Reconstruction of Neutrino Events at the SBN Program with SPINE Machine Learning

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I. The Short-Baseline Neutrino Program at Fermilab

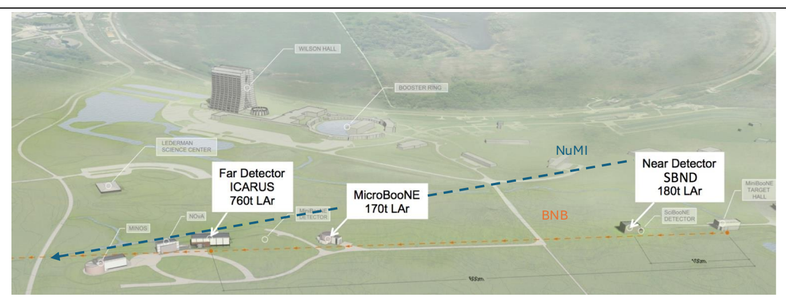

Figure 1: Map of the SBN Program at Fermilab with the NuMI and BNB neutrino beams highlighted [1]

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, the far detector, began its physics data-taking phase in **2021**.

Protons on Target

- Total BNB data: 7.44e20 POT
- Total NuMI data: 3.42e20 POT (Neutrino mode), 2.02e20 POT (Anti-neutrino mode)

The SBND (Short-Baseline Near Detector), the near detector for the program, began its physics data-taking in **2024**.

- Total BNB data: 3.27e20 POT

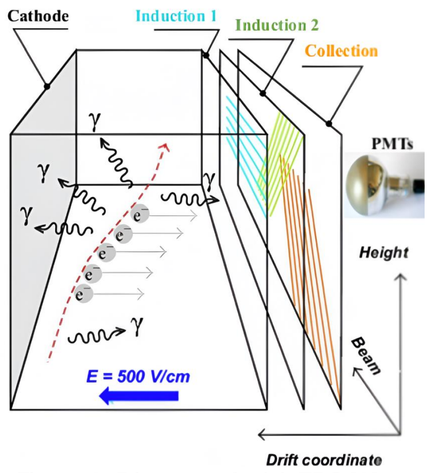

Figure 2: Diagram of a LArTPC [2]

II. SPINE Machine Learning Reconstruction

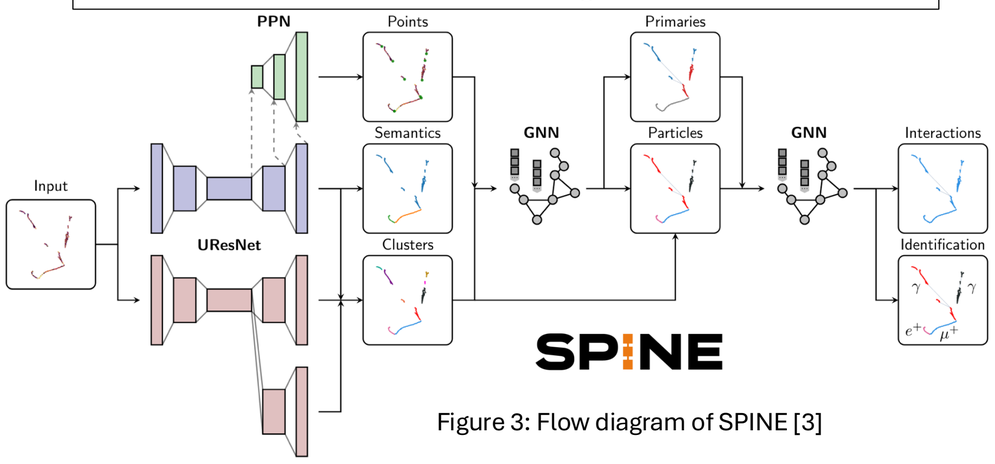

Figure 3: Flow diagram of SPINE [3]

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 minimize bias

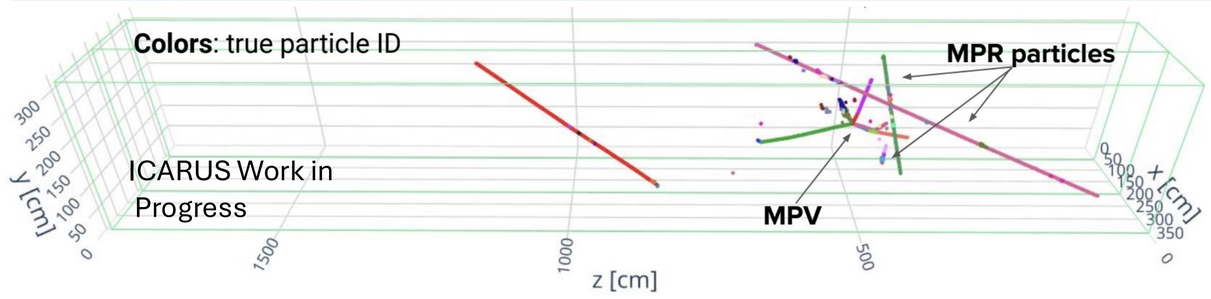

Figure 4: Single ML training event in a single drift volume

III. SBND Analyses

Figure 5: Selected 1μ1π⁰ candidate from data with a Michel electron

SBND Selected Simulated 1μ1π⁰

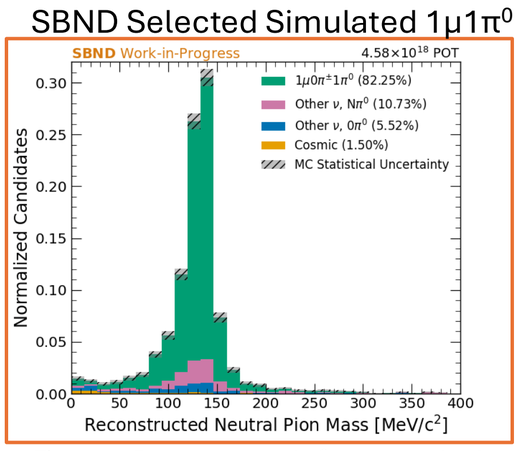

Figure 7: Reconstructed π^0 mass peak of simulated selected 1μ1π⁰ from SBND

SBND Selected Michel e⁻ Candidates

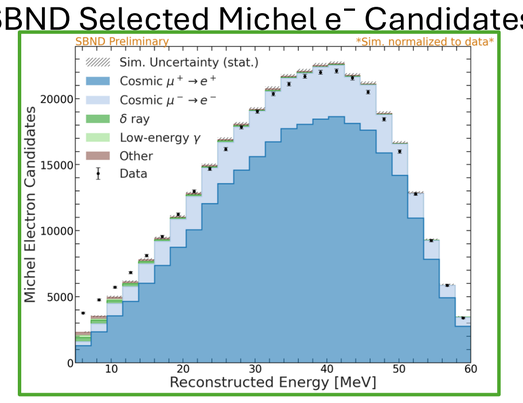

Figure 6: Reconstructed energy spectrum of selected Michel electrons from SBND including data

$\pi^0 \rightarrow \gamma\gamma$ and Michel e⁻ Reconstruction

- EM shower reconstruction validated with $\pi^0 \rightarrow \gamma\gamma$ decays
- Michel e⁻ from muon decay reconstructed with good agreement between data and simulation

Selection	Purity	Efficiency
1μ1π⁰	82%	68%
Michel e⁻	97%	81%

IV. ICARUS BNB Analyses

ICARUS Selected BNB 1μNp (N>0)

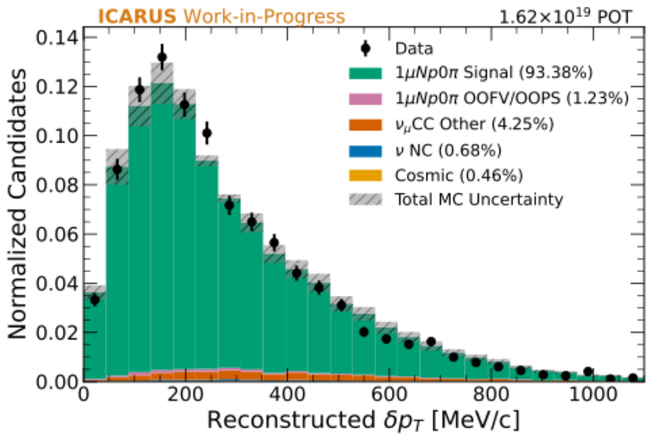

Figure 8: Reconstructed missing transverse momentum δp_T for BNB 1μNp candidates with partial dataset of BNB data

CC 1μNp : For precise ν_μ disappearance and cross section measurements.
CC 1μ1π⁰ : Important for shower energy scale studies and background characterization.
NC π⁰ : Critical background rejection in ν_e appearance searches.

Selection	Purity	Efficiency
1μNp	93%	82%
1μ1π⁰	83%	72%
NC 1π⁰	81%	68%

ICARUS Selected BNB 1μ1π⁰

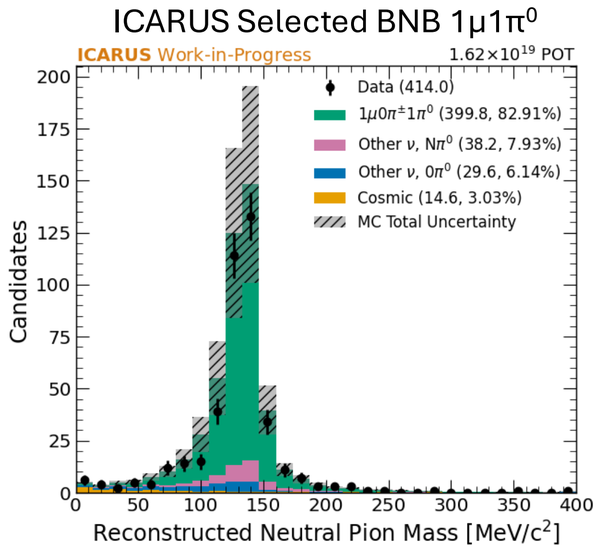

Figure 9: Reconstructed π^0 mass peak of selected 1μ1π⁰ from ICARUS with partial dataset of BNB data

ICARUS Selected BNB NC 1π⁰

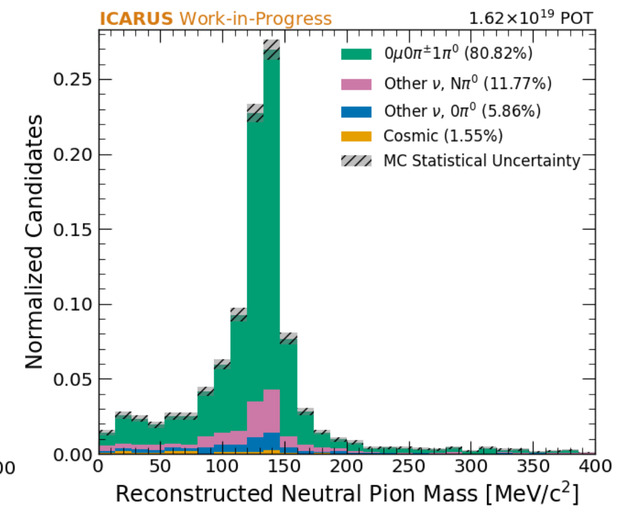

Figure 10: Reconstructed π^0 mass peak of selected NC 1π⁰ from ICARUS simulation

V. ICARUS NuMI Analyses

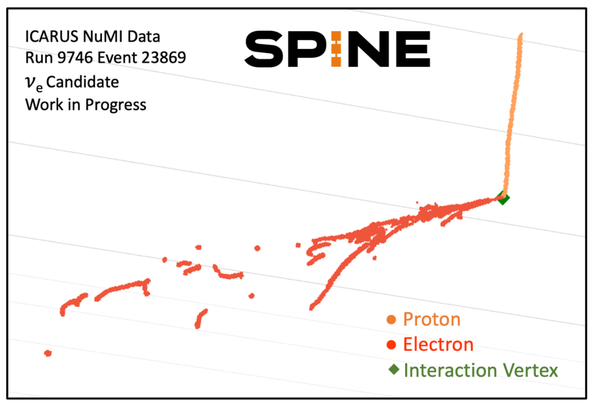

Figure 11: Reconstructed 1e1p neutrino candidate

ICARUS Selected NuMI 1eNp (N>0)

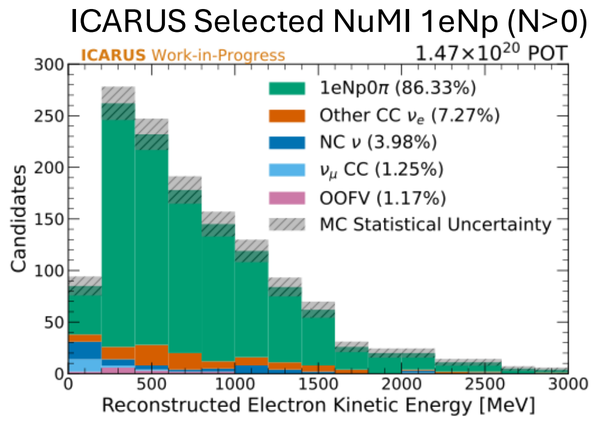

Figure 12: Reconstructed electron kinetic energy for NuMI 1eNp simulated candidates

ICARUS Selected NuMI 1μNp (N>0)

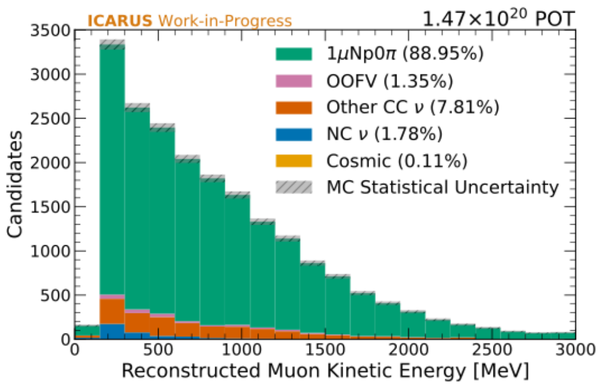

Figure 13: Reconstructed muon kinetic energy for NuMI 1μNp simulated candidates

CC 1eNp : For precise ν_e cross section measurements.
CC 1μNp0π : Validating SPINE by comparing with other analyses and precisely measuring ν_e/ ν_μ cross section ratio

Selection	Purity	Efficiency
1μNp	89%	76%
1eNp	86%	72%

Future Work

Use π^0 and NuMI beamline analyses to perform cross section measurements, improving constraints on neutrino interaction models.
Incorporate results into joint SBND+ICARUS analyses to enhance sensitivity to sterile neutrino oscillations.
Refine the SPINE framework to improve particle reconstruction for future analyses and detectors.

VI .References

[1] Machado, P.A.N., Palamara, O. and Schmitz, D.W. (2019) "The short-baseline neutrino program at Fermilab," Annu. Rev. Nucl. Part. Sci., 69(1), pp. 363–387.
[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).
[3] SPINE GitHub repository, https://github.com/DeepLearnPhysics/spine

VII. Acknowledgments

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