Electron Neutrino Reconstruction for the ICARUS Experiment

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Neutrino Physics and Machine Learning 2024

Overview

- Short Baseline Program (SBN) and ICARUS at Fermilab
- Deep learning for LArTPC Event Reconstruction – A bird’s eye view
- Preliminary Results on BNB and NuMI ν_e Reconstruction
- Conclusion & Future Work

Neutrino Oscillations

- **Neutrino Oscillations** is one major example modification to the Standard Model (SM) from experiment
  - Neutrino flavor state from a W^+ decay is a superposition of mass eigenstates, where mixing is governed by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

Flavor Eigenstates $|\nu_e>, |\nu_\mu>, |\nu_\tau>$

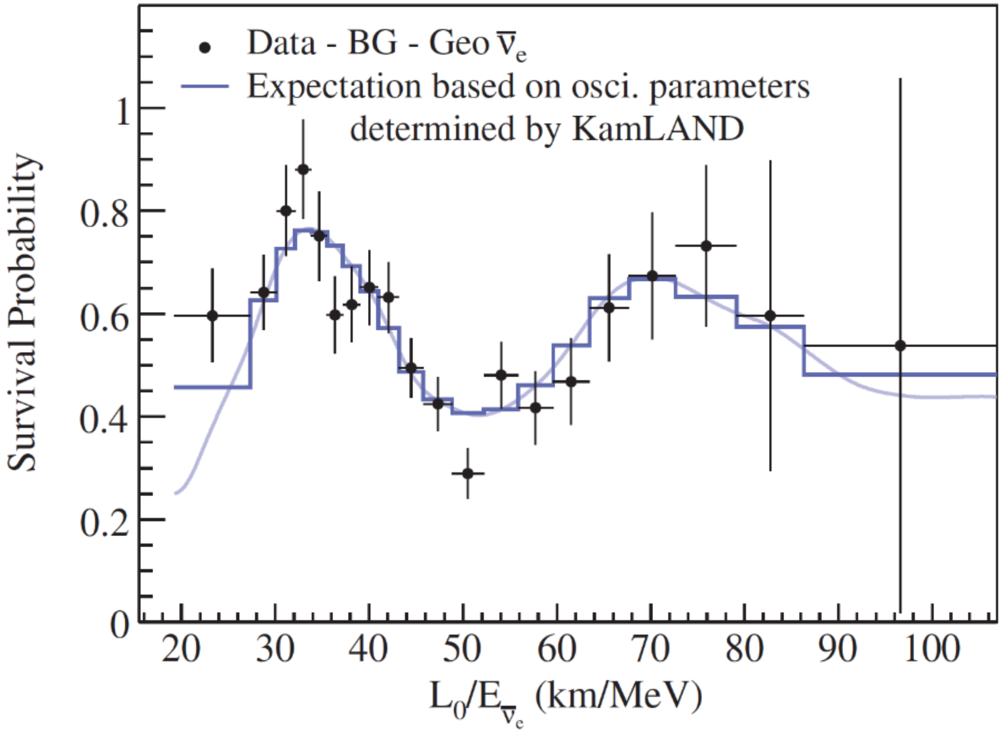
$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$$

Mass Eigenstates $|\nu_1>, |\nu_2>, |\nu_3>$

- Two-flavor approximation:

$$\mathrm{P}(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) = \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})$$

- Experiments control the L/E parameter, where L is usually referred to as the **baseline**.

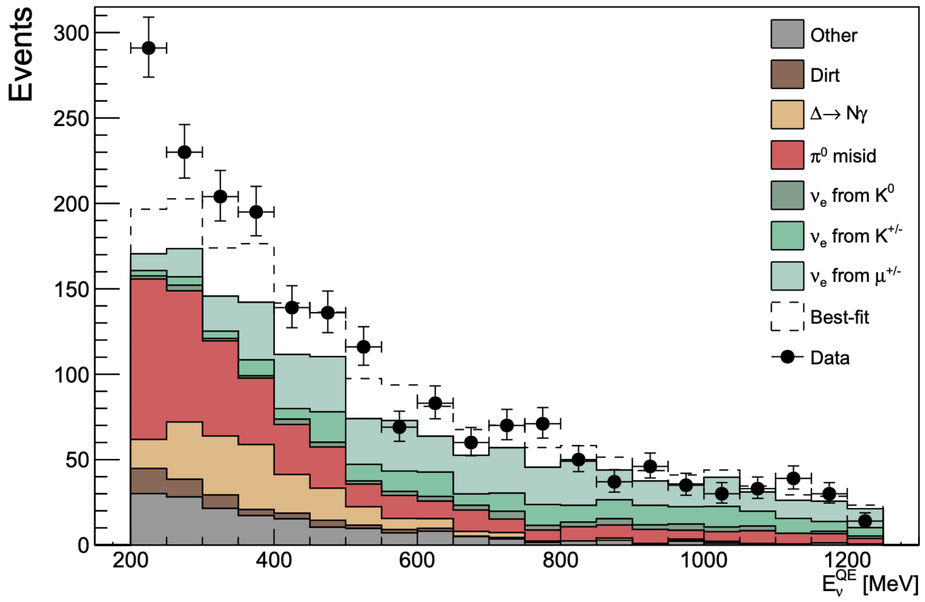


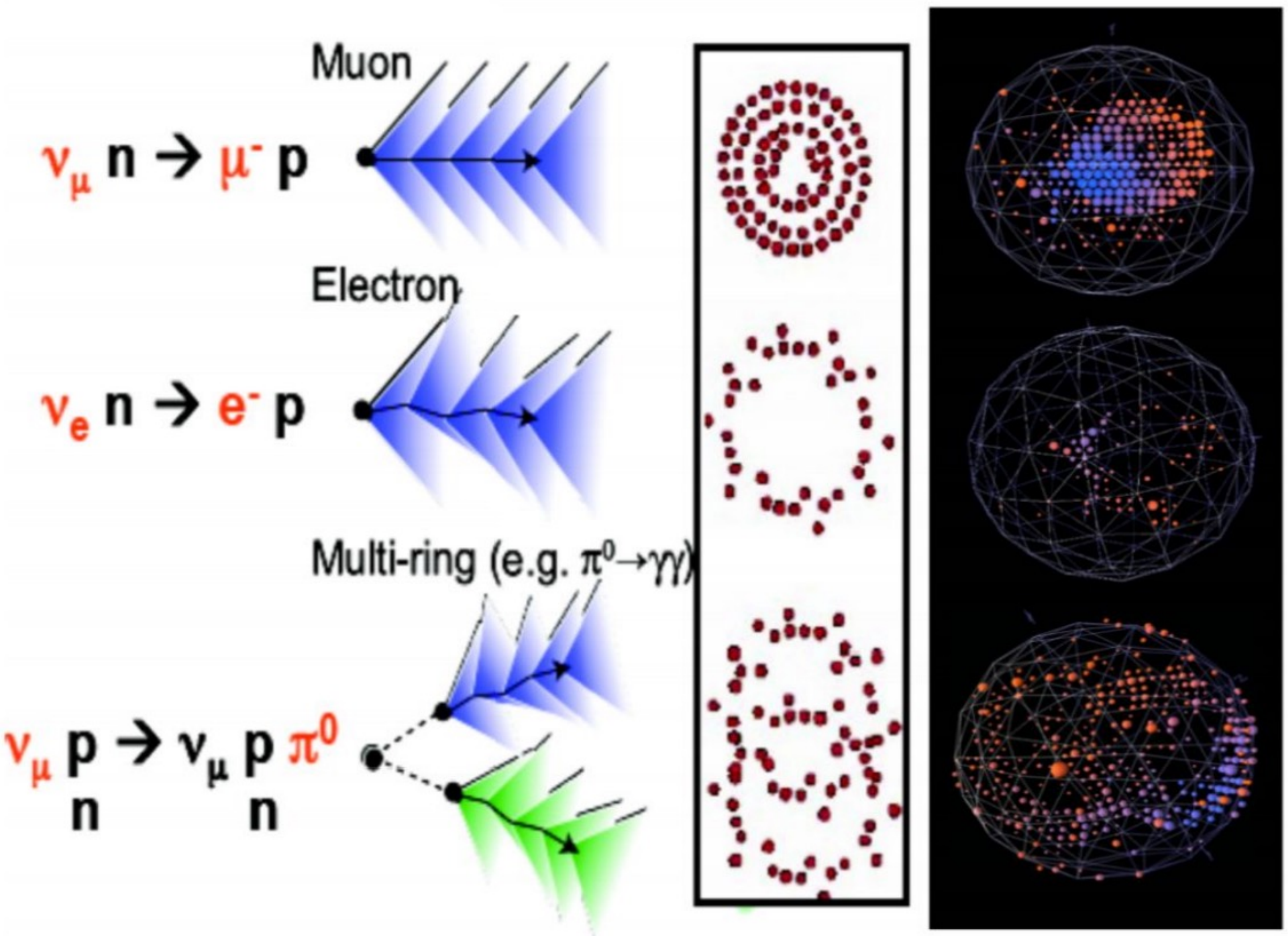
Neutrino Oscillation pattern observed by KamLAND

Image Credit: DOI: 10.1016/j.revip.2016.04.003

Short Baseline Anomalies: An Example from MiniBooNE

- **MiniBooNE**: Excess of ν_e events in $\nu_\mu \to \nu_e$ mode observed over backgrounds, 4.5σ deviation from expectation.
- This excess cannot be explained by the Standard Model (sterile neutrinos?)

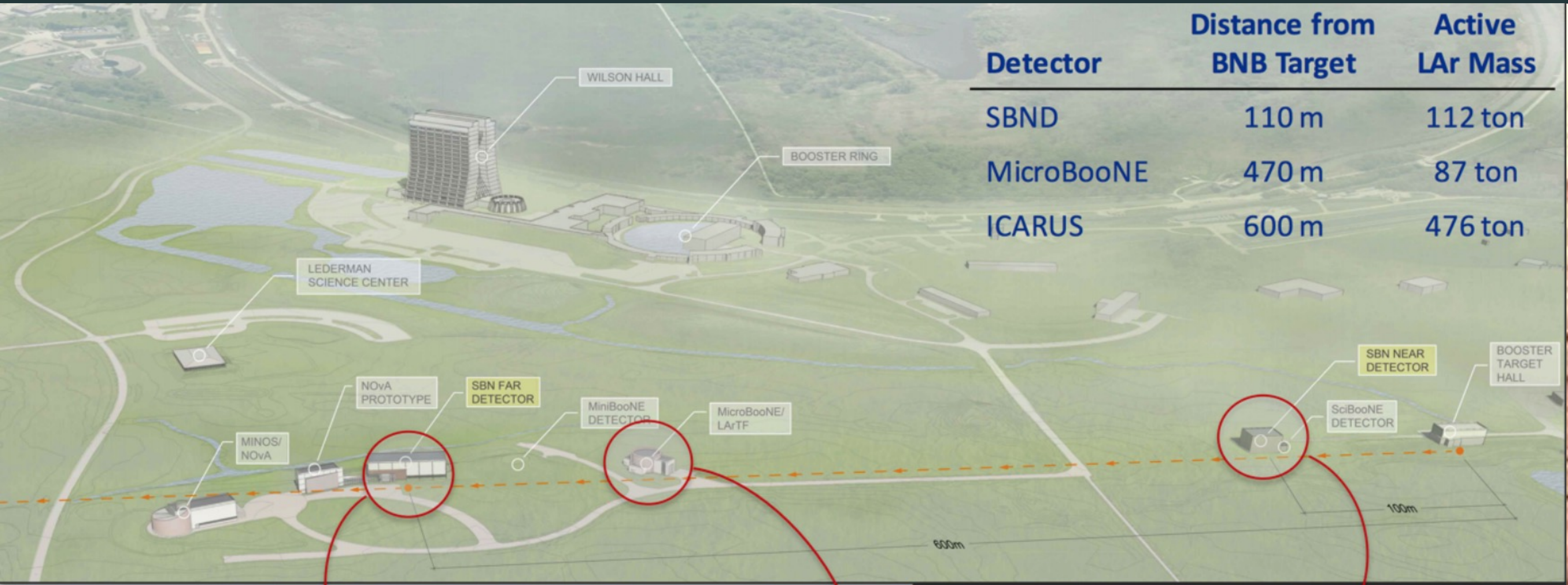


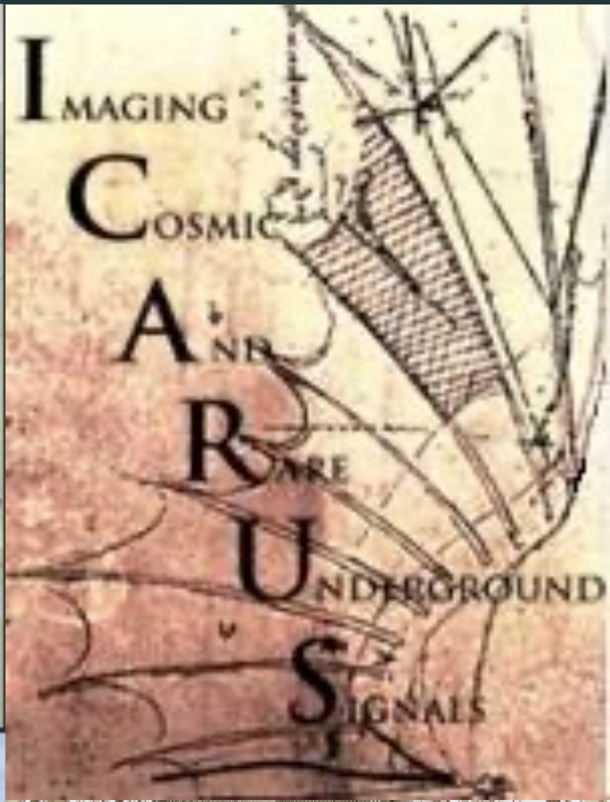


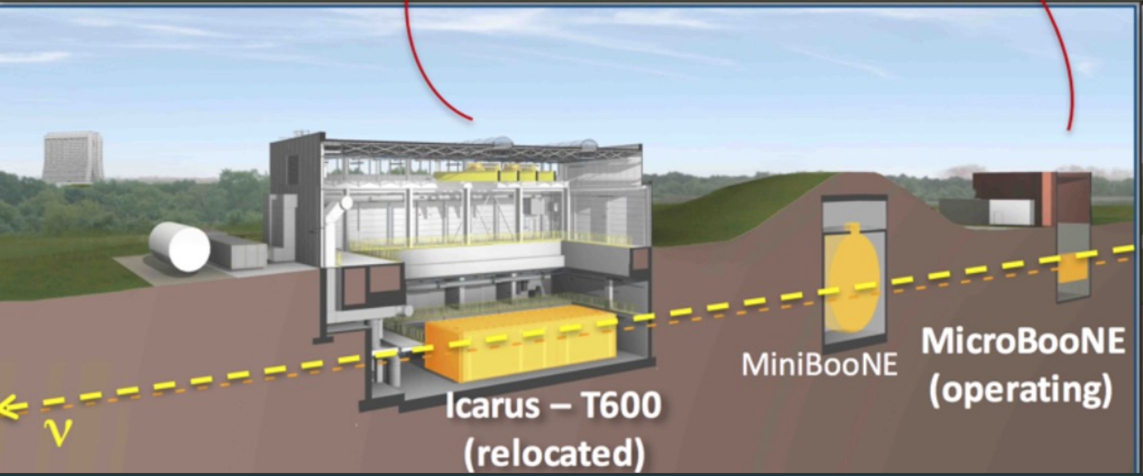
II. The Short Baseline Neutrino Experiment and ICARUS

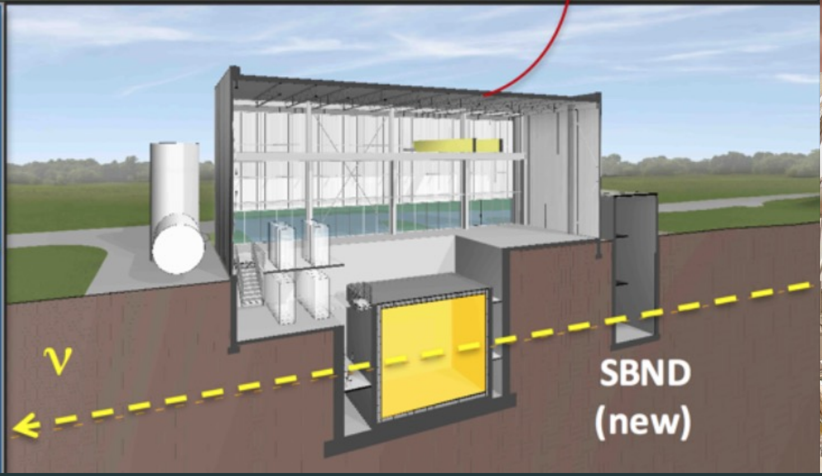
The Short Baseline Neutrino (SBN) Program at Fermilab

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton









Booster Neutrino Beam (BNB)

- The **Booster Neutrino Beam (BNB)** produces neutrinos using 8.89 GeV momentum Booster synchrotron protons incident on a Beryllium target.
- $p + Be \rightarrow \pi^+, K^+, K_L^0 \rightarrow \nu_\mu + \mu^+ + \ ...$
- In neutrino mode, the flux is dominated by
  - **ν_μ (93.6%) and $\bar{\nu}_\mu$ (5.9%)**
  - **Intrinsic $\nu_e/\bar{\nu}_e$ contamination of ~0.5%**
- Majority of ν_μ flux from pion decay in flight ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) until ~2GeV, where K^+/K_L^0 decay dominates.

Expected BNB Neutrino Flux observed at the SBN Far detector (ICARUS)

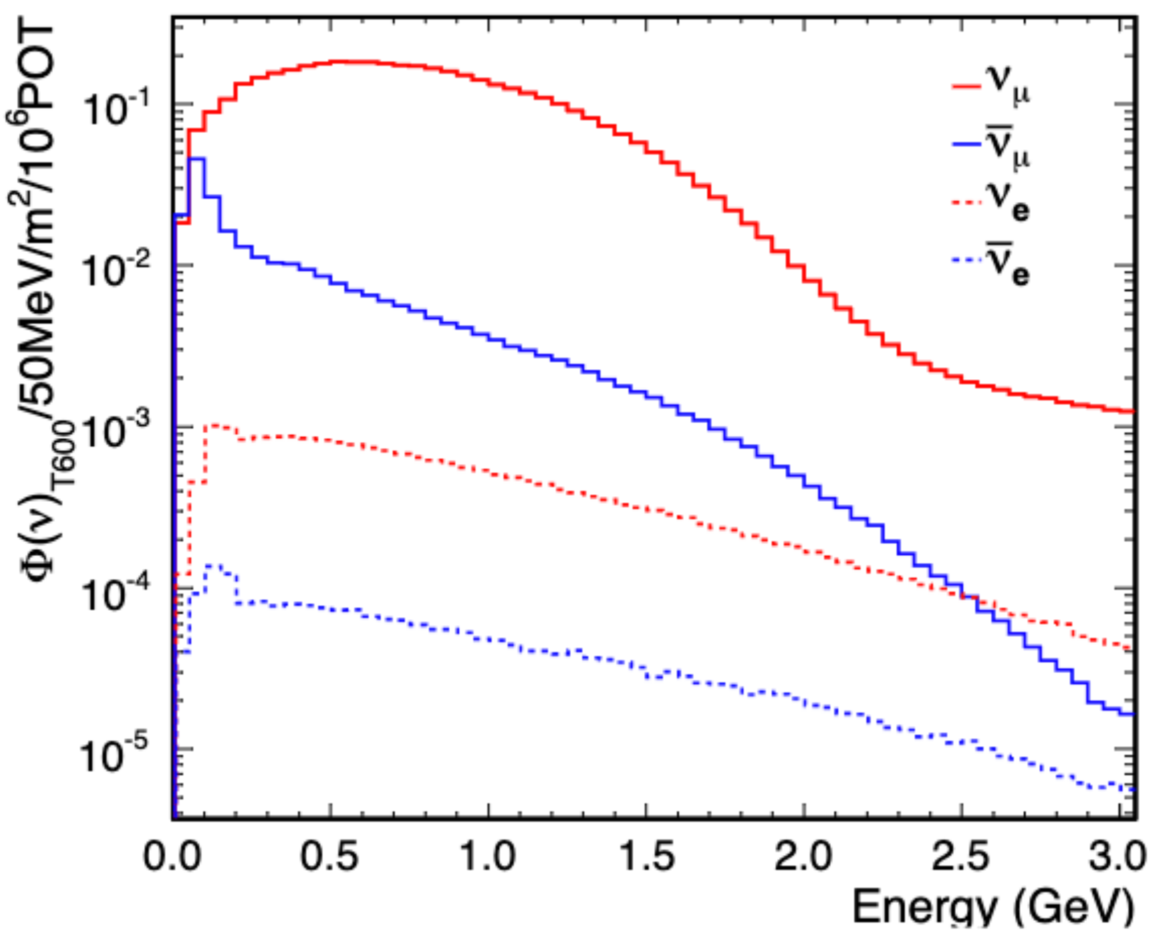


Image Credit: **A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam,** ICARUS-WA104, LAr1-ND, MicroBooNE Collaboration, C. Rubbia (CERN, GSSI, Aquila, INFN LNGS, Assergi) for the collaboration.

Neutrinos at the Main Injector (NuMI) Beam

- **The Neutrinos at the Main Injector (NuMI) Beam** produces neutrinos using 120 GeV protons incident on graphite target.
- Higher primary proton beam energy → more K production → relatively **high ν_e content (~4-5%)**.
- ICARUS is 6° **off-axis** from the NuMI beam line.
- Rich physics programs using NuMI beam at ICARUS: $\nu - Ar$ cross section measurements, BSM searches, etc.

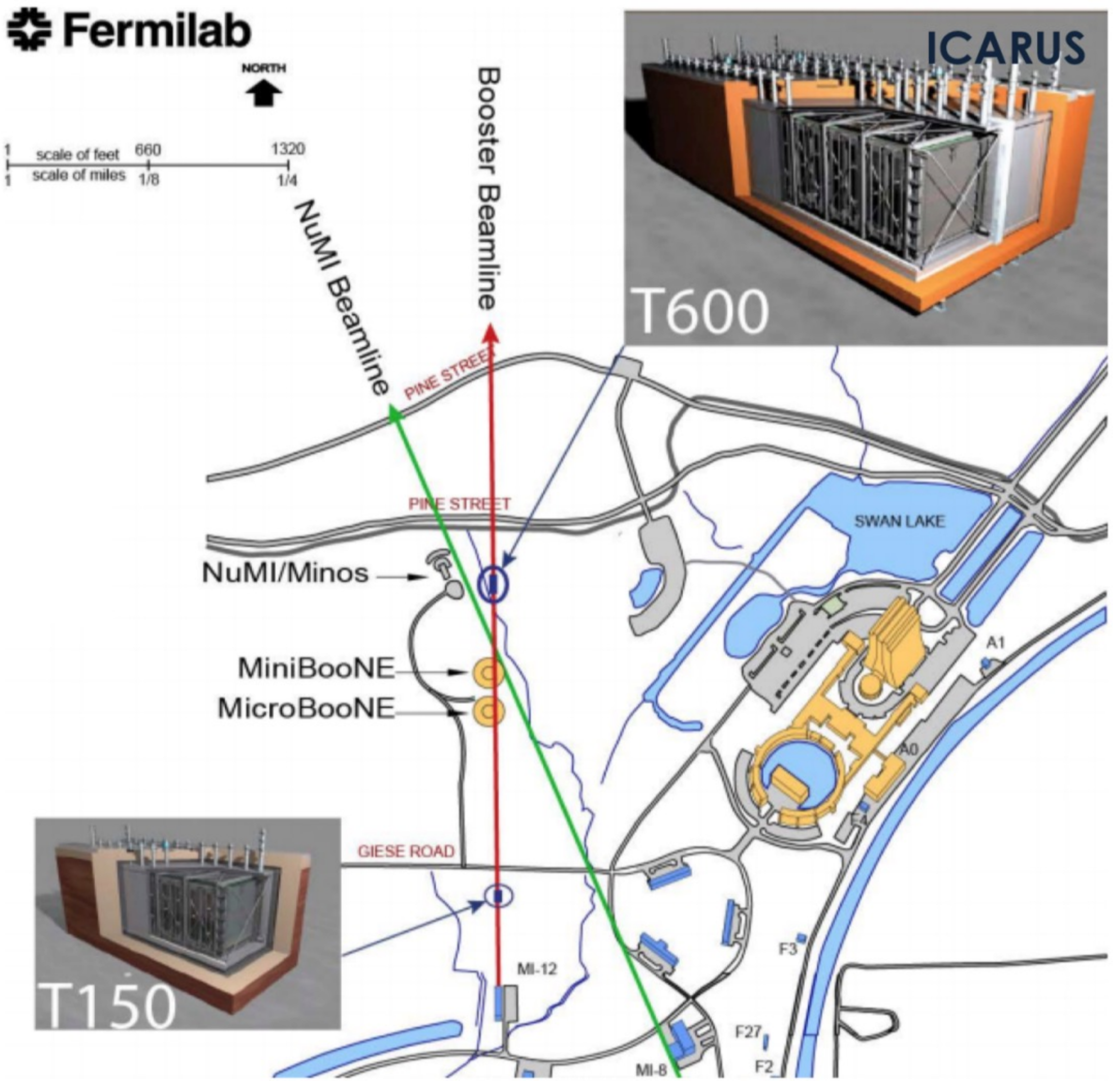
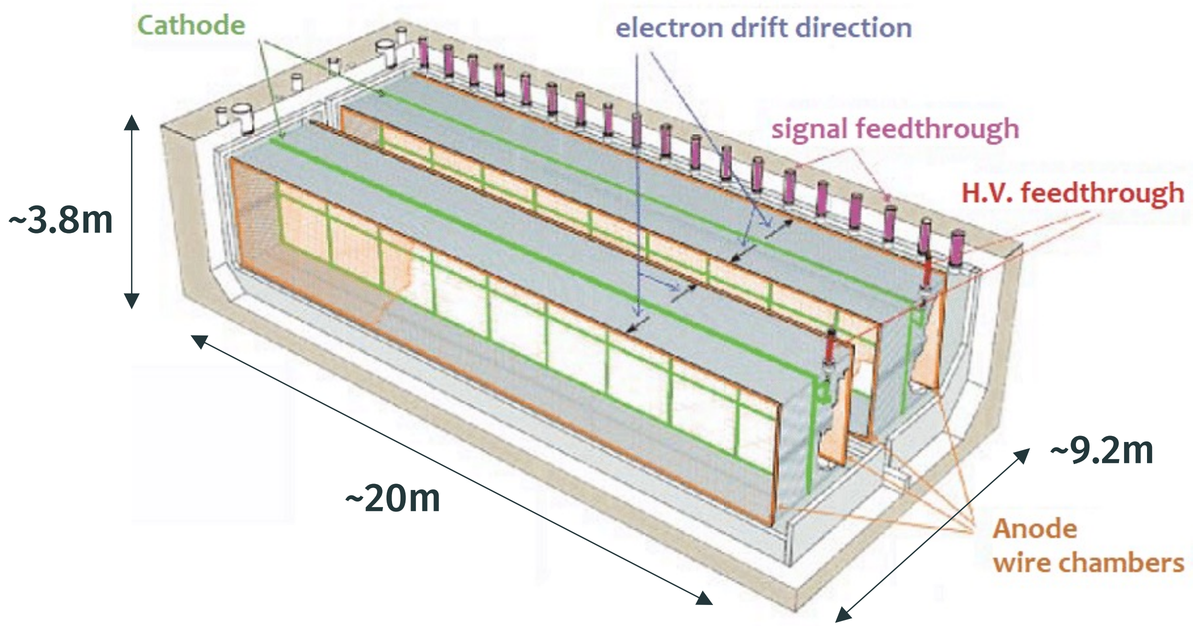
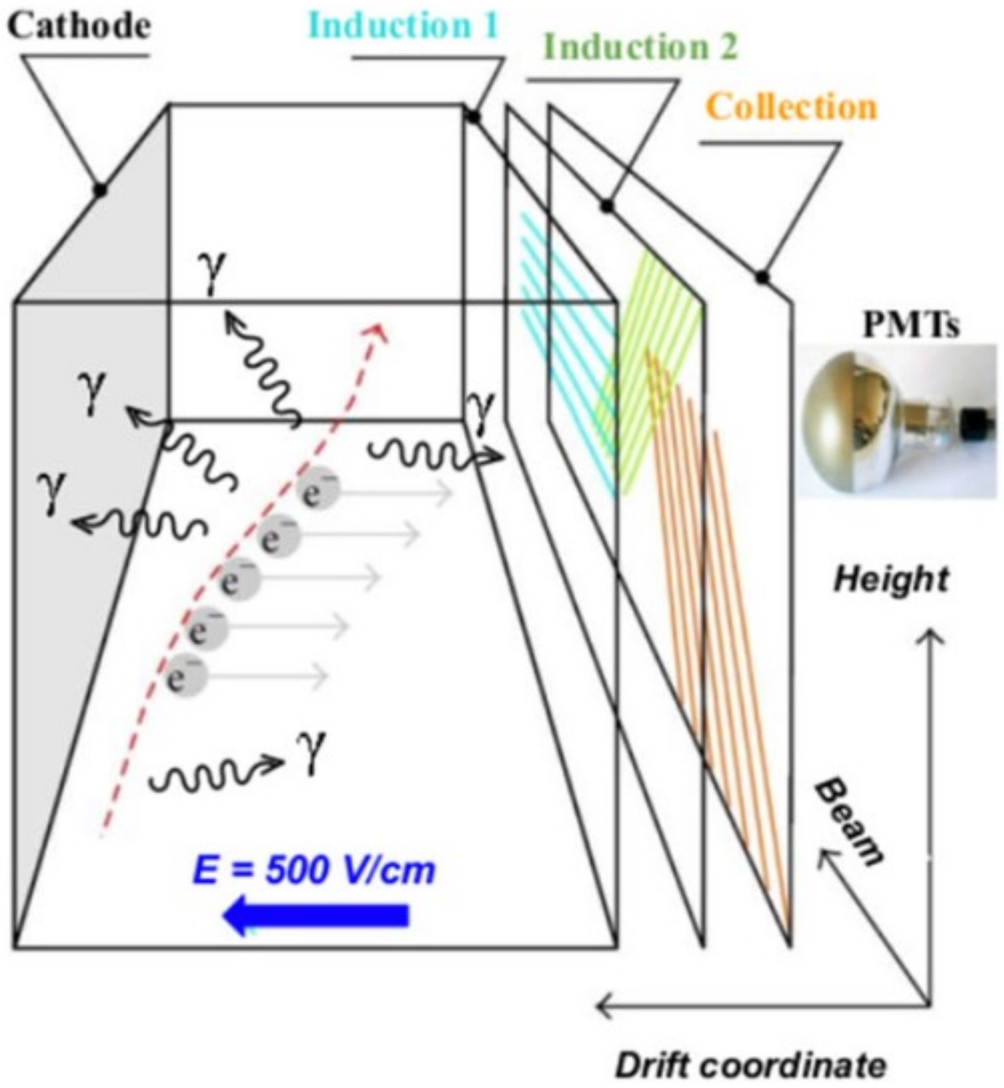


Image Credit: Marta Babicz, *ICARUS T600 Trigger Study at the Short-Baseline Neutrino Experiment (EP-NU meeting)* https://indico.cern.ch/event/864614/contributions/3859763/attachments/2038762/3413897/EPNU_talk.pdf.

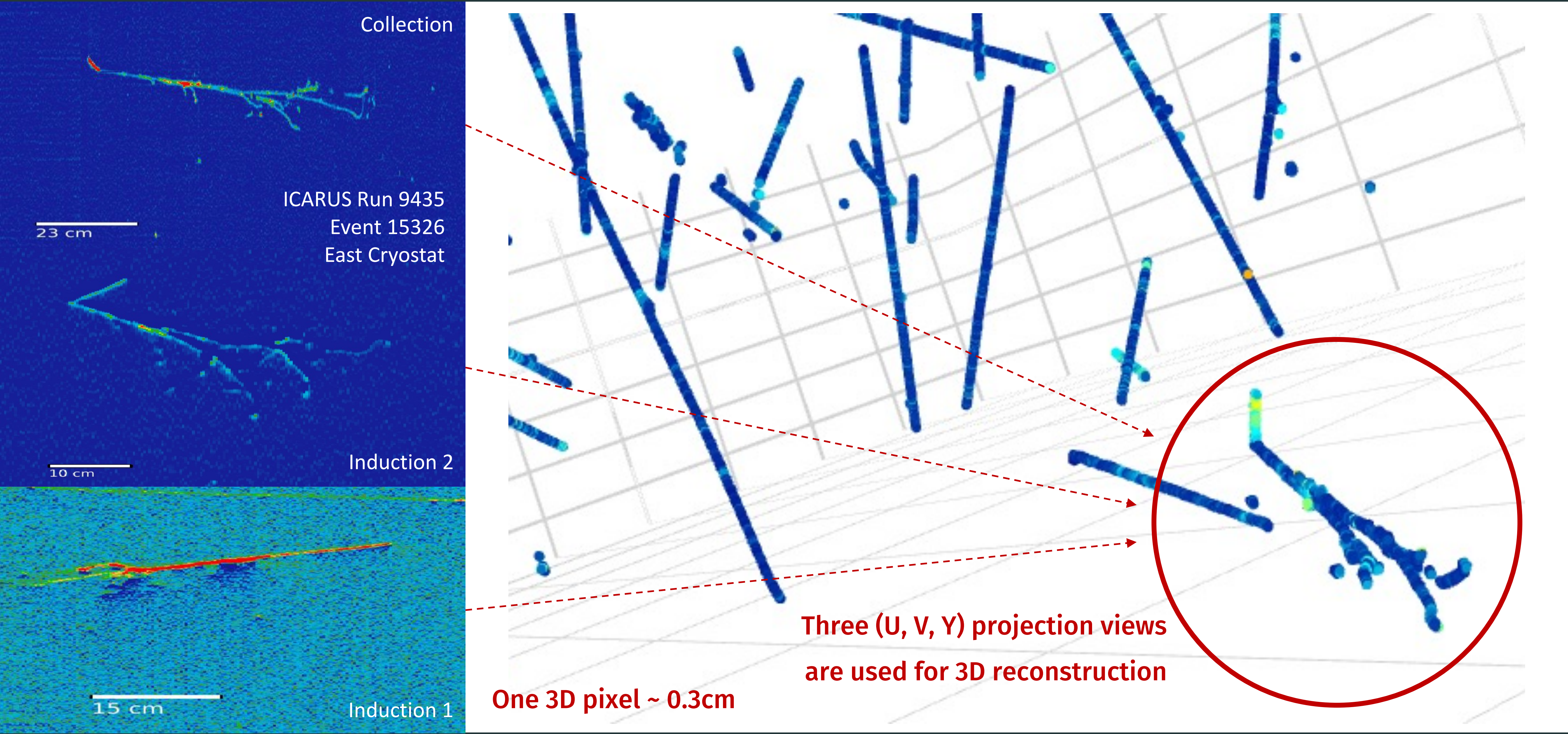
The ICARUS T600 Detector

- **Time projection chamber with 760-ton liquid argon medium**, 500 V/cm nominal electric field applied between cathode and anode plane.
- Neutrino-argon interaction creates charged particles, which in turn releases **ionization electrons that drift towards the anode plane.**
- **Maximum electron drift time is ~1ms** with 500 V/cm
- **Photon signals detected within ~ns at PMTs.**





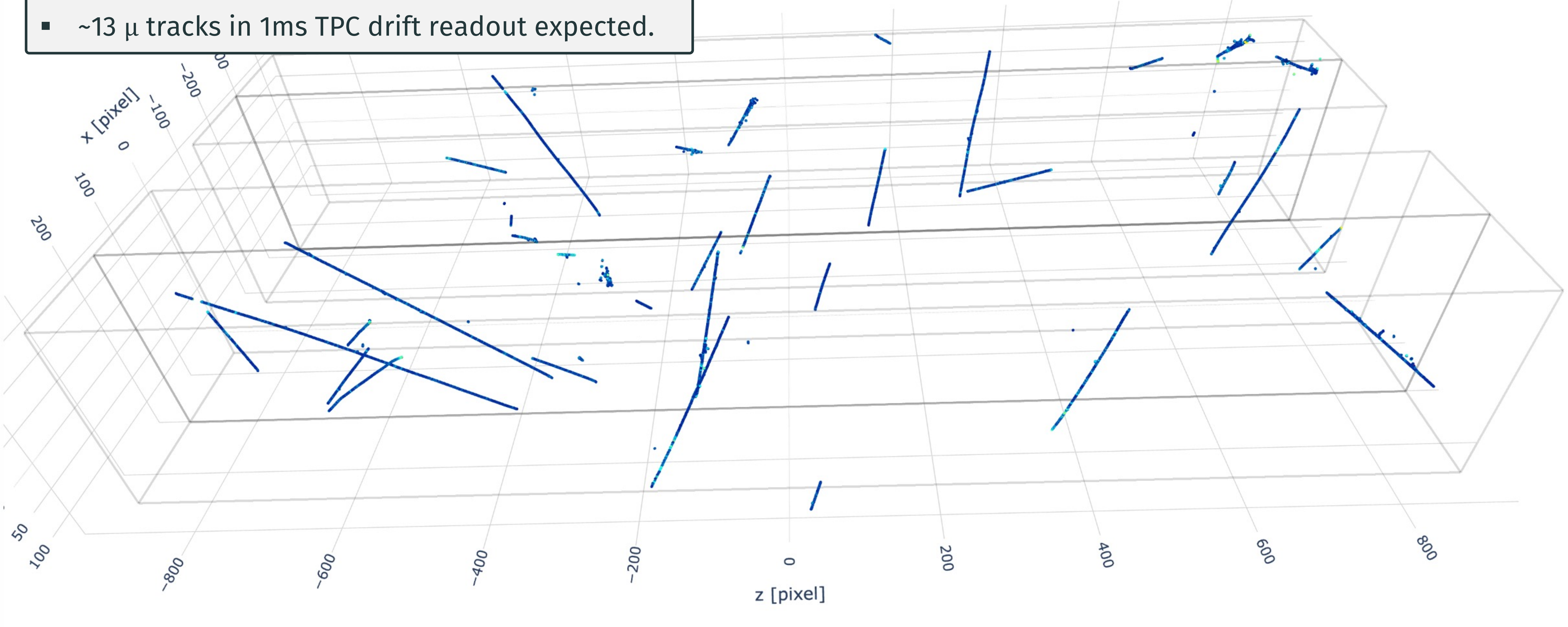
ICARUS Detector: Example Neutrino Candidate Event



ICARUS Detector: Example Neutrino Event

- ~13 μ tracks in 1ms TPC drift readout expected.

ICARUS Run 9435, Event 15326



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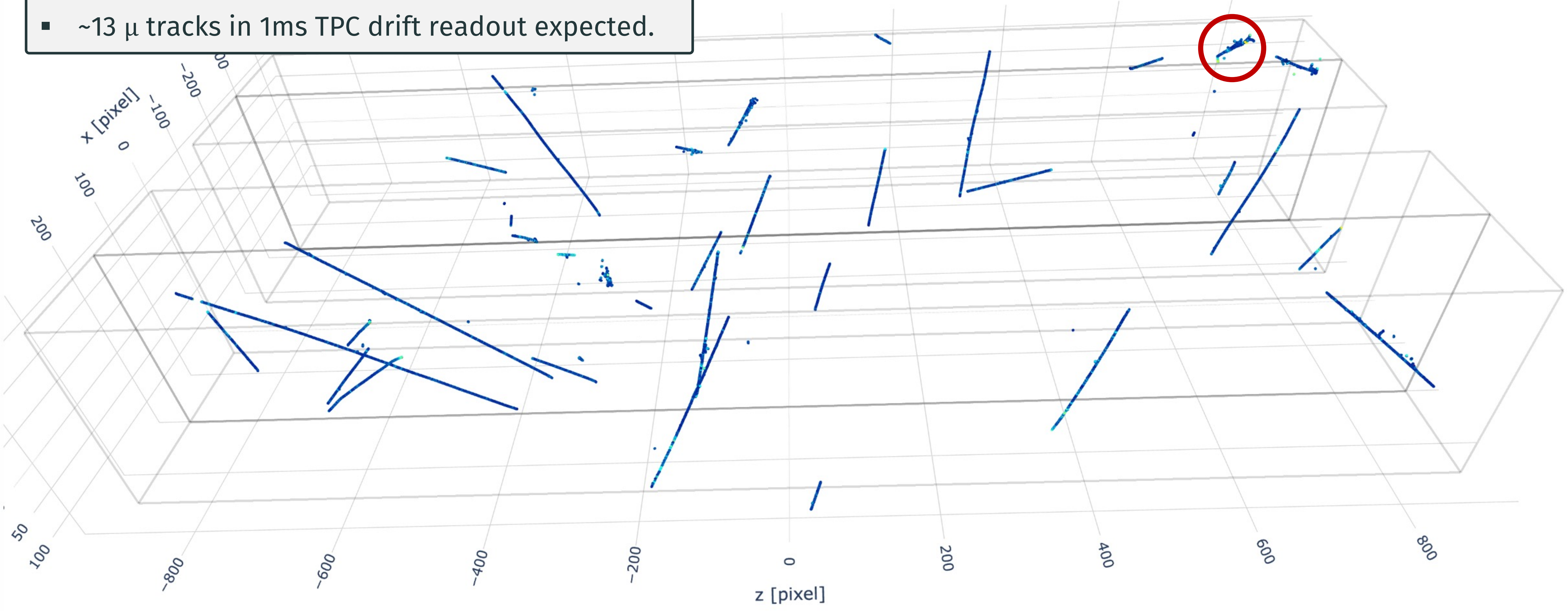
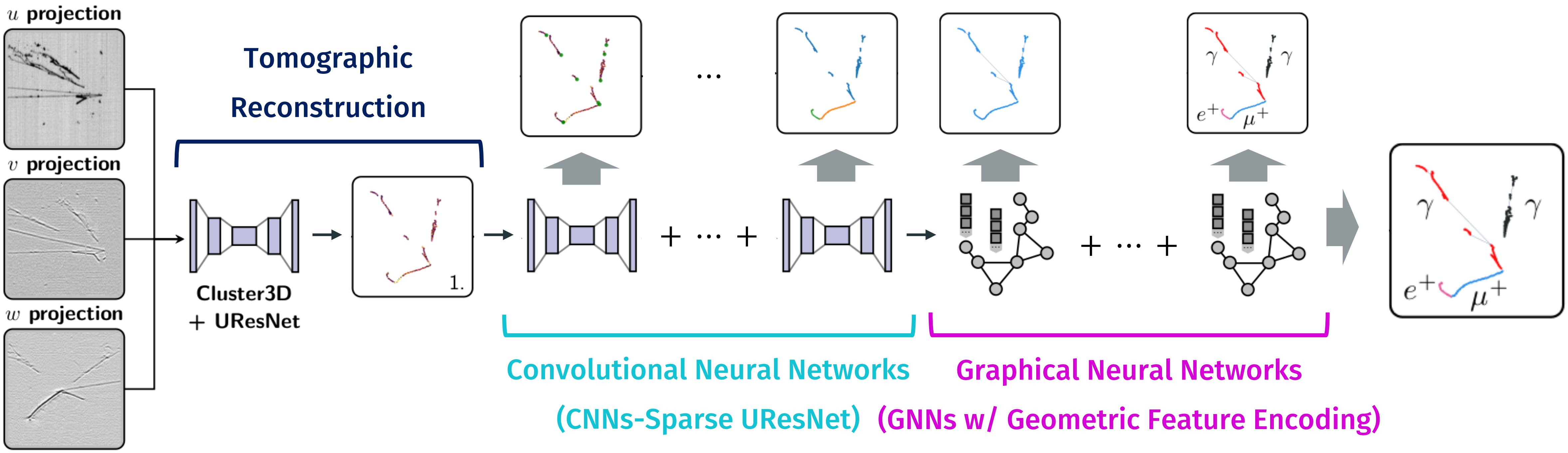


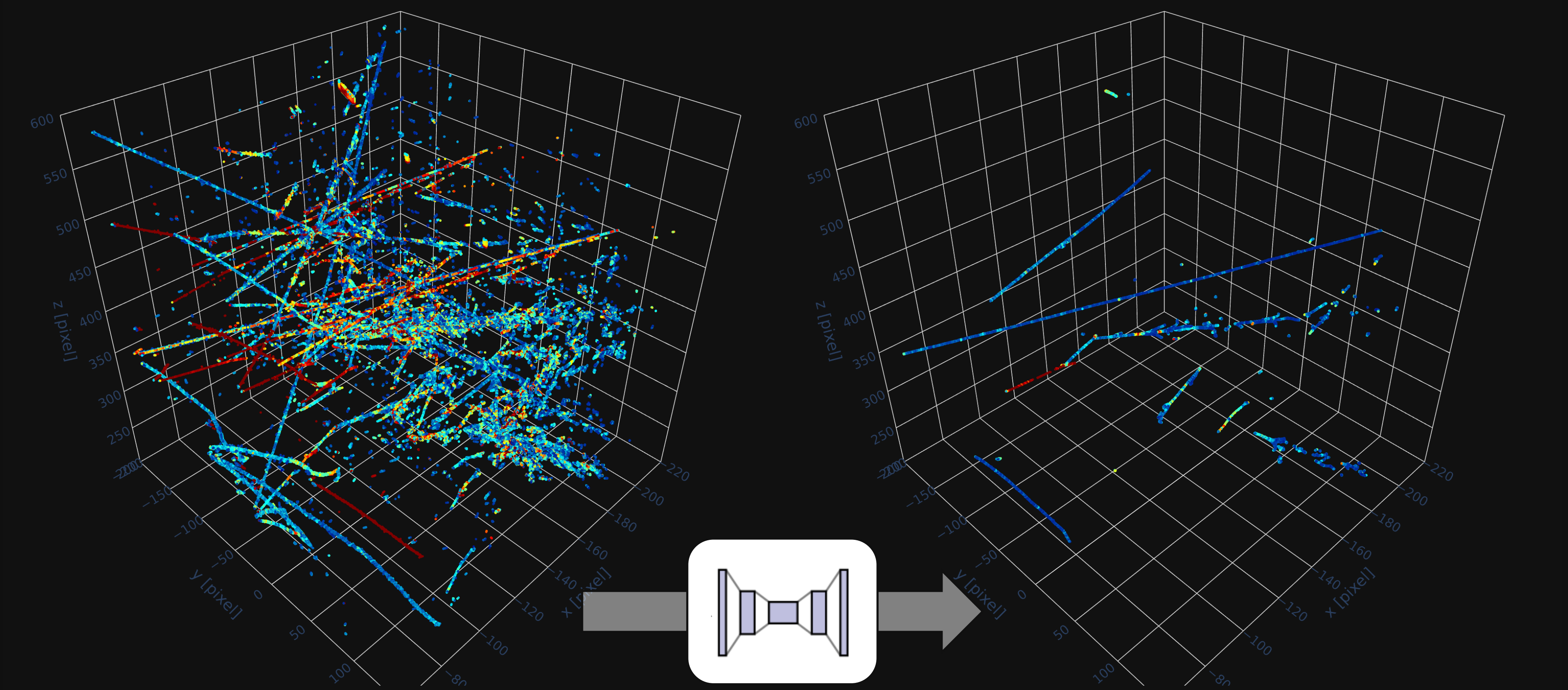
III. Deep learning for LArTPC Event Reconstruction

SPINE: Scalable Particle Imaging with Neural Embeddings

- **Goal: Automated feature extraction for from LArTPC images**
  - **Interpretable**: chain of neural networks specializing in various sub-tasks
    - Allows detailed and informative error analysis, if certain parts of the chain fails
  - **Automatic optimization**: entire chain is trainable simultaneously using gradient-based optimization

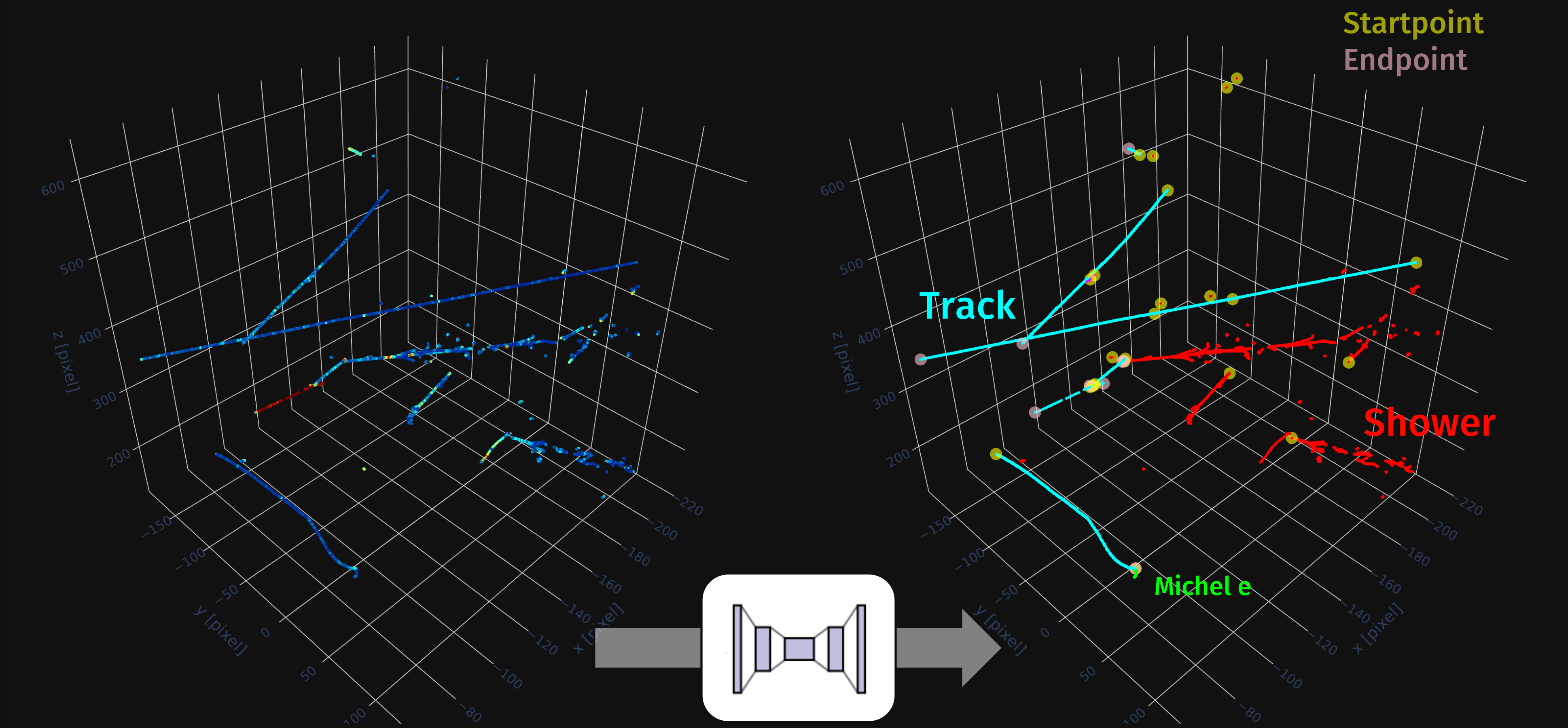


Deep learning for LArTPC Event Reconstruction



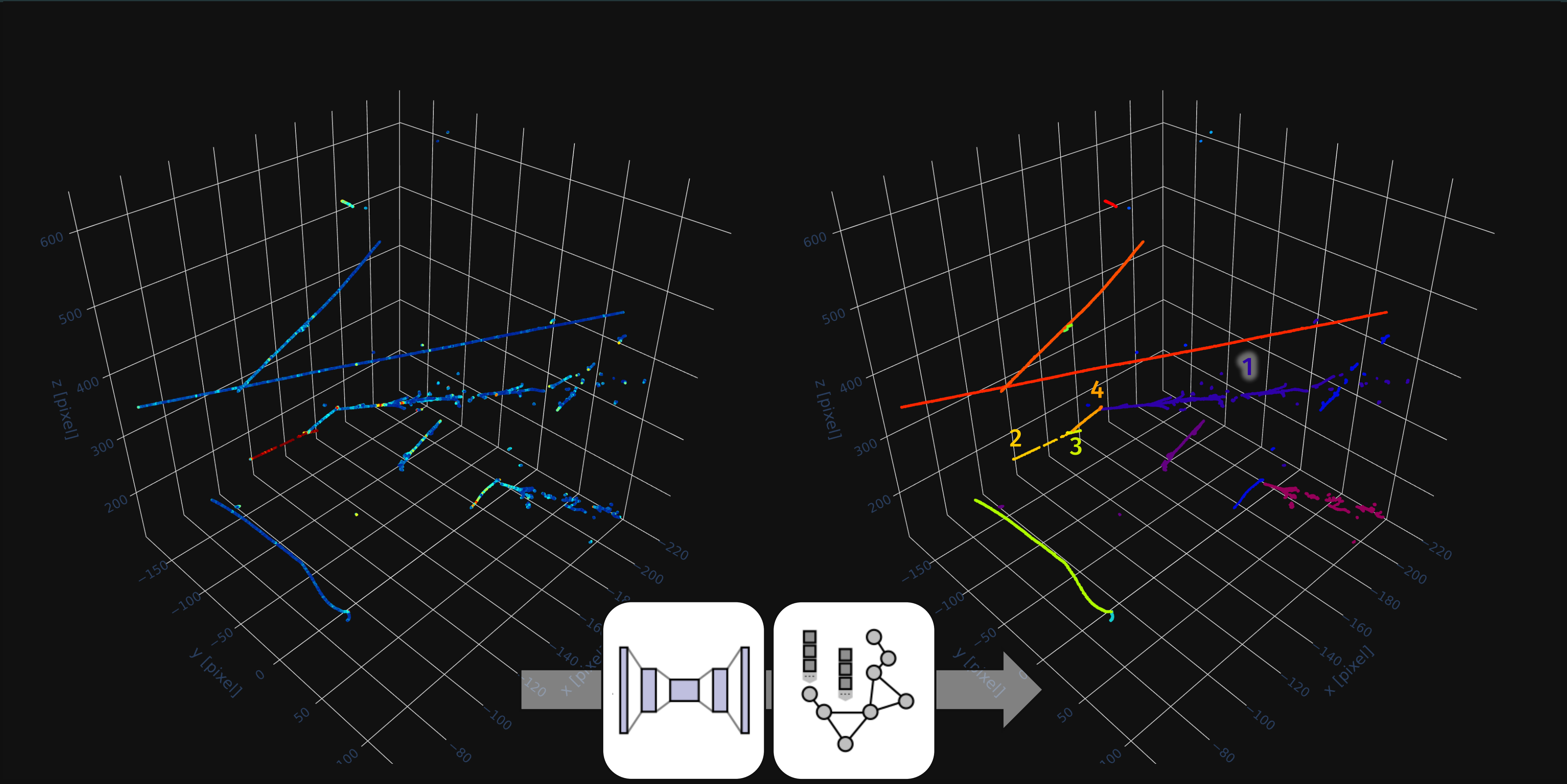
Step 0: Remove 2D->3D Reconstruction Artifacts (Deghosting)
Later ML stages use the cleaned image on the right

Deep learning for LArTPC Event Reconstruction



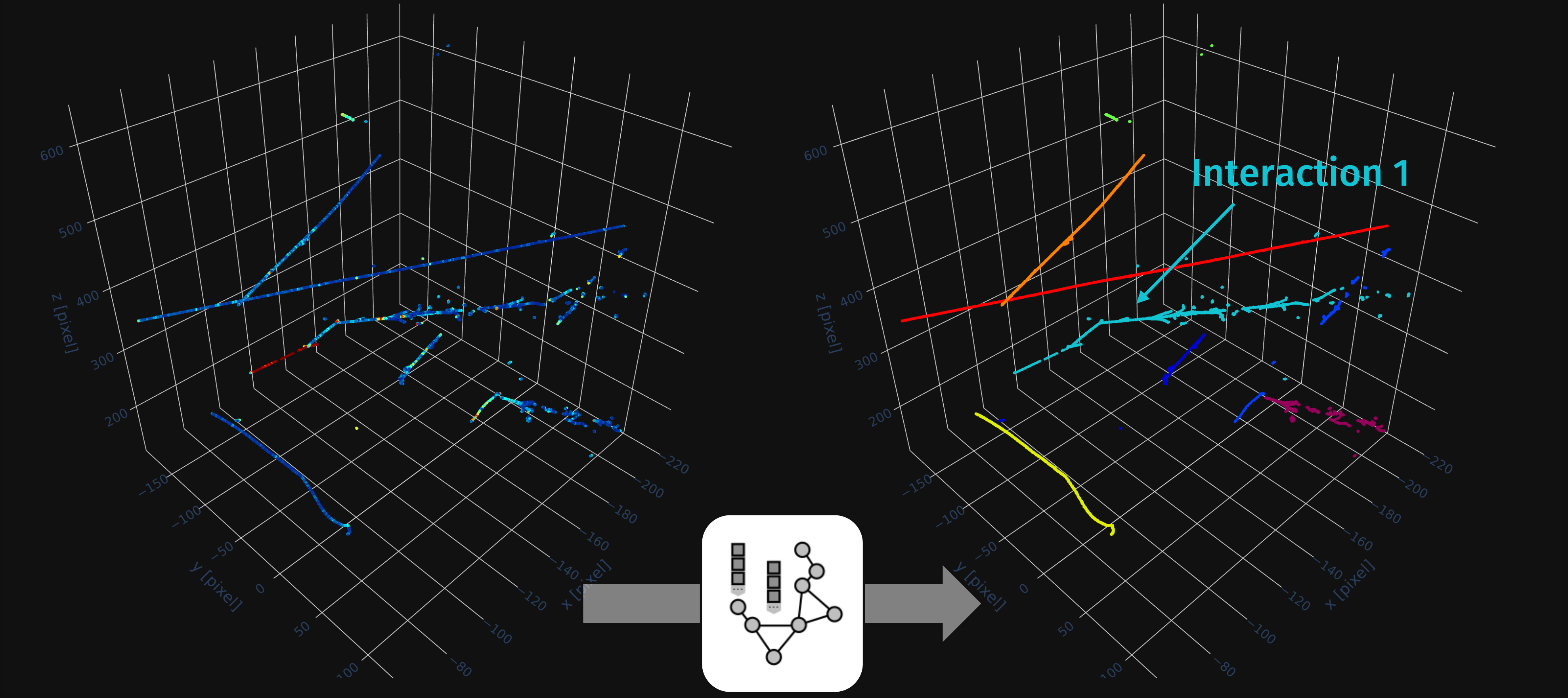
Step 1: Identify Pixel-Level Features
Sparse-CNN for shape classification and interest point detection

Deep learning for LArTPC Event Reconstruction



Step 2: Identify Individual Particles
CNN for pixel-to-fragment clustering, GNN for fragment-to-particle aggregation

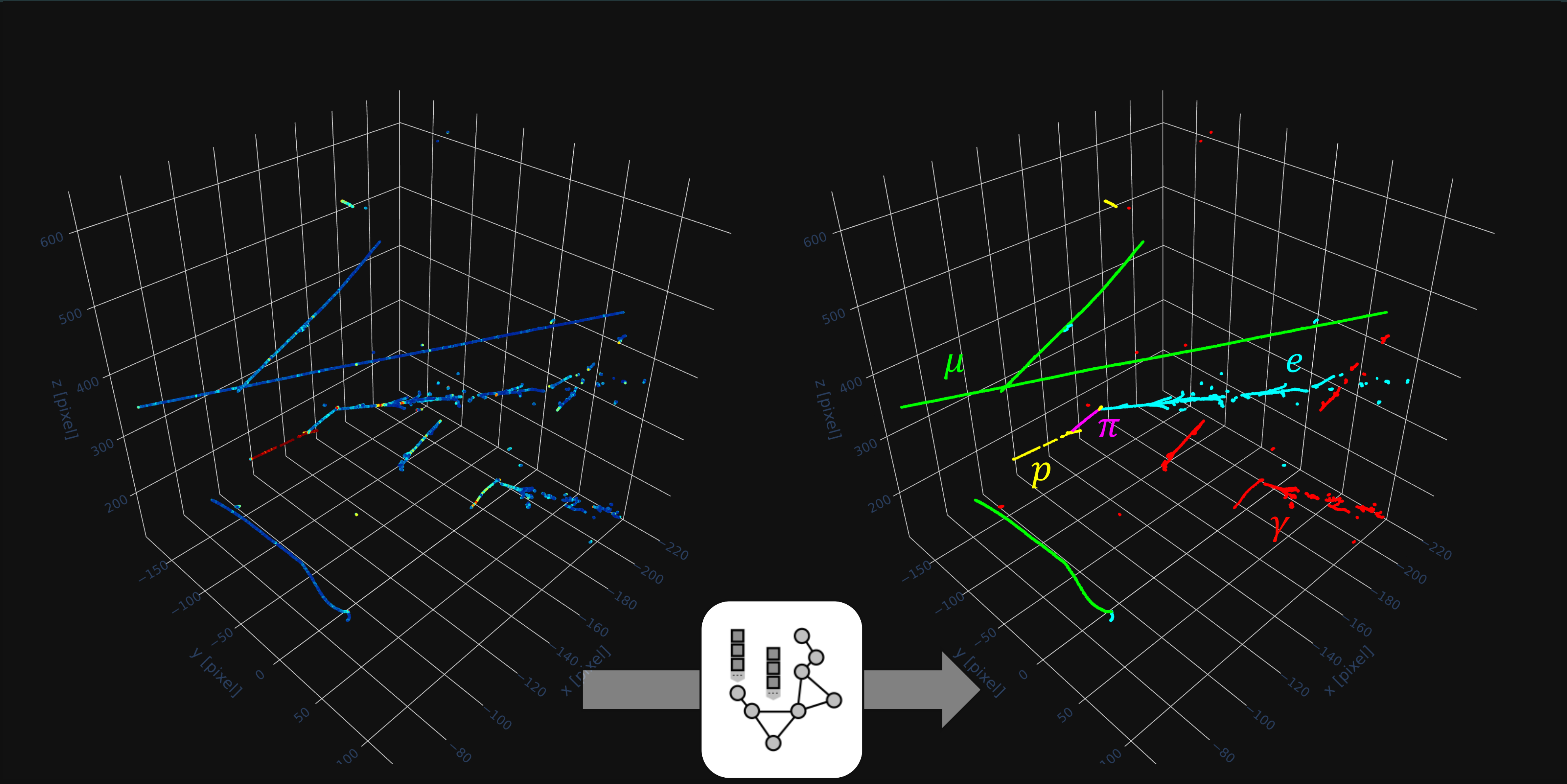
Deep learning for LArTPC Event Reconstruction



Step 3: Group particles to parent interactions

GNN, predict which particles have common ancestral interactions (edge prediction)

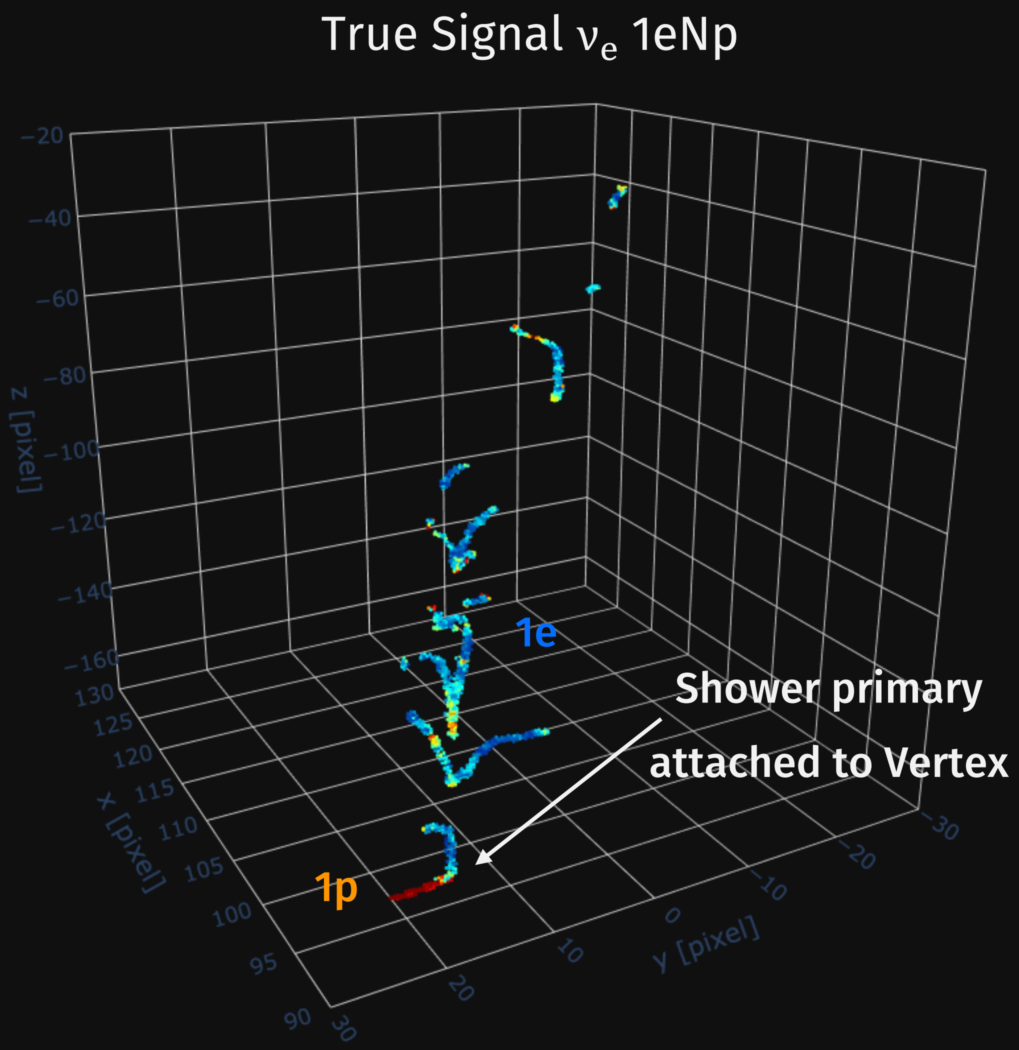
Deep learning for LArTPC Event Reconstruction



Step 4: Identify Cross-Particle Correlations
(GNN for particle type prediction, inference with contextual information)

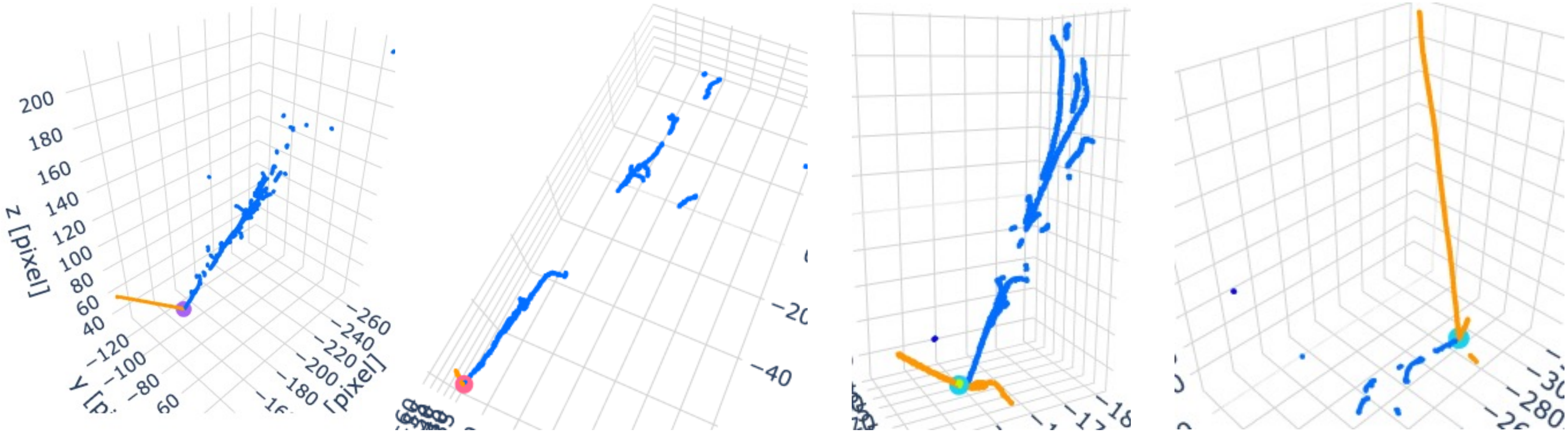
IV. Preliminary Results

Preliminary Results: Cuts (BNB)



- **Signal Definition:** $1\mathrm{eNp}0\pi^{\pm}0\gamma$ **Topology** with a **tagged PMT** information consistent with the **[0, 1.6us]** beam window **("1eNp+FM").**
- ***Visible* 1eNp:** 1eNp topologies in which all participating particles deposit ≥ 25 MeV (30 MeV for protons)

- **Fiducial Cut**:
  - True and reconstructed vertex must be inside fiducial volume.
- **Conversion Distance Cut:**
  - Photons can travel some distance before pair-producing to EM shower cascade; e showers deposit energy from the beginning.
  - Require ≤ 0.8cm for electrons

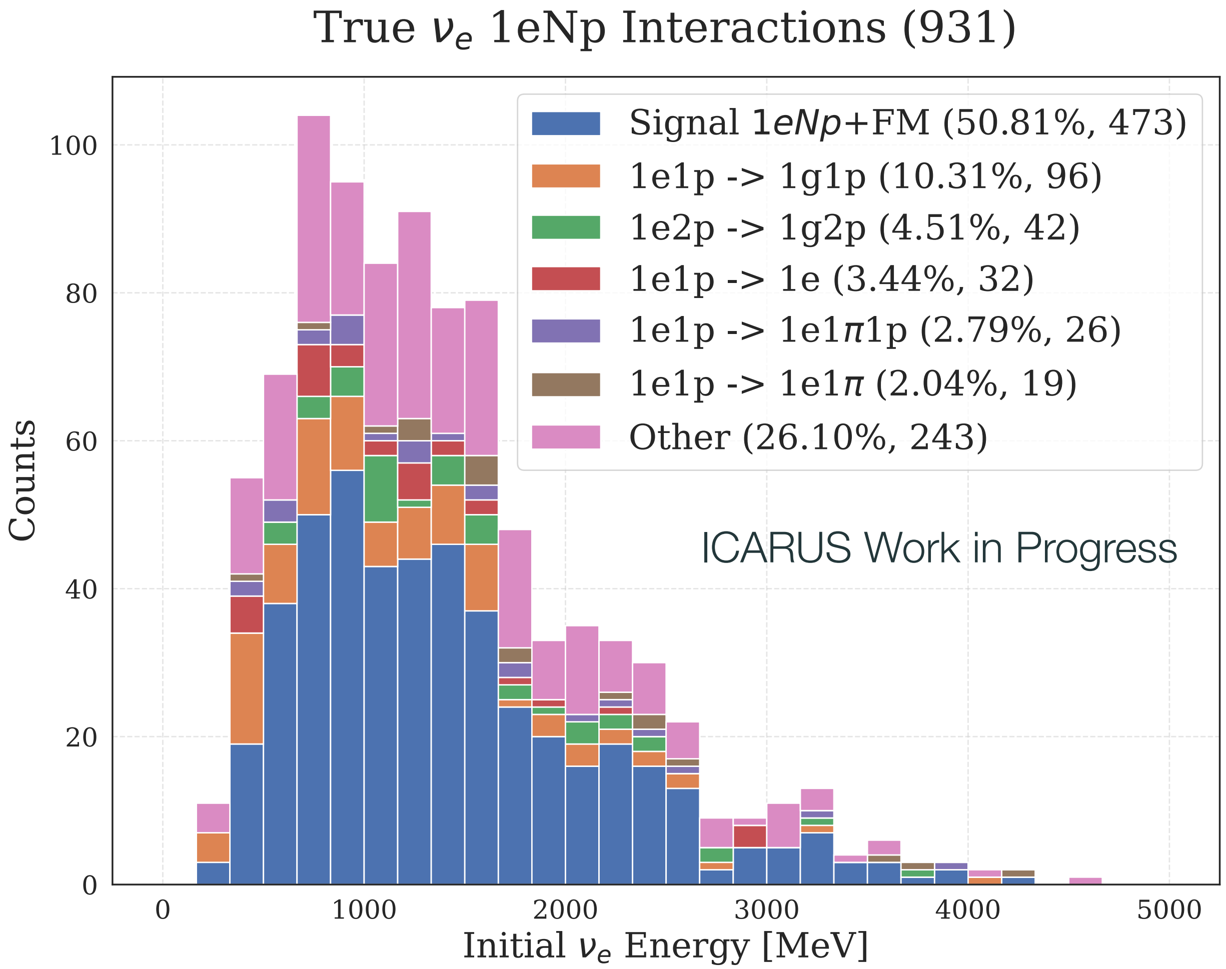


Selected 1eNp Signals (True ν_e's) from BNB ν_μ + intrinsic ν_e + Out-of-time Cosmics

(Reconstruction with predicted particle types)

Preliminary Results (1. BNB ν_e Intrinsic + Cosmic)

- To estimate efficiency, we use a **BNB intrinsic ν_e only MC dataset. (~3.5k ν_e interactions with nonzero deposited E).**
- **Reconstruction efficiency is ~51%,** with dominant error mode due to $1eNp \rightarrow 1\gamma Np$.
- **Energy Reconstruction:**
  - E_e **(Electron Energy):**
    - **Calorimetric reconstruction** from wire plane charge information
  - $E_p^{(i)}$**(Proton Energy):**
    - **Bethe-Bloch range-based energy estimation**

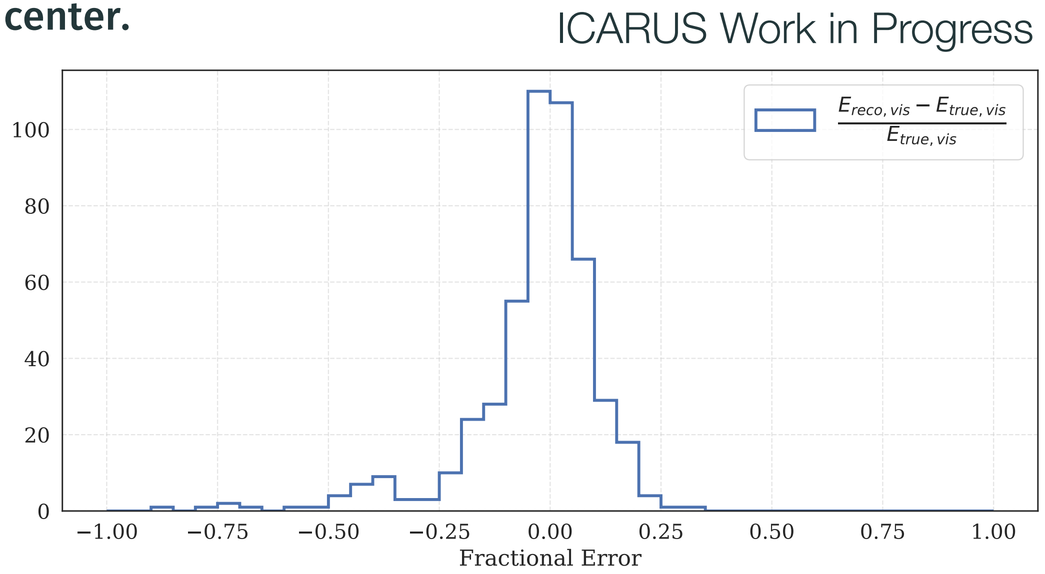


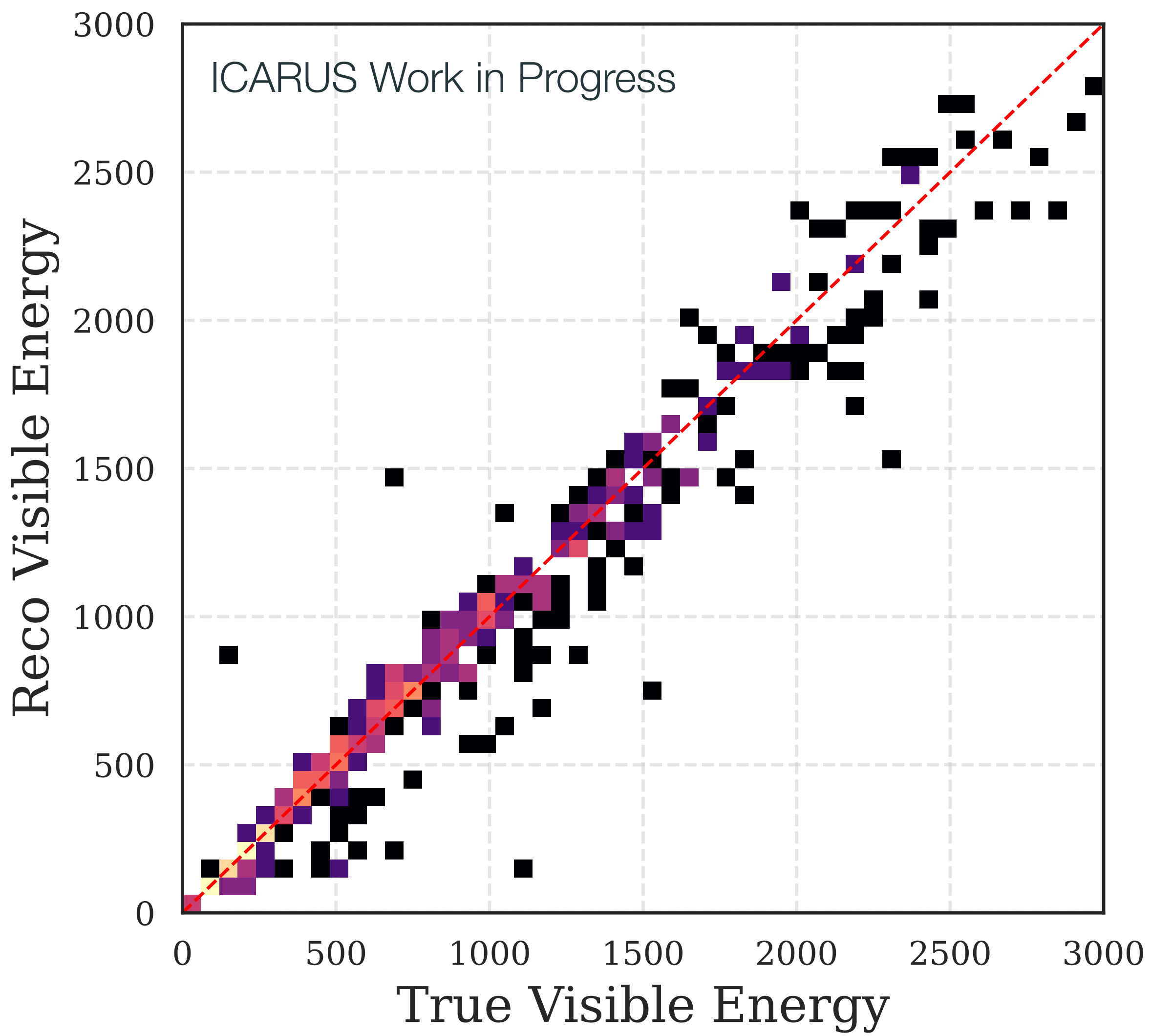
Preliminary Results (1. BNB ν_e Intrinsic + Cosmic)

- The **neutrino interaction visible energy** is defined as a simple sum of the constituent particles' reconstructed energy:

$$E_{\nu_e} = E_e + \sum_i E_p^{(i)}$$

- **FWHM is ~20% for the fractional error $\left(\frac{E_{reco}-E_{true}}{E_{true}}\right)$ about center.**





Preliminary Results (2: BNB ν_μ + ν_e + out-of-time cosmic)

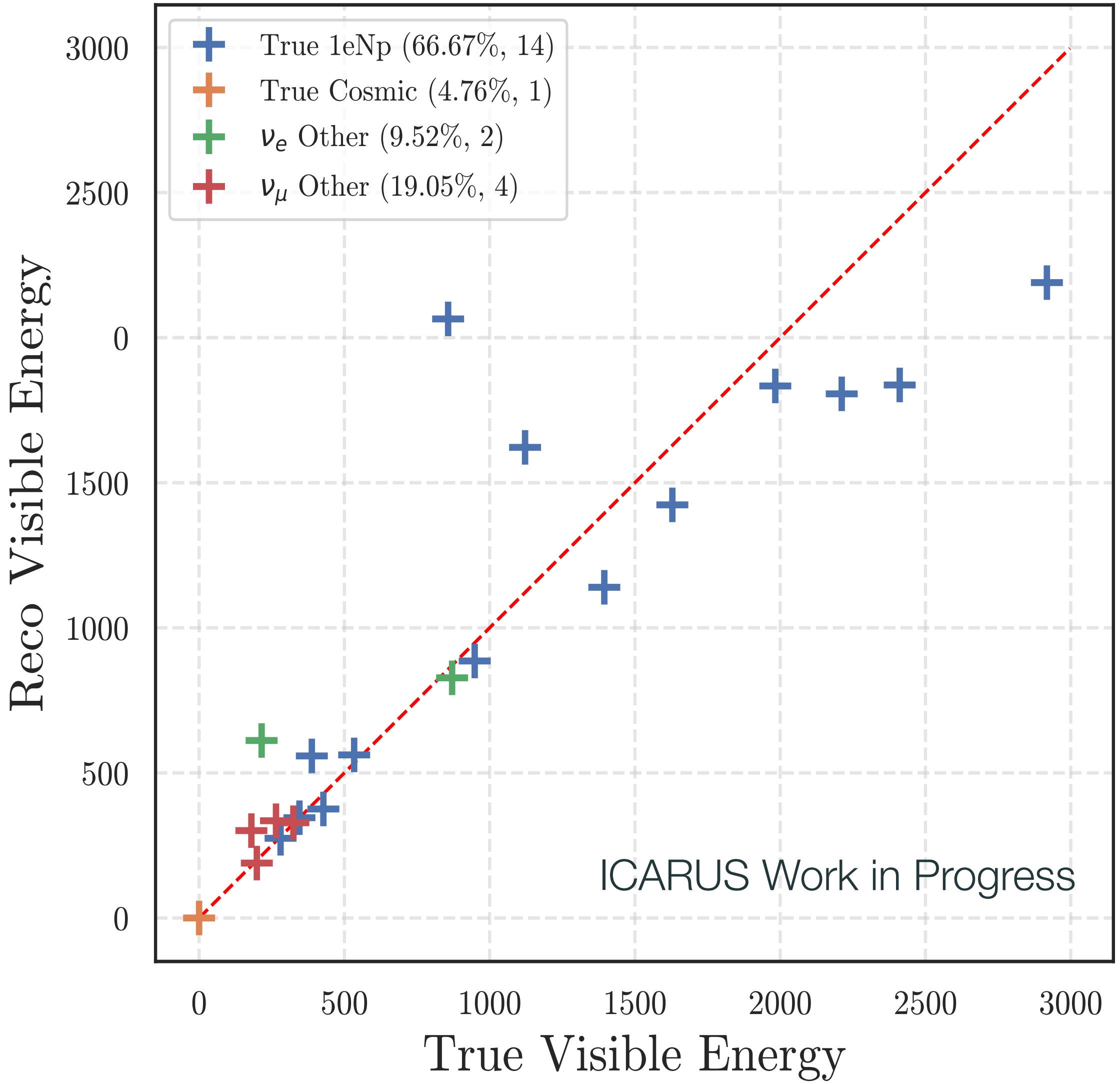
- For purity and background rejection estimates, we use the BNB ν Flux (~13k neutrinos, 99.5% ν_μ, 0.5% ν_e) simulation.

- **Estimated Purity: 66.67%**

- **MicroBooNE ν_e $1eNp0\pi$ Efficiency/Purity:** ~~15%/80%~~ with 40 MeV proton energy threshold

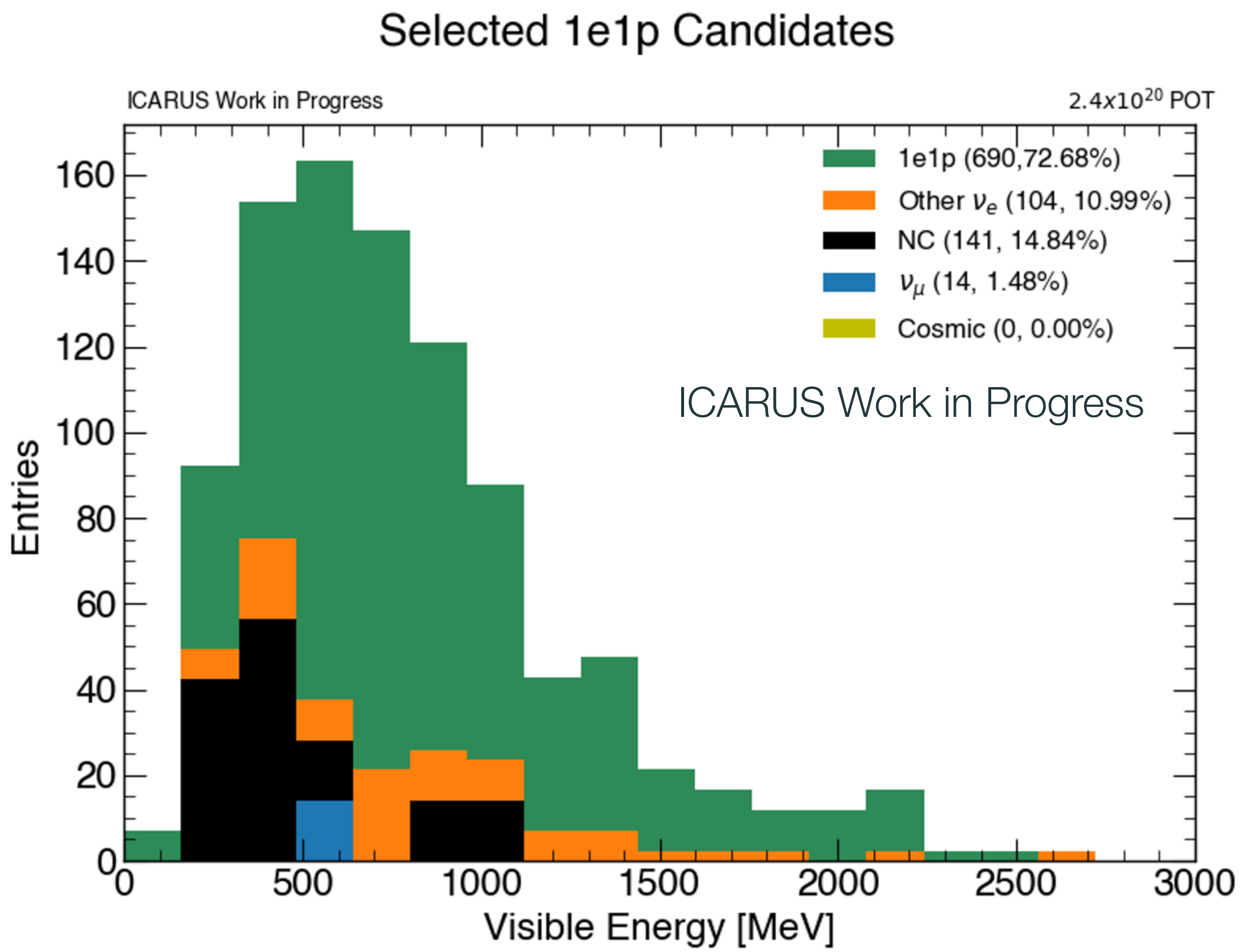
  DOI:https://doi.org/10.1103/PhysRevD.105.112004

- Selection rejects **all (100%) simulated in-time cosmic (~291k cosmic ray dataset) backgrounds.**



Preliminary Results (4: NuMI + out-of-time cosmic)

- NuMI ν_e candidates (D. Carber):
  - Containment required for visible particles (5cm margin from detector boundaries)
  - Optical flash timing within NuMI Beam window (9.6μs wide)
  - ≥ 1 reconstructed e with $E_e \geq 10$ MeV.
  - ≥ 1 reconstructed p with $E_p \geq 40$ MeV.
- **1e1p: Efficiency: 73.3%, Purity: 72.7%**



Conclusion

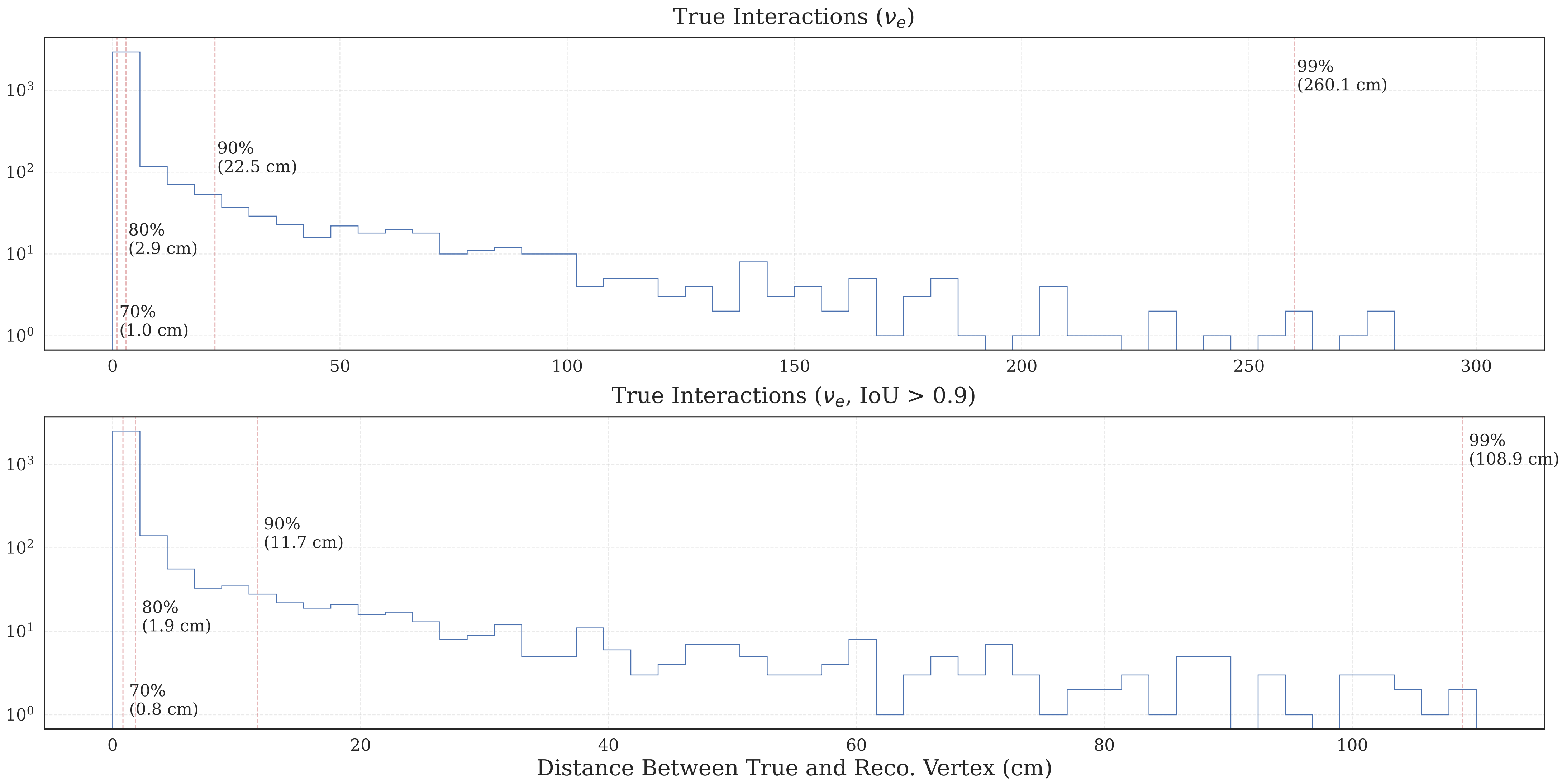
- Demonstrated application of SPINE ML-based reconstruction chain to ICARUS BNB and NuMI electron neutrino reconstruction
- Selection Purity and Efficiency:
  - BNB 1eNp: 51% / 67%
  - NuMI 1e1p: 73% / 73%
- BNB Visible Reconstructed Neutrino Energy resolution: FWHM is ~20% for the fractional error

Future Work

- Validate analysis on large-statistics sample
- Integrate flux, interaction, and detector systematic uncertainties
- Data vs. Simulation Studies

A. Reserve Slides

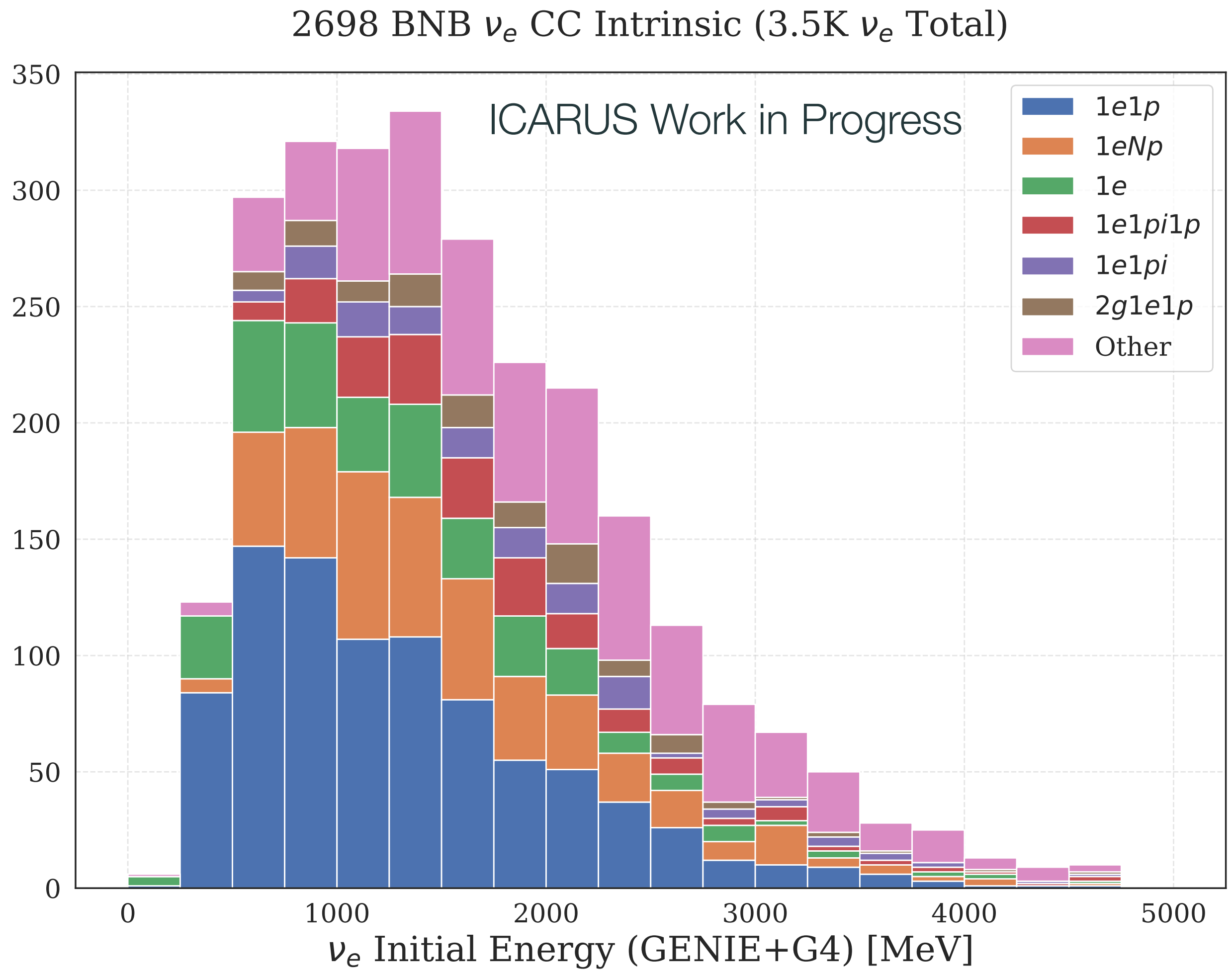
Vertex Reconstruction Resolution



Defining the Signal (BNB)

- Event topology for ν_e selection:
  - Aim for simple and abundant electron neutrino topology
    - $1eNp$, with $N \geq 1$.
  - Single electron ($1e$) topology prone to background contamination from NC $\pi^0 \rightarrow \gamma\gamma$ decays
  - Require no primary photons for ν_μ NC π^0 rejection
- **Conclusion:**
  - $\mathrm{1eNp0\pi^{\pm}0\gamma}$ **Topology for ν_e candidate**

- Left: simulated 2.7K charge-current electron neutrino interactions (ν_e CC) in ICARUS



Deep learning for LArTPC Event Reconstruction

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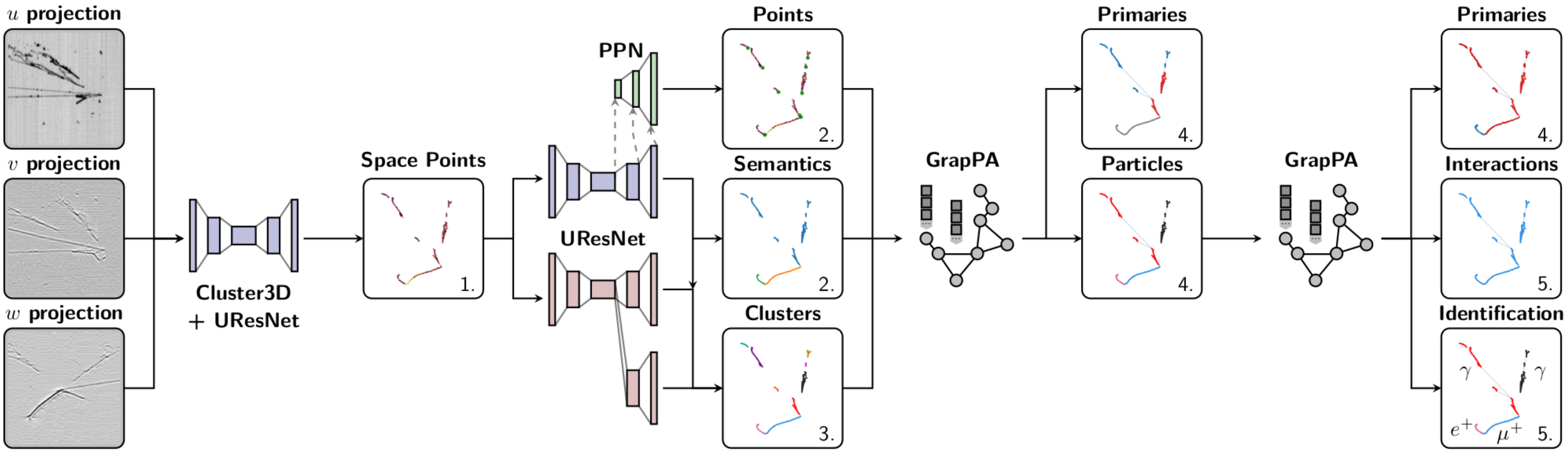
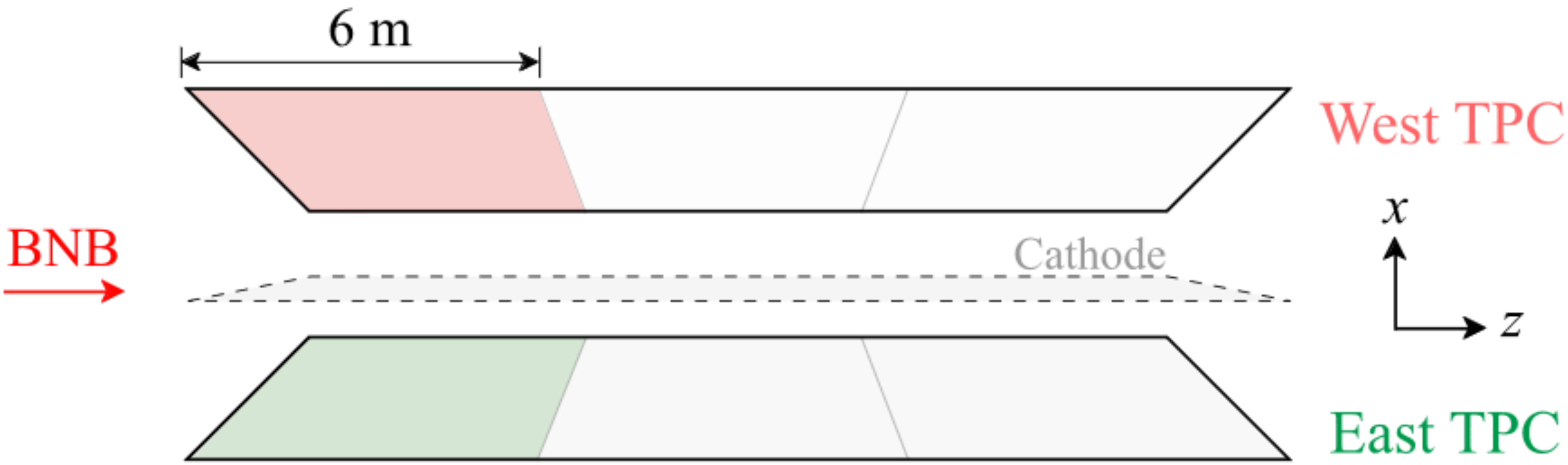


The ICARUS T600 Detector

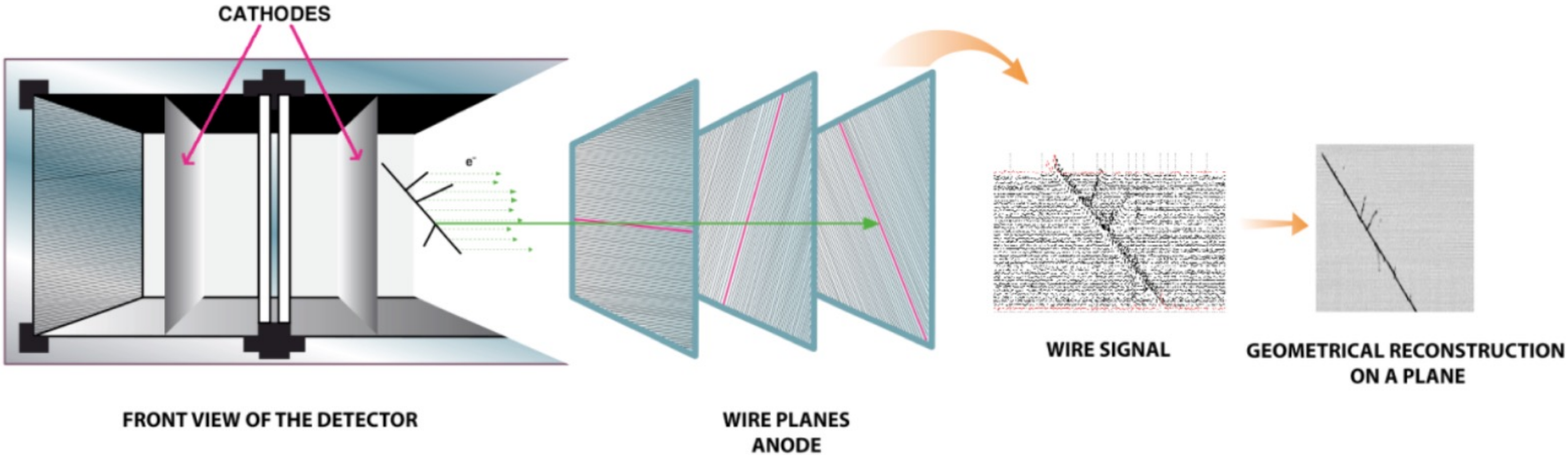


Top View of West ICARUS T300 module (West and East T300 combine to form the T600 Detector)

Image Credit: https://thesis.unipd.it/handle/20.500.12608/52881

The ICARUS T600 Detector

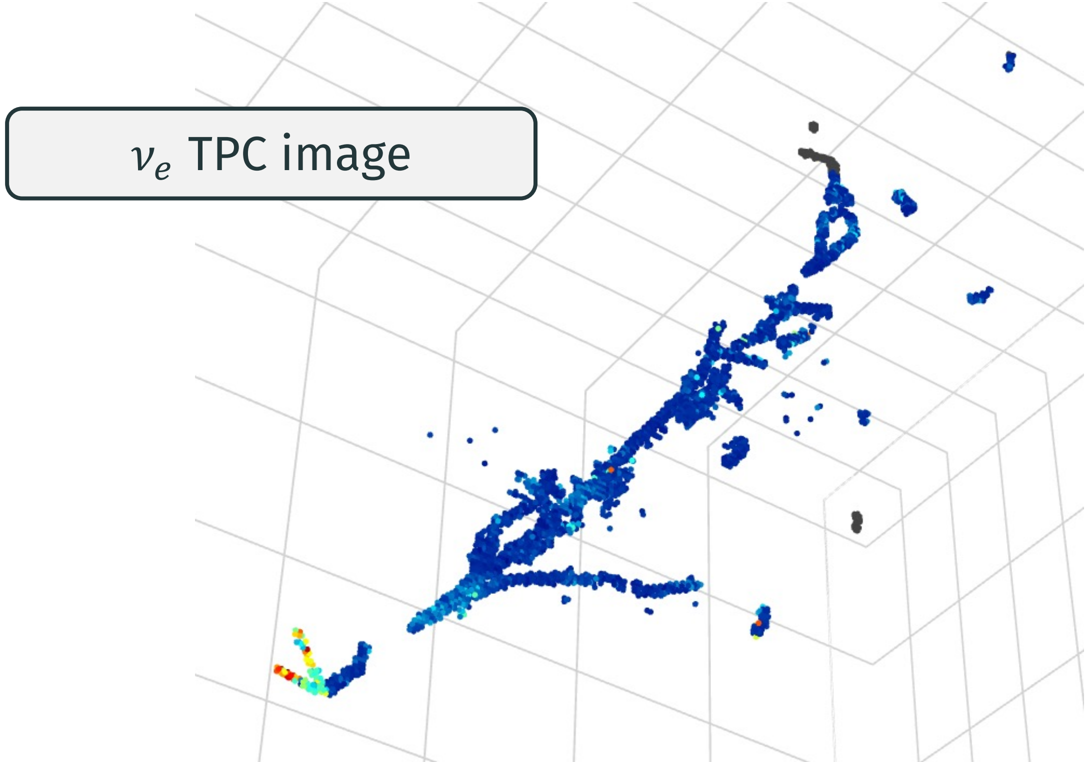
- Each U, V, and Y wire planes provide a 2D projection view of the charged particle ionization path
- A 3D representation of a charge particle ionization path may be reconstructed from the 2D views, provided the initial timing information.

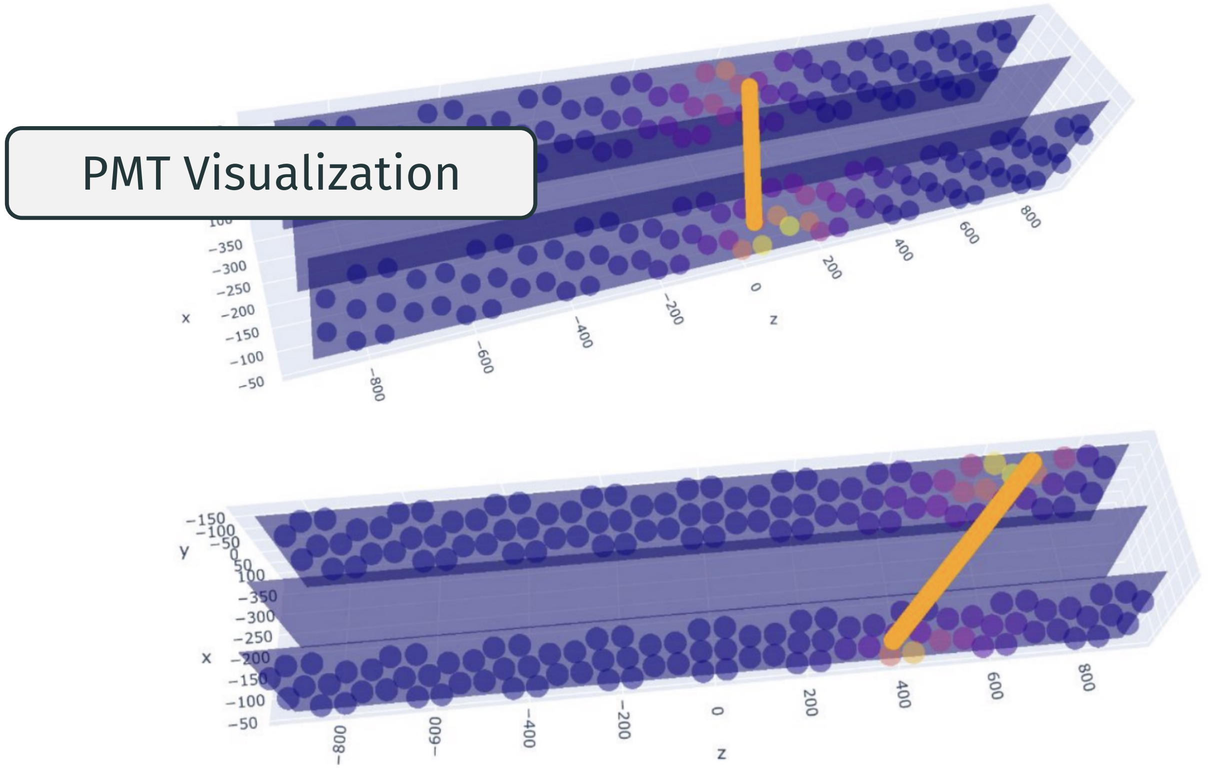


Rubbia, C & Antonello, Matteo & Aprili, P. & Baibussinov, B. & Baldo-Ceolin, M. & Barze, Luca & Benetti, P & Calligarich, E & Canci, Nicola & Carbonara, F. & Cavanna, Flavio & Centro, Sandro & Cesana, A & Cieslik, Krzysztof & Cline, D. & Cocco, Alfredo & Dabrowska, Anna & Dequal, Daniele & Dermenev, A & Zmuda, J.. (2011). Underground operation of the ICARUS T600 LAr-TPC: first results. Journal of Instrumentation - J INSTRUM. 6. 10.1088/1748-0221/6/07/P07011.

The ICARUS T600 Detector

- The ICARUS T600 detector is composed of three major subsystems:
  - **Time Projection Chambers (TPCs):** allow high resolution imaging of particle trajectories.
  - **Photomultiplier Tubes (PMTs):** scintillation light from charged particles used for interaction timing information
  - Cosmic Ray Tagger (CRTs): tagging system for crossing and exiting particles





The ICARUS T600 Detector: Trigger System

- ICARUS Trigger system exploits 360 PMTs installed behind TPC wire planes to recognize beam-related neutrino events within the 1.6μs spills of the Booster Neutrino Beam (BNB).
- Detector receives “early warning” signals 35ms before the protons hit the BNB target, hence the beam spill windows are known.

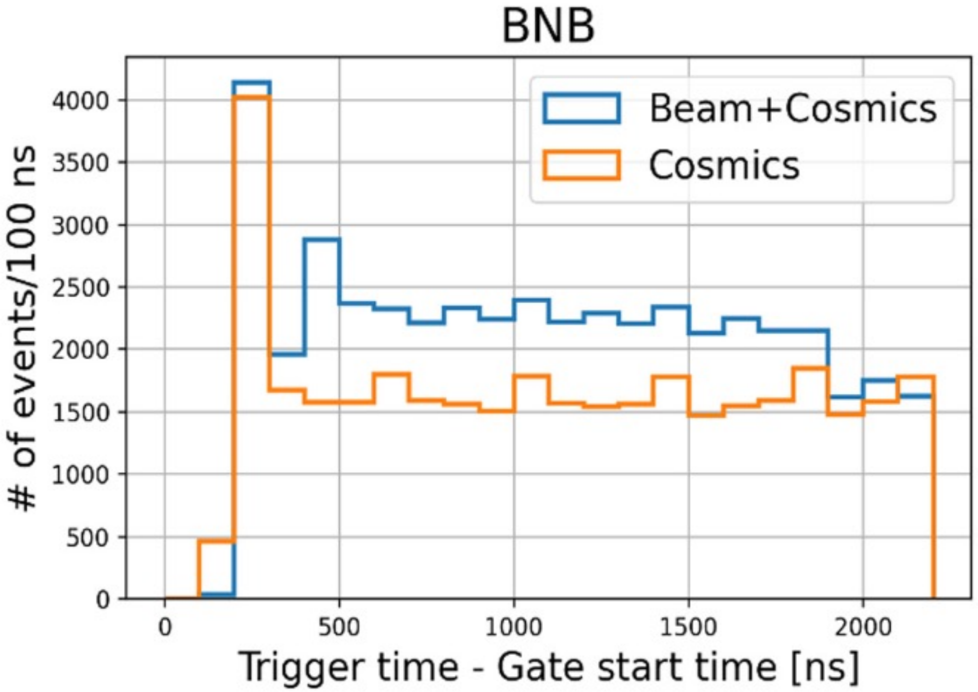
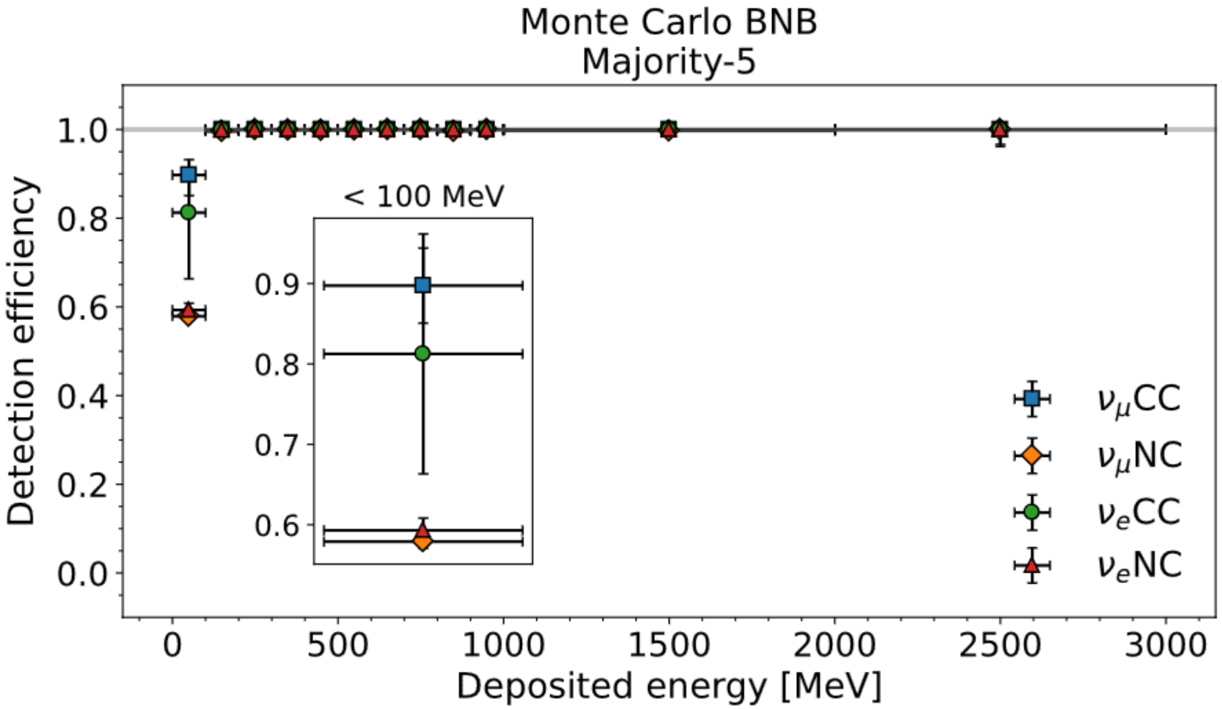


Image Credit: https://doi.org/10.1016/j.nima.2022.167498



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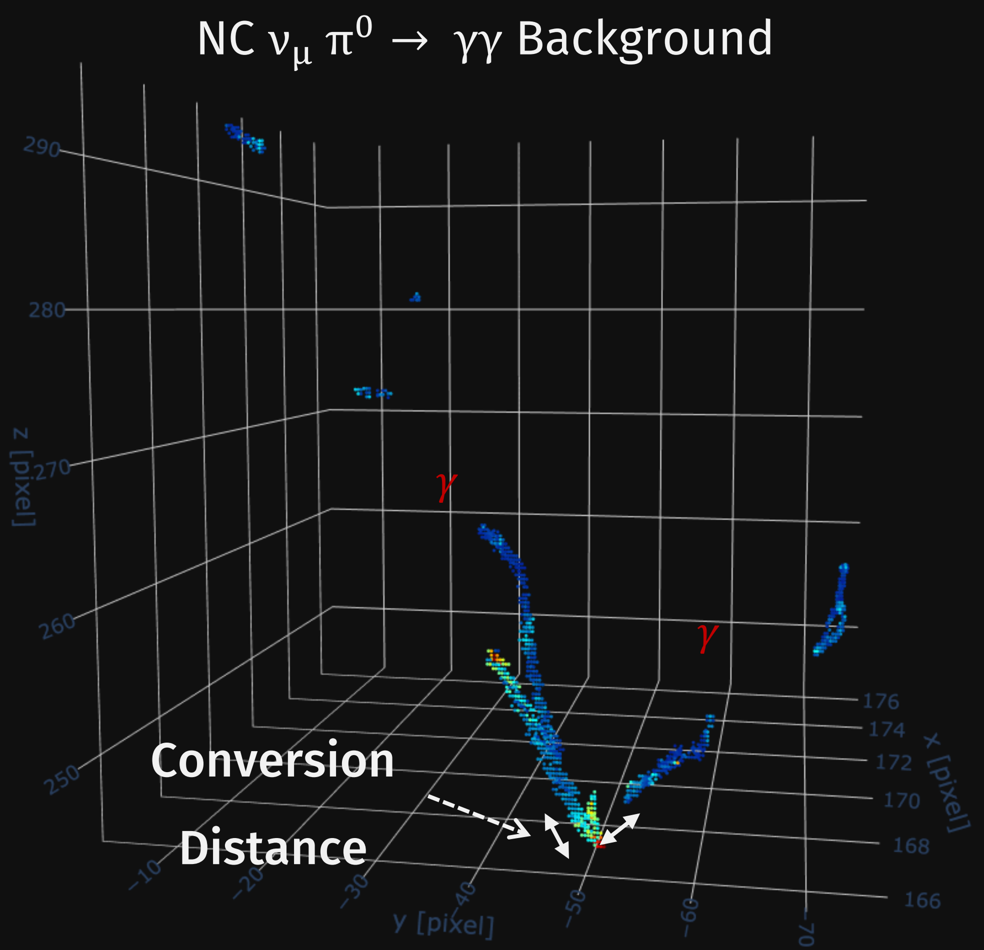
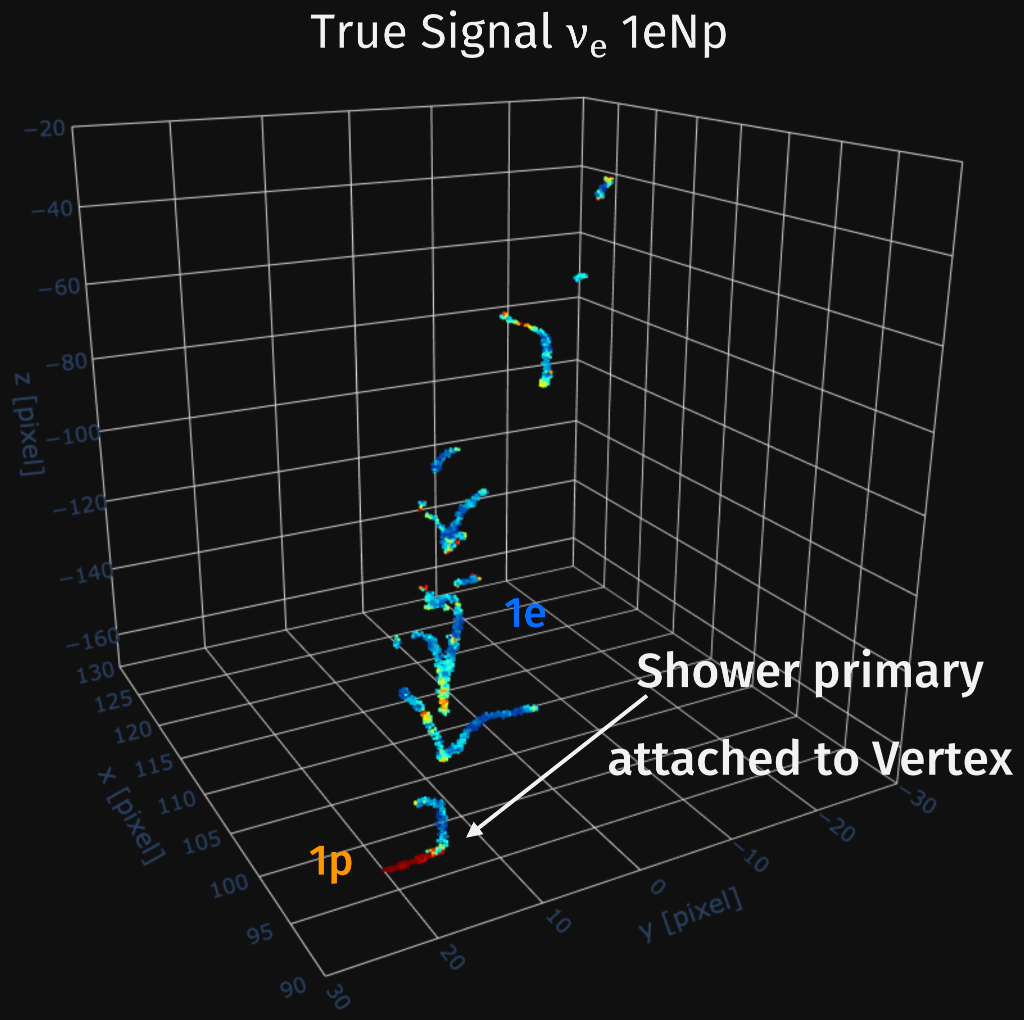
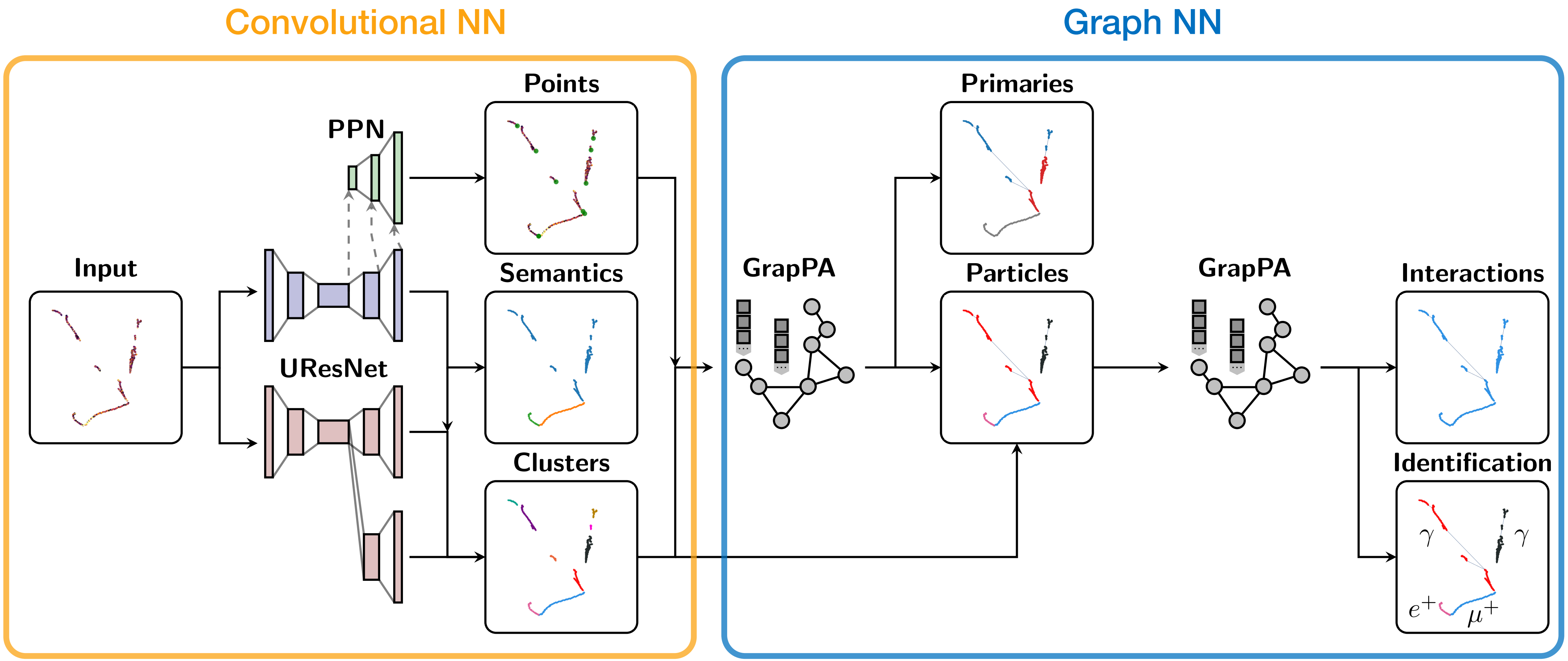
Preliminary Results: Cuts (BNB)





Deep learning for LArTPC Event Reconstruction

- The reconstruction chain may be separated into two submodules: **convolutional** and **graphical** neural network branches.



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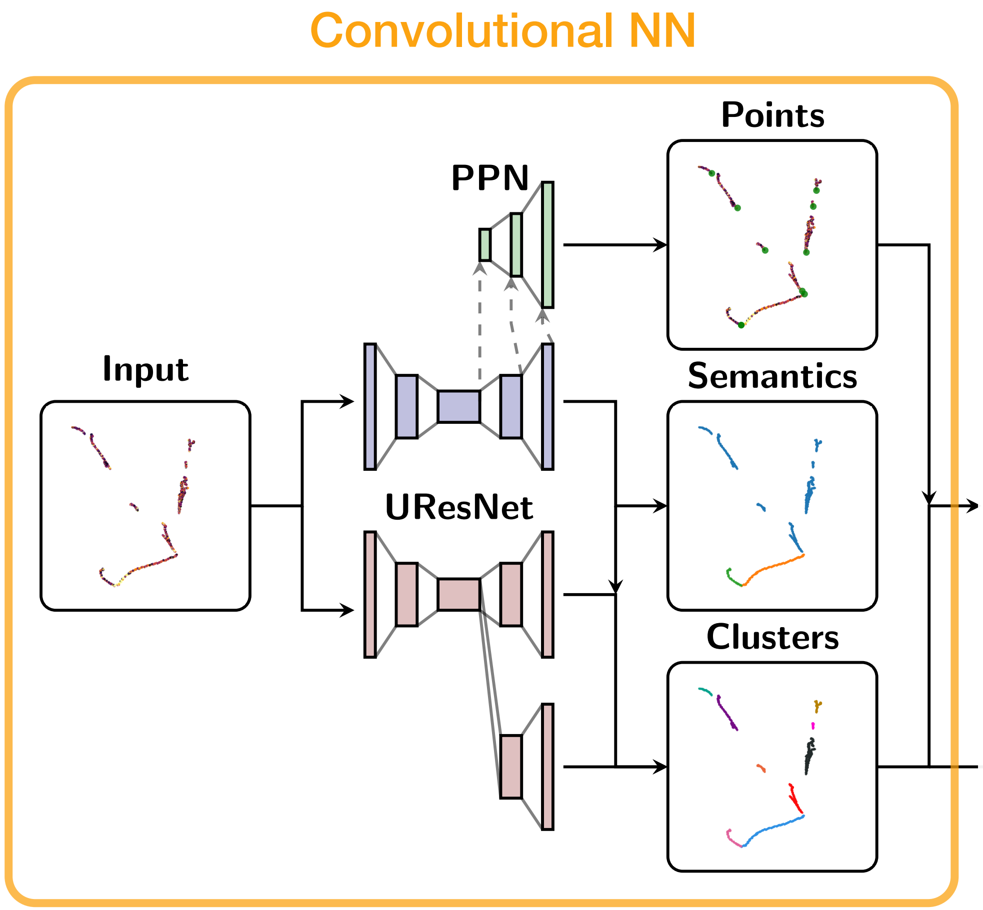
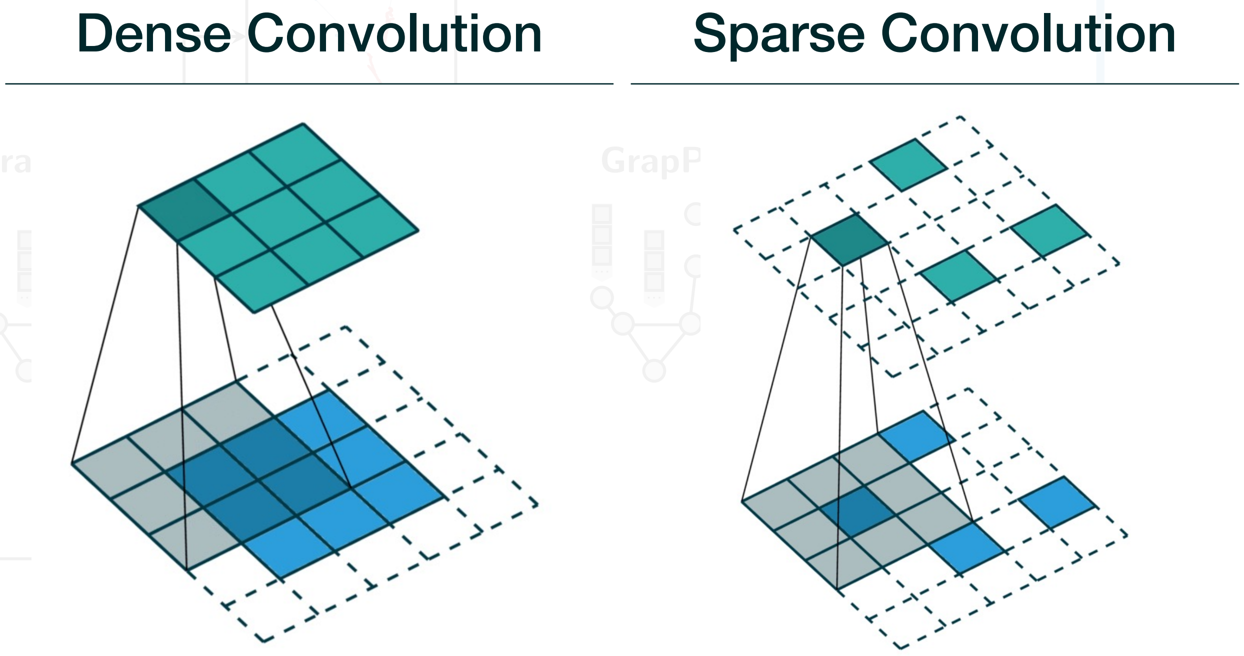


- **Sparse Convolutional Neural Networks** allows fast, efficient, and superior processing of LArTPC images.



Deep learning for LArTPC Event Reconstruction

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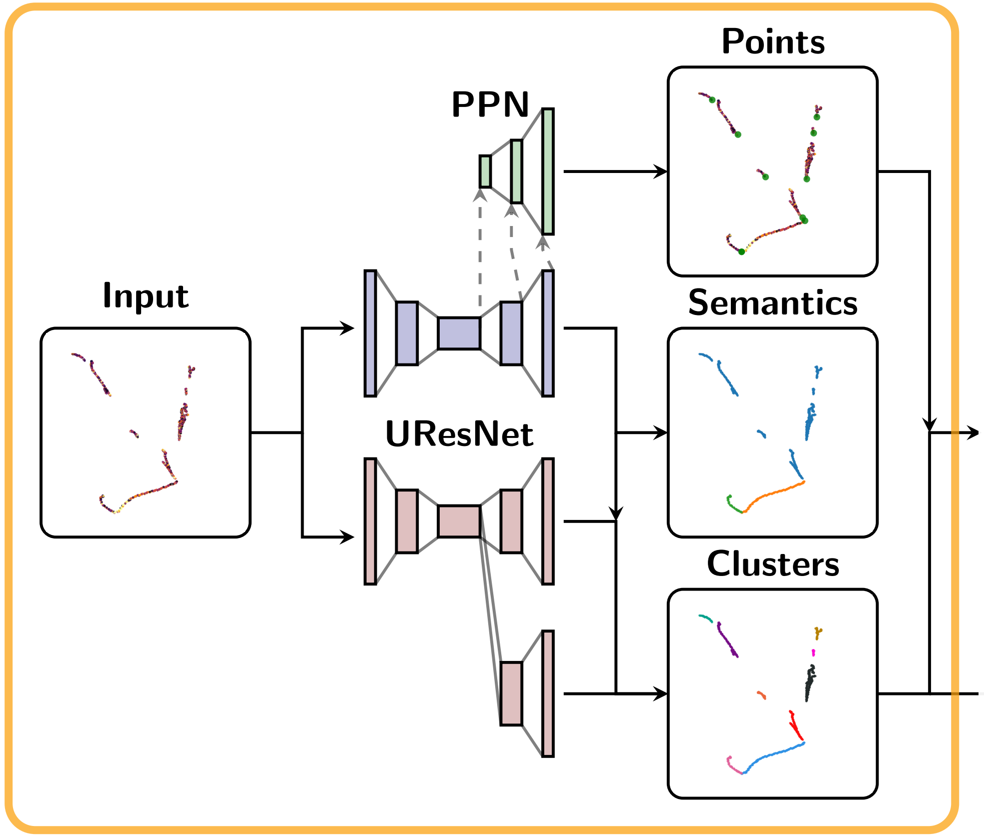
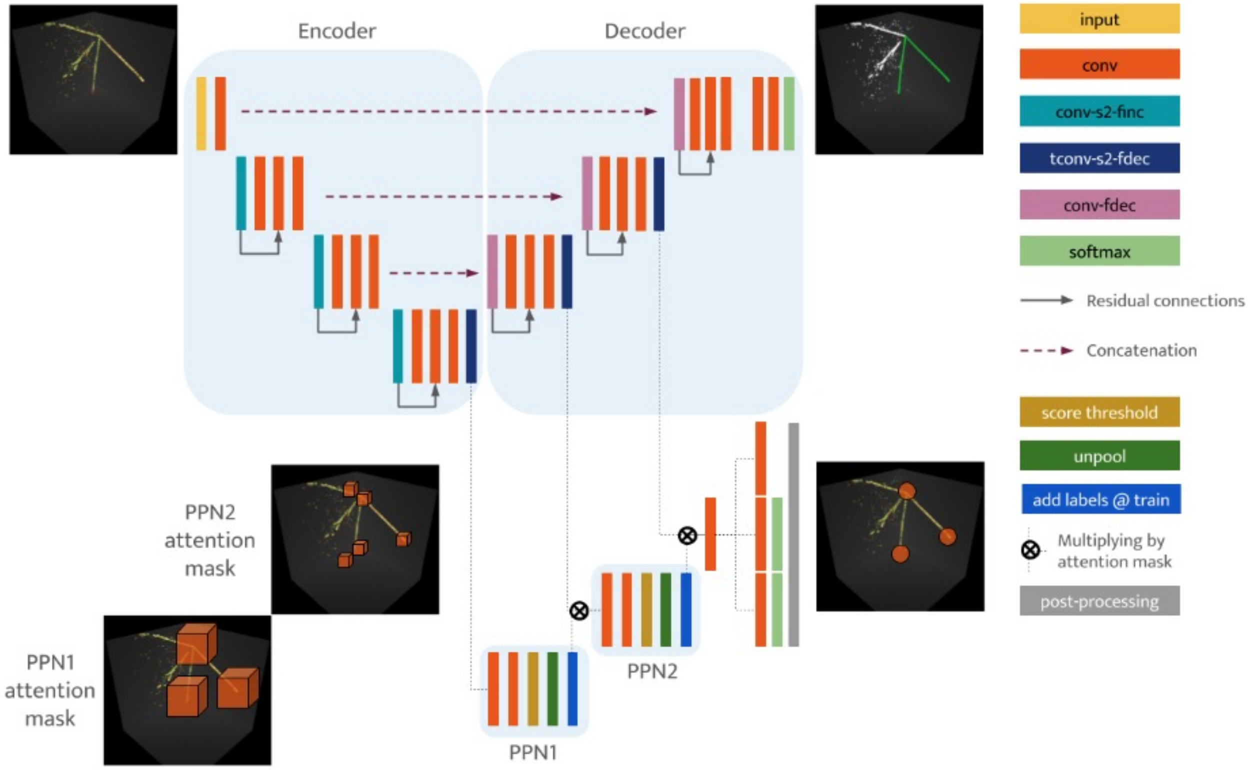
Convolutional NN



- **Pixel-level Tasks** are handled by a sparse-convolutional neural network architecture called **Sparse-UResNet**.



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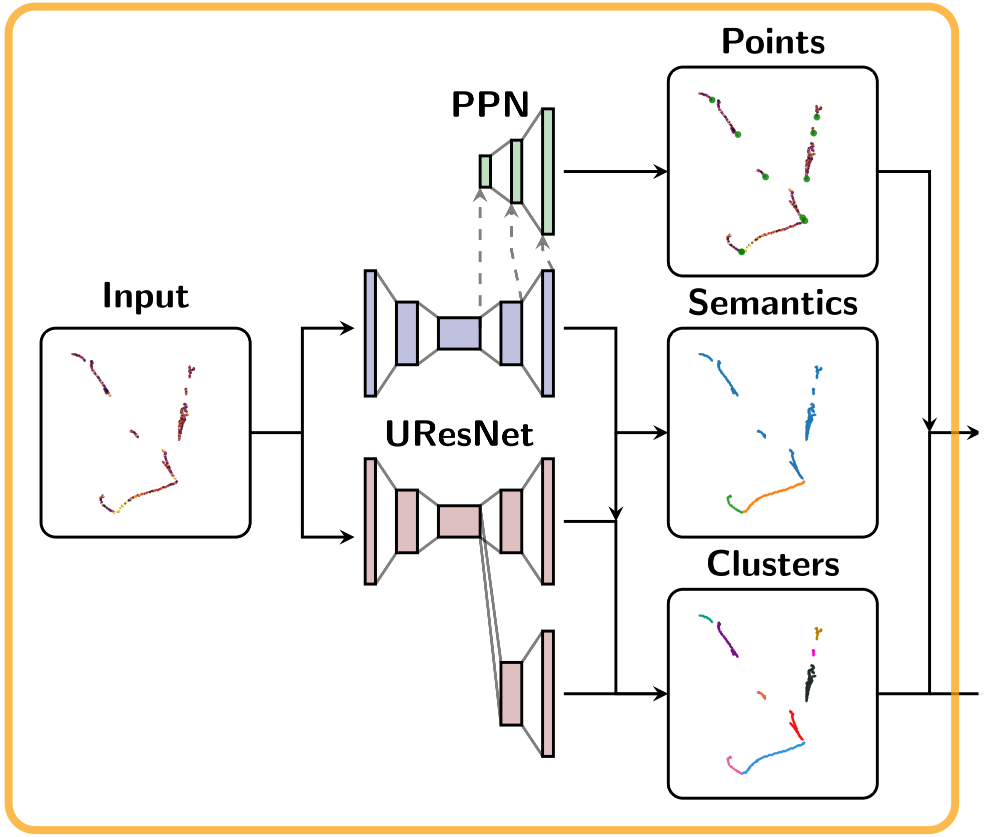
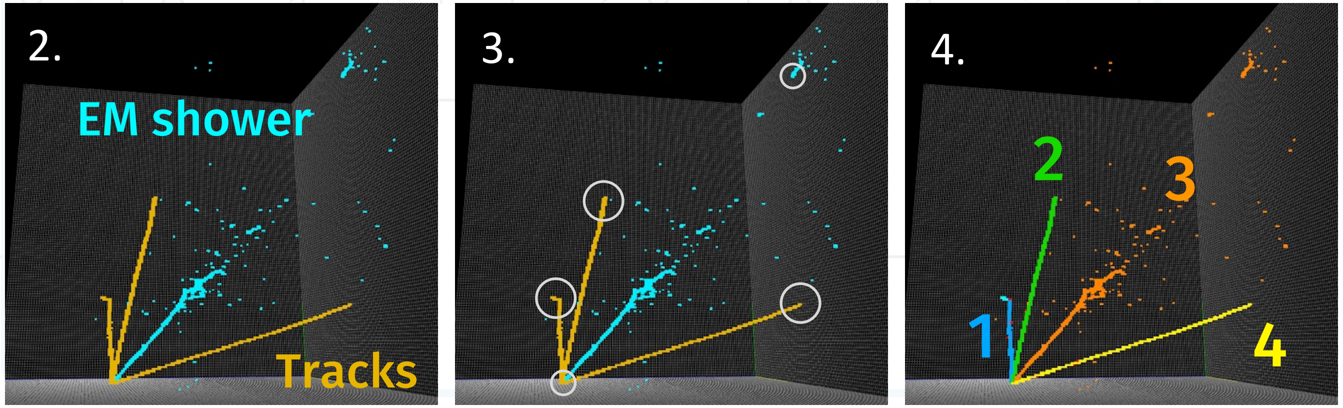
Convolutional NN

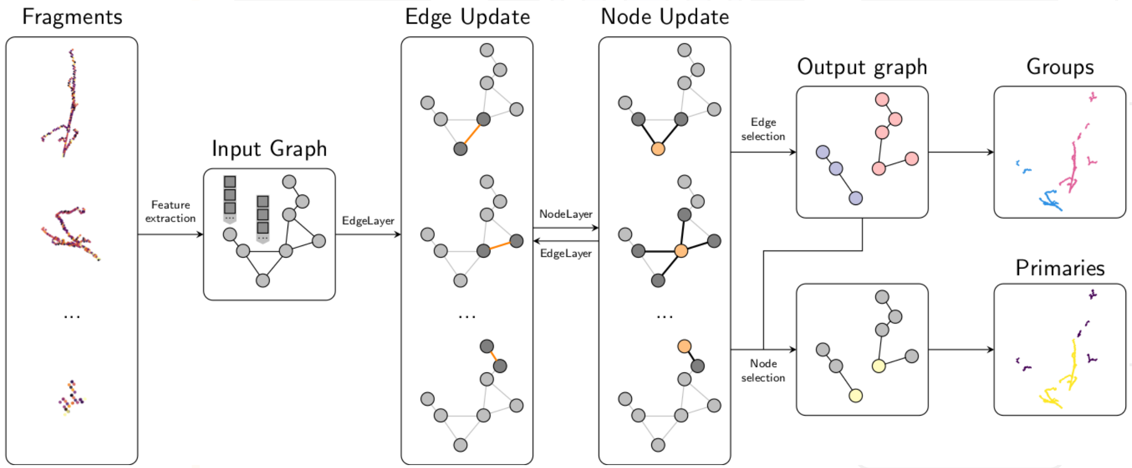


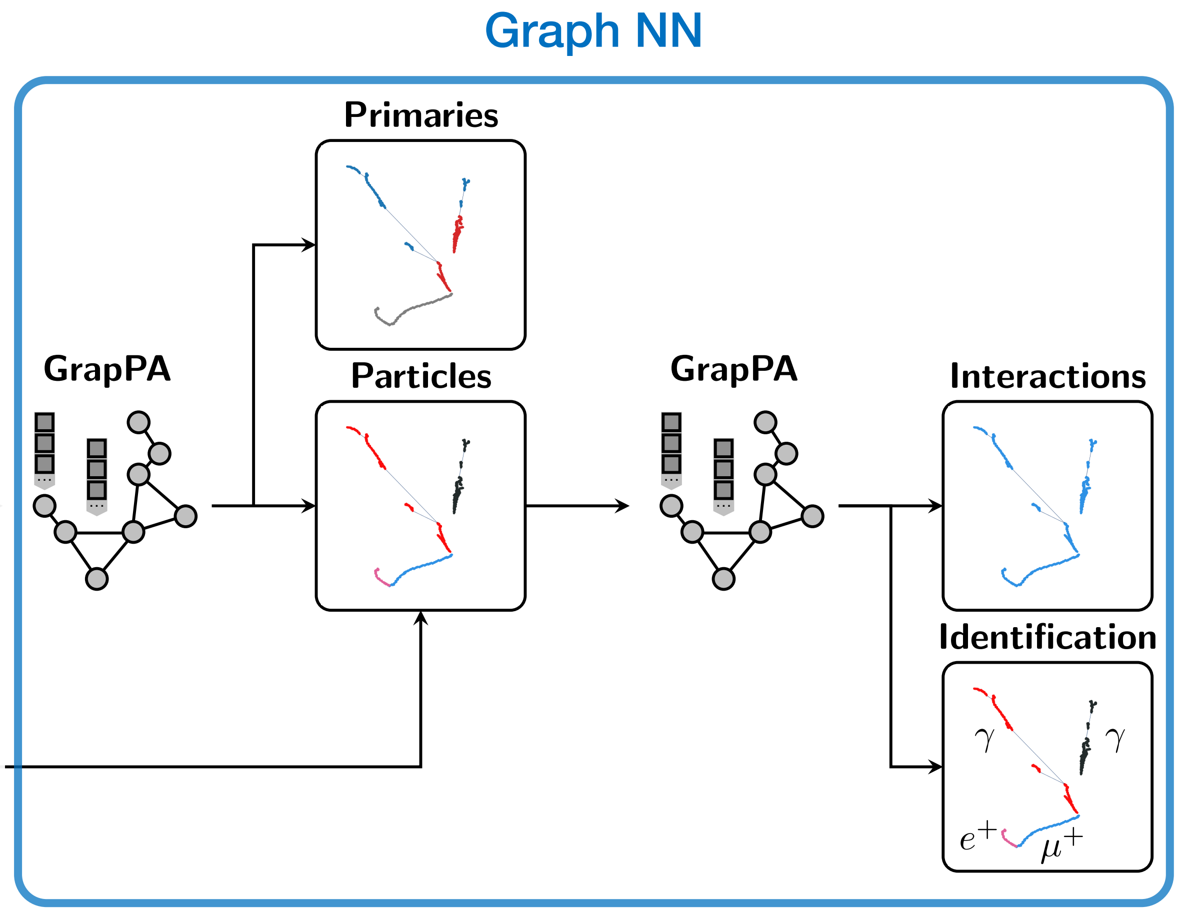
- **Pixel-level Tasks** are handled by a sparse-convolutional neural network architecture called **Sparse-UResNet**.
    1. **Tomographic Artifact Removal**: remove false positive 3D spacepoints from 2D -> 3D tomographic reconstruction.
    2. **Semantic Segmentation**: classify each pixel to activity type
    3. **Point of Interest** (track start/end, EM shower start) detection.
    4. **Particle Clustering**: cluster pixel into different ancestral particles.



Deep learning for LArTPC Event Reconstruction

- After particle clustering, each group of pixels realized from the same particle is **abstracted into a node feature vector of a graph.**
- **Graphical Neural Networks (GNNs)** are best-suited for inference involving contextual reasoning across distinct objects.
- Tasks such as **particle type classification, grouping particles to interactions** are handled using GNNs.

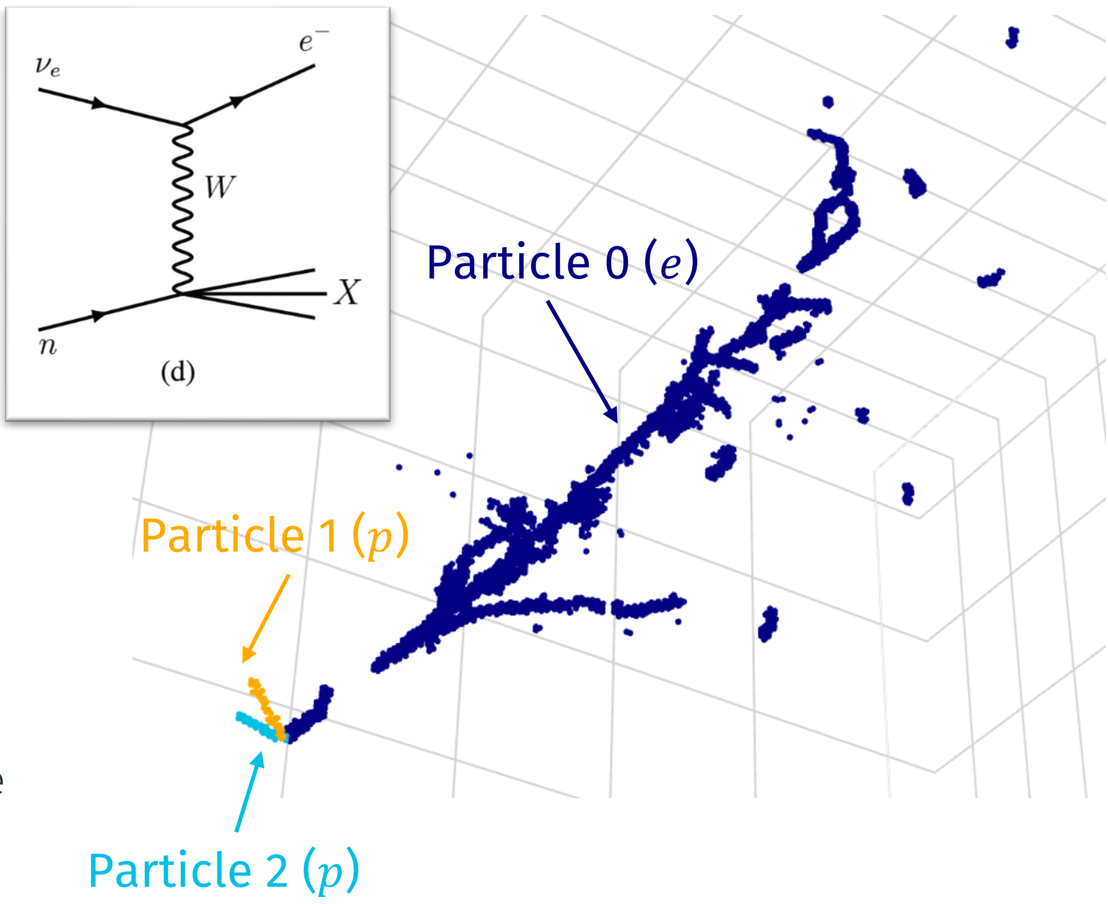




Deep learning for LArTPC Event Reconstruction

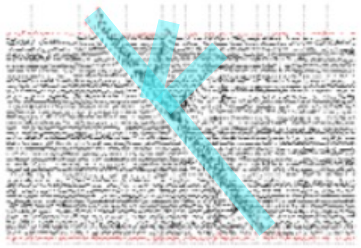
- By aggregating all outputs from the ML chain, we can reconstruct the **full geometric information of a given LArTPC image.**
- **For each particle, we predict its**
  - **Type** (γ, e, μ, π, p)
  - **Primary Score** (indicates whether a particle is a primary deposition of an interaction)
  - **Parent Interaction Group**
- **Example:**
  - for every interaction (group of particles) in an image, search for interactions with one primary electron and more than one primary proton.

Image Credit: DOI: 10.1103/PhysRevD.103.075023

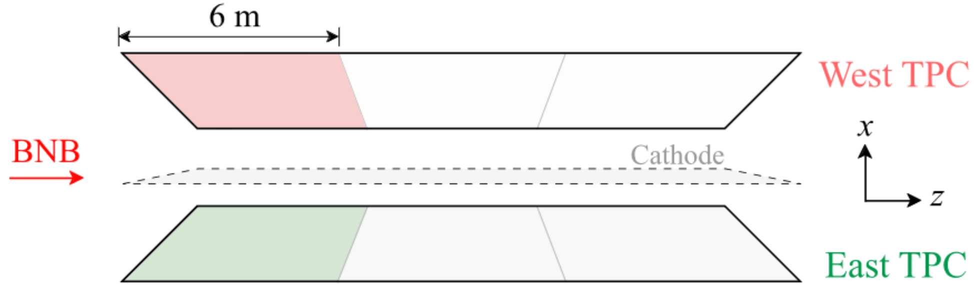


Tomographic Reconstruction: Building 3D Spacepoints

- ML Based reco. Chain is developed for 3D images
- **Tomographic Reconstruction (three 2D projections -> 3D) essential for ML-reco. Chain on Wire LArTPCs**
- In each U, V, and Y projections (indexed by $p = 0,1,2$), let $h_p^{(i)} = \left(t_p^{(i)}, w_p^{(i)}\right)$ be a single i-th 2D hit:
  - $t_p^{(i)}$: time measured along drift-axis ($\hat{e}_x$ basis, by convention)
  - $w_p^{(i)}$: wire number measured along the wire-direction basis $\hat{e}_p = \lambda_p \hat{e}_y + \kappa_p \hat{e}_z$, since wire planes are slanted at $\pm 60°$ (basis transform).
- **Cluster3D** is a traditional algorithm which combines 2D hits that are compatible in time and wire to propose 3D positions.
  - Find pairs of hits $\left(h_p^{(i)}, h_q^{(j)}\right)$ which are compatible in time: $\left|t_p^{(i)} - t_q^{(j)}\right| < \delta_t$
  - Form a 3D "doublet" candidate spacepoint: $x_{ij} \coloneqq \underbrace{\frac{1}{2}\left(t_p^{(i)} + t_q^{(j)}\right)}_{\text{Best estimate of time}} \hat{e}_x + \underbrace{\begin{bmatrix} \boldsymbol{e}_p \\ \boldsymbol{e}_q \\ \boldsymbol{e}_p \times \boldsymbol{e}_q \end{bmatrix}^{-1} \begin{bmatrix} w_{p,i} \\ w_{q,j} \\ 0 \end{bmatrix}}_{\text{Change of Basis}}$



Wire 2D hits in given projection



- If a third plane hit $h_r^{(k)}$ is compatible with x_{ij}, register it as a "triplet" x_{ijk}.
- **In short, find pairs of wires that meet each other (have crossing point) and find wire hits that are compatible in time.**

Liquid Argon Time Projection Chamber (LArTPC)

- Several detector properties affect event reconstruction:
- TPC-related:
  - **Recombination**:
    - Ionization electrons may recombine with nearby argon ions, underestimating yield.
  - **Diffusion**:
    - Smearing of electron cloud as function of drift time.
  - **Electron Lifetime**:
    - Average capture time of a free ionization electron by an electronegative impurity in Lar.
  - **Space-charge Effect**:
    - Accumulation of positive argon ions induce local distortions of electric field
  - **Transparency**

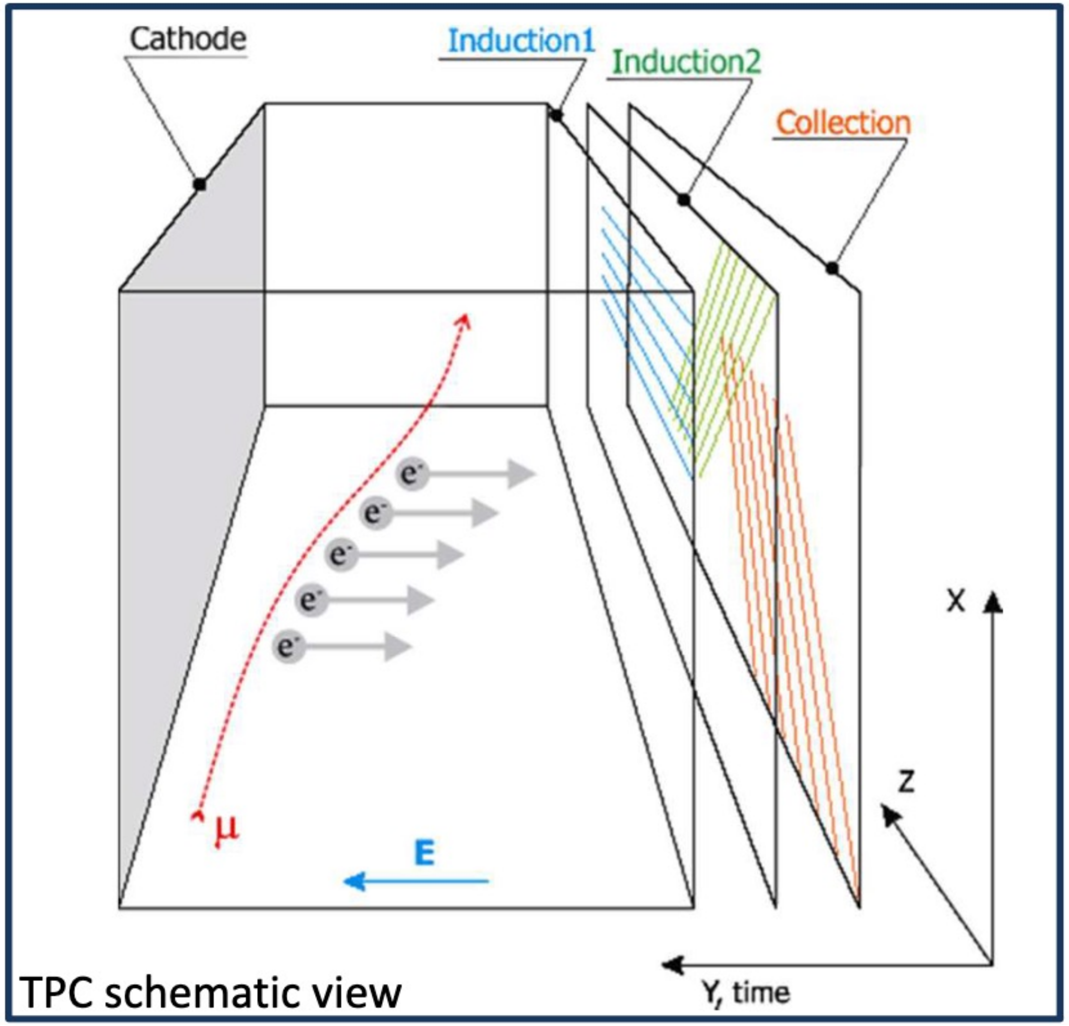


Image Credit:
https://indico.cern.ch/event/286883/contributions/654014/attachments/533407/735520/PrezentacjaNCBJ_6-12-2013.pdf

Conversion Distance Cut

- Electron and Photon Electromagnetic Showers can be distinguished in LArTPCs using **the displacement of the EM shower's start position from the neutrino interaction vertex.**
- **Conversion Distance**: compute the minimum distance between all primary track startpoints and EM shower.
- If the conversion distance exceeds 0.8cm, override shower particle type to photon.

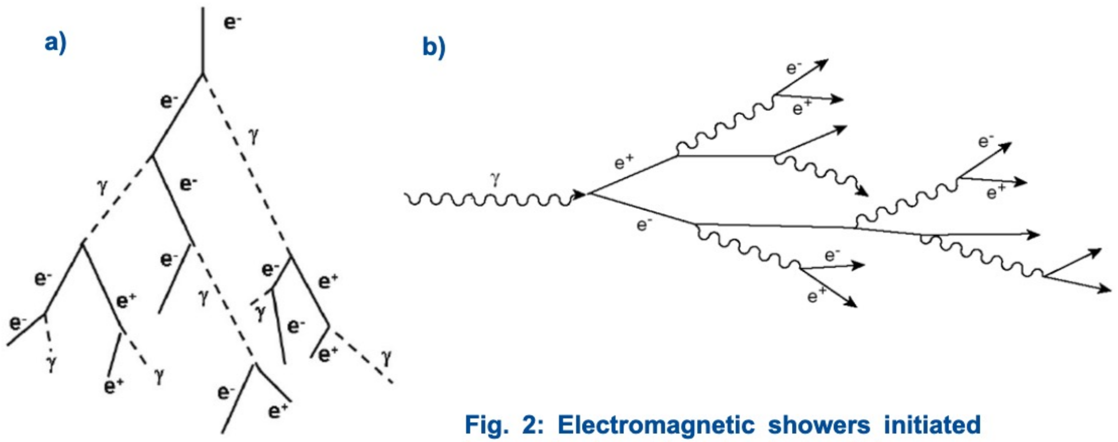
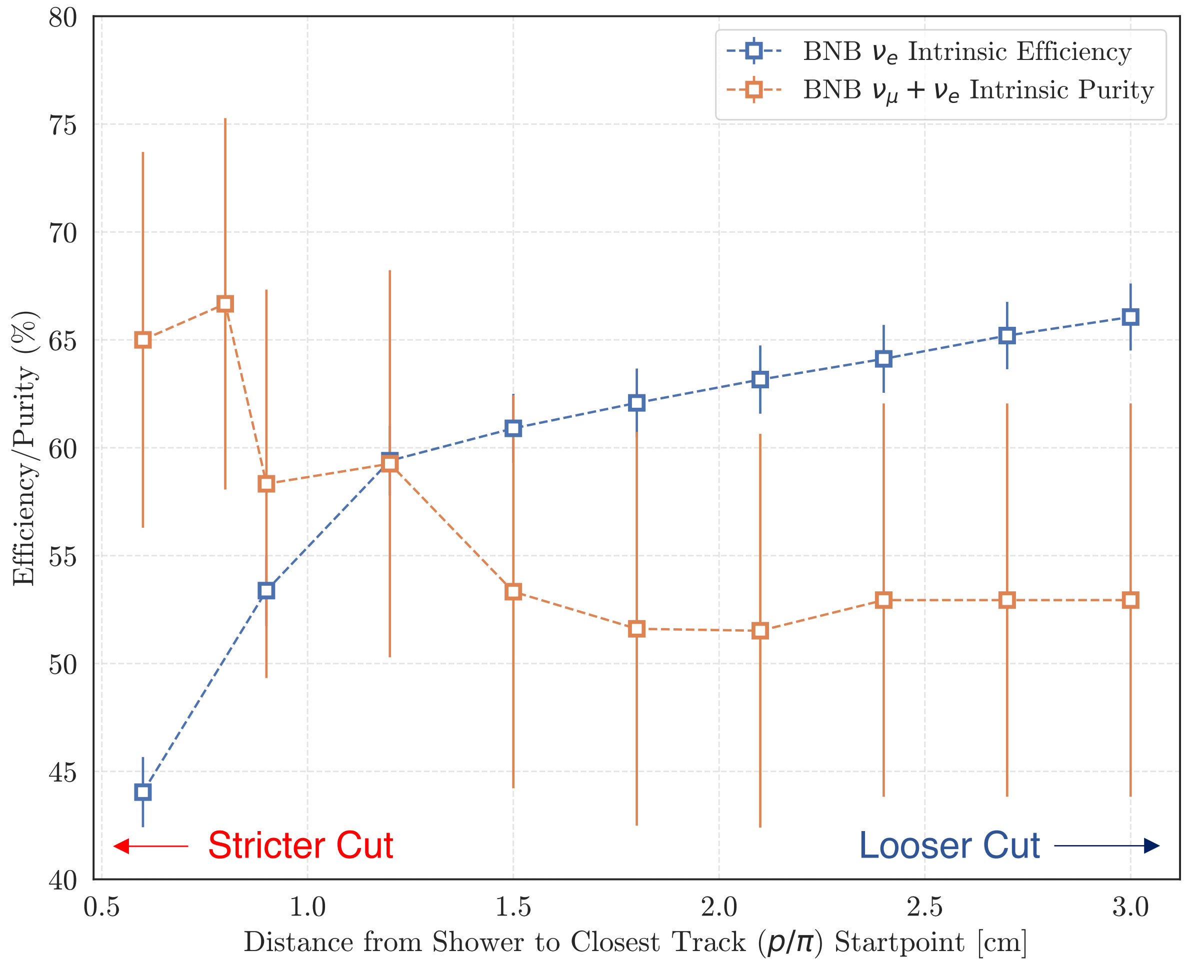


Fig. 2: Electromagnetic showers initiated by an electron (a) and a photon (b).

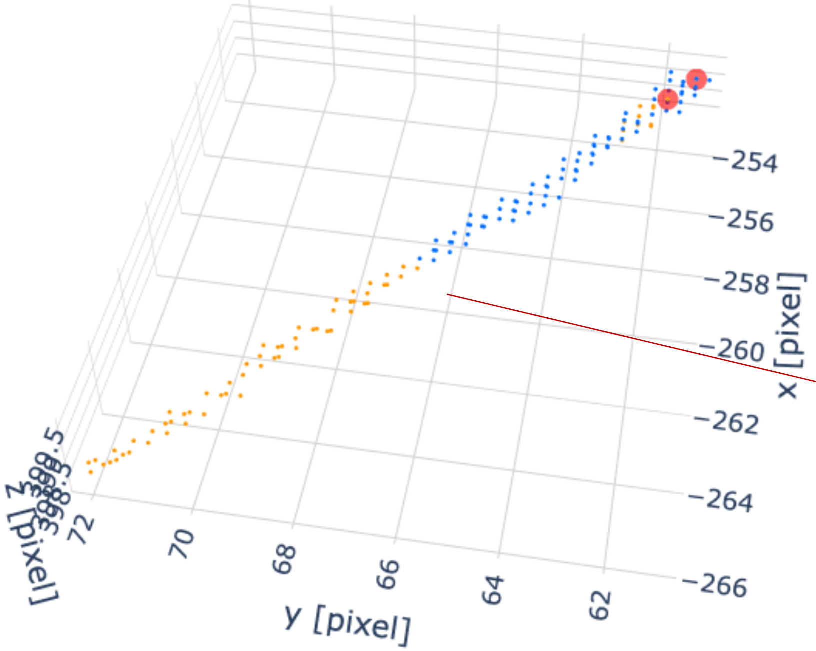
Image Credit: DOI: 10.2172/1996518



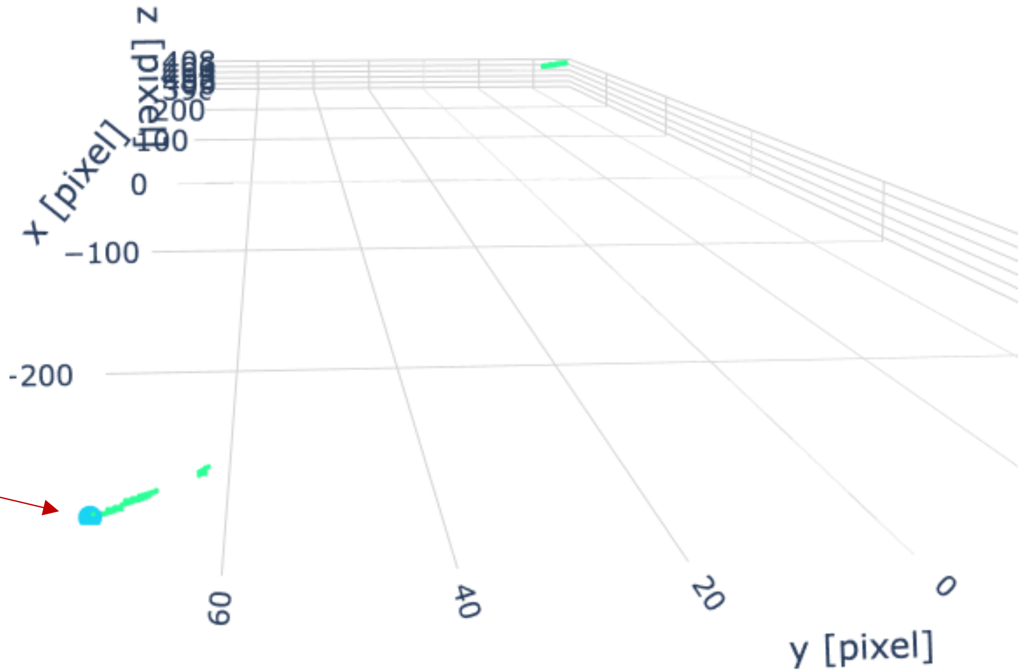
Cosmic

4.76%
(1)

Prediction



Truth



Event Displays

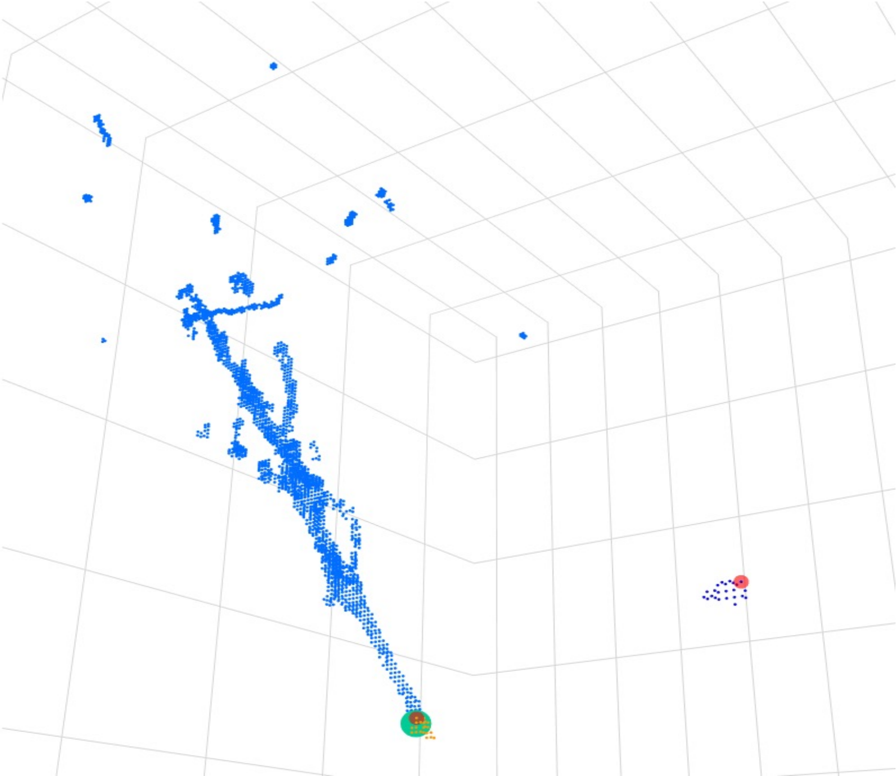
ν_e Other

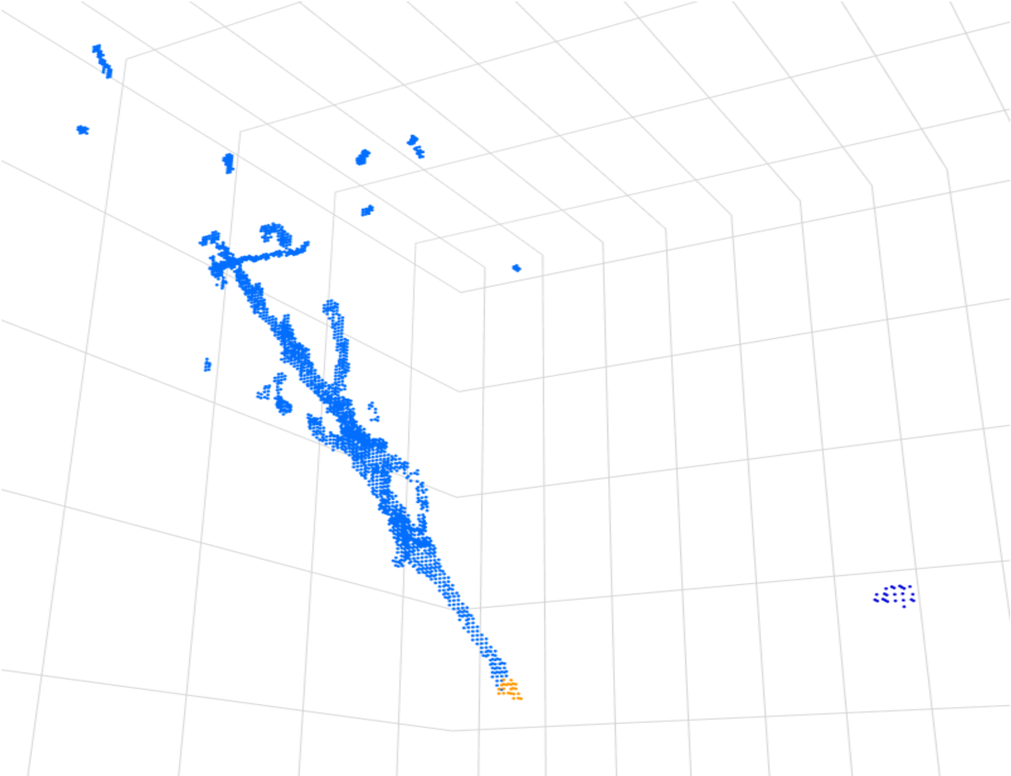
9.52%
(2)

Prediction

Small proton in ground truth, but does not pass the true visibility cut

Truth





Event Displays

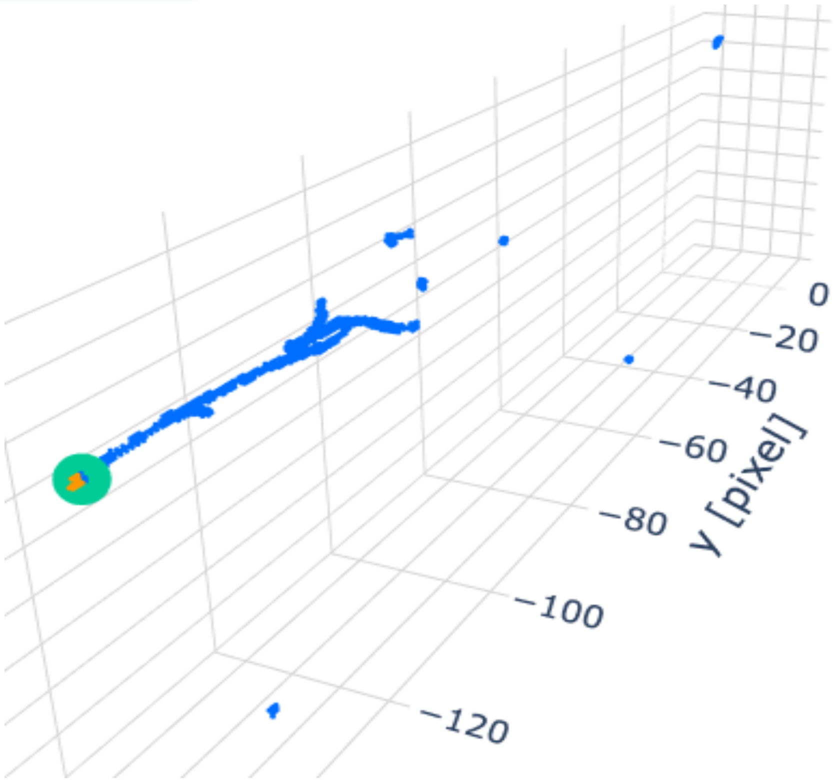
ν_e Other

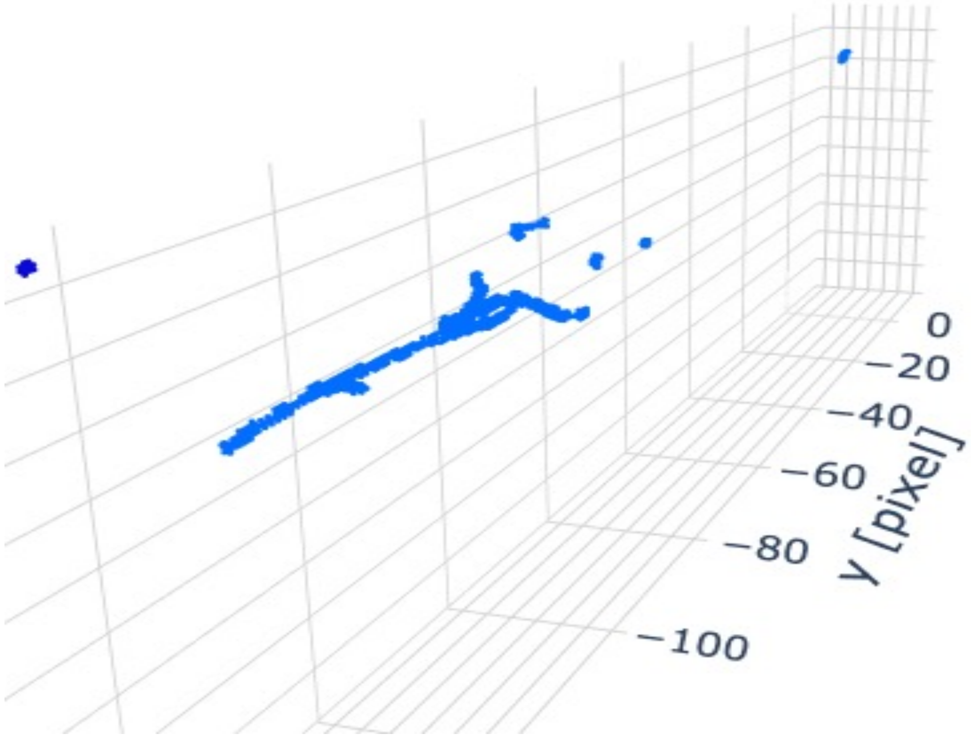
9.52%
(2)

Prediction

True 1e Nue, but high depositions near the shower start -> reconstructed as proton

Truth





Start point and Vertex Reconstruction

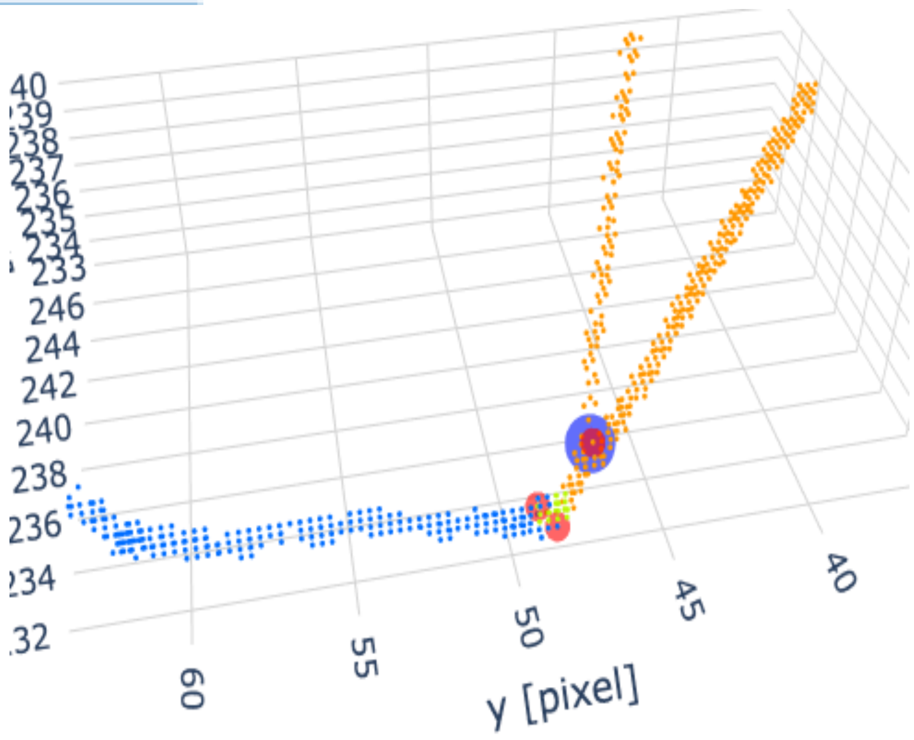
ν_μ Other

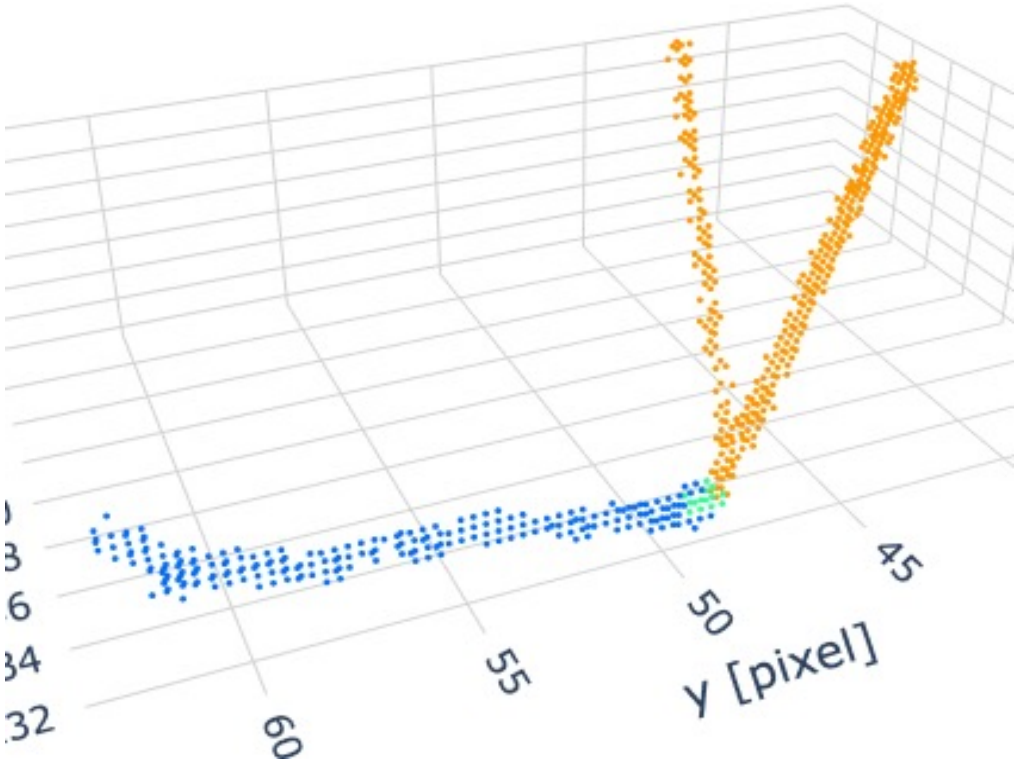
19.05%
(4)

Prediction

Misclassified Michel -> Electron Primary

Truth





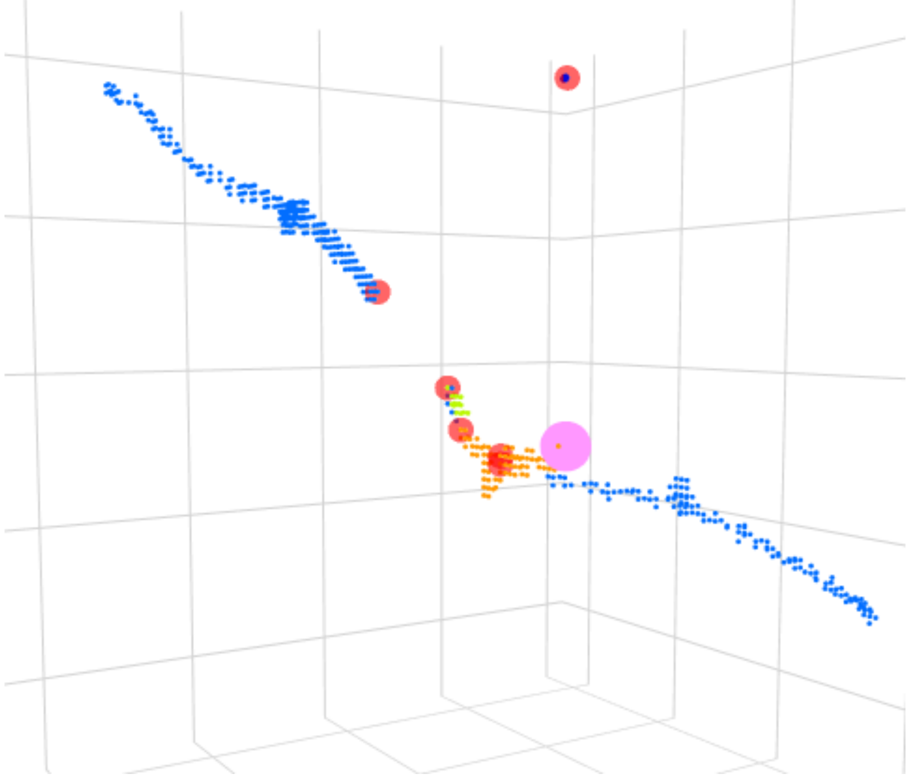
Start point and Vertex Reconstruction

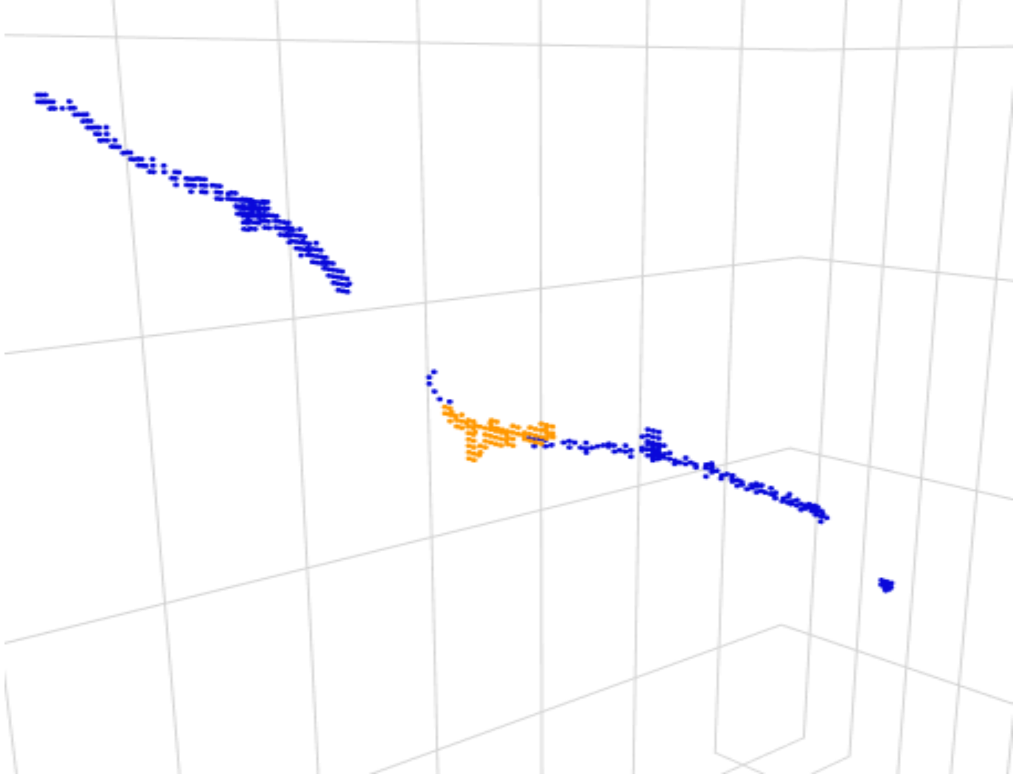
ν_μ Other
19.05% (4)

Prediction

Two gamma showers grouped together erroneously and predicted as primary electron

Truth





Start point and Vertex Reconstruction

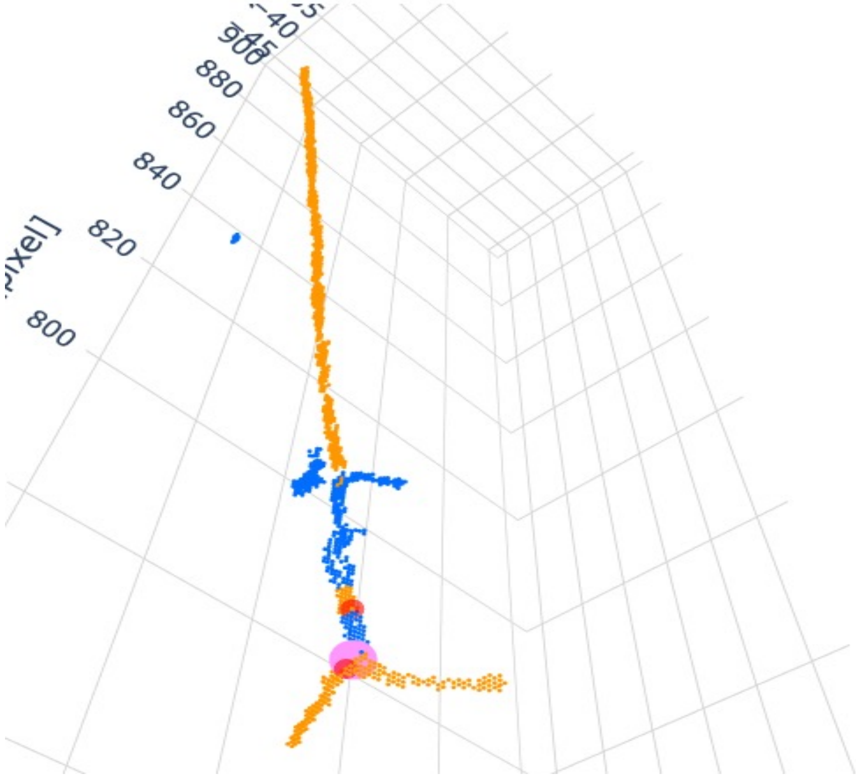
ν_μ Other

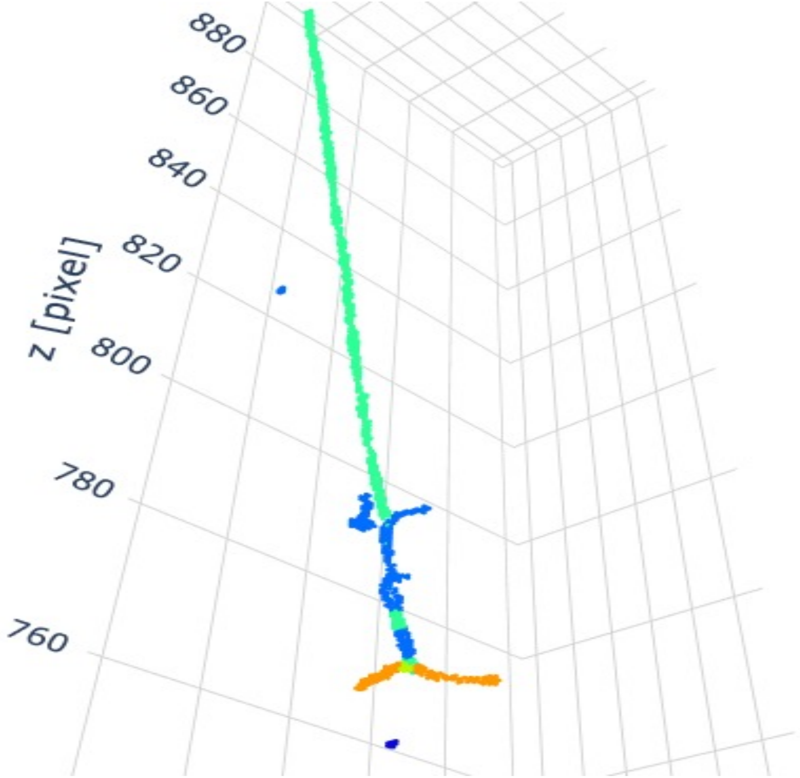
19.05%
(4)

Prediction

High energy delta, True 1muNp

Truth





ν_μ Other

19.05% (4)

Prediction

True Michel reconstructed as electron primary

Truth