Deep Learning applications for ν_e reconstruction in the ICARUS experiment.

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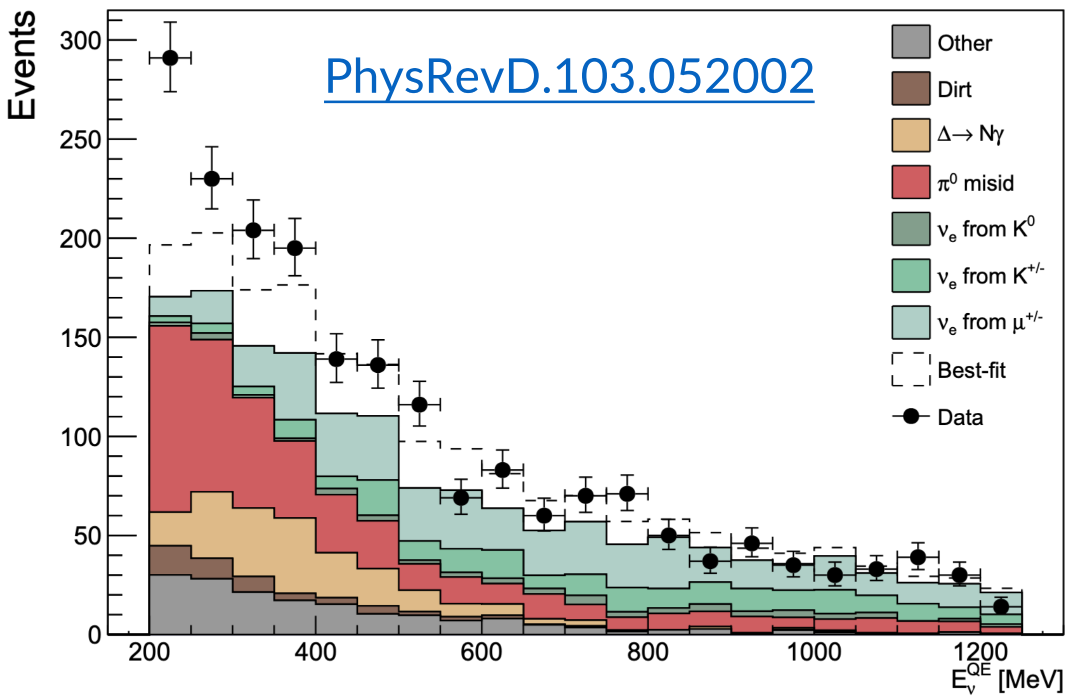
Neutrino Physics and Machine Leearning 2023

Search for sterile neutrinos with the ICARUS T600 Detector

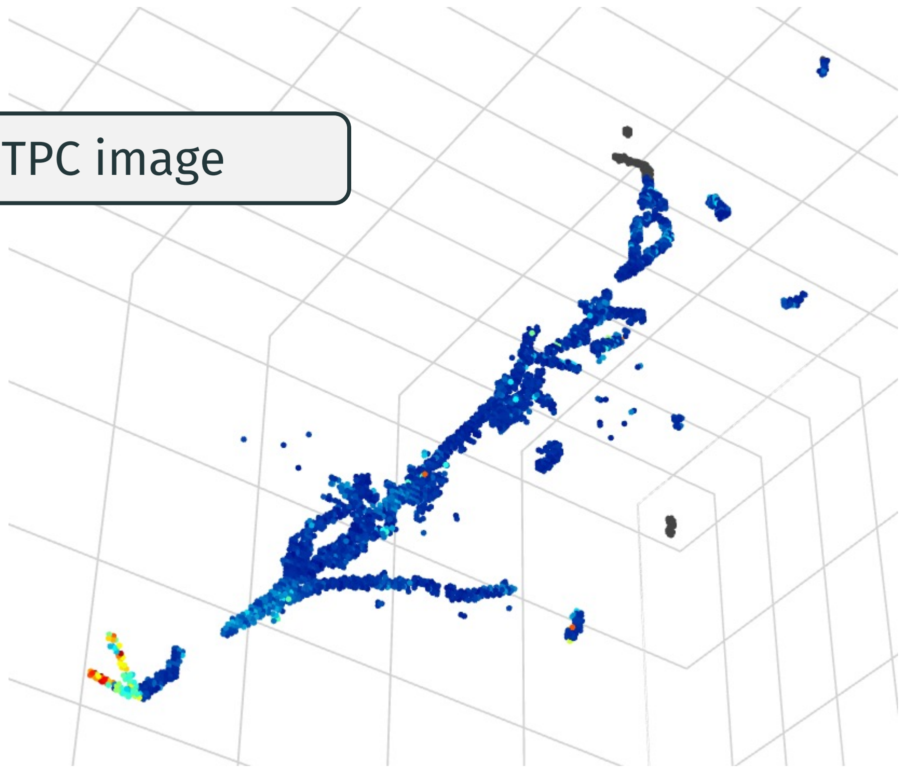
- **Low-Energy Excess (LEE)** is an excess of electron-like neutrino events in the 200-600 MeV energy range, observed by LSND and MiniBooNE.
- Search for **sterile neutrinos** and investigating ν_e appearance/ ν_μ disappearance in these regions are one of the flagship analysis goal of the SBN program.
- The e/γ **separation capability** of the **liquid argon time projection chamber (LArTPC)** technology, and information from other subsystems will allow ICARUS to resolve the common confounding backgrounds **(CC-π^0, $\Delta \rightarrow N\gamma$)** in the MiniBooNE analysis.



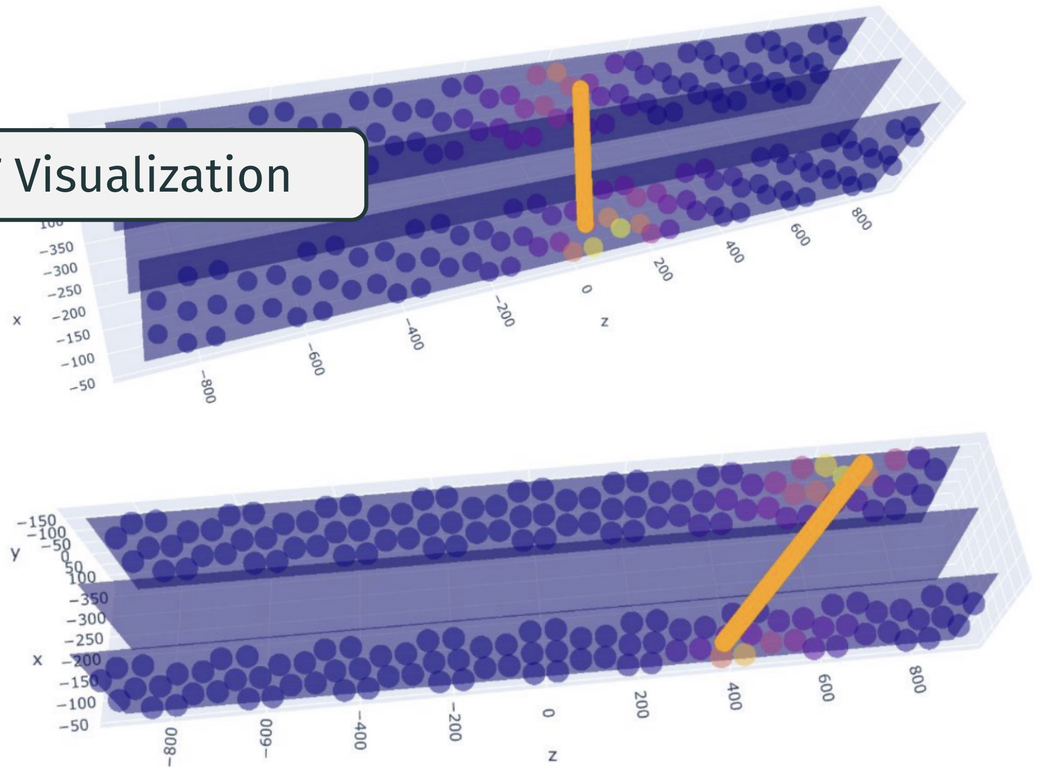
The ICARUS T600 Detector

- 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

ν_e TPC image



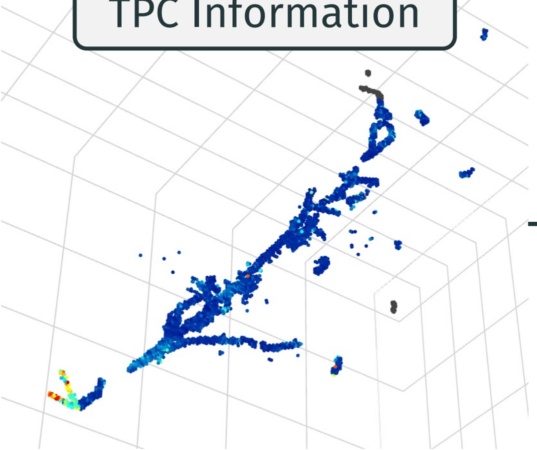
PMT Visualization



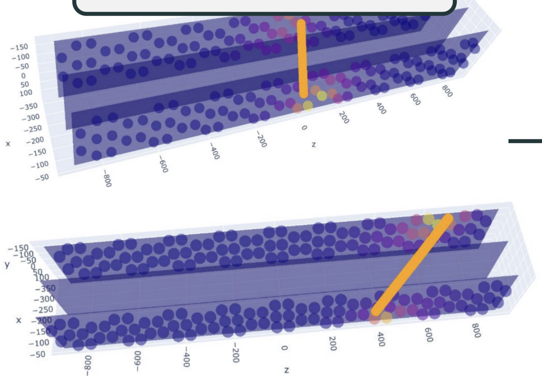
Electron Neutrino Reconstruction

- In this talk, we use TPC and PMT information to identify candidate electron neutrino events.

TPC Information



PMT Information



Particles

- PDG Code
- Primariness
- Reco E
- …

Interactions

- Particles
- TPC points
- Flash Hypothesis
- …

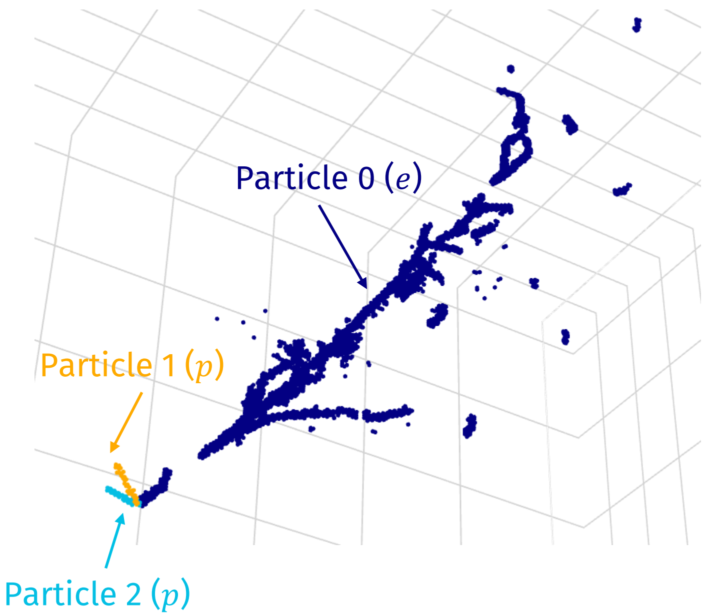
OpFlash

- Flash Time
- Observed Flash
- …

Event Topology

Flash Matching

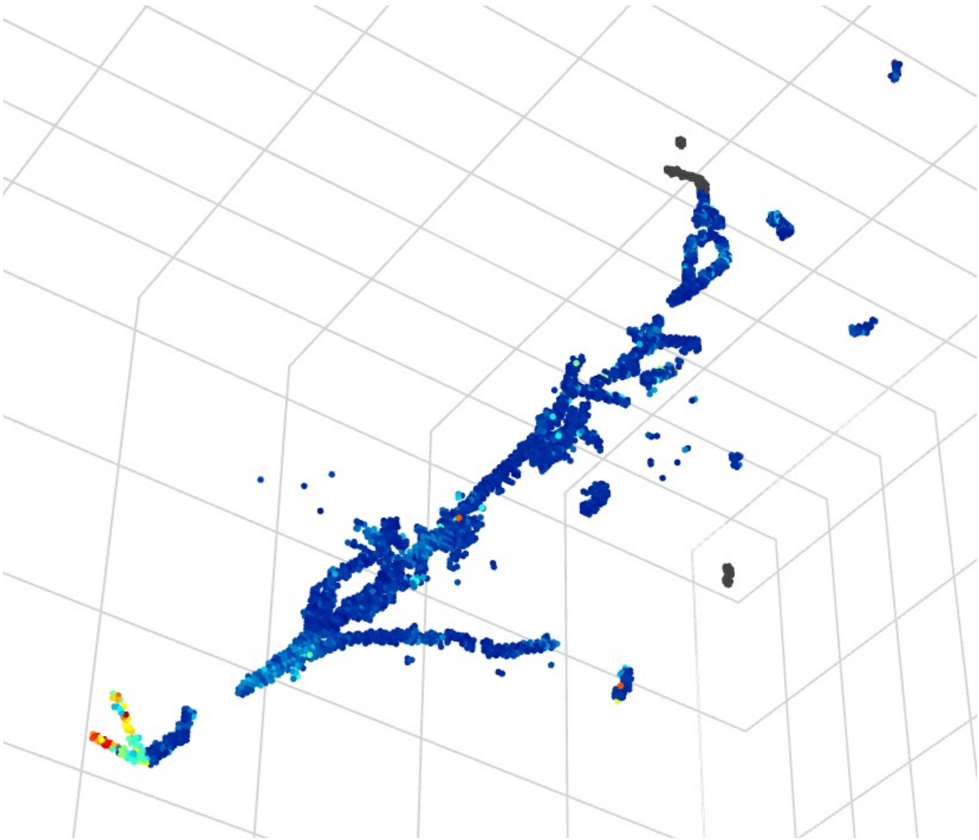
Full Reconstructed Event



- Topology: 1e2p
- Reco E_{ν_e}: …
- Flash-Compatible?: Yes
- …

Particle and Interaction Reconstruction using ML

- Analysis using ML tools is a two-stage process:
  1. **Organize neural network predictions** to human-readable objects:



Particle and Interaction Reconstruction using ML

- Analysis using ML tools is a two-stage process:
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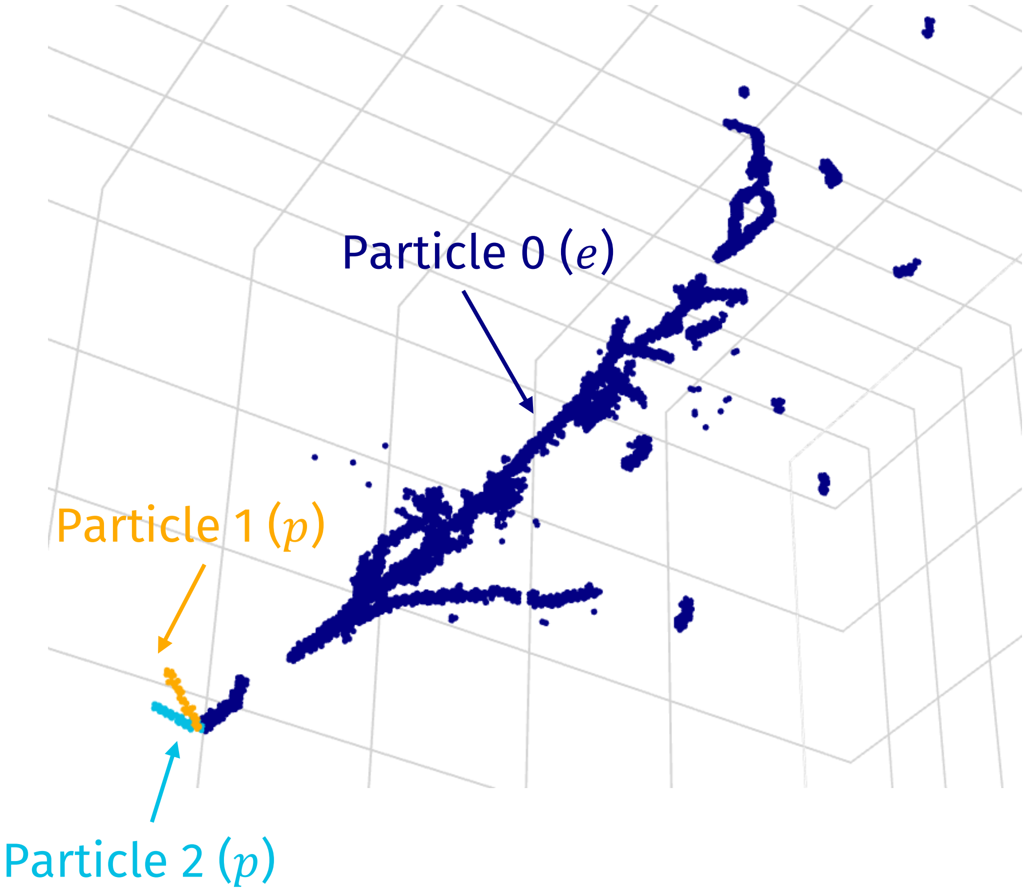
     - **Particle:** depositions that are predicted to belong to the same particle
       - ex. PDG code, primary indicator, interaction clustering labels



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     - **Particle:** depositions that are predicted to belong to the same particle
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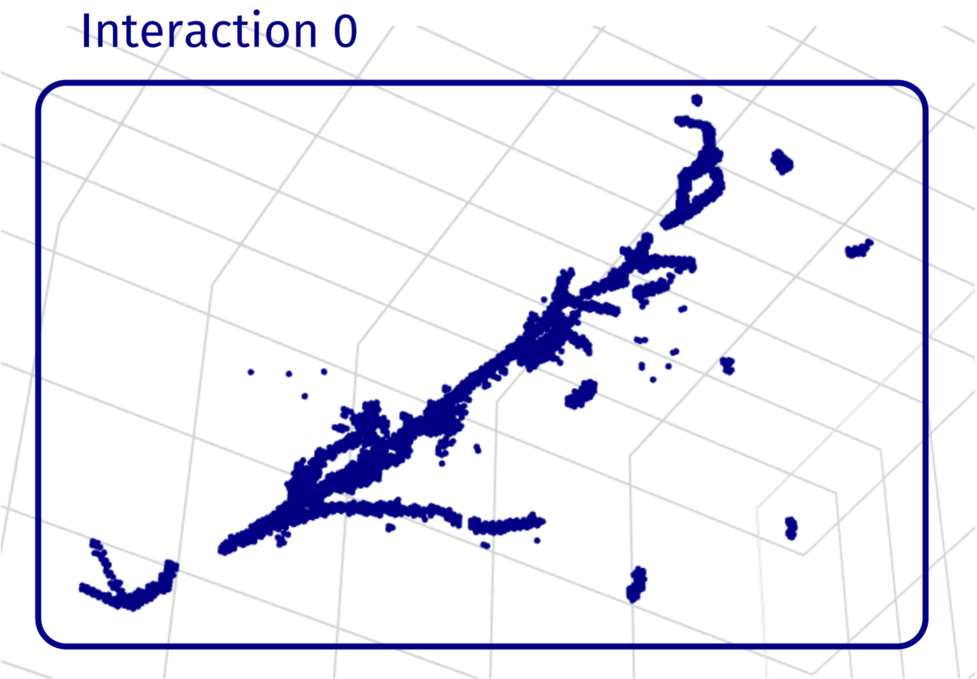
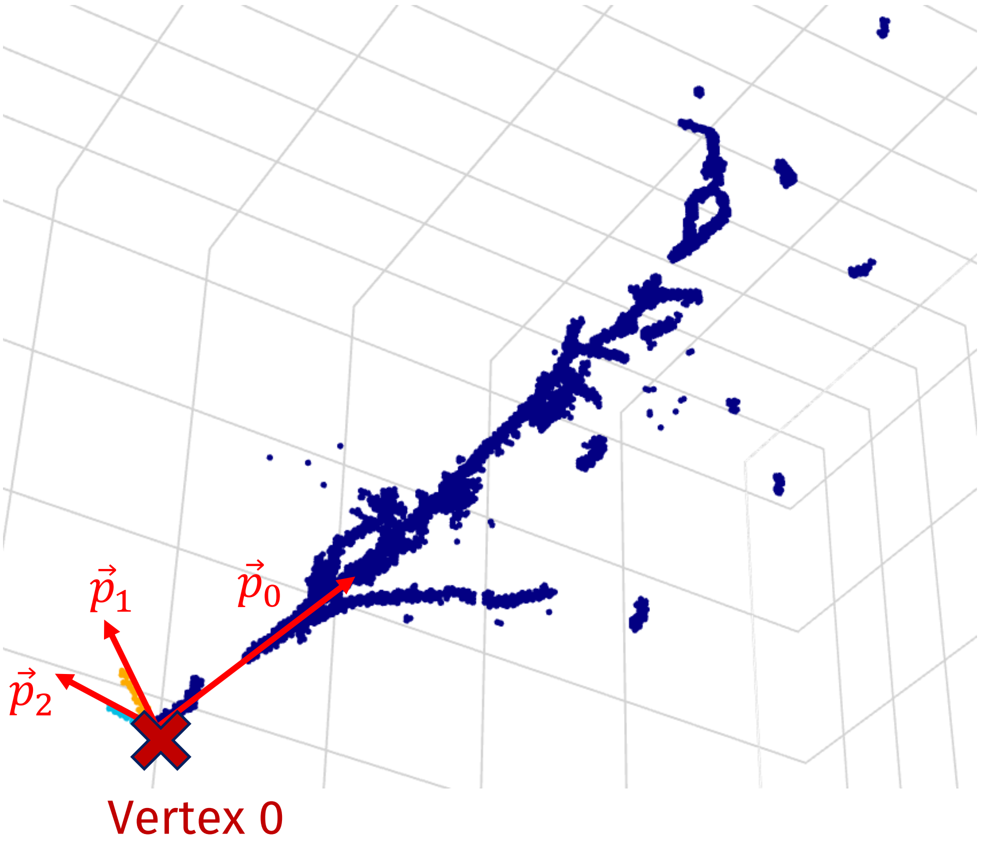
     - **Interaction:** collection of particles that originate from the same vertex
       - ex. constituent particles, PMT flash timing,

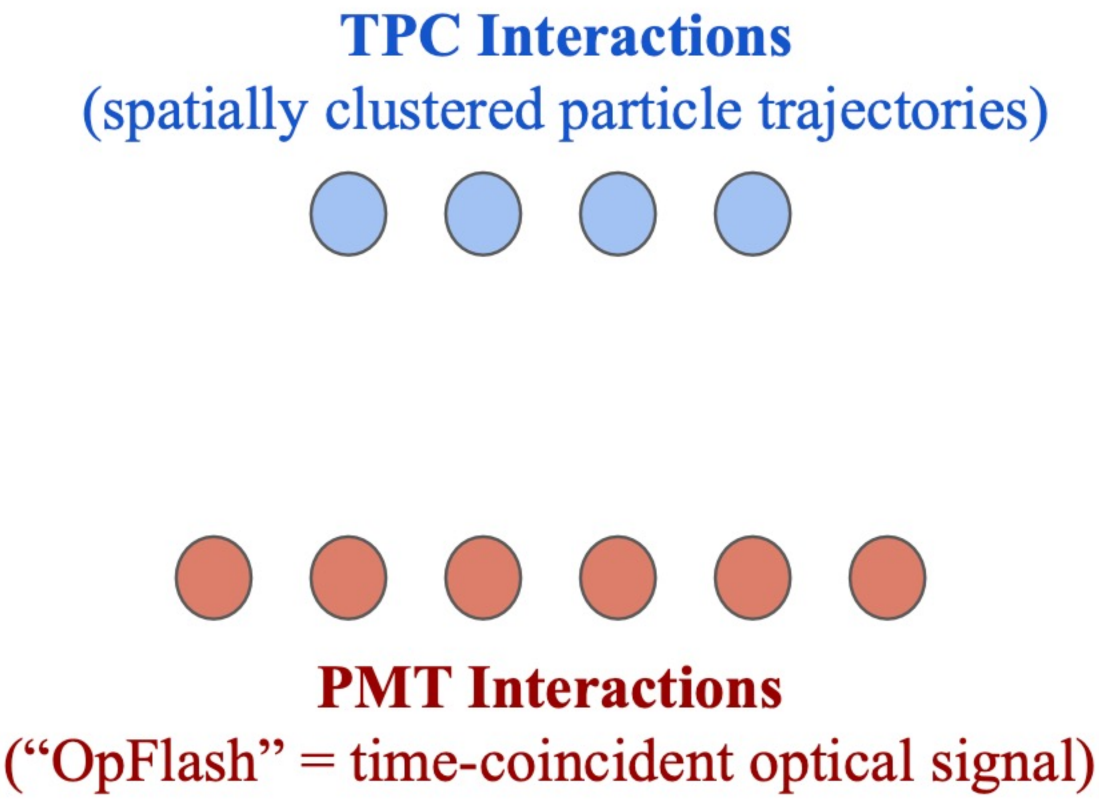


Particle and Interaction Reconstruction using ML

- Analysis using ML tools is a two-stage process:
  1. **Organize neural network predictions** to human-readable objects:
     - **Particle:** depositions that are predicted to belong to the same particle
     - **Interaction:** collection of particles that originate from the same vertex
  2. **Run post-processing algorithms** to further compute useful quantities for reconstruction and append information to **Particle** and **Interaction** instances.
     - ex. Range-based track energy estimation, vertex reconstruction, particle direction estimation

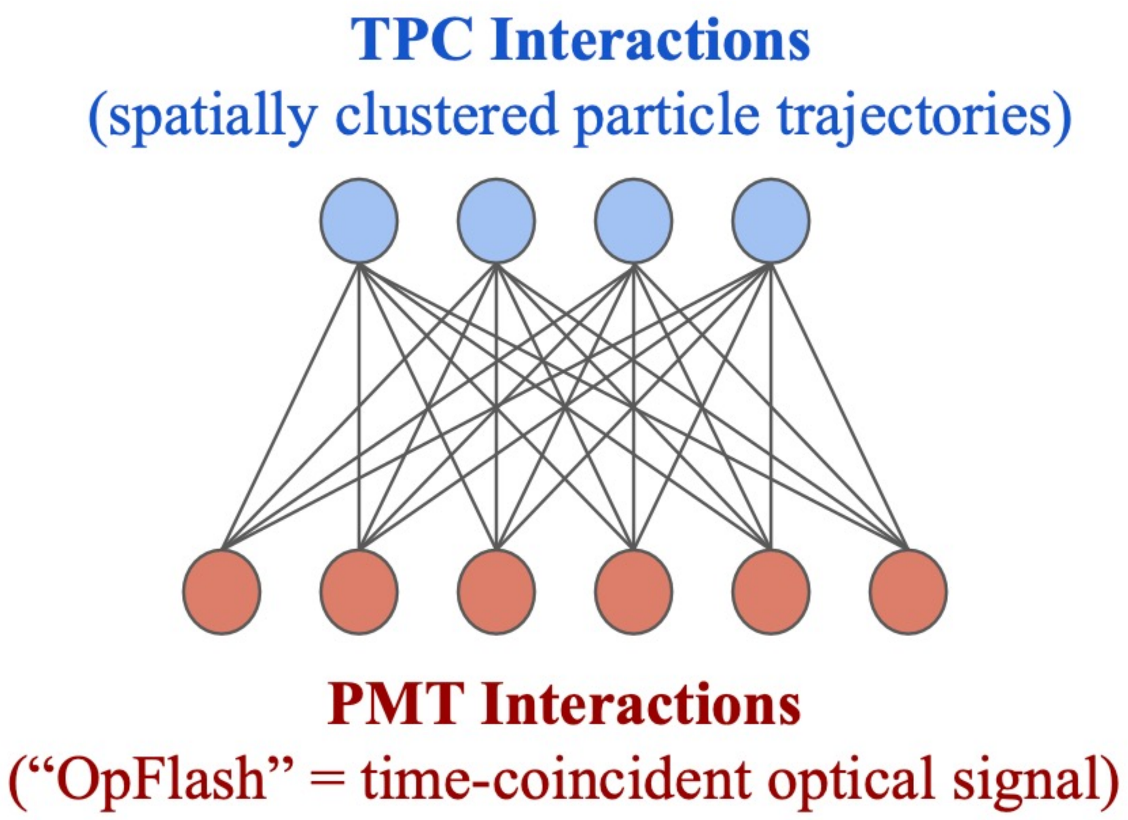


How OpT0Finder works



- **TPC Interactions**: group of particle depositions that have the same originating parent (**Qcluster_t**)
- **PMT Interactions**: collection of time-coincident optical signals across PMTs. (**Flash_t**)
- **Goal**: which TPC and PMT interaction share the same underlying interaction / root particle?

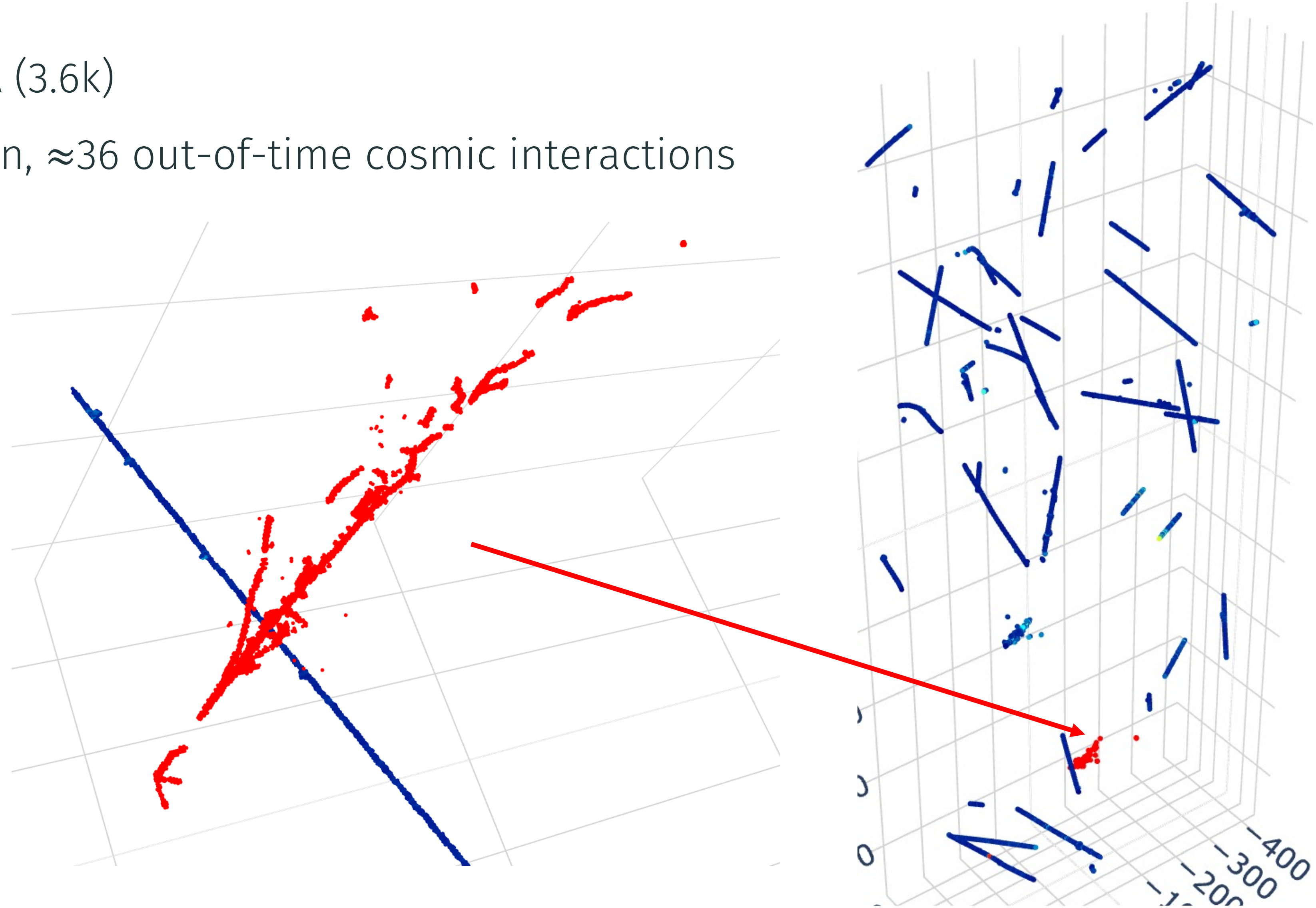
How OpT0Finder works



- A form of **weighted-edge bipartite matching problem**.
- For each pair **(QCluster_t, Flash_t)**:
  - Exclude space/time-wise impossible matches
  - Compute the charge-based log-likelihood (LL) score
  - Find the combination of pairs that maximize the combined LL from all chosen pairs (Greedy, or Munkres/Hungarian Matching algorithm)

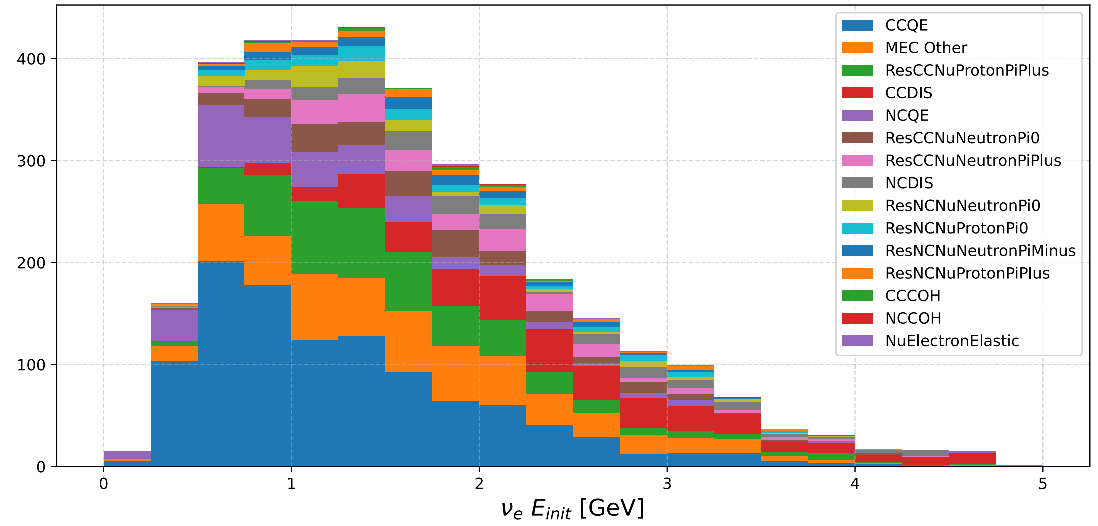
Electron Neutrino Selection: Dataset

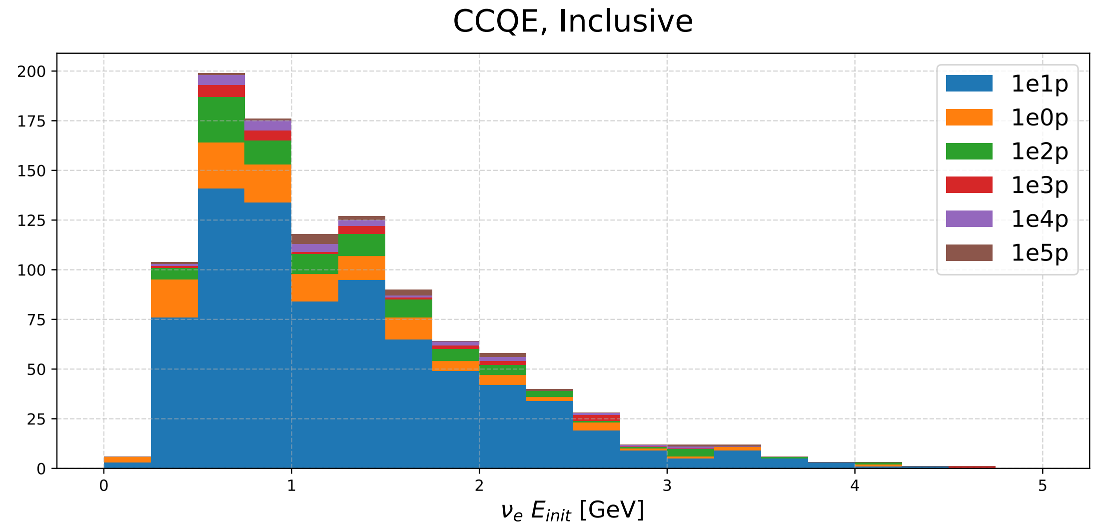
- Dataset: BNB ν_e + CORSIKA (3.6k)
  - One $\nu_e + Ar$ interaction, ≈36 out-of-time cosmic interactions per image.



Electron Neutrino Selection: Dataset

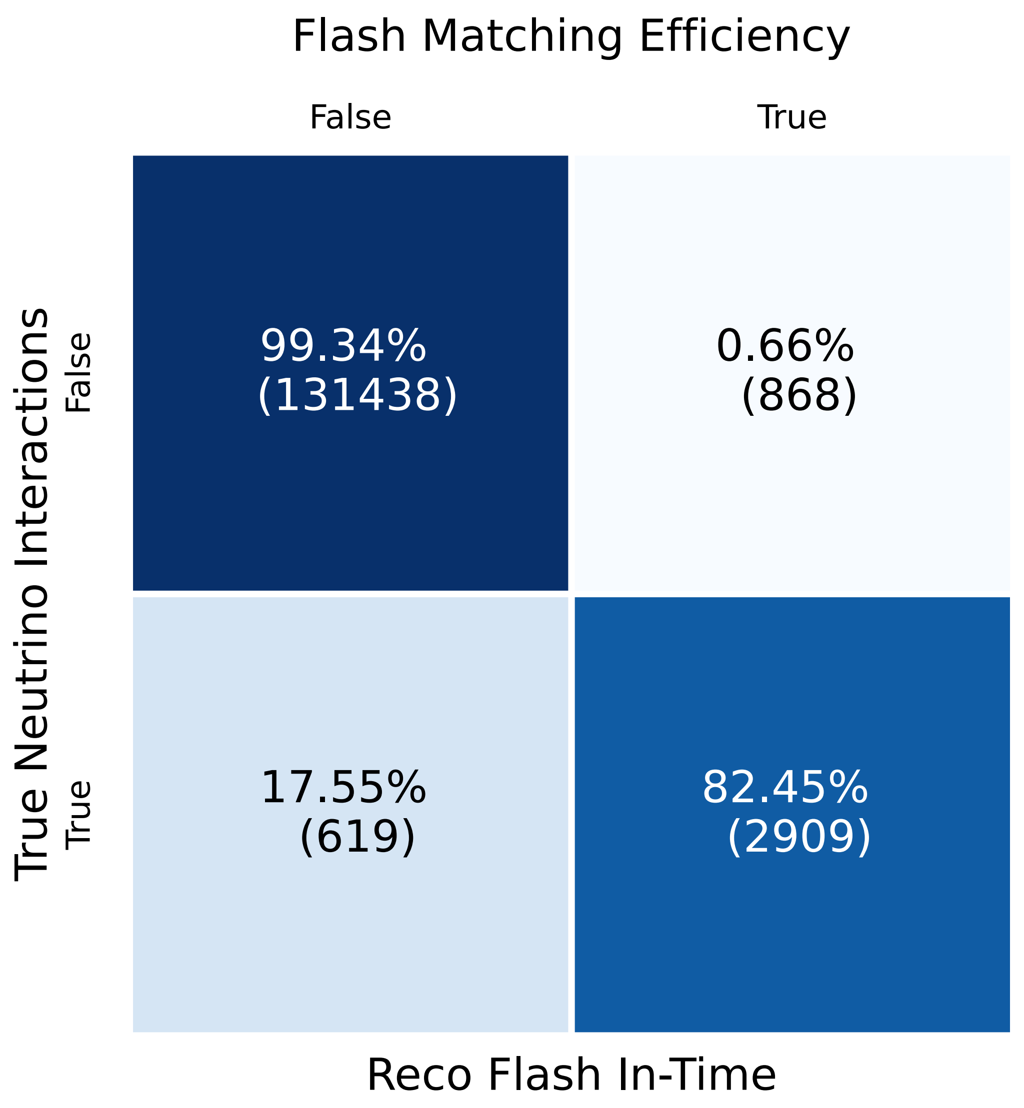
- Dataset: BNB ν_e (G4, simulated) + CORSIKA (3.6k)
  - One $\nu_e + Ar$ interaction and ≈36 out-of-time cosmic interactions per image.
  - In 200-1000 MeV region, CCQE interaction mode with 1e1p topologies are dominant.





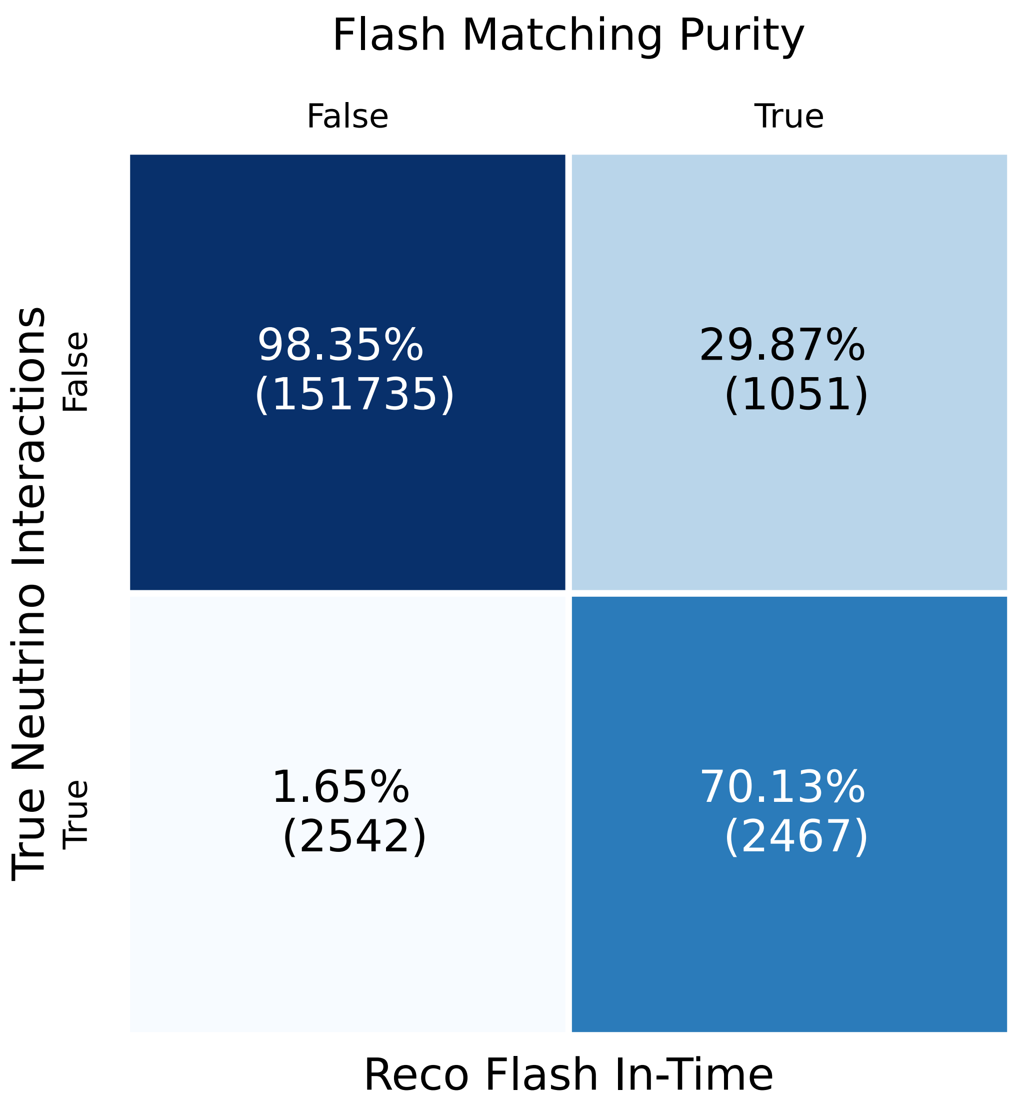
Electron Neutrino Selection: Flash Matching

- Using PMT information alone, we can reject a significant number of cosmic interactions:
  - **82.45%** of all True ν_e's are matched to a PMT flash within the beam window $(0, 1.6\mu s)$.



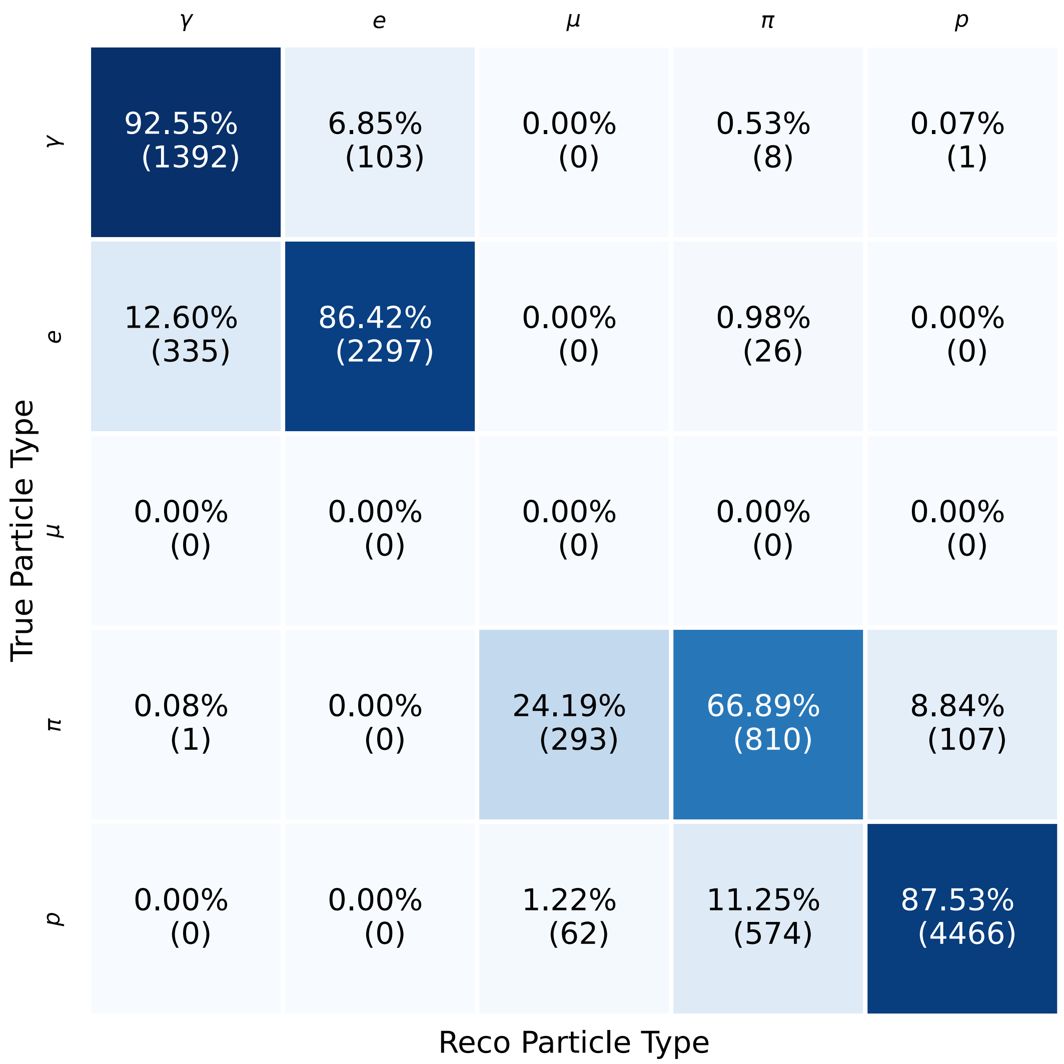
Electron Neutrino Selection: Flash Matching

- Using PMT information alone, we can reject a significant number of cosmic interactions:
  - **82.45%** of all True ν_e's are matched to a PMT flash within the beam window (0, 1.6μs).
  - **70.13%** of all reconstructed PMT flashes that are within the beam window are true ν_e's.



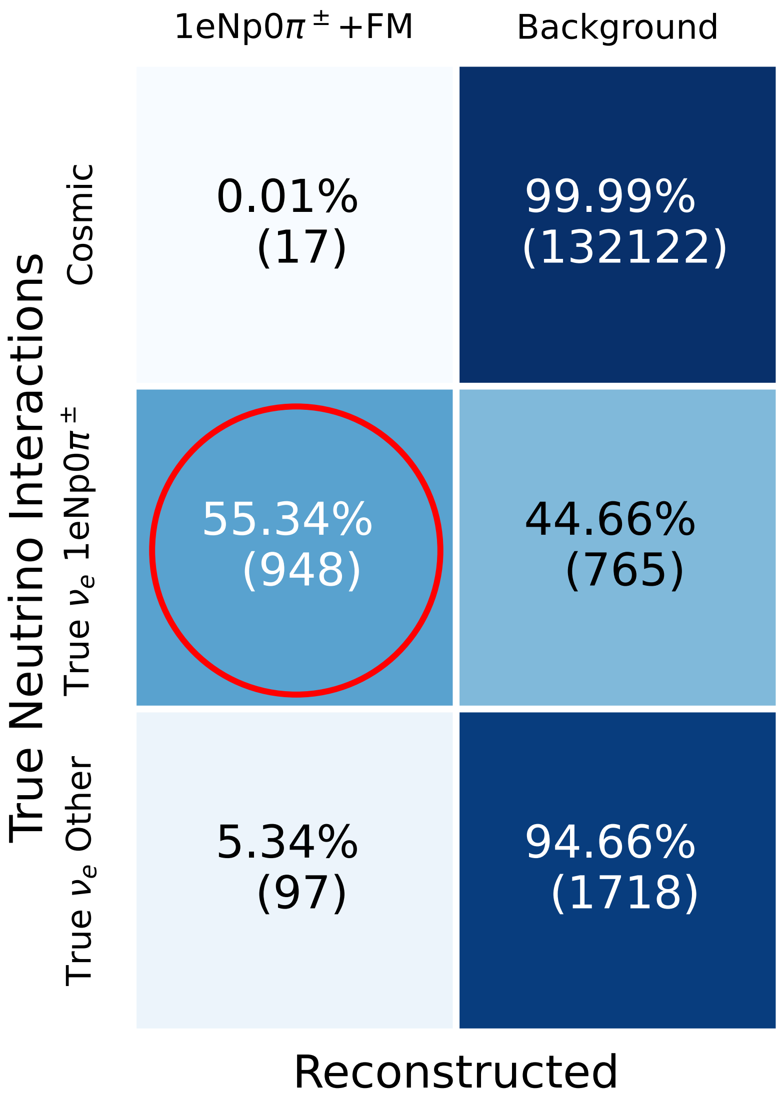
Electron Neutrino Selection: Particle Identification

- Particle Identification with GNNs
- Left**: BNB ν_e Primaries Only**
- e **vs.** γ **separation** is comparable to generic dataset, in good shape.
- Significant $\pi \rightarrow \mu$ and $p \rightarrow \pi$ confusion.
  - Issue in particle energy distribution within interaction at fixed total energy (WIP)



Electron Neutrino Selection: $1eNp0\pi^{\pm}$

- **Signal Definition**: $1eNp0\pi^{\pm}$ Predicted Interactions with PMT flash time within the beam window ($1eNp0\pi^{\pm}$ +FM)
- **Efficiency**: measure of how well the reconstruction method captures true ν_e $1eNp0\pi^{\pm}$ interaction as signal.
  - *Efficiency = # of true positives / # of True 1eNp0pi*



Row-Normalized
Truth -> Reco

Electron Neutrino Selection: $1eNp0\pi^{\pm}$

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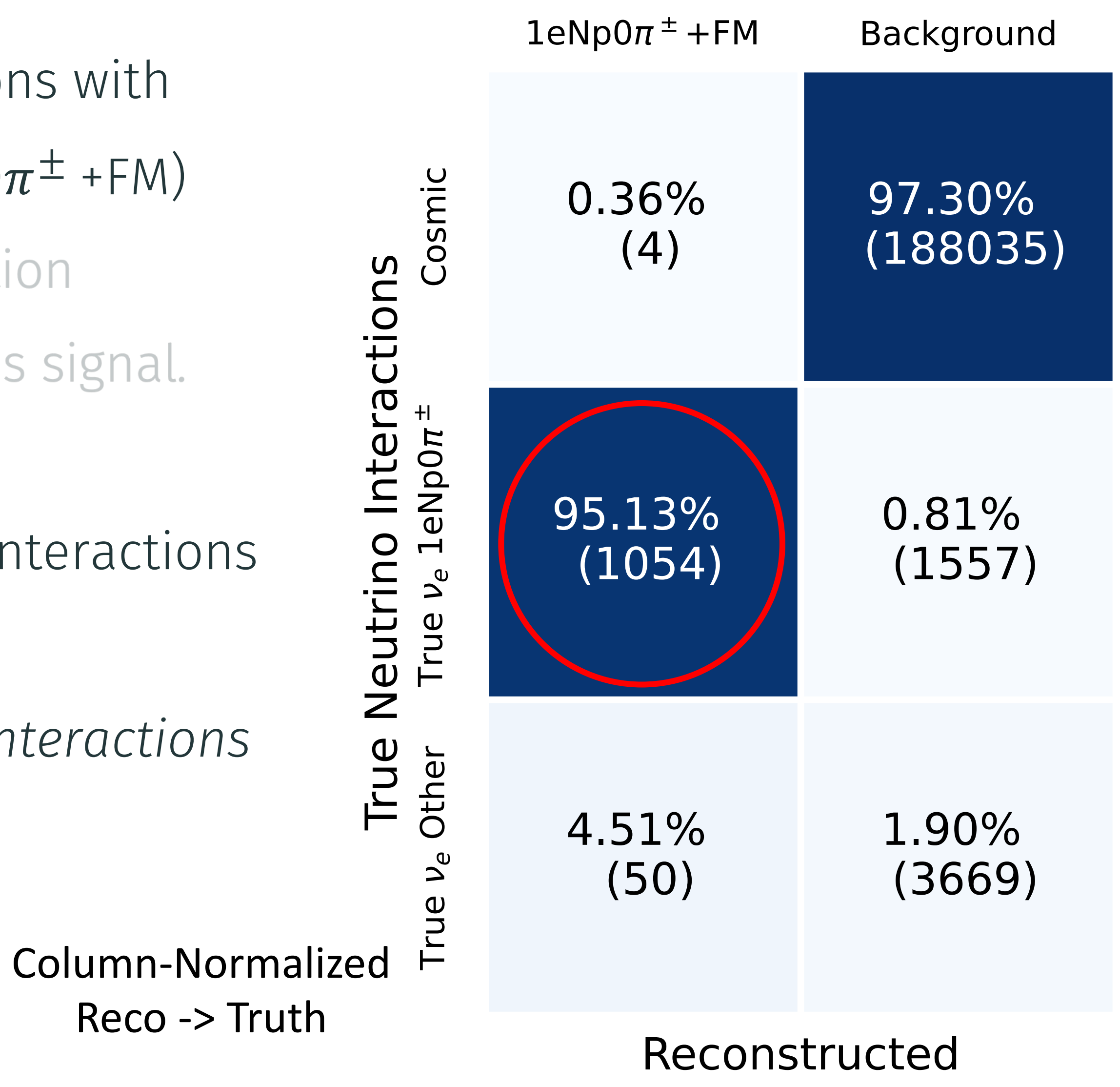
- **Purity**: measure of how many predicted signal interactions actually correspond to a true signal.
  - *Purity = # of true positives / # of all signal interactions*



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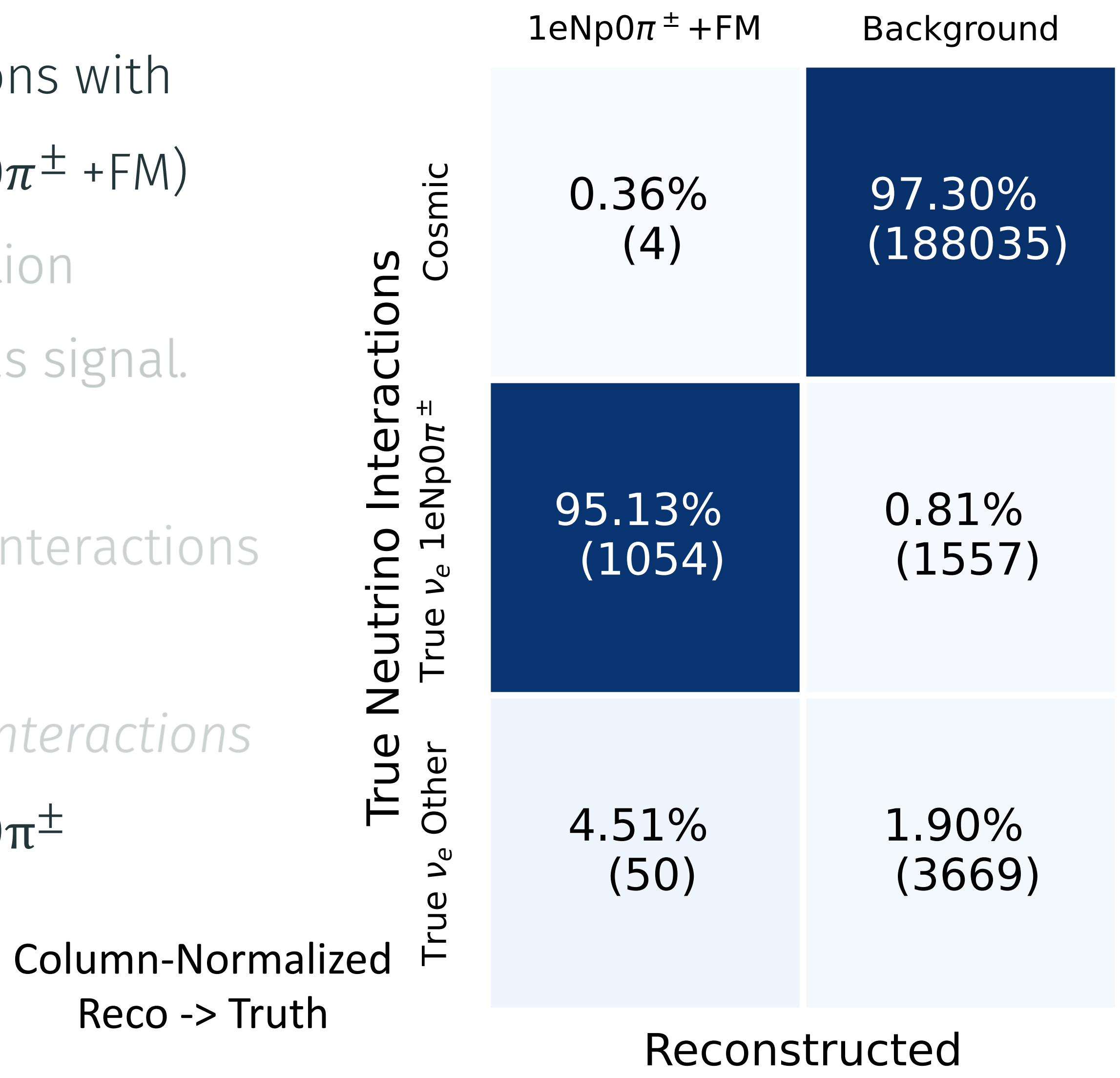
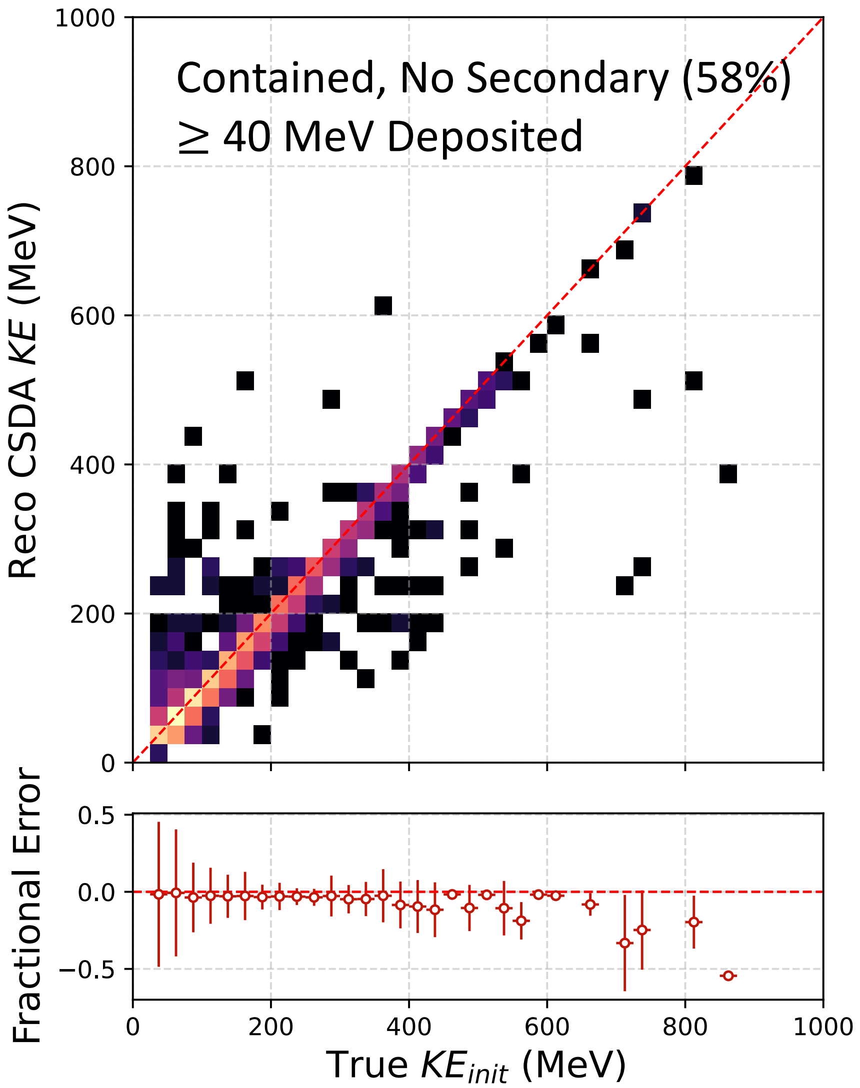
  - *Efficiency = # of signal / # of True 1eNp0pi*
- **Purity**: measure of how many predicted signal interactions actually correspond to a true signal.
  - *Purity = # of true positives / # of all signal interactions*
- **Summary: 55% Efficiency, 95% Purity for** $1\text{eNp}0\pi^{\pm}$



Electron Neutrino Selection: Proton Energy Estimation

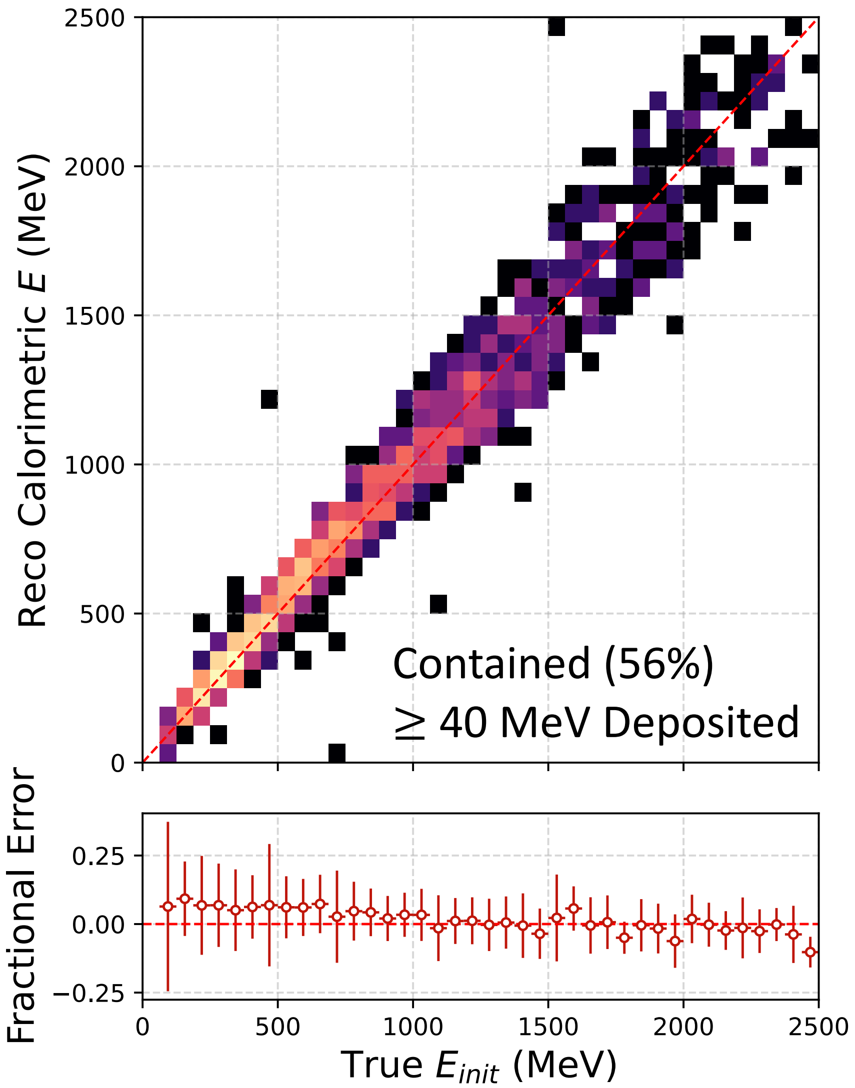
- For **protons**, we use the integrated Bethe-Bloch relation to compute the initial kinetic energy KE in terms of the particle travel range R.
- **Fractional Error**: $\epsilon = \left(\widehat{KE} - KE_{true}\right)/KE_{true}$



Electron Neutrino Selection: Electron Shower Energy Estimation

- For **protons**, we use the integrated Bethe-Bloch relation to compute the initial kinetic energy KE in terms of the particle travel range R.
- **Fractional Error**: $\epsilon = \left(\widehat{KE} - KE_{true}\right)/KE_{true}$
- For **electron showers**, the ADC total sum is converted to MeV via a calibration factor:

$$\widehat{KE}_e = \rho \, * \, (total\ sum\ of\ ADC)$$

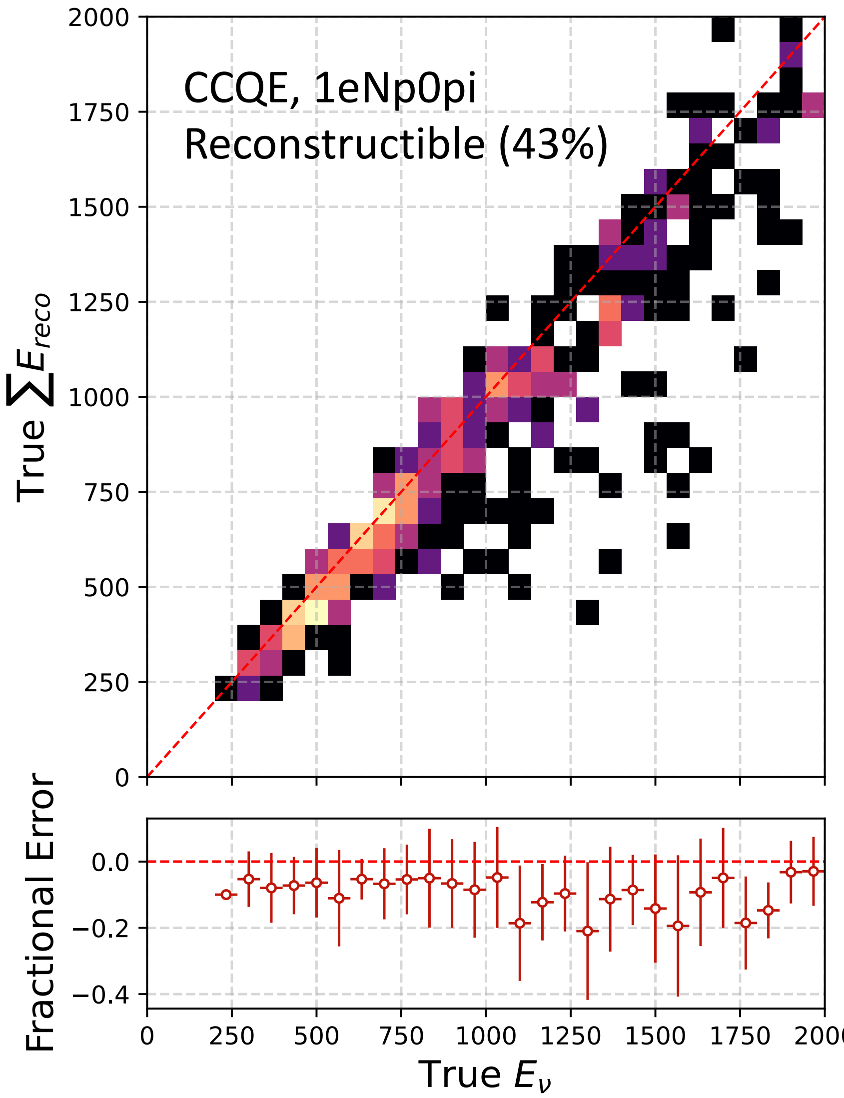


Electron Neutrino Selection: Neutrino Energy Reconstruction

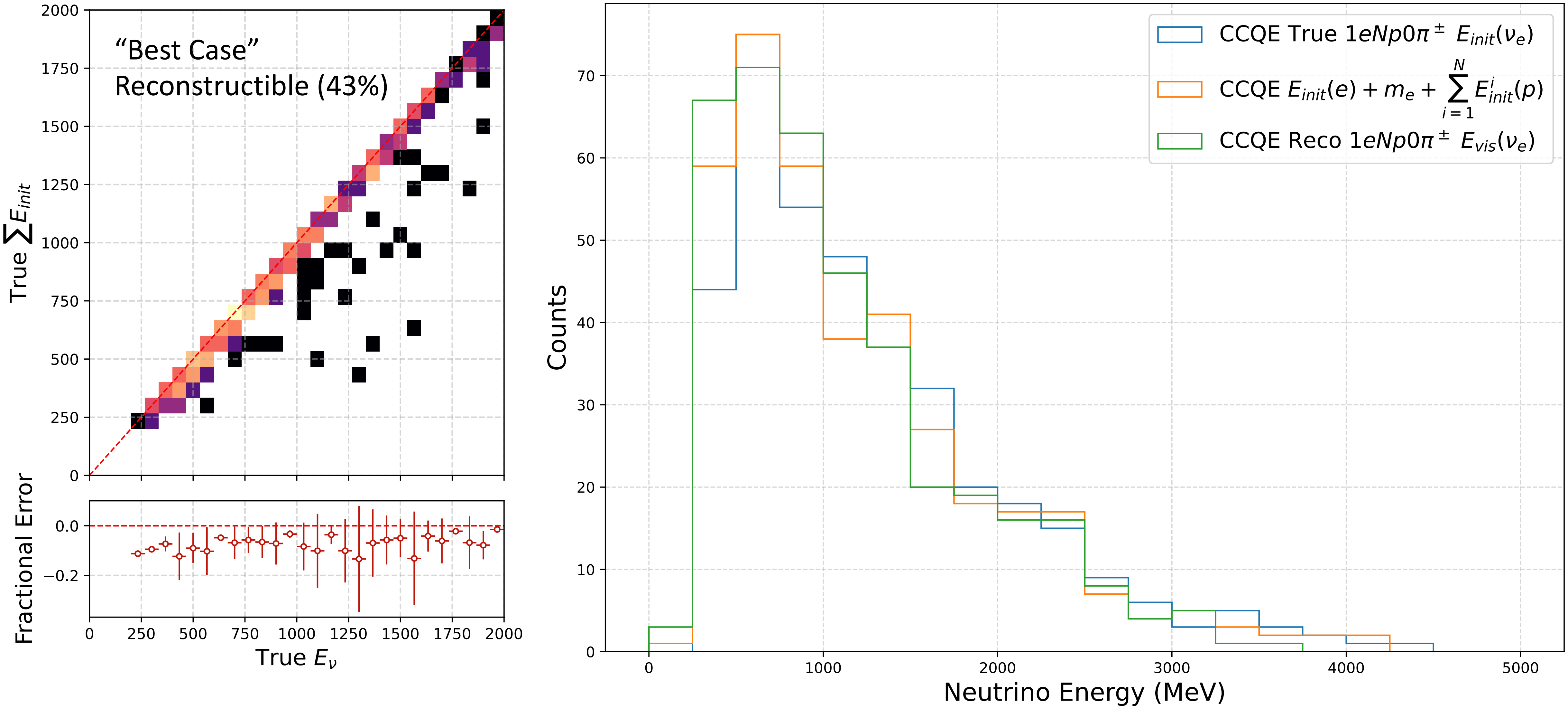
- Since the initial KE of protons and electrons are known, the total visible energy is is given as:

$$E_{vis} = KE_e + m_e + \sum_{i=1}^{N} KE_p^i$$

- Any energy carried by outgoing neutrons or nucleon binding energy is not accounted for.
- “Reconstructible”: all constituent electrons and protons pass the cuts.

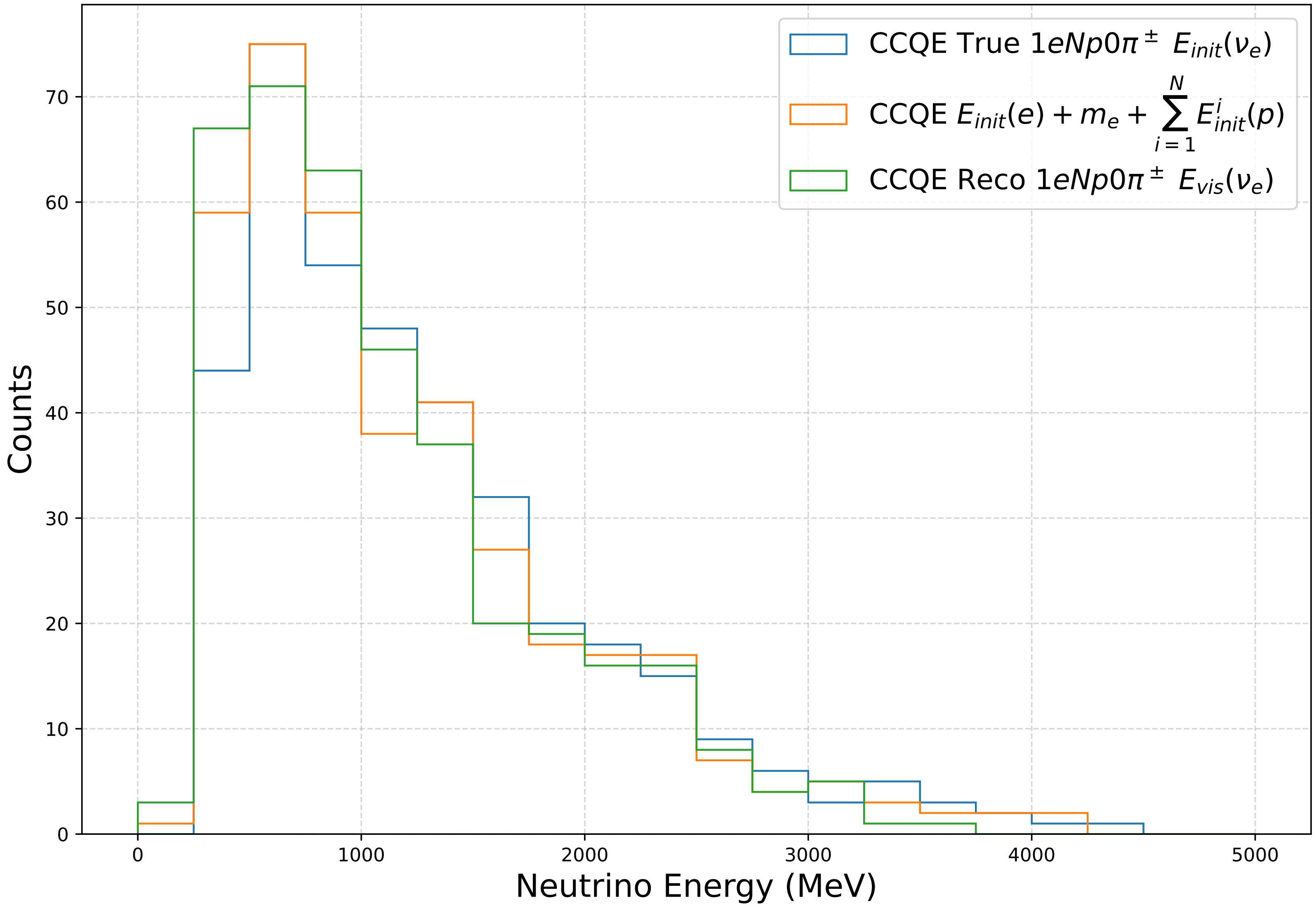


Electron Neutrino Selection: Neutrino Energy Reconstruction



Electron Neutrino Selection: Neutrino Energy Reconstruction

- Currently, E_{vis} falls short of estimating the true initial energy of the neutrino.
- Work in progress on more robust calorimetry methods for proton length estimation.
- Shower Energy Reconstruction (L. Kashur) validation using CC-π^0



Conclusion

- Outline for CCQE electron neutrino selection and energy reconstruction using ML tools and traditional calorimetry algorithms.
- 55% Efficiency and 95% Purity in 1eNp0π Exclusive Selection on BNB ν_e + OOT(out of time) cosmic background simulation dataset.
- Higher statistics study with both out-of-time and in-time cosmic background
- Simulation vs. Data Study with run9435 data and hand-scanned events.
- Further fine-tuning of calorimetric post-processing algorithms.