NuMI Electron Neutrino Selection at ICARUS with Machine Learning Reconstruction

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I. ICARUS Detector and Short-Baseline Neutrino Program

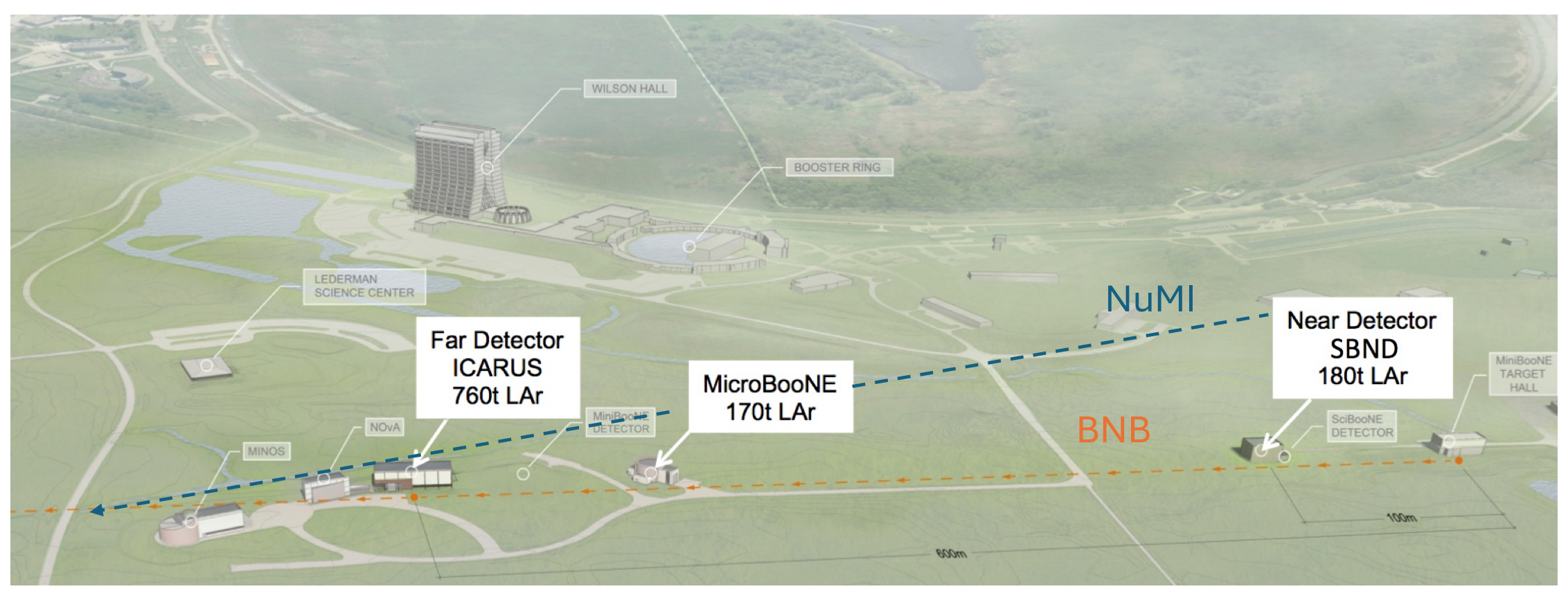

Figure 1: Map of the SBN Program at Fermilab with the NuMI and BNB neutrino beams highlighted [1]

The Short-Baseline Neutrino (SBN) Program, located at Fermilab, is comprised of three detectors making use of the Liquid Argon Time Projection Chamber (LArTPC) technology:

- Designed to investigate the anomalous results from the LSND and MiniBooNE experiments that can be explained by one or more sterile neutrinos
- Advance LArTPC R&D for experiments like DUNE

ICARUS is the far detector of the SBN Program and collects neutrinos from both the NuMI and BNB neutrino beams.

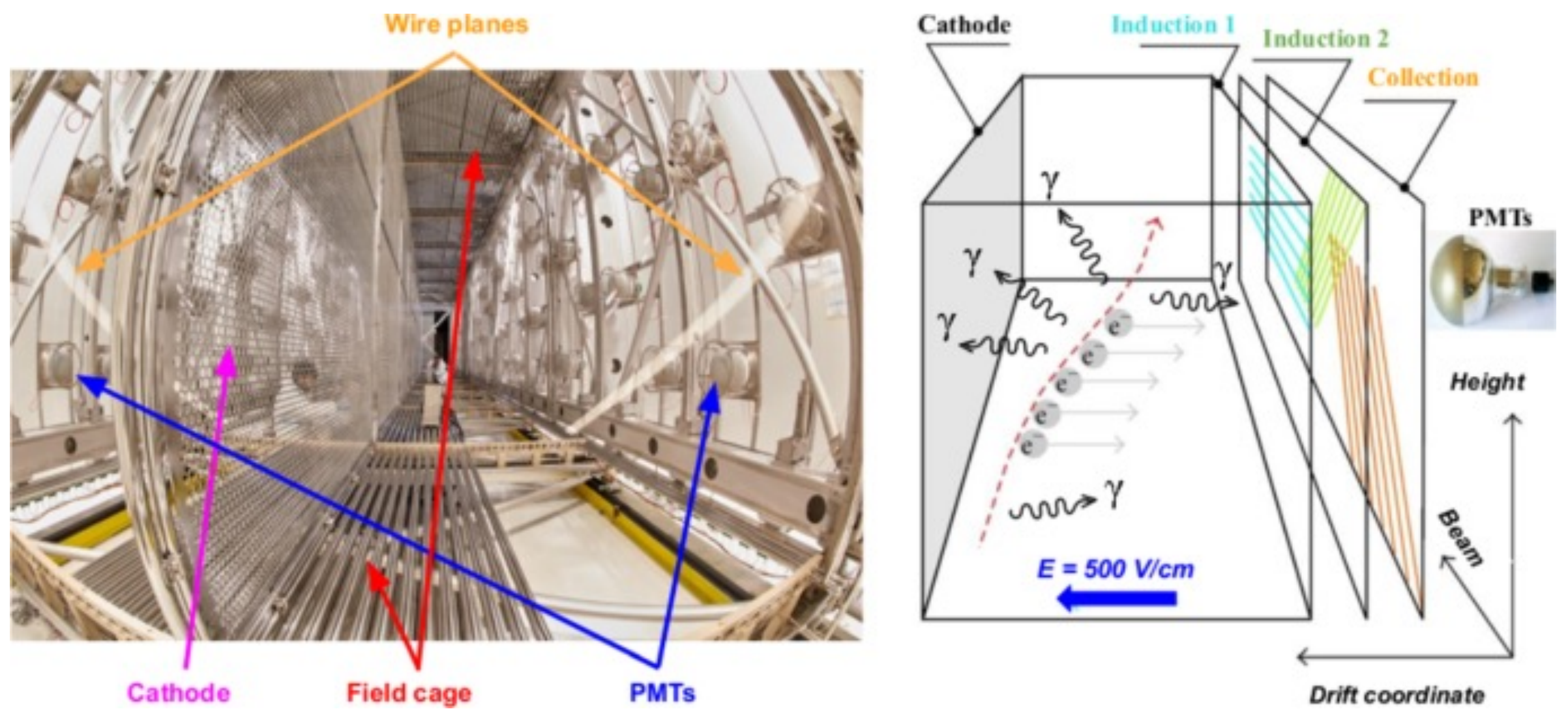

Figure 2: Inside of the ICARUS detector and diagram of LArTPCs [2]

II. LArTPC Machine Learning Reconstruction

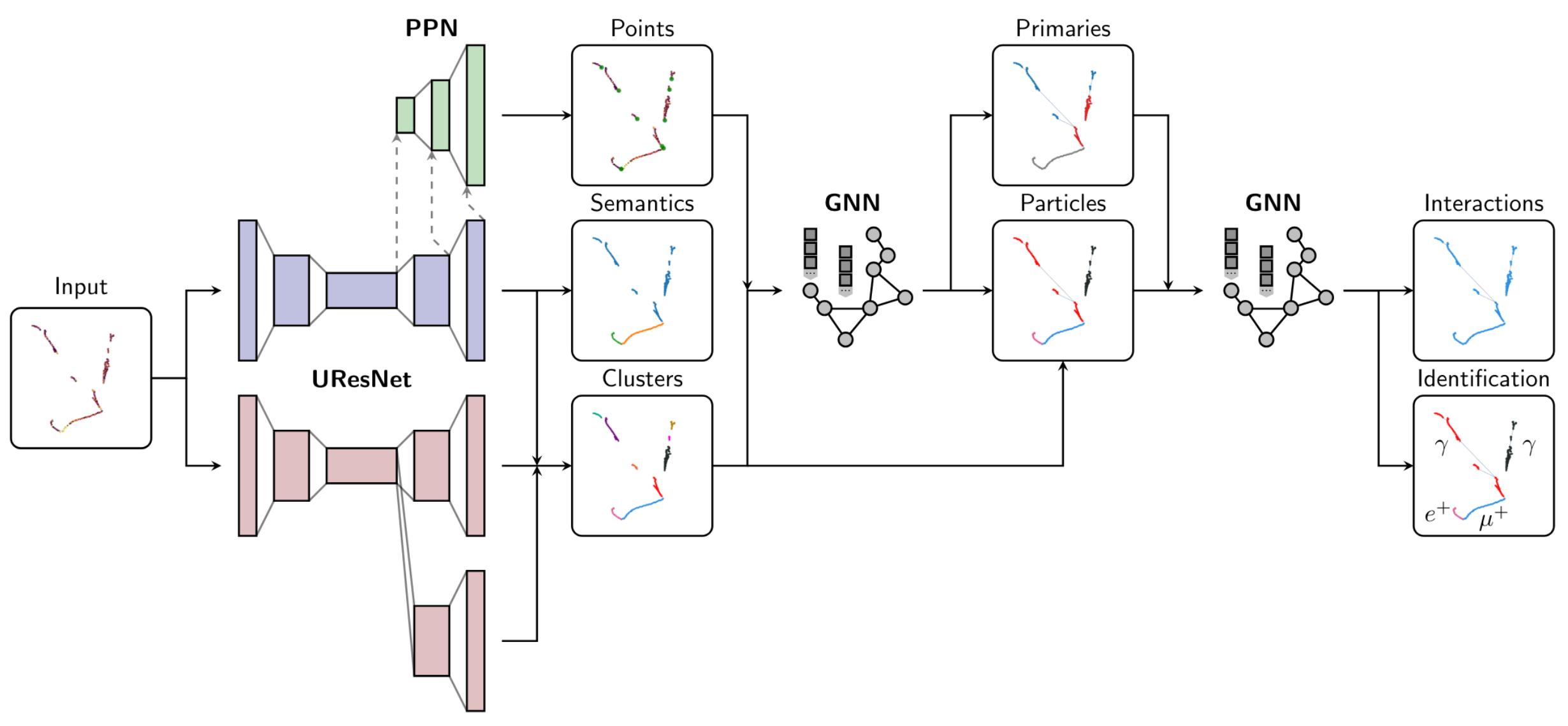

Figure 3: Flow diagram of SPINE [3]

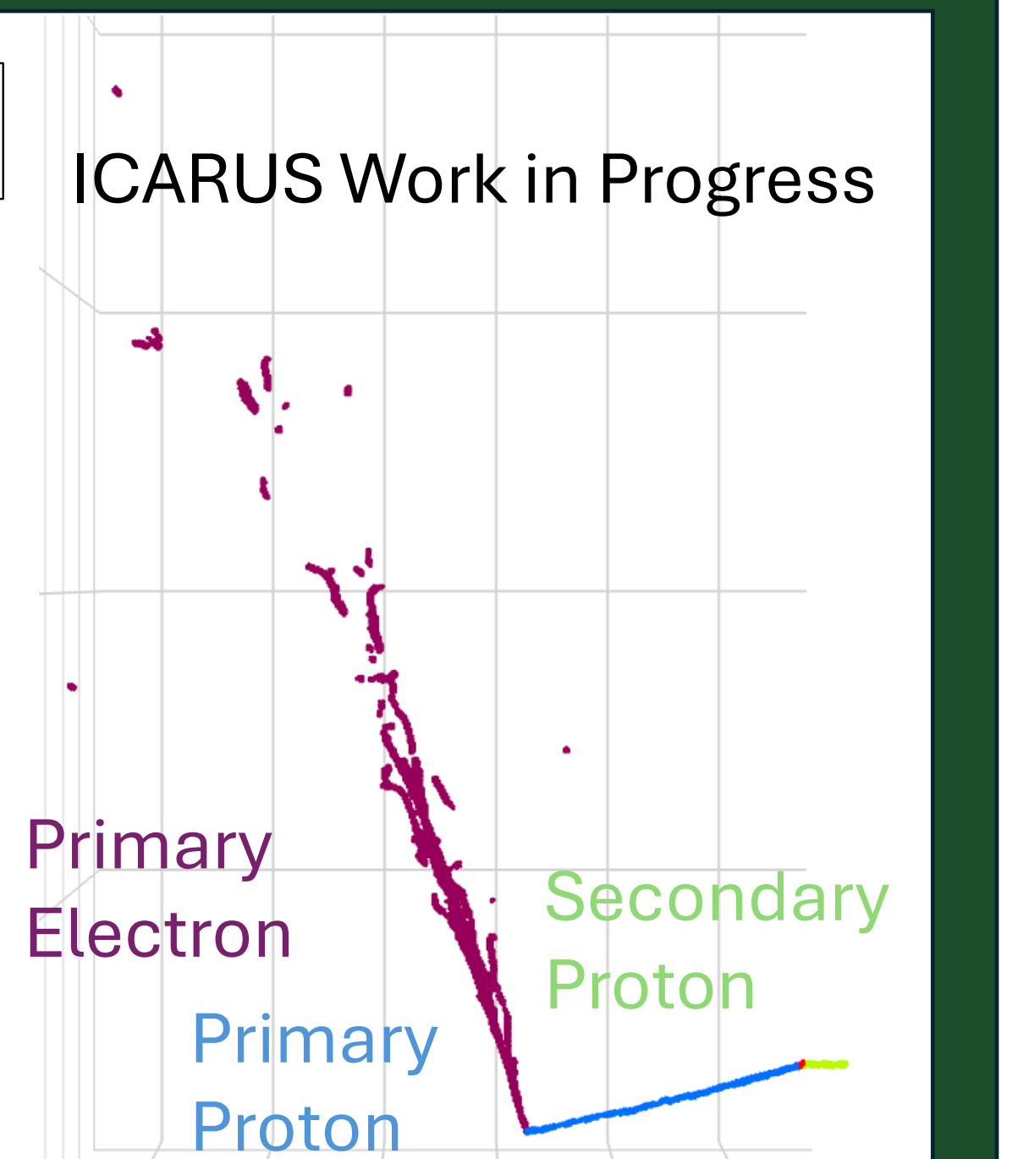

Figure 4: Reconstructed 1e1p simulated neutrino event

- **SPINE**: Machine-learning-based package used to reconstruct 3D images of LArTPC events
- The network was trained on a simulated sample of particles produced from a common vertex (Multiple Particle Vertex or MPV) and downward-going particles like cosmic rays (Multiple Particle Rain or MPR) to minimum bias.
- Reconstructed 3D space points from the TPC readout are clustered into particles and further grouped into individual interactions. The network also identifies the species of each particle within the interaction.

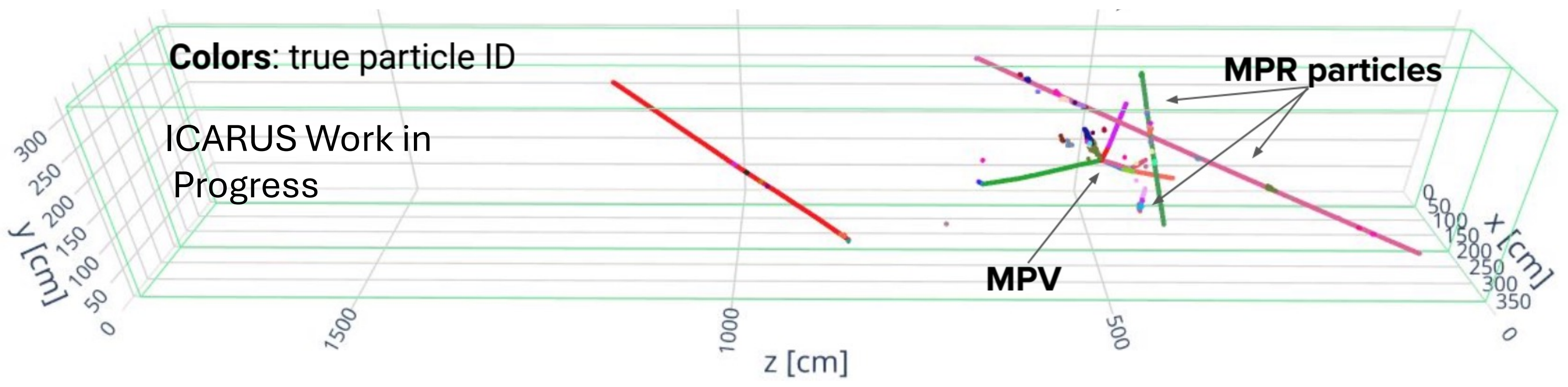

Figure 5: Single ML training event in a single drift volume

III. Electron Shower Energy Reconstruction

$$E_{reco} = \sum_{dep} W_i \left[\frac{MeV}{e^-}\right] * C\left[\frac{e^-}{ADC}\right] * C_{shower} * e^{\frac{t_{drift}}{\tau}} * \frac{1}{R} * dep[ADC]$$

W_i : Ionization work function of liquid argon

C_{shower} : Shower calibration factor to account for sub-threshold charge

R : Electron-ion recombination factor

C : TPC electronics gain

τ : Electron lifetime

t_{drift} : Ionization drift time for charge deposition

dep : Shower charge deposition in individual 3D voxel

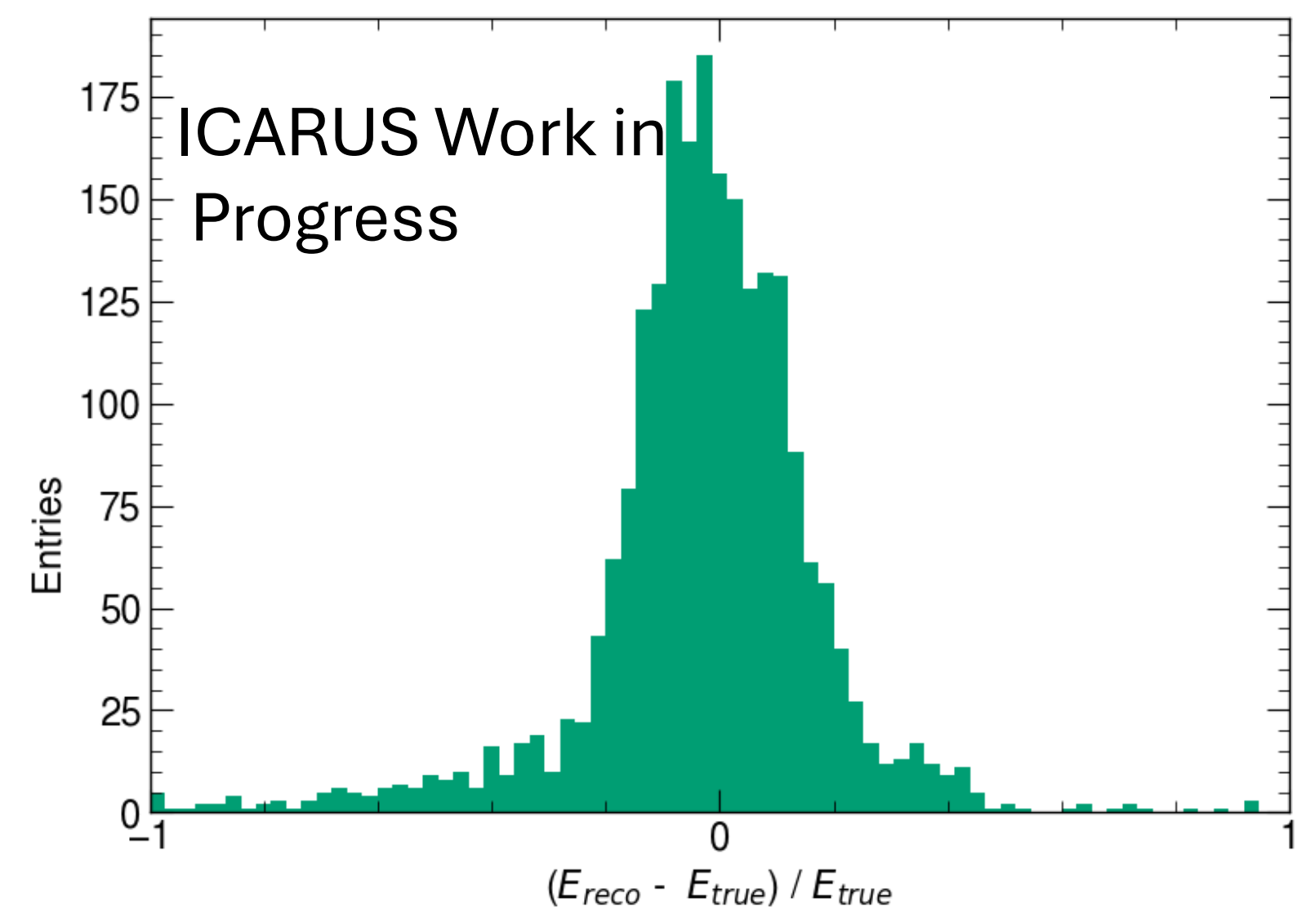

Figure 6: Electron energy reconstruction bias

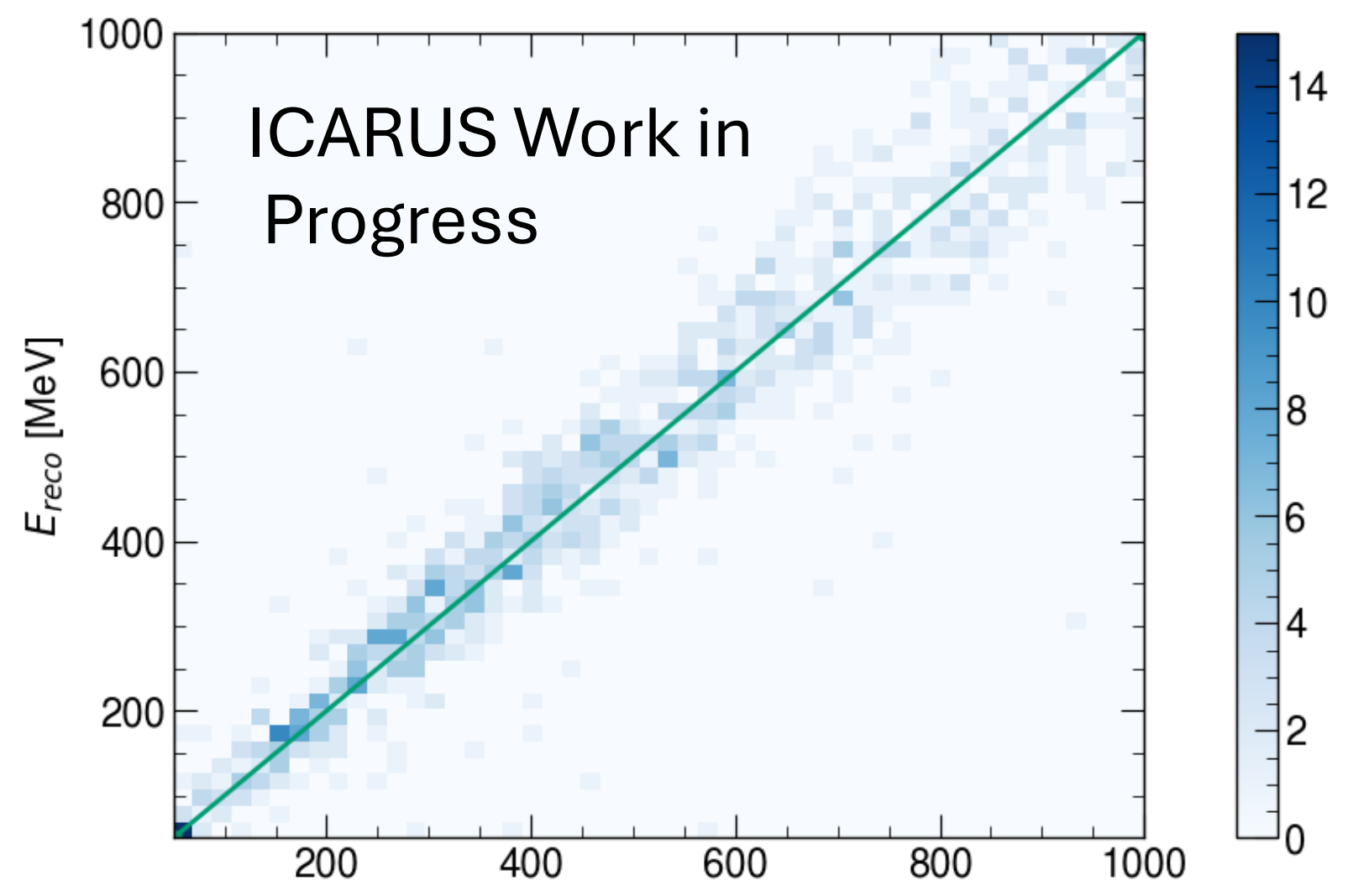

Figure 7: Comparison of reconstructed electron energy to true energy

IV. NuMI 1e1p/1eNp Selections

Selected electron neutrino candidates require:

- Containment of particles within 5 cm from boundaries of TPC active volume
- Timing of associated PMT optical flash to be within NuMI beam window that is 9.6 μs in extent
- Require one reconstructed electron with energy of at least 10 MeV and one (at least one) reconstructed proton with energy of at least 40 MeV for 1e1p (1eNp) selection

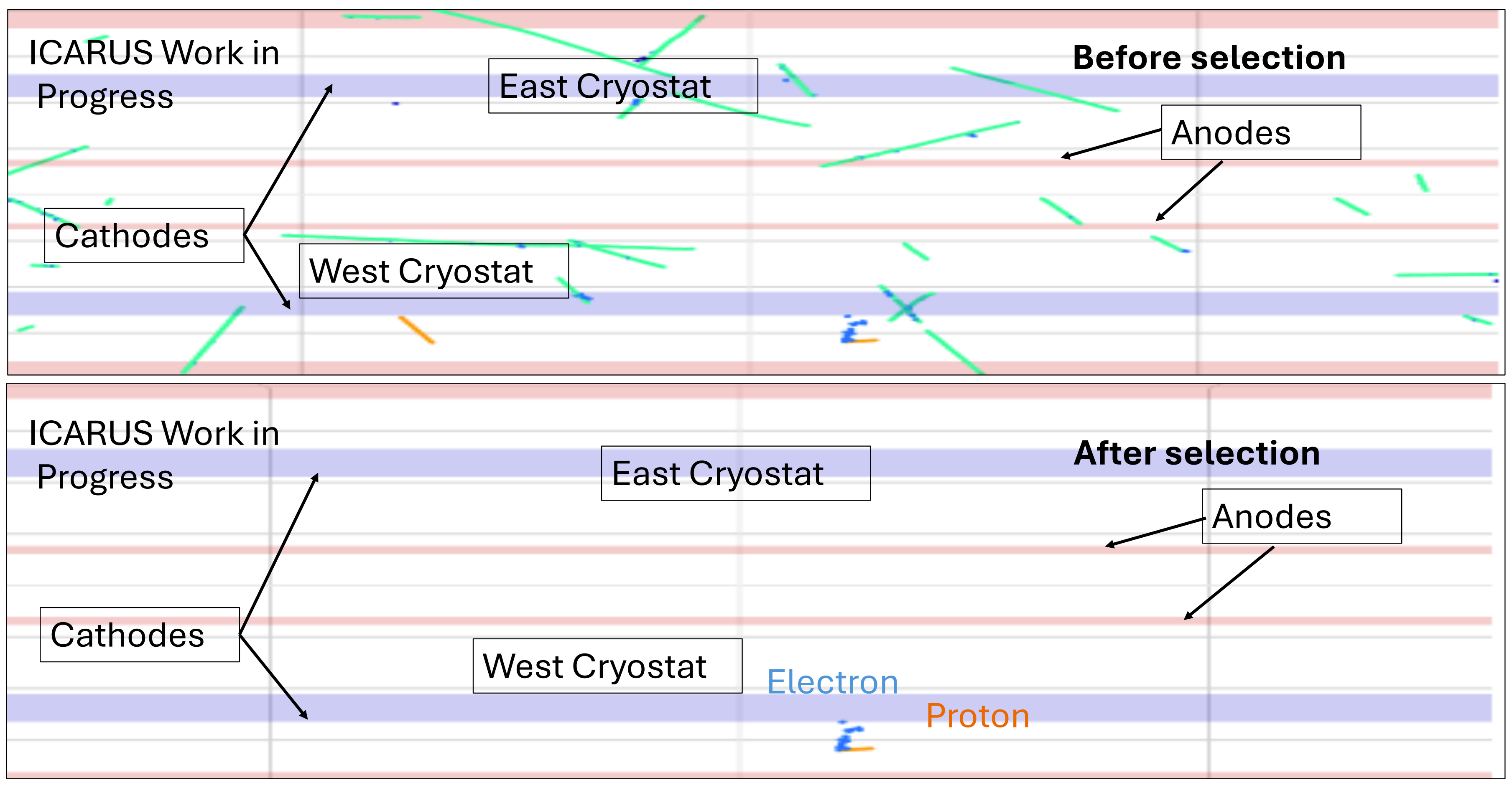

Figure 8: Event display of simulated neutrino event before and after the selection

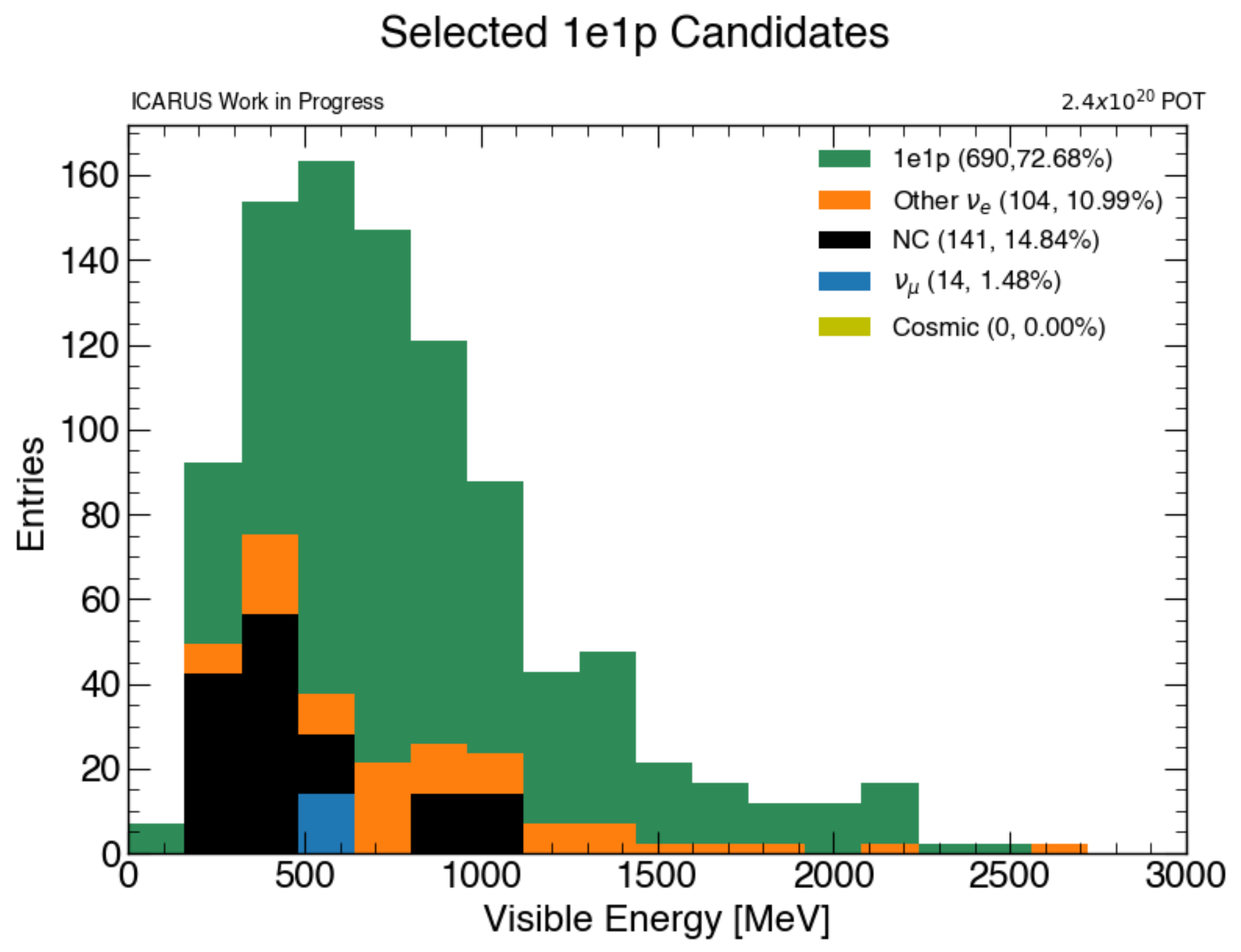

Figure 9: Energy spectrum of 1e1p selection

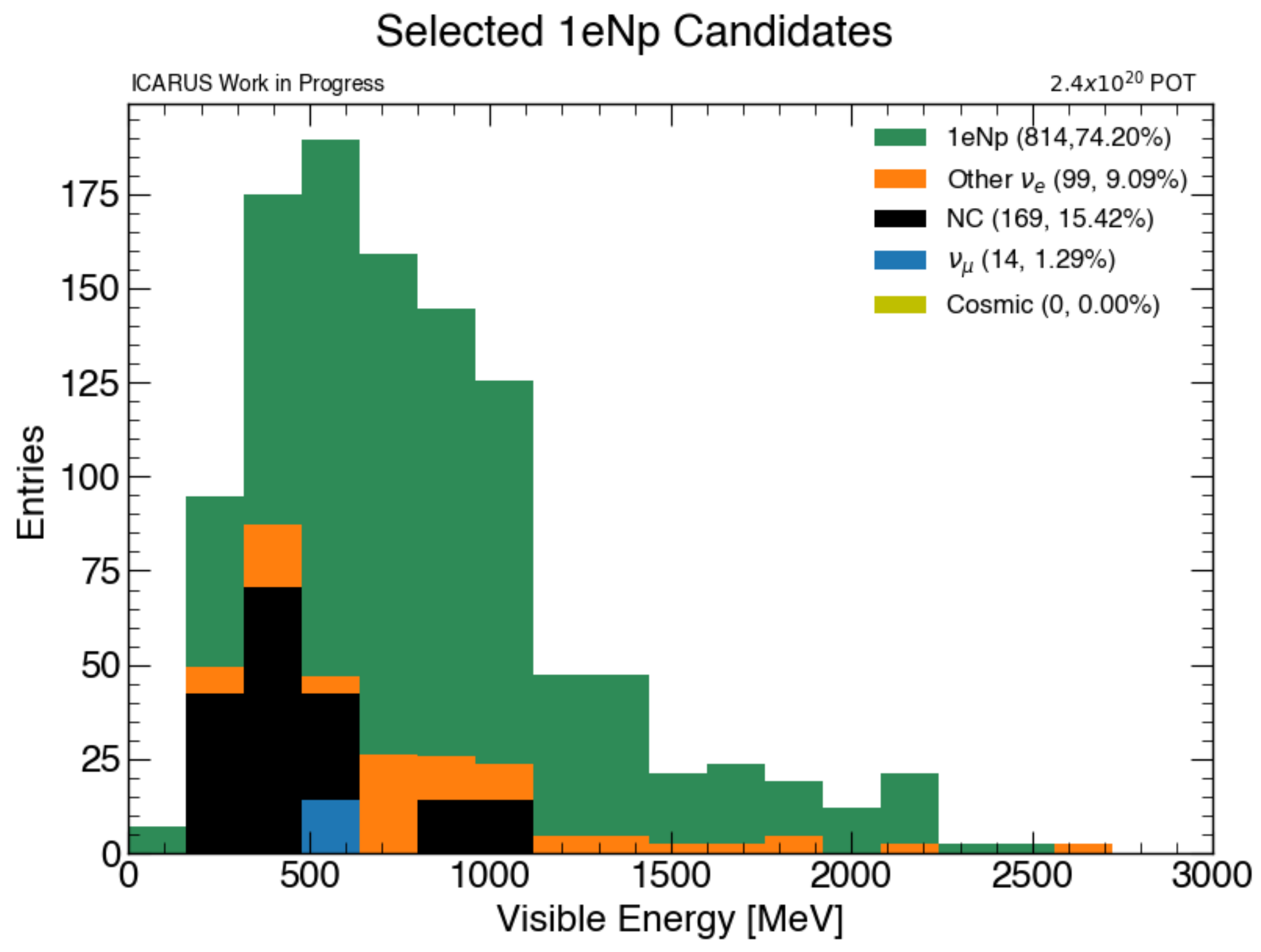

Figure 10: Energy spectrum of 1eNp selection

Selection	Purity	Efficiency	Expected Signal Events for ICARUS Run 2 (2.4×10^{20} POT)
1e1p	72.7%	73.3%	690
1eNp	74.2%	57.7%	814

Table 1: Selection performance and expected events from Run 2

Next Steps

- Recreate analysis with a larger Monte Carlo simulation sample
- Carry out selection on ICARUS NuMI data and compare to Monte Carlo simulation
- Include systematic uncertainties in analysis

V .References

[1] Machado, P.A.N., Palamara, O. and Schmitz, D.W. (2019) "The short-baseline neutrino program at Fermilab," *Annual Review of Nuclear and Particle Science*, 69(1), pp. 363–387. doi:10.1146/annurev-nucl-101917-020949.

[2] Abratenko, P., Aduszkiewicz, A., Akbar, F. et al. "ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation," Eur. Phys. J. C 83, 467 (2023). https://doi.org/10.1140/epjc/s10052-023-11610-y

[3] SPINE GitHub repository, https://github.com/DeepLearnPhysics/spine

VI. Acknowledgments

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