Λ detection in the ZDC

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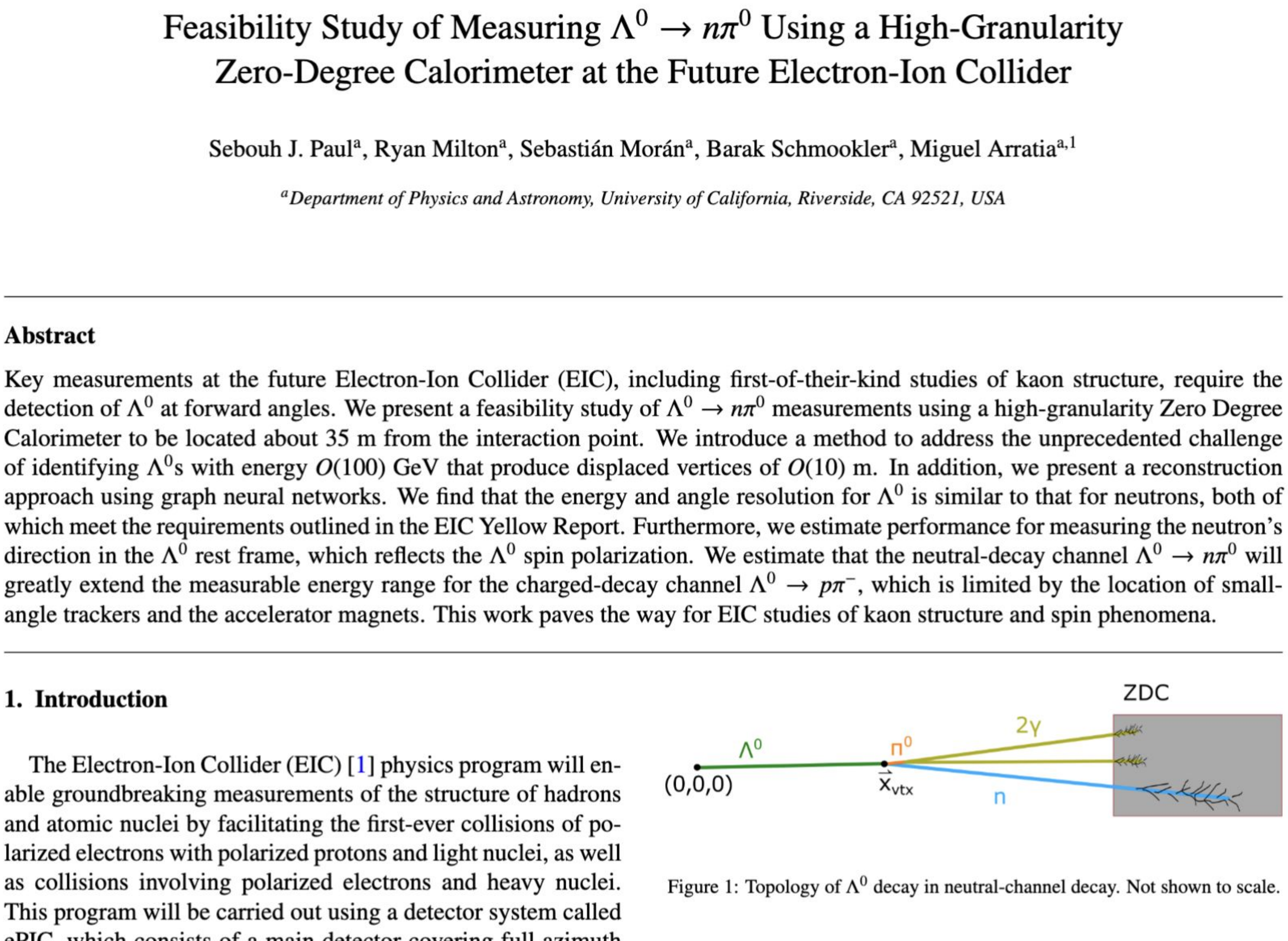

Feasibility Study of Measuring $\Lambda^0 \rightarrow n\pi^0$ Using a High-Granularity Zero-Degree Calorimeter at the Future Electron-Ion Collider

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Abstract

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^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 $\Lambda^0 \rightarrow n\pi^0$ 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.

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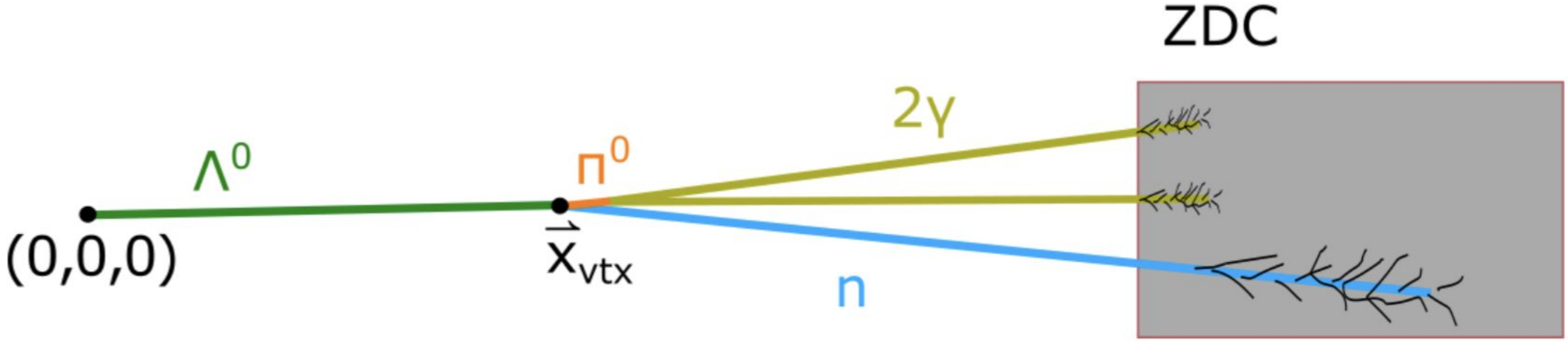
1. Introduction

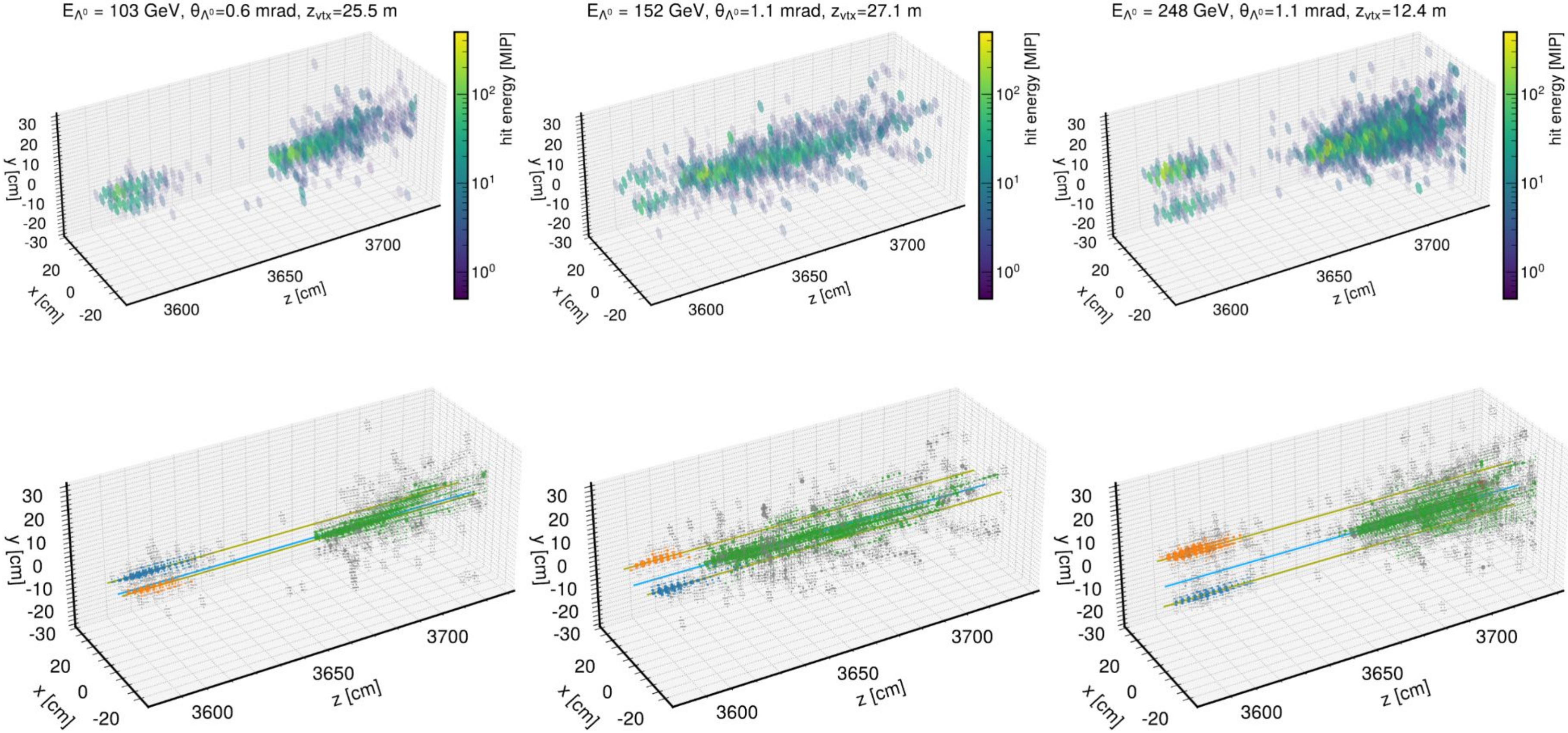
The Electron-Ion Collider (EIC) [1] physics program will enable groundbreaking measurements of the structure of hadrons and atomic nuclei by facilitating the first-ever collisions of polarized electrons with polarized protons and light nuclei, as well as collisions involving polarized electrons and heavy nuclei. This program will be carried out using a detector system called

Figure 1: Topology of Λ^0 decay in neutral-channel decay. Not shown to scale.

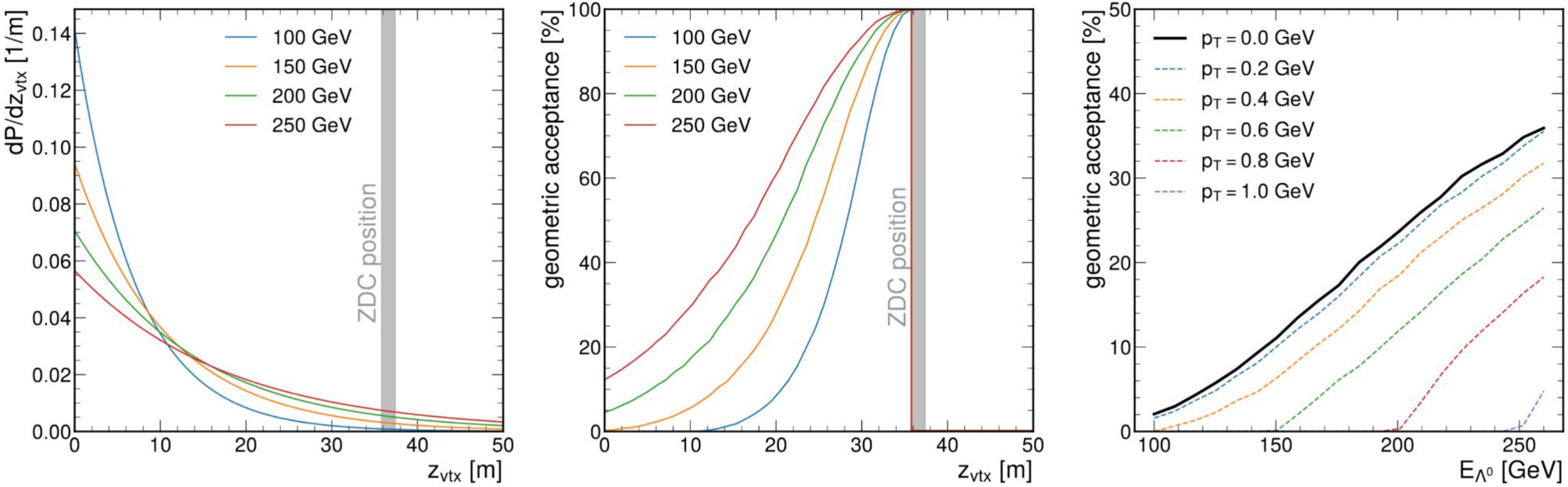
Event topology



Example events

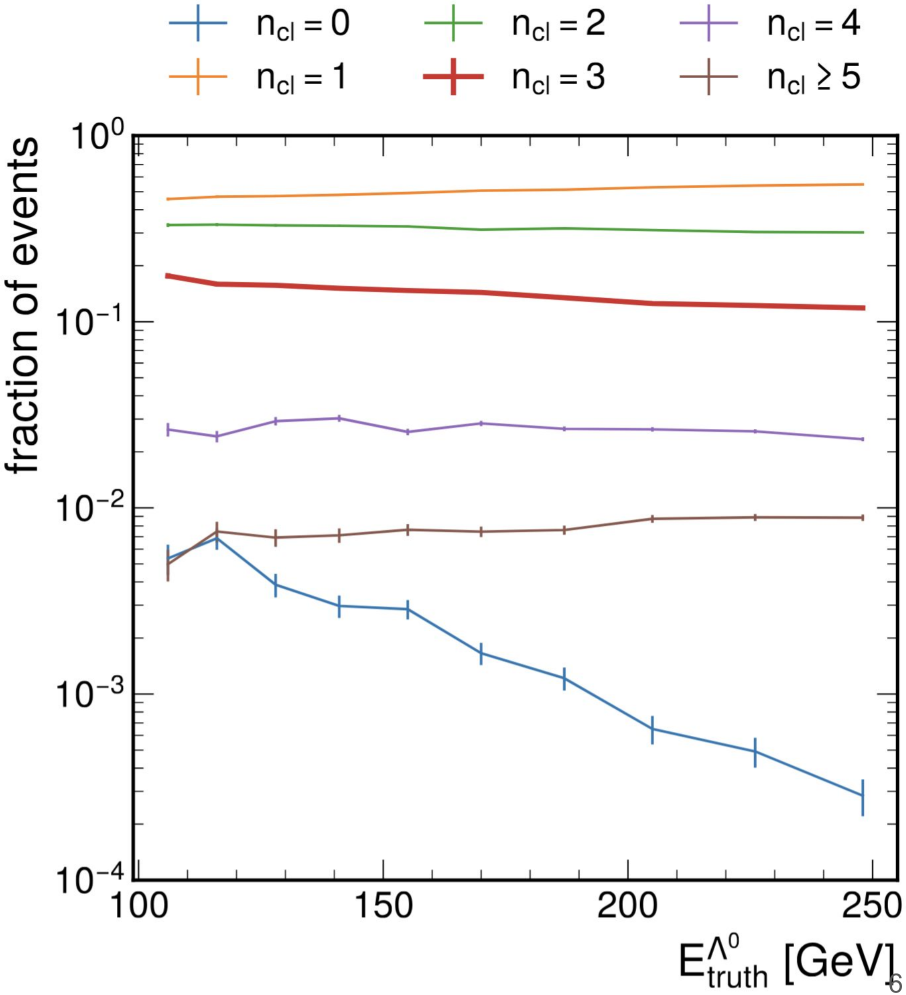


Geometric Acceptance



Clustering in conventional reconstruction

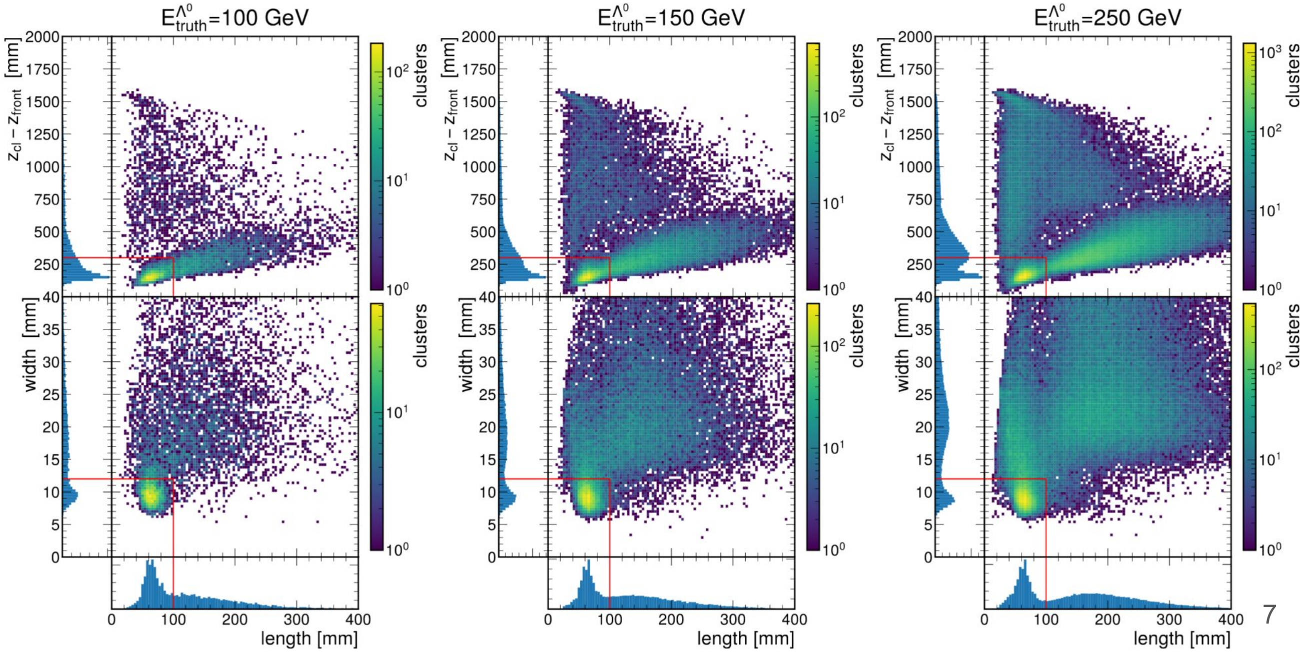
- We used the HEXPLIT algorithm followed by topoclustering algorithm to get the clusters
- Ideally we want to have 3 or more clusters (2 of which are from the photons, and the rest from the neutron).
- About O(10%) of events within acceptance have 3 or more clusters
- This may improve with further modifications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



Photon-cluster identification

Clusters from photon showers:

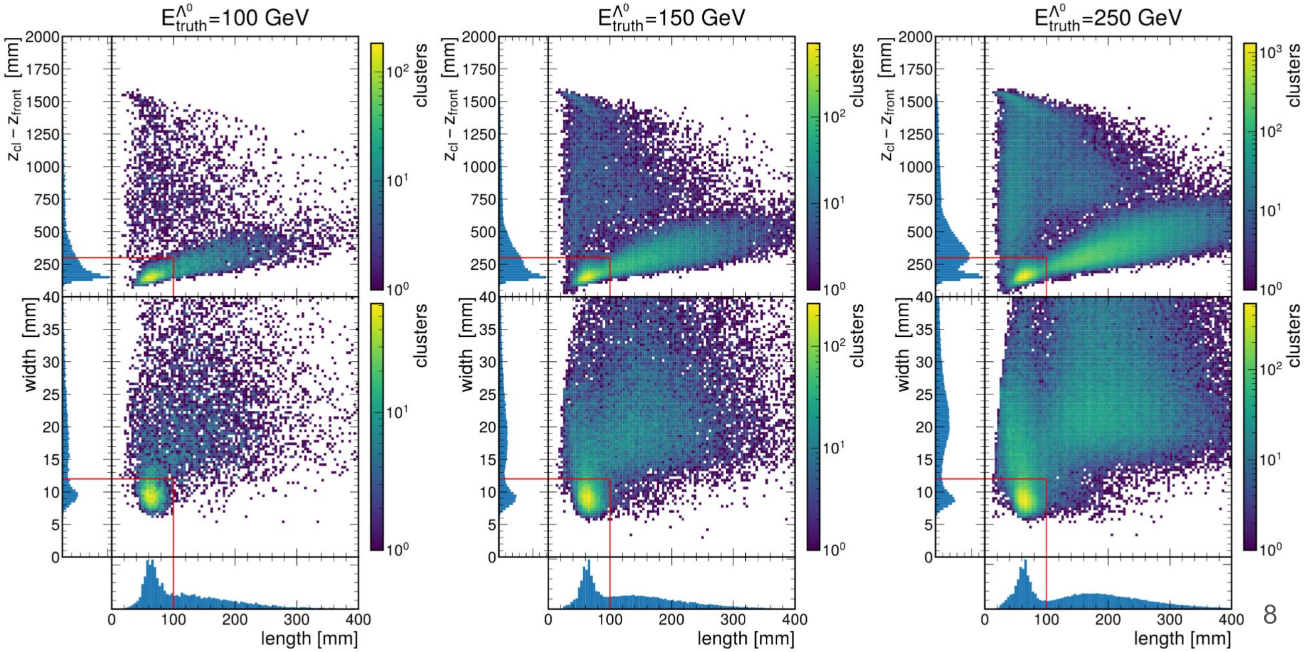
- Start near the face of the detector
  - Cut on the longitudinal position of the log-weighted CoG of the cluster)



Photon-cluster identification

Clusters from photon showers:

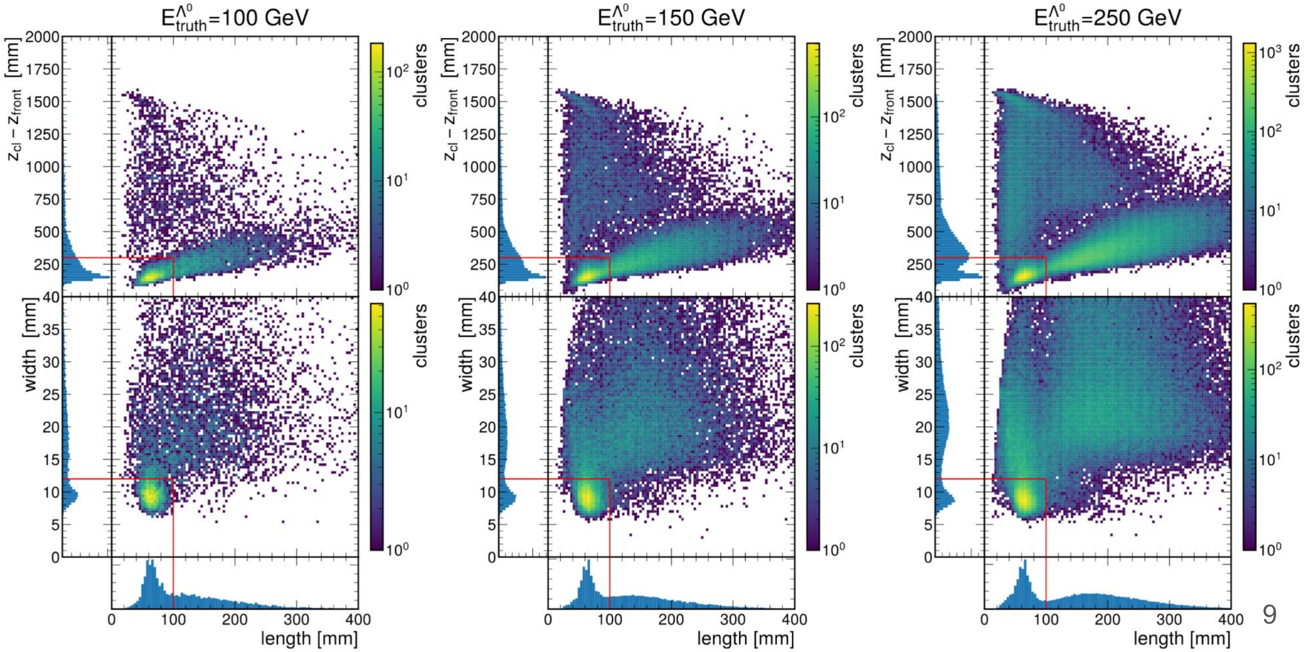
- Start near the face of the detector
- Small longitudinal extent
    - Cut on the largest eigenvalue of the moment matrix (“length”) of the cluster
-



Photon-cluster identification

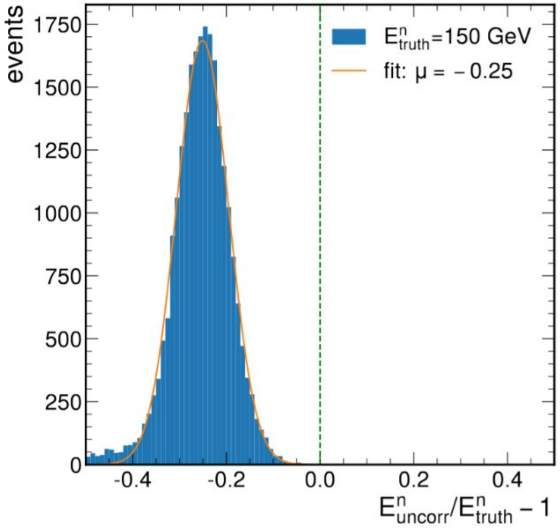
Clusters from photon showers:

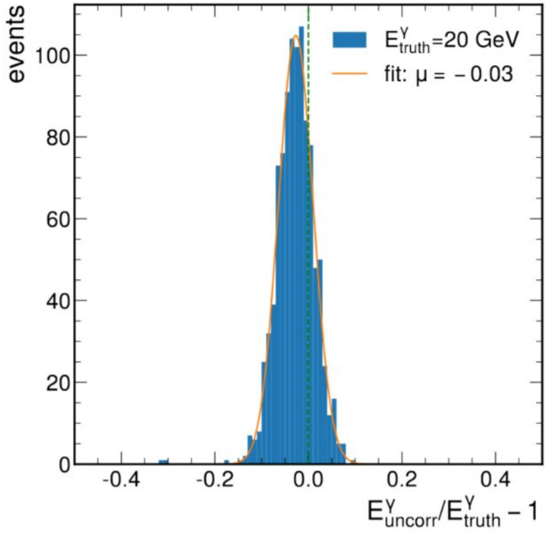
- Start near the face of the detector
- Small longitudinal extent
- Small transverse size:
  - Cut on the second-largest eigenvalue of the ("width").

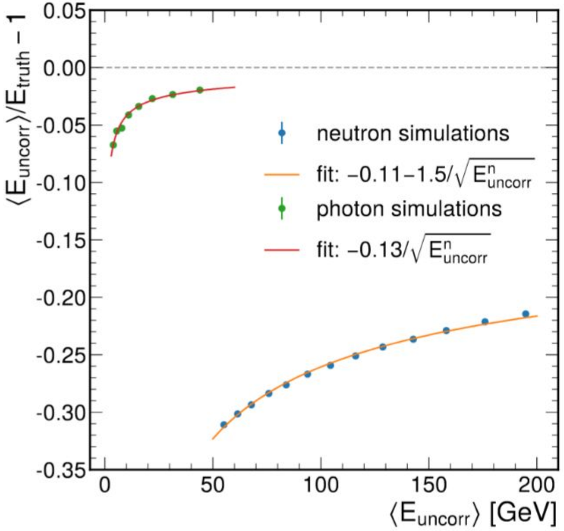


Energy corrections

- 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)

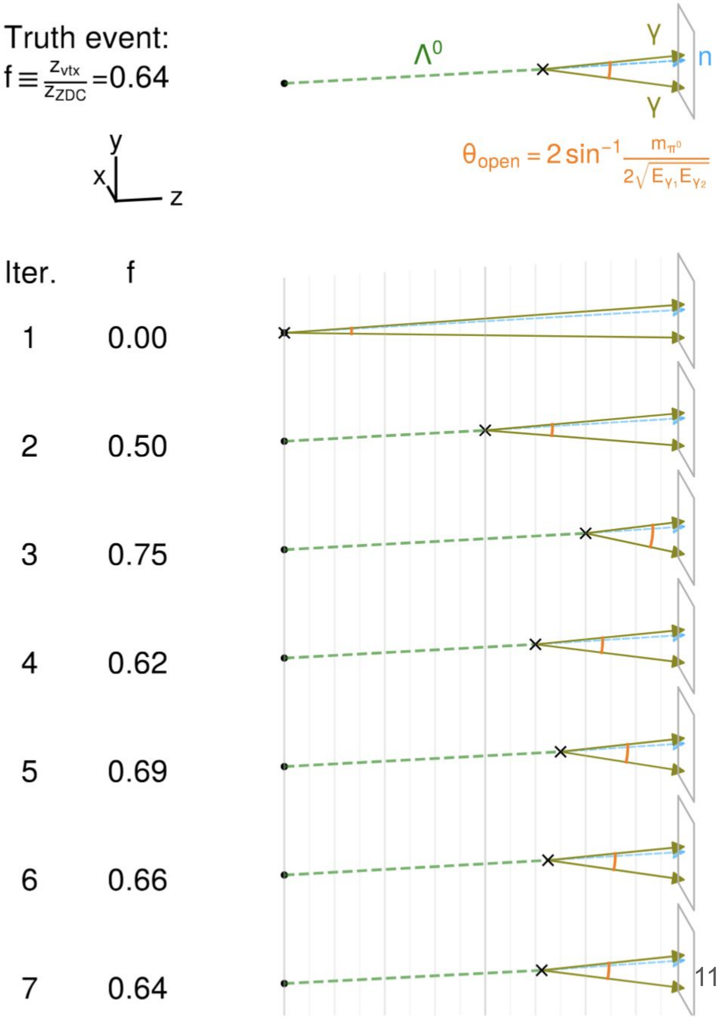






IDOLA algorithm

- “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.



Truth event:

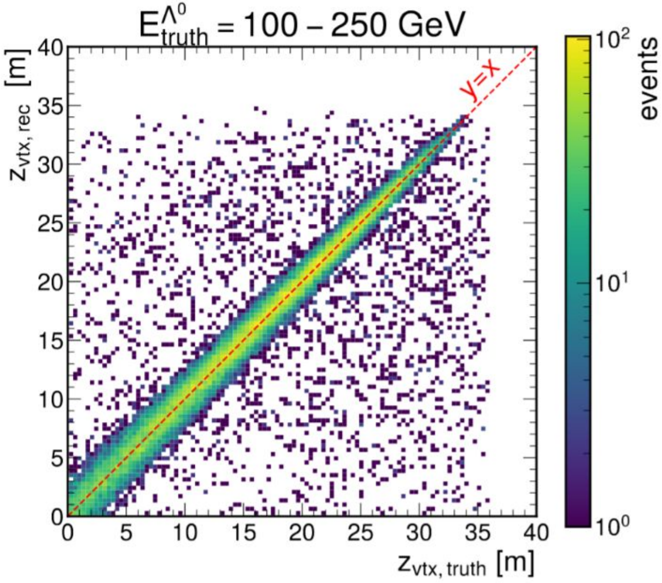
$f \equiv \frac{z_{vtx}}{z_{ZDC}} = 0.64$

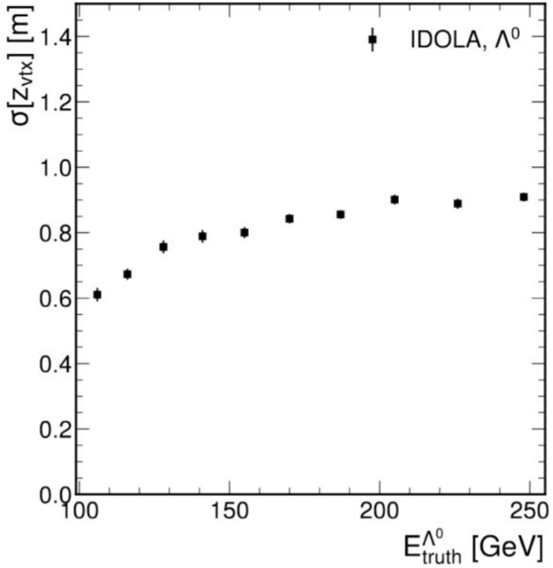
$\theta_{open} = 2\sin^{-1}\frac{m_{\pi^0}}{2\sqrt{E_{\gamma_1}E_{\gamma_2}}}$

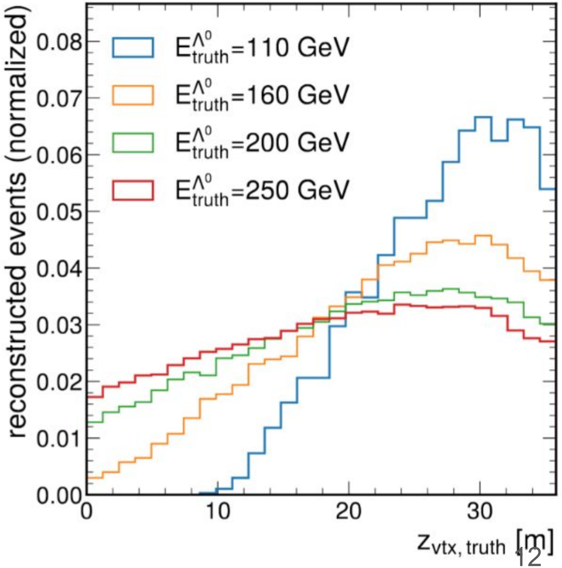
Iter.	f
1	0.00
2	0.50
3	0.75
4	0.62
5	0.69
6	0.66
7	0.64

Results for the IDOLA algorithm

Resolution O(1 m)

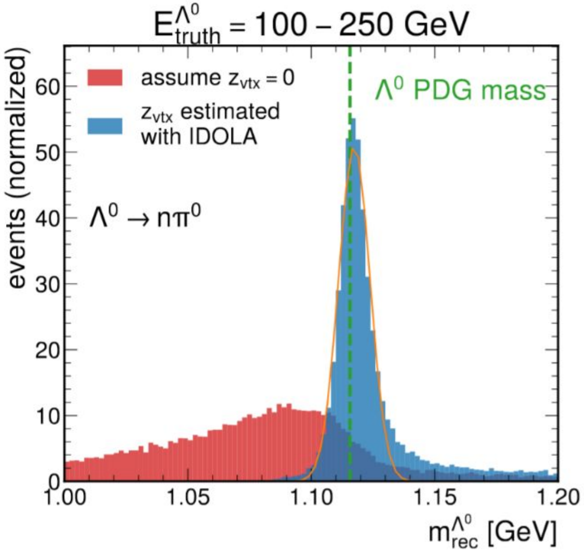


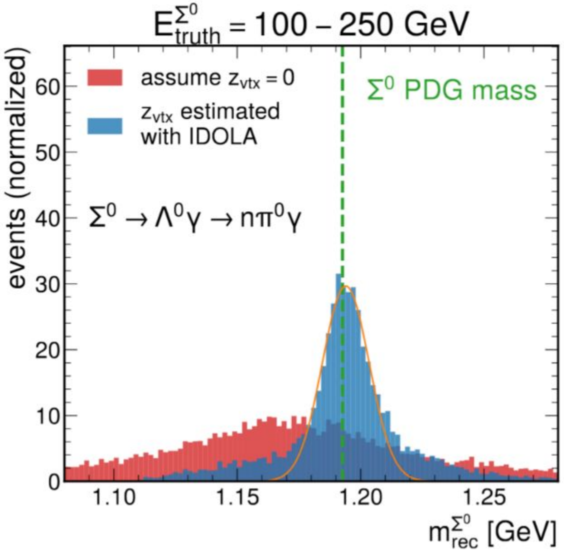


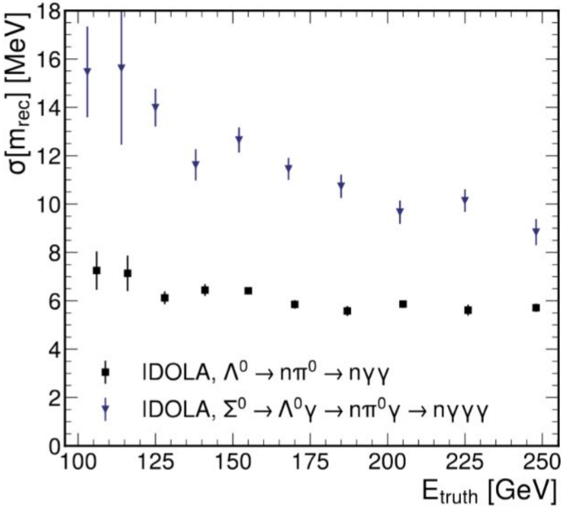


Results for the IDOLA algorithm (continued)

- Reconstructs mass of Λ^0 to within about 6-8 MeV
- Somewhat worse resolution for Σ^0, but not bad either







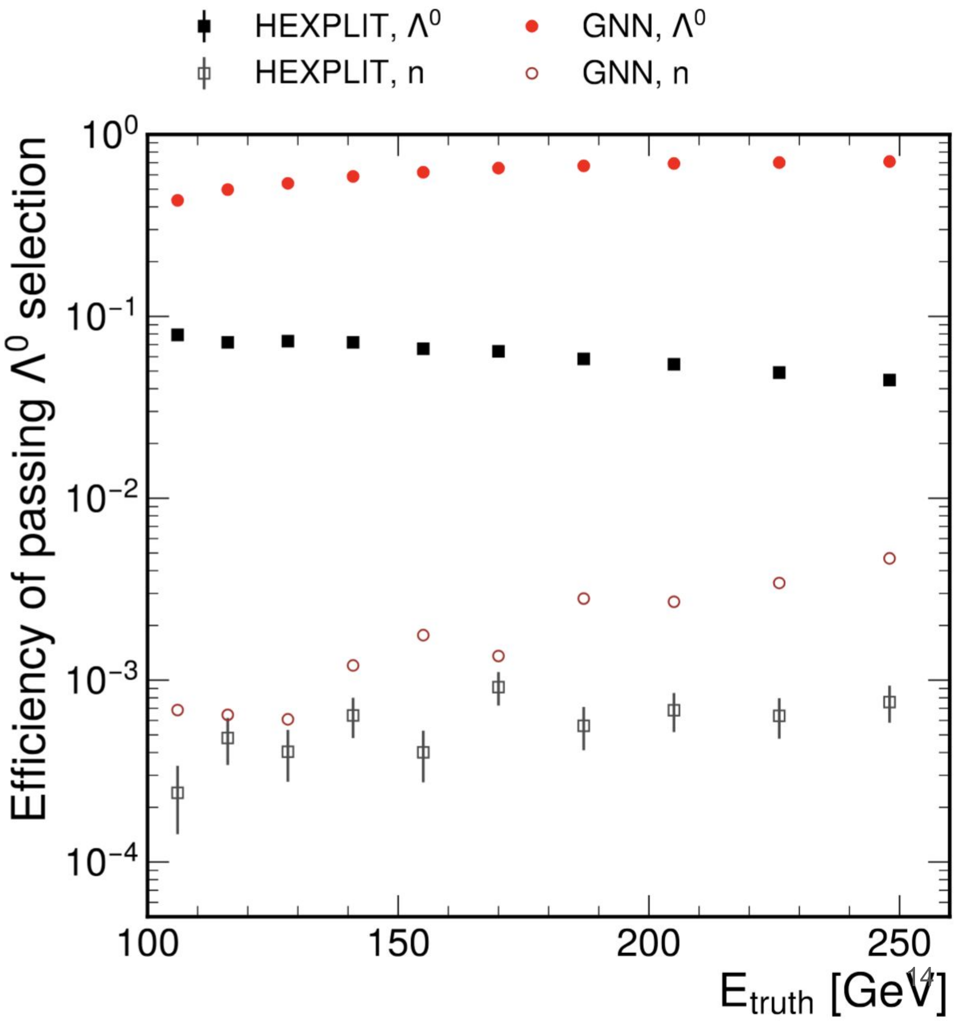
Λ^0 selection efficiency

Conventional recon:

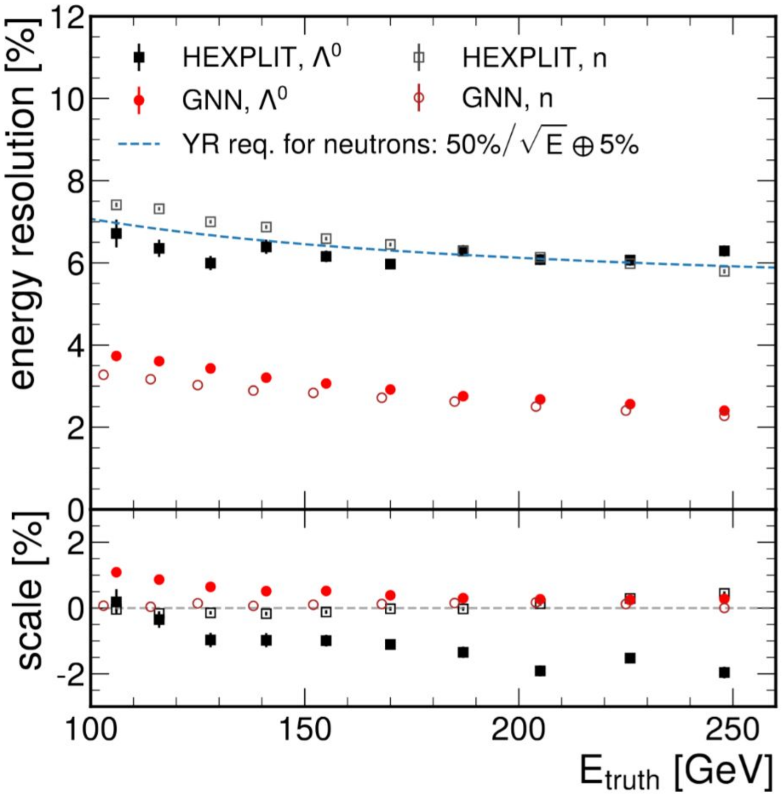
- Require ≥3 clusters, exactly 2 of which are photons
- Λ^0 mass should be reconstructed within 30 MeV of PDG value
- Efficiency: ~4-8%

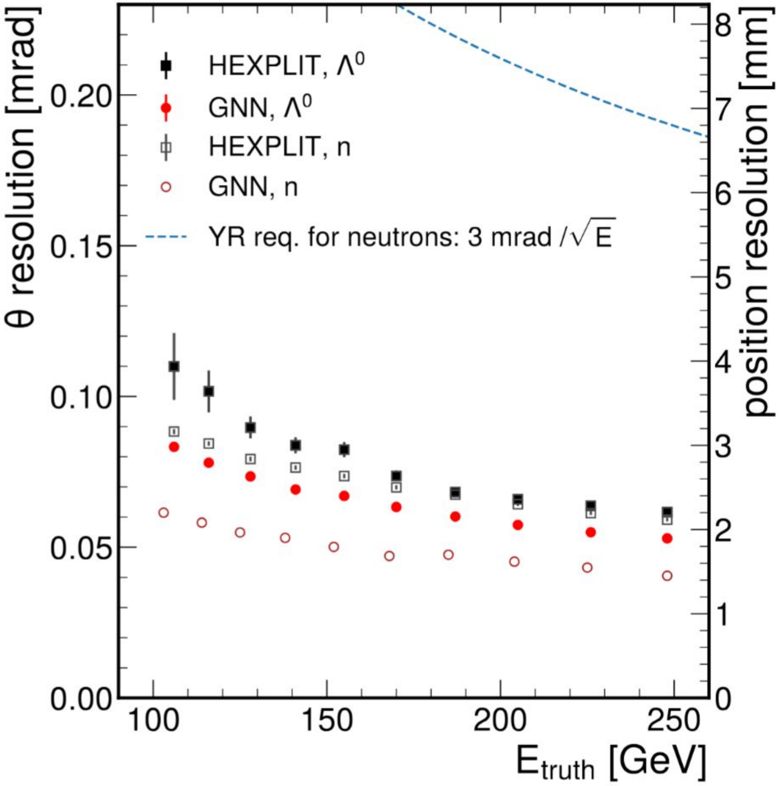
AI/ML recon

- 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

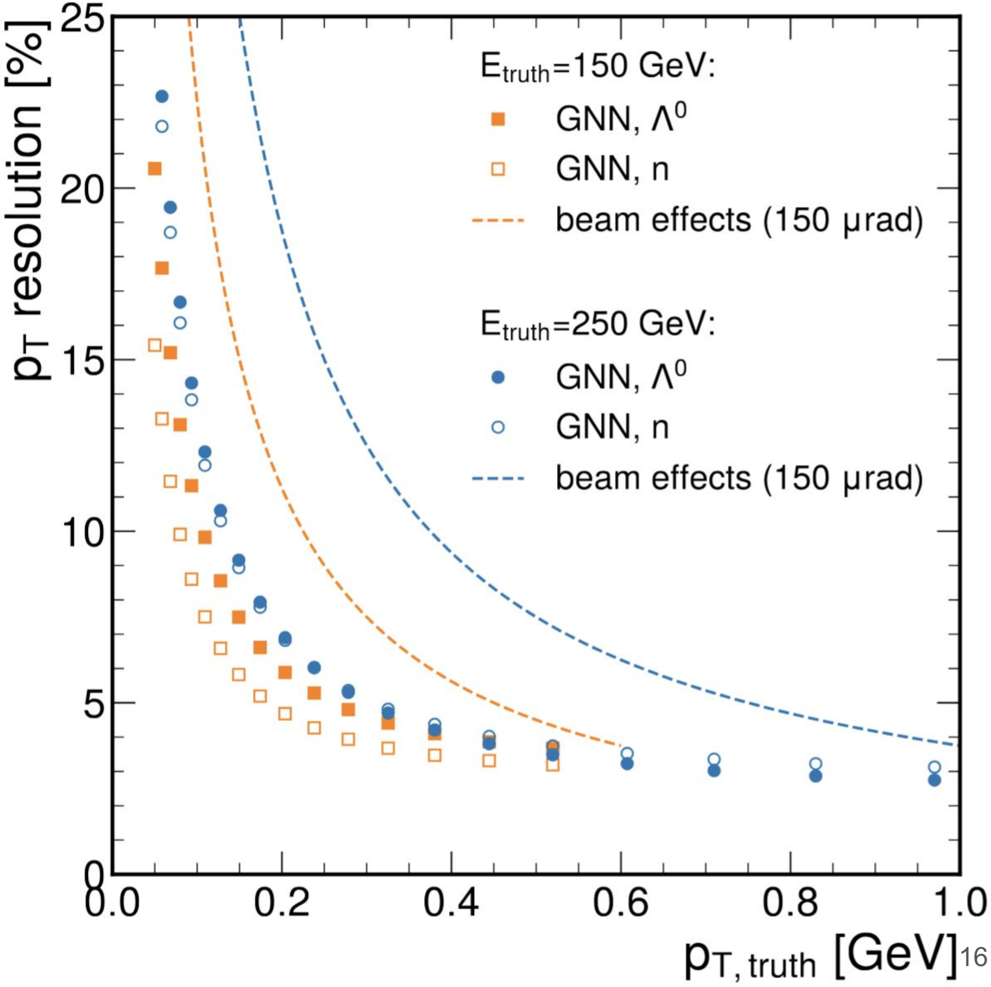




pT resolution

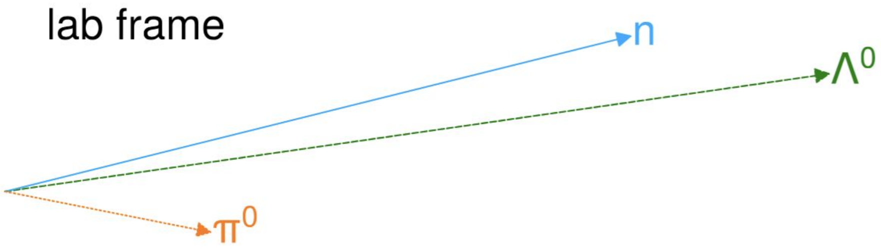
Dominated by beam effects

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

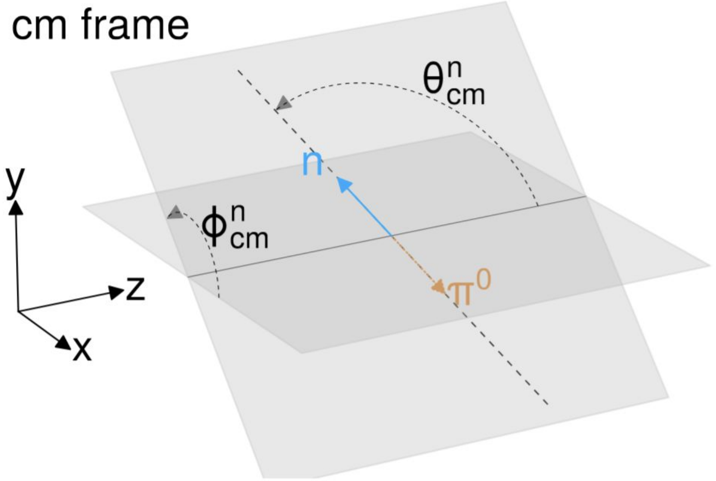


Polarization measurements

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



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

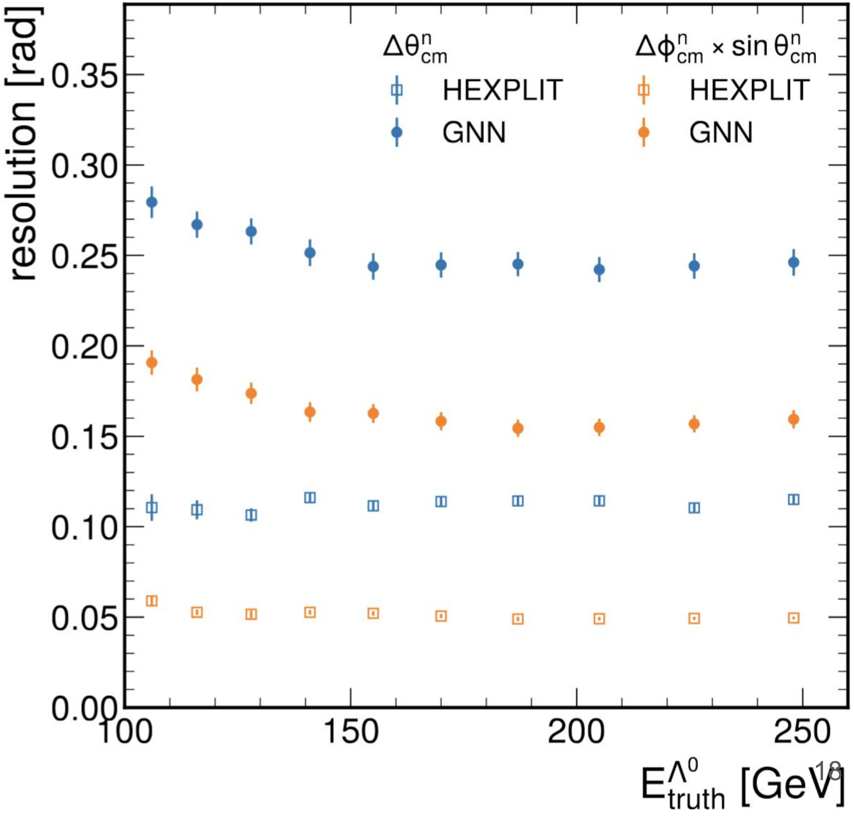


Neutron-axis resolution

Determined using Gaussian fits to the $\Delta\theta^{n}_{cm}$ 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 $\Lambda^0 \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ events, and reconstructed them with conventional and AI-based methods
- 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).