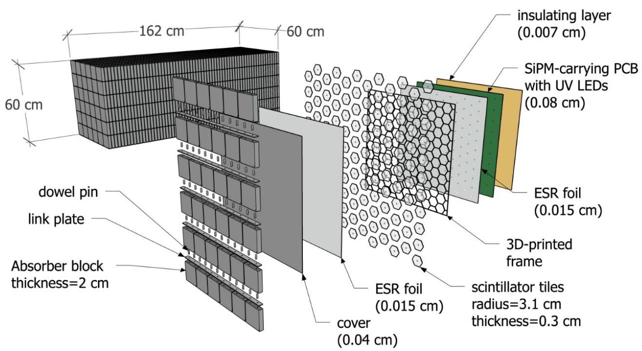
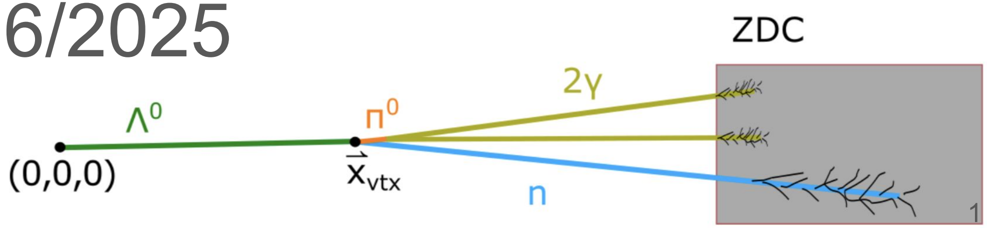
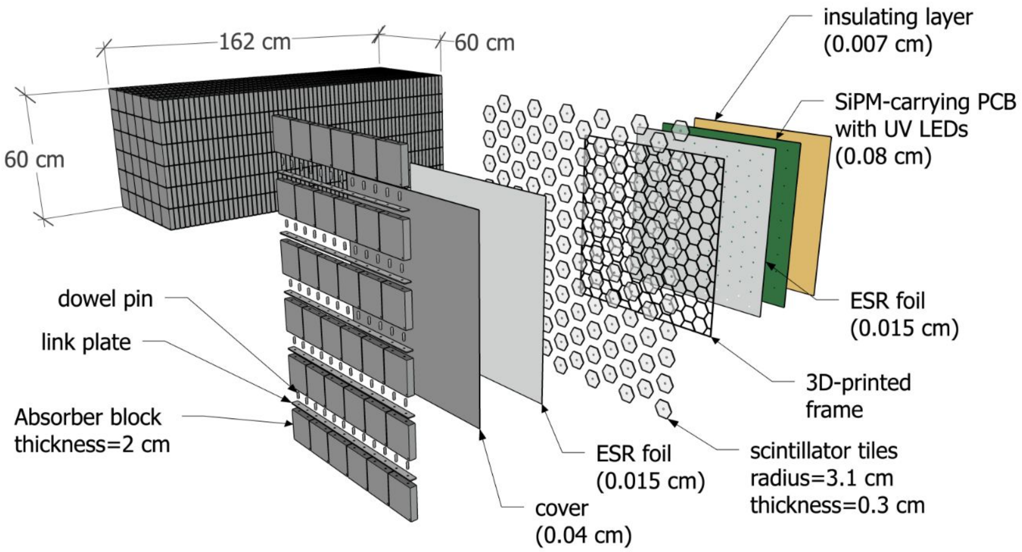
7/16/2025





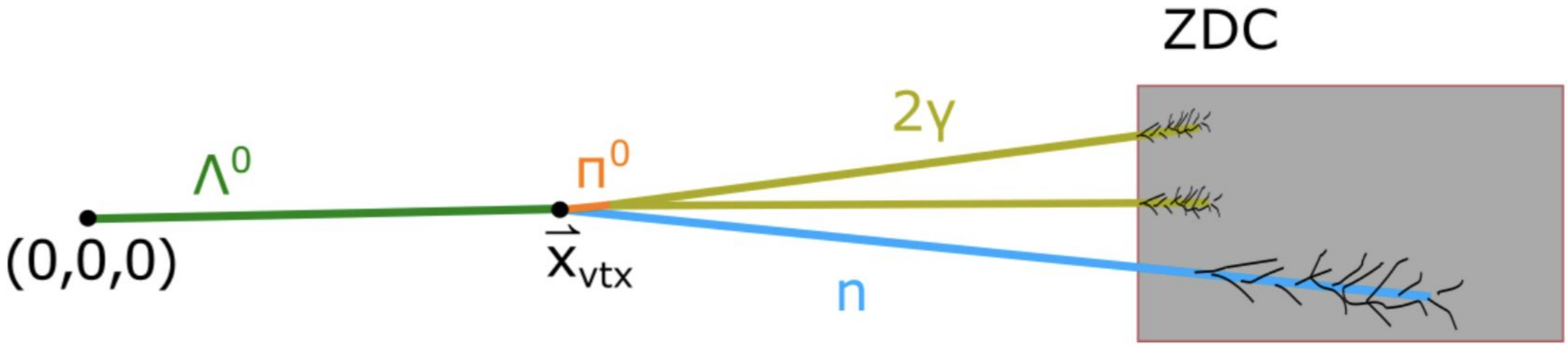
Zero-Degree Calorimeter

- 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



NIM A 1079 (2025) 170613

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 $\Lambda^0 \to n\pi^0$ using a high-granularity zero-degree calorimeter at the future electron-ion collider

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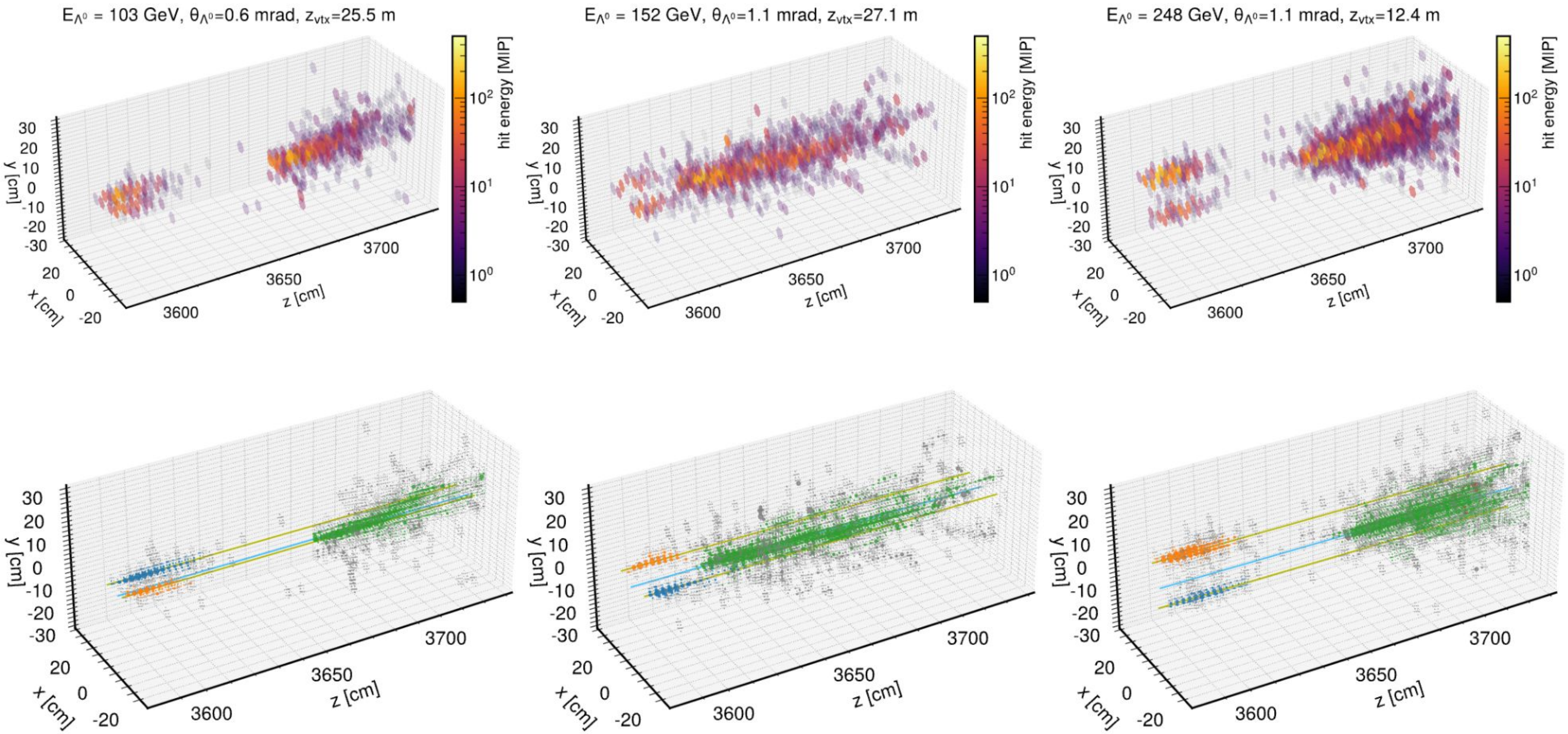
(Received 26 March 2025; accepted 13 May 2025; published 27 May 2025)

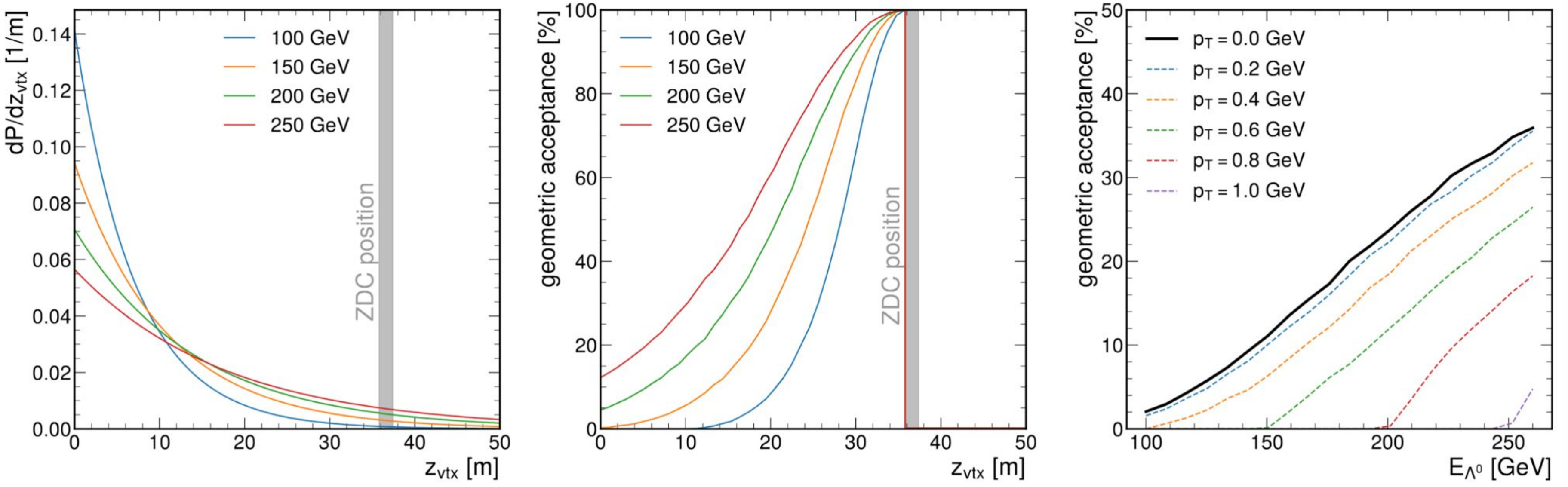
Key measurements at the future electron-ion collider (EIC), including first-of-their-kind studies of kaon structure, require the detection of Λ^0 at forward angles. We present a feasibility study of $\Lambda^0 \to n\pi^0$ measurements using a high-granularity zero-degree calorimeter to be located about 35 m from the interaction point. We introduce a method to address the unprecedented challenge of identifying Λ^0s 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 $\Lambda^0 \to n\pi^0$ will greatly extend the measurable energy range for the charged-decay channel $\Lambda^0 \to p\pi^-$, 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

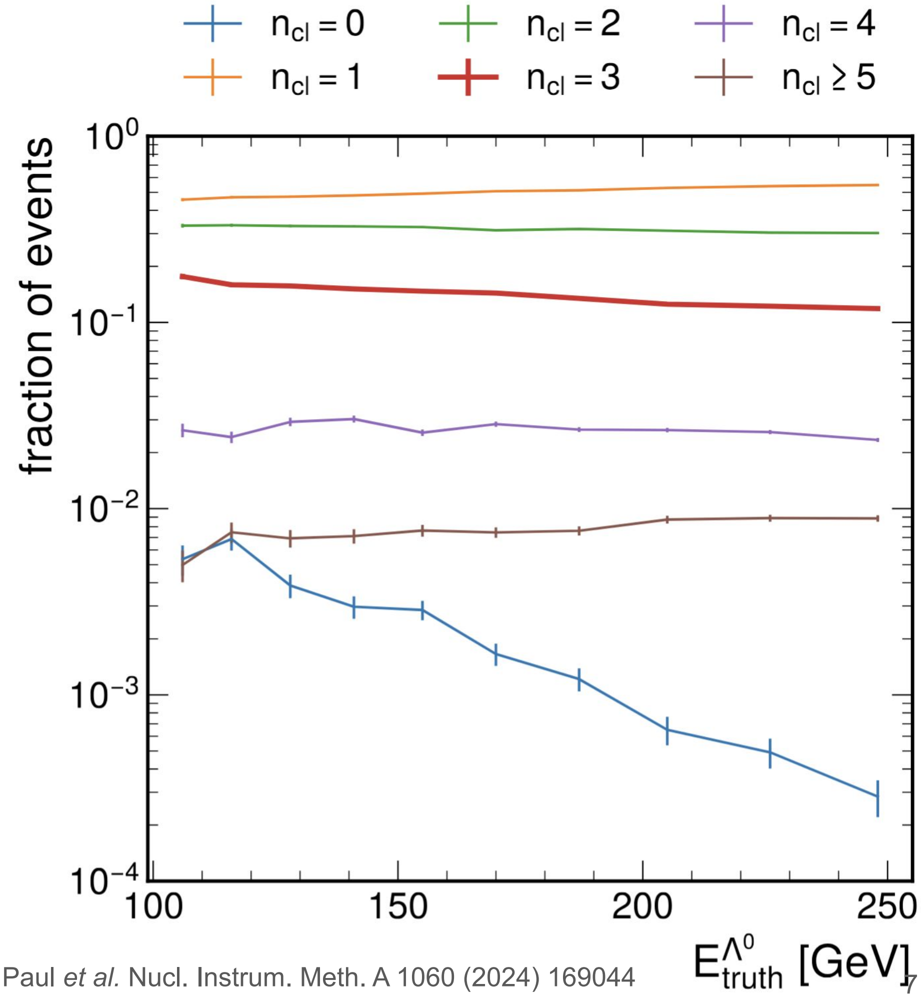


Geometric Acceptance



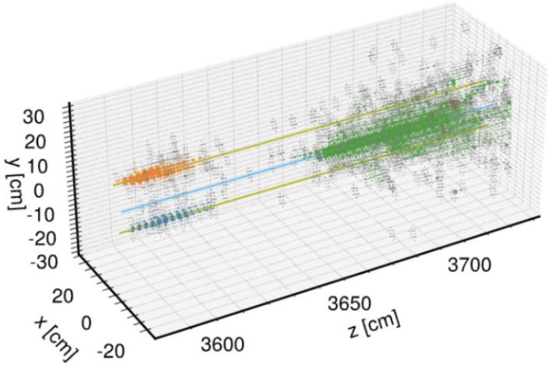
Clustering in conventional reconstruction

- 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



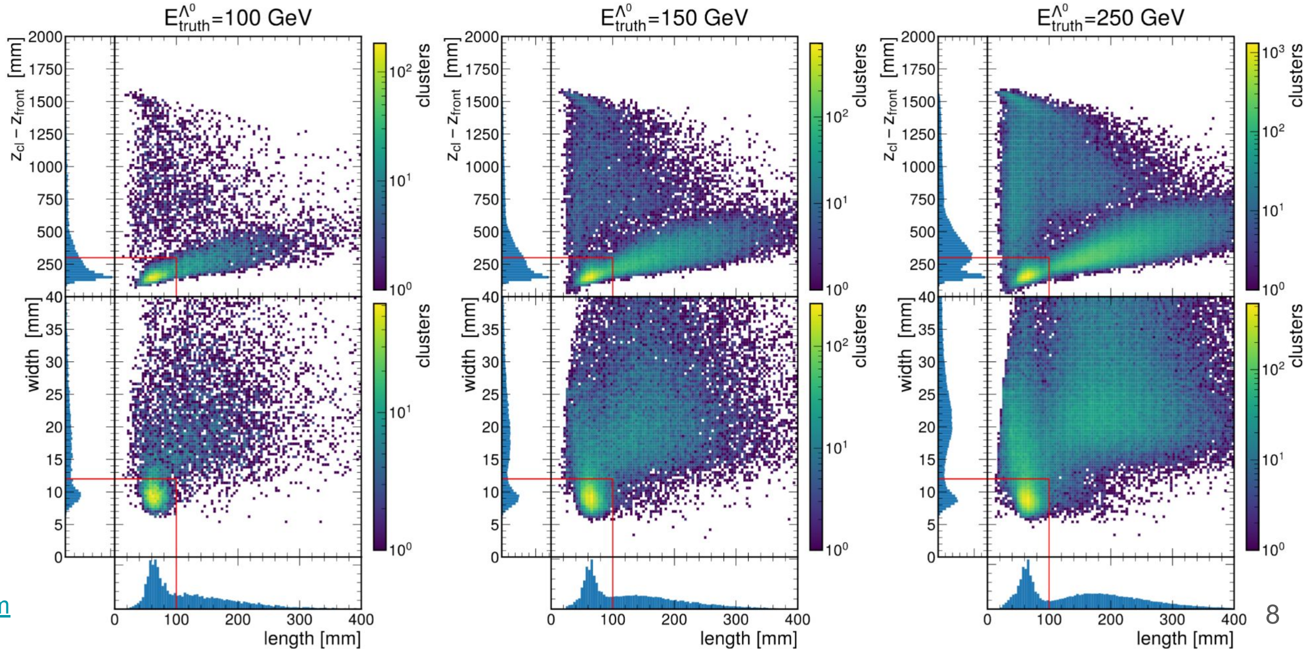
*S.J. Paul *et al.* Nucl. Instrum. Meth. A 1060 (2024) 169044
**ATLAS Collaboration, G. Aad *et al.* Eur. Phys. J. C 77 (2017) 490

Photon-cluster identification



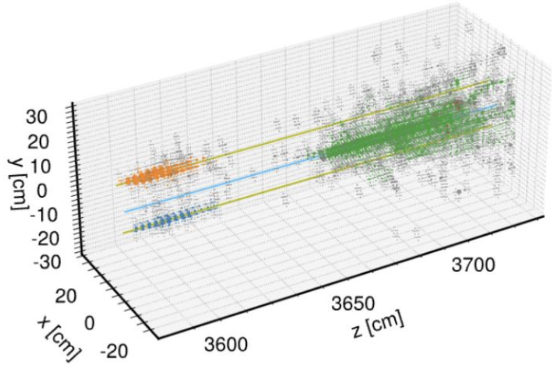
Clusters from photon showers:

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



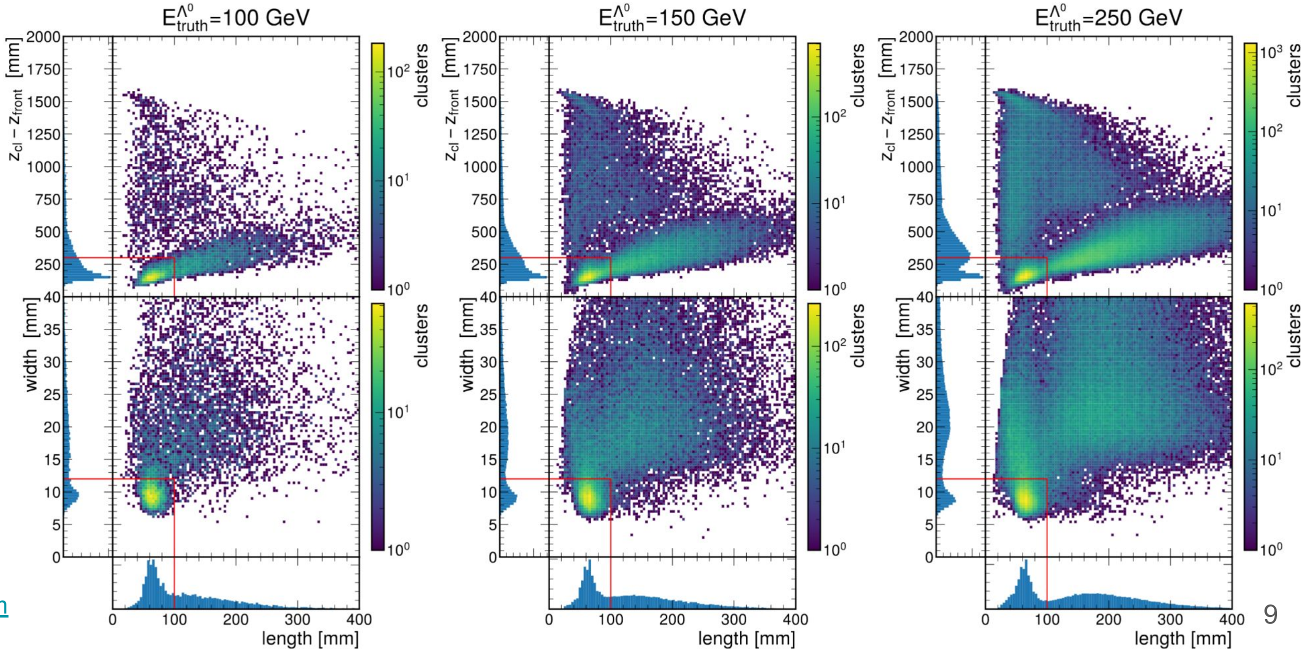
https://github.com/eic/EICrecon/blob/main/src/algorithms/reco/FarForwardNeutralsReconstruction.cc

Photon-cluster identification

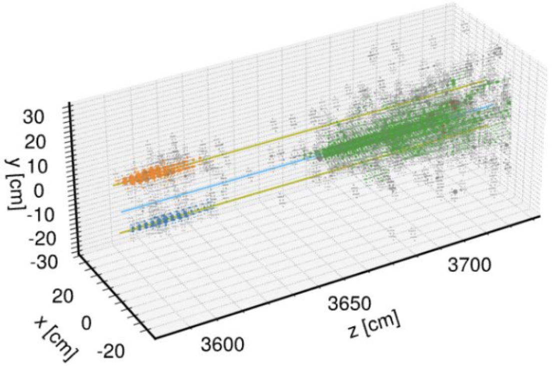


Clusters from photon showers:

- Start near the face of the detector
- Small longitudinal extent
    - Cut on the largest eigenvalue of the moment matrix (“length”) of the cluster
- https://github.com/eic/EICrecon/blob/main/src/algorithms/reco/FarForwardNeutralsReconstruction.cc

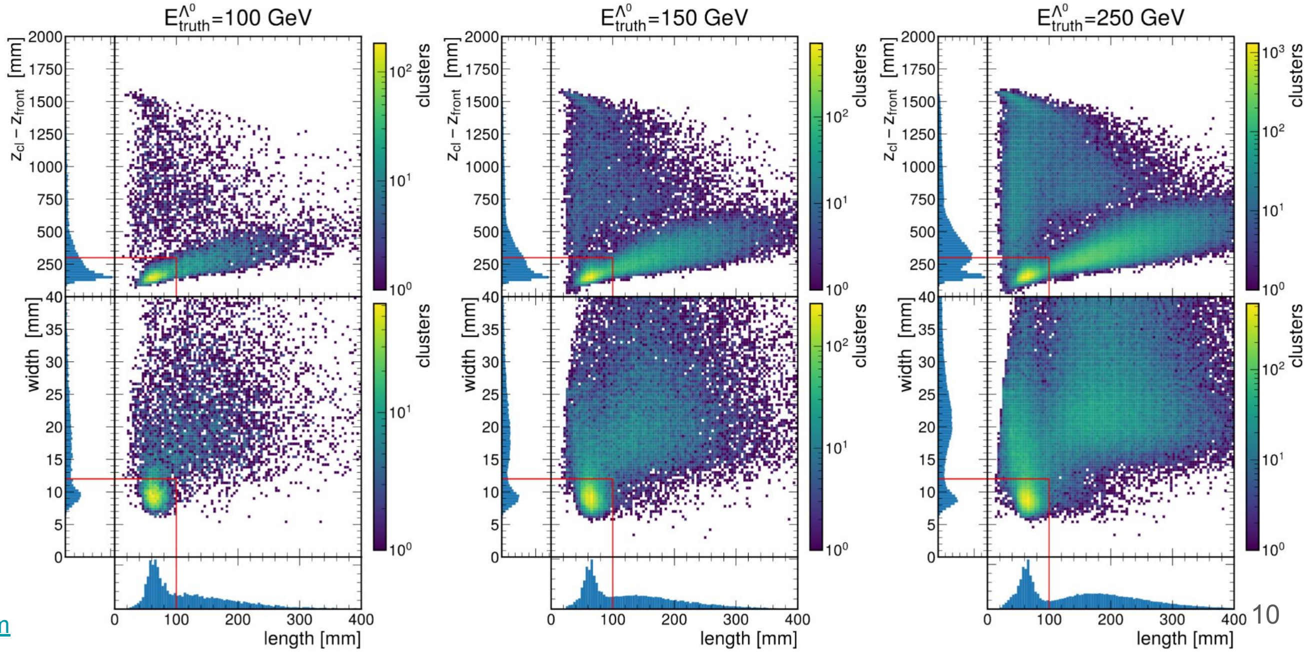


Photon-cluster identification



Clusters from photon showers:

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

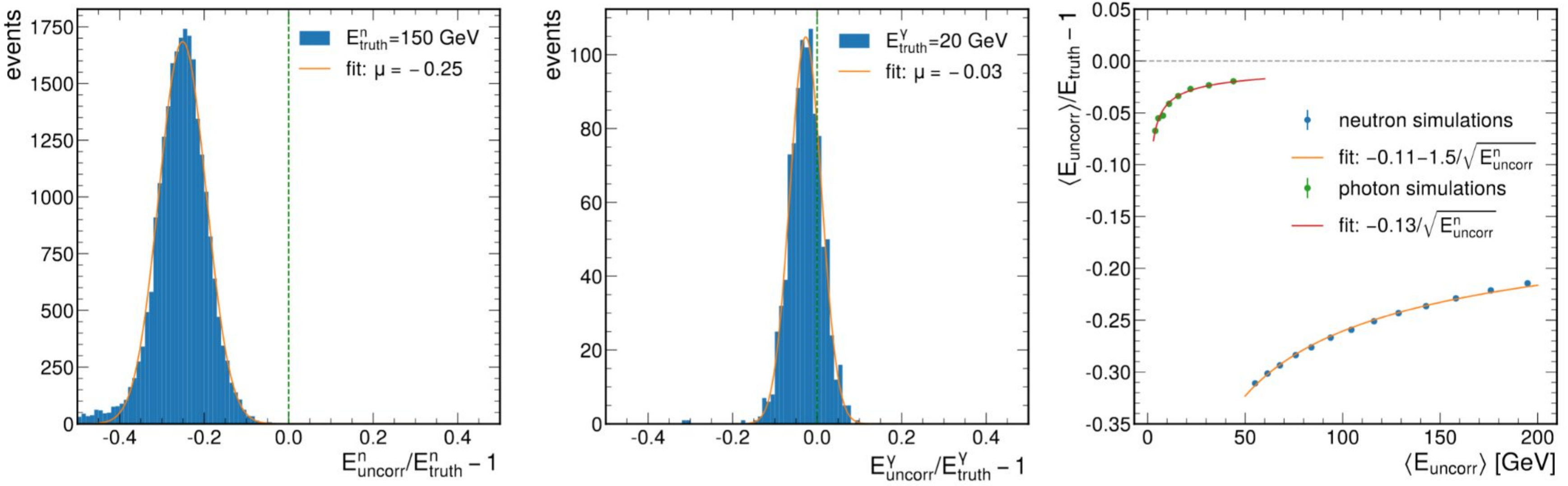


https://github.com/eic/EICrecon/blob/main/src/algorithms/reco/FarForwardNeutralsReconstruction.cc

Energy corrections

https://github.com/eic/EICrecon/blob/main/src/algorithms/reco/FarForwardNeutralsReconstruction.cc

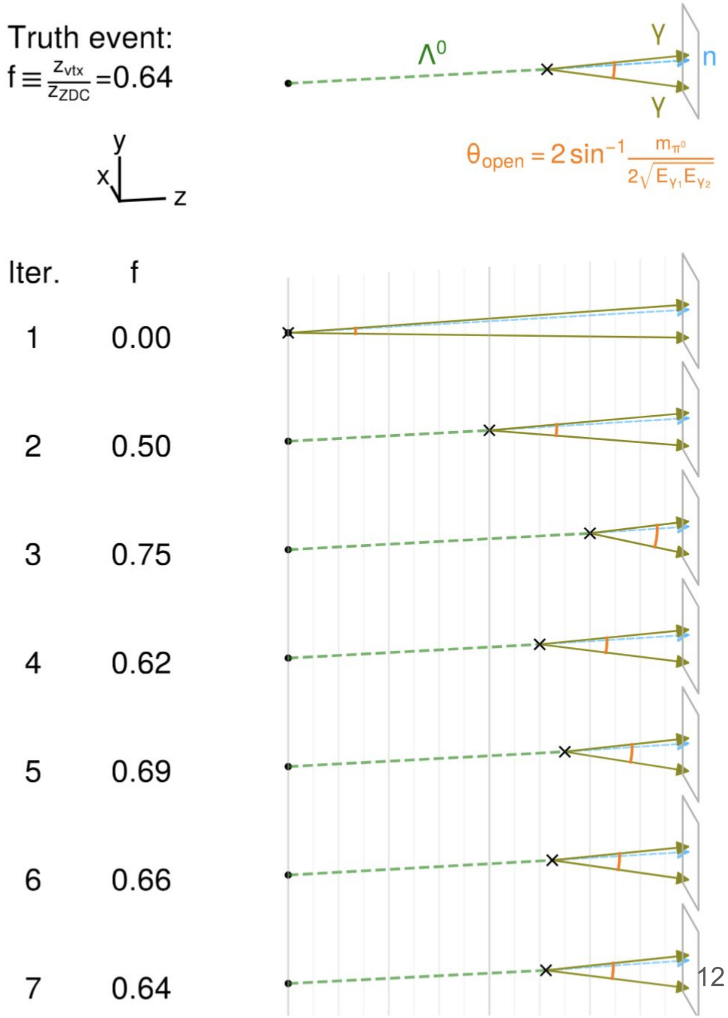
- Start with sum of energies of hits in cluster(s) associated with particle
- Divide by EM sampling fraction (determined with single-electron simulations)
- Apply energy correction (determined by a fit):
  - Hadronic vs EM scale (neutrons only)
  - not all energy of shower included in cluster (photons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



IDOLA algorithm

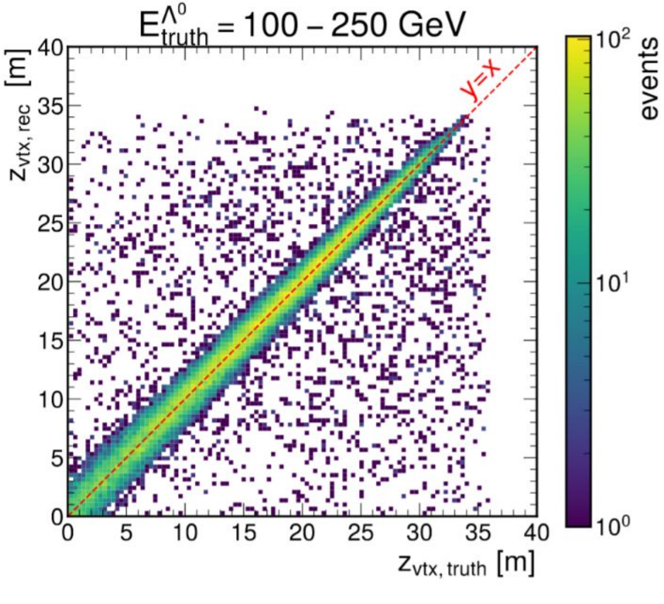
- “Iterative Determination of Origin in Lambda Analyses”
- Applies a binary search to find the longitudinal position of the lambda decay vertex such that the reconstructed π^0 mass matches the PDG value.
- Inspired in “kinematic fitting” but has aim to get displaced vertex, not improve energy or position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

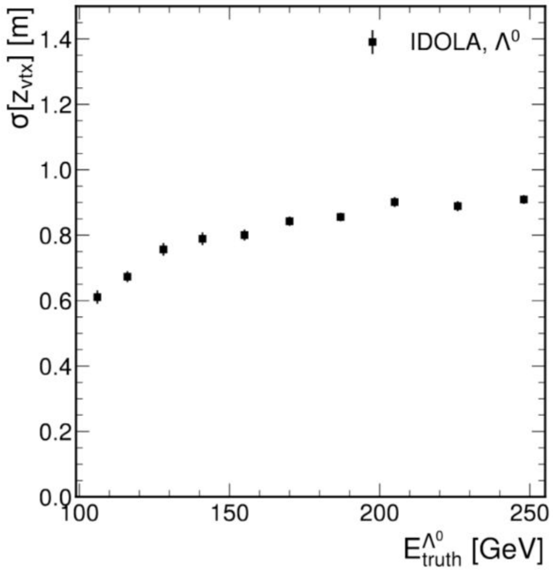
https://doi.org/10.5281/zenodo.14518550

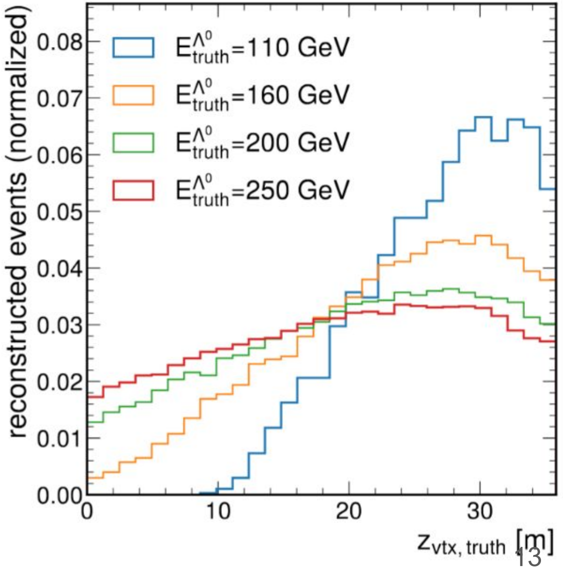


Results for the IDOLA algorithm

Resolution O(1 m)

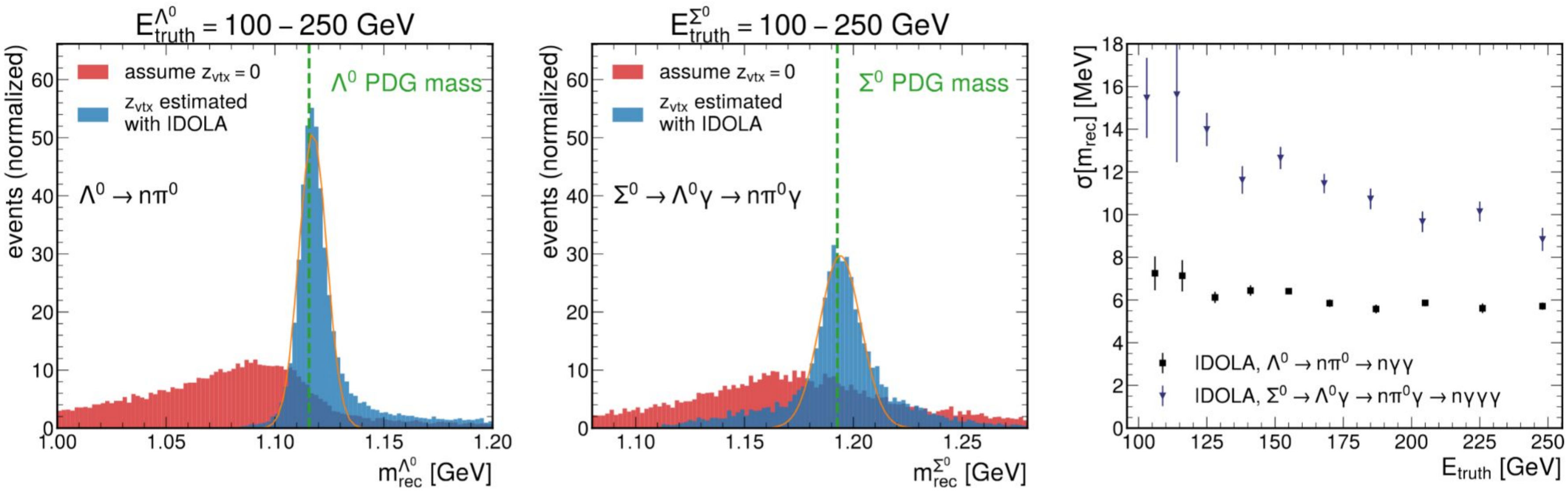






Results for the IDOLA algorithm (continued)

- 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



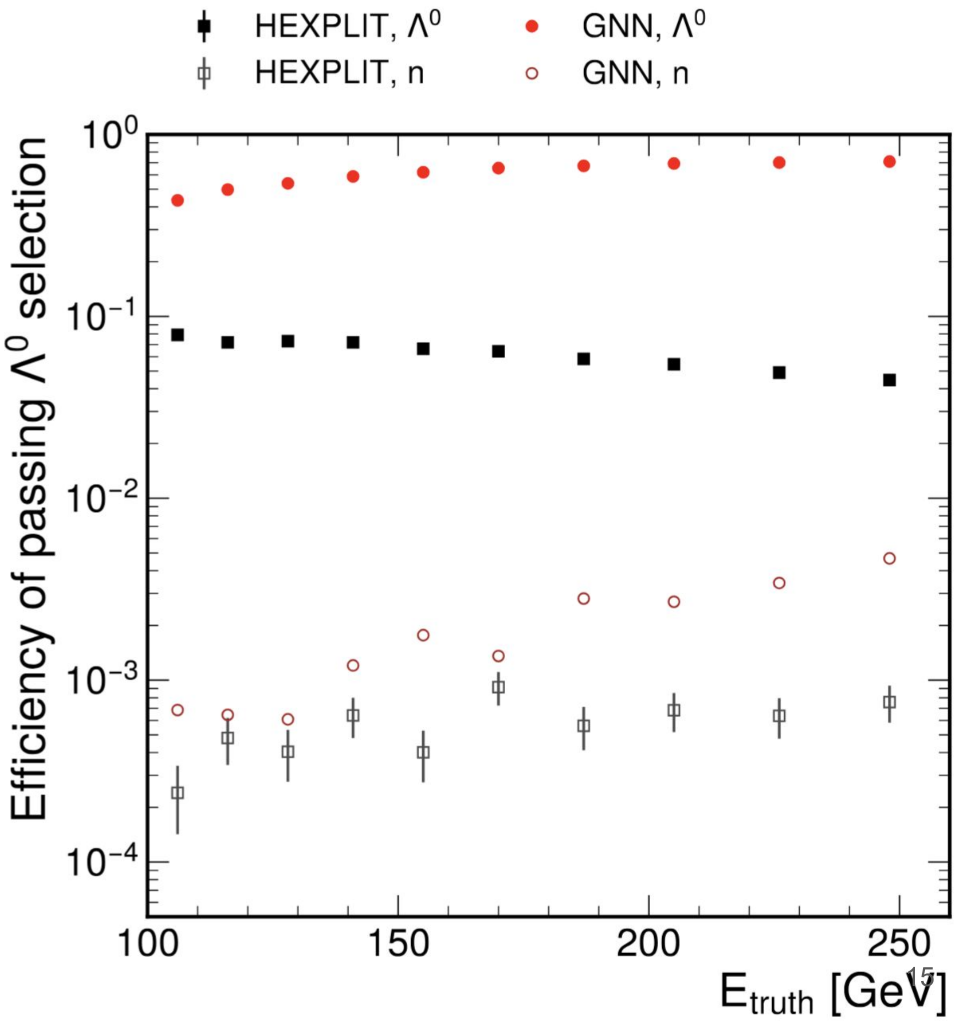
Λ^0 selection efficiency

Conventional recon:

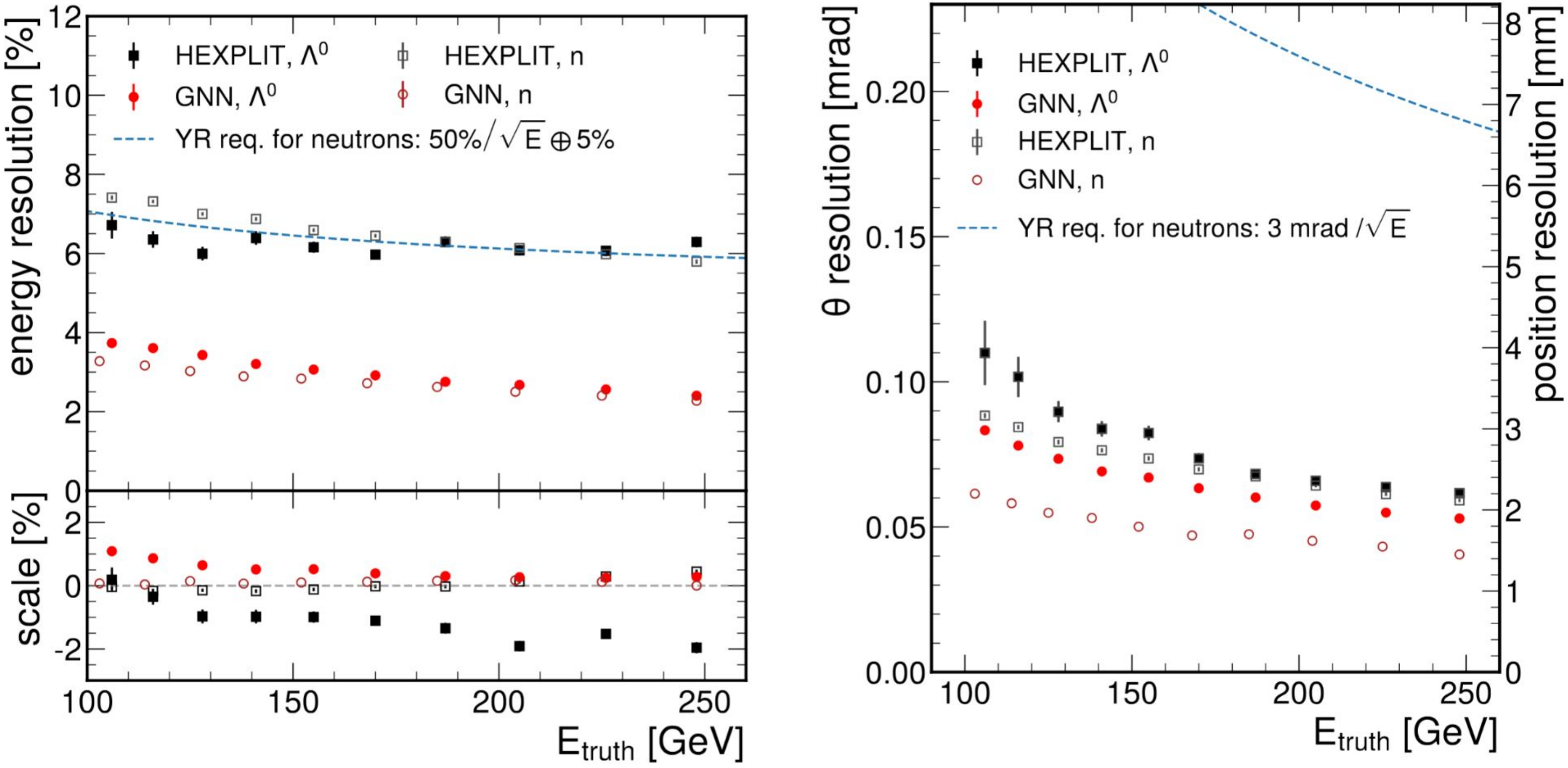
- Require ≥3 clusters, exactly 2 of which are photons
- Λ^0 mass should be reconstructed within 30 MeV of PDG value
- Efficiency: ~4-8%

AI/ML recon

- Graph Neural Network
- Uses a classifier trained to distinguish Λ^0 events from single-neutron events
- Efficiency: ~40-70%



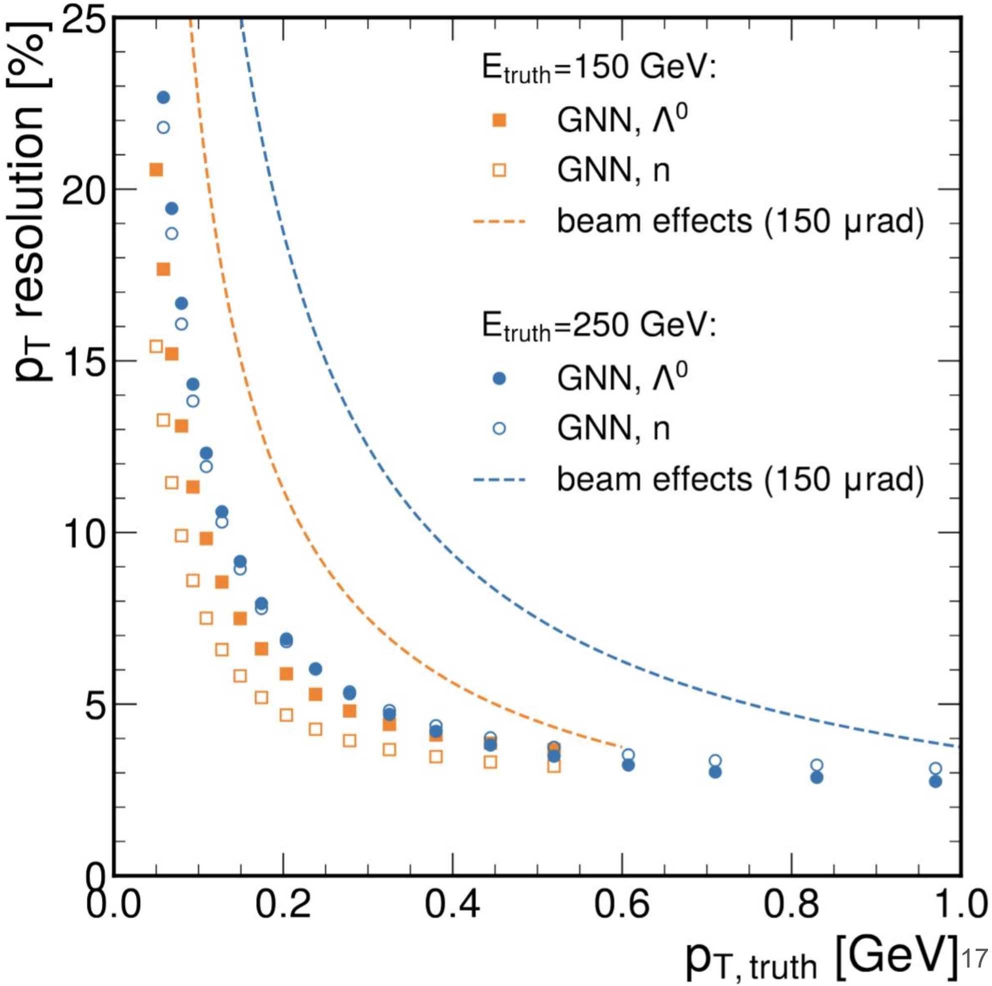
Energy and polar angles reconstructed better than YR requirements for neutrons



p_T resolution

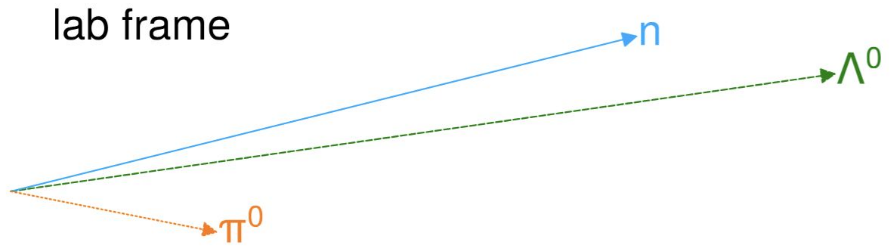
Dominated by beam effects

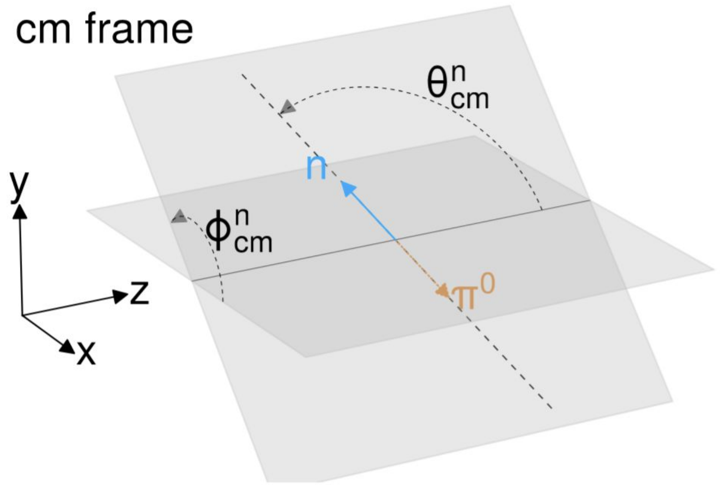
$$\frac{\Delta p_T}{p_T} \approx \frac{\Delta E}{E} \oplus \frac{E\,\Delta\theta}{p_T} \oplus \frac{E\,\sigma_{\text{beam}}}{p_T}.$$



Polarization measurements

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



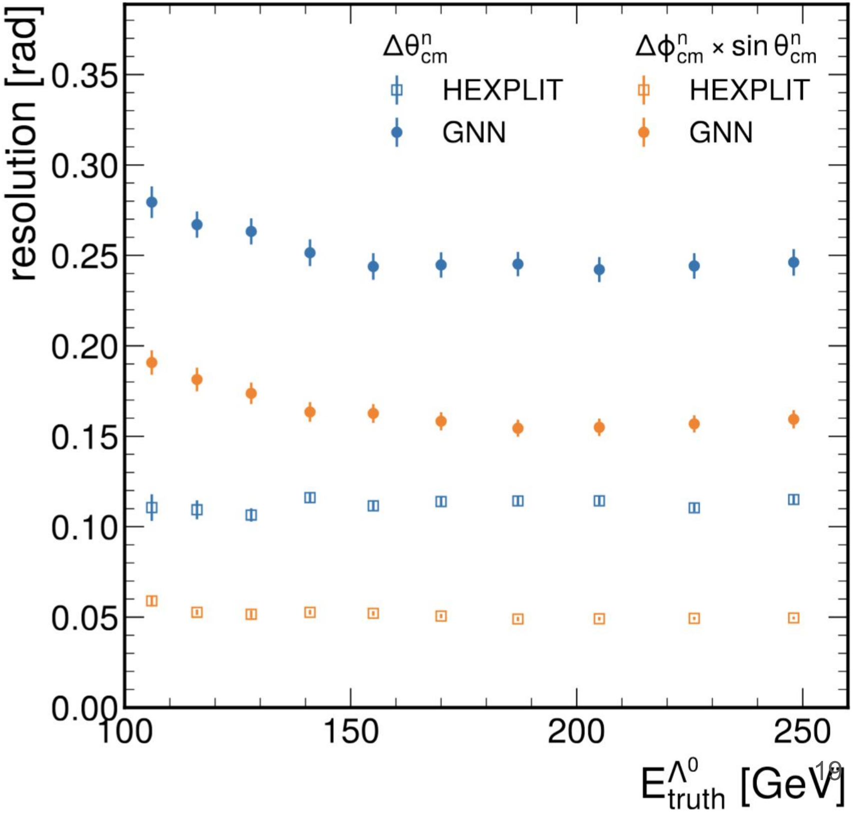


$$\frac{dP}{d\Omega_n} = 1 + \alpha \vec{\mathscr{P}}^{\Lambda^0}_{\mathrm{cm}} \cdot \hat{p}^n_{\mathrm{cm}}$$

α=0.74±0.05 from PDG

Neutron-axis resolution

- Determined using Gaussian fits to $\Delta\theta^{n}_{cm}$ and $\Delta\phi^{n}_{cm} \times \sin\theta^{n}_{cm}$ 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 $\Lambda^0 \to n\pi^0 \to n\gamma\gamma$ 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 mrad).
  - Compliments $\Lambda \to p\pi$- recon with near-beamline trackers at low energy
- Reconstruction of Λ has been implemented in EICrecon* and incorporated into detector benchmarks** for continuous integration of EIC software

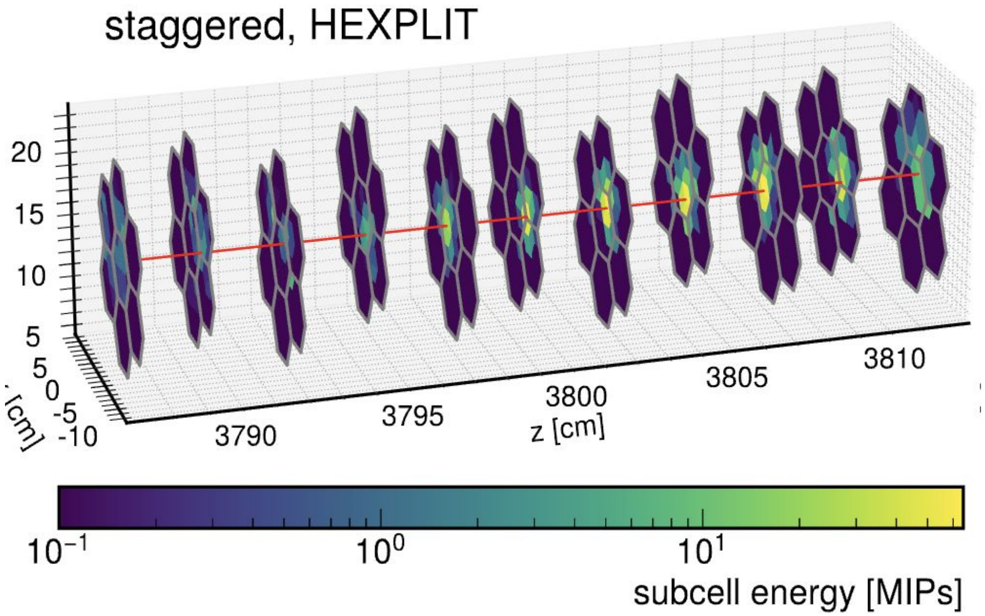
*https://github.com/eic/EICrecon/blob/main/src/algorithms/reco/FarForwardLambdaReconstruction.cc

**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)

https://github.com/eic/EICrecon/blob/main/src/algorithms/calorimetry/ImagingTopoCluster.h