Muon Neutrino Reconstruction at ICARUS with Machine Learning

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ICARUS and the SBN Program

Serving as the far detector for the Short Baseline Neutrino (SBN) Program at Fermilab, ICARUS is a 470-ton liquid argon time projection chamber (LArTPC) that images neutrino interactions from the Booster Neutrino Beam (BNB).

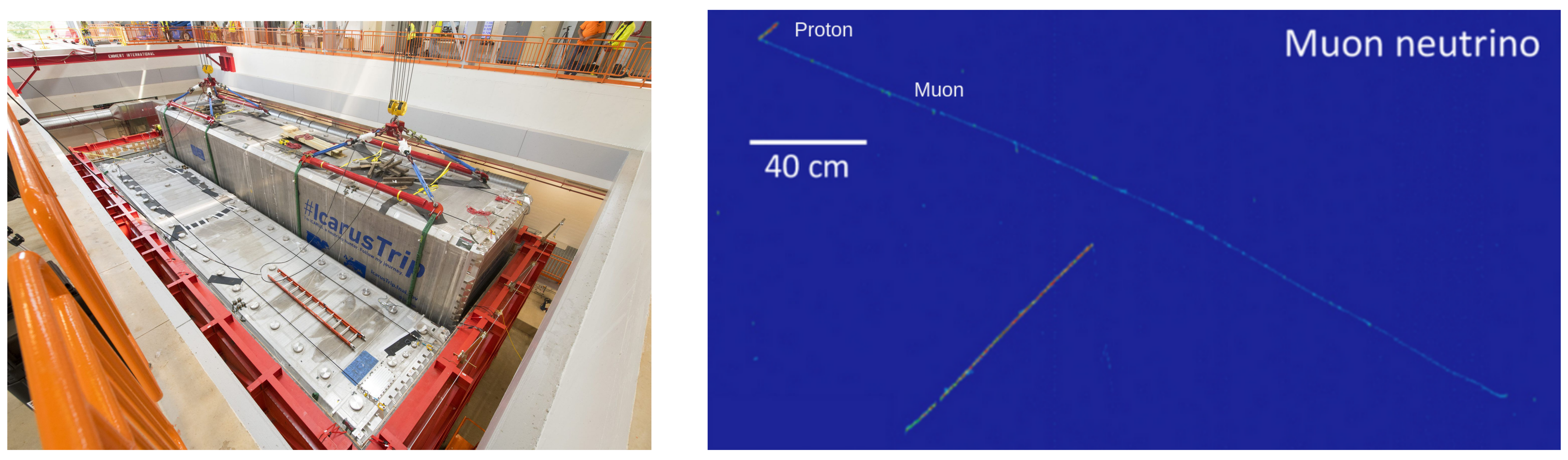

Figure 1. Left: ICARUS at Fermilab [1]. Right: An example muon neutrino interaction imaged by ICARUS.

Muon Neutrino Selection

ICARUS, which has been collecting data since 2021, hosts a rich physics program that is centered around a search for a hypothetical sterile neutrino. **Toward this end, event selections for the following signal definitions have been developed using machine learning techniques:**

- $1\mu1p$ (1 muon, 1 proton)
- $1\mu Np$ (1 muon, 1 or more protons)
- ν_μ CC (1 muon, inclusive)
  - ⇒ Including $1\mu1\pi^0$ (1 muon, 1 neutral pion)

Machine Learning Reconstruction

A novel, end-to-end machine-learning-based reconstruction chain has been developed at ICARUS. Known as SPINE (Scalable Particle Imaging with Neural Embeddings), this framework extracts particle identification and primary classification of neutrino interaction products using 2D images from each wire plane as input [2].

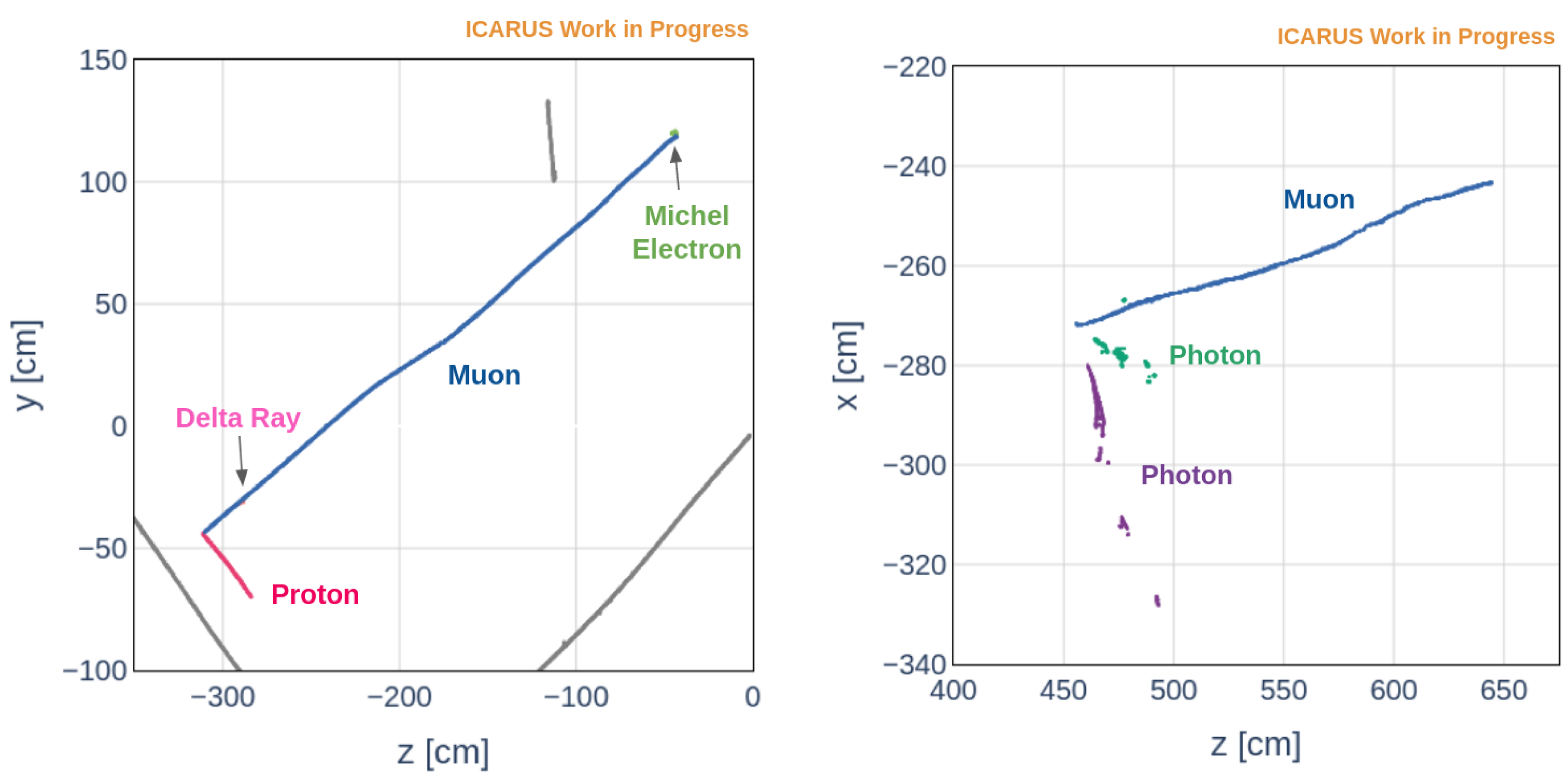

Figure 2. Left: Example of a reconstructed $1\mu1p$ interaction in data. Right: Example of a reconstructed $1\mu1\pi^0$ interaction in data. Photons originate from a $\pi^0 \to \gamma\gamma$ decay.

Sample Composition

Data:

- On-beam data collected from BNB in 2022/2023 corresponding to 1.92e19 POT (unblinded 10% of Run 2 data)
- Off-beam data used to estimate cosmic background

Simulation: Monte Carlo simulation consisting of BNB neutrinos (GENIE) and cosmics (CORSIKA)

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$1\mu1p$ / $1\mu Np$ / ν_μ CC Selections

$1\mu1p$ / $1\mu Np$: Simple final states, straightforward neutrino energy reconstruction

ν_μ CC: Statistically powerful, covers broad range of neutrino interaction topologies

For each selection, reconstructed visible energy (energy deposited in detector by neutrino interaction) is calculated.

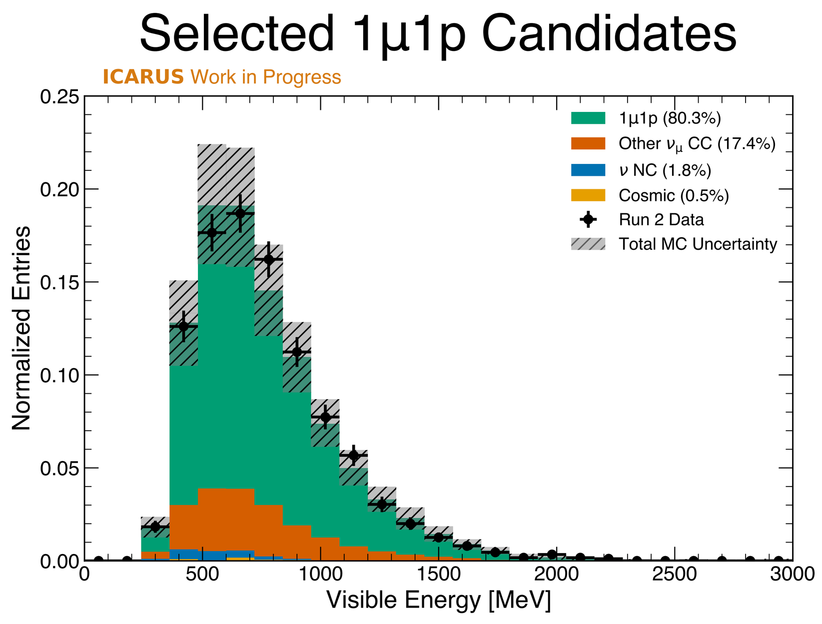

Figure 3. Reconstructed visible neutrino energy for $1\mu1p$ candidates.

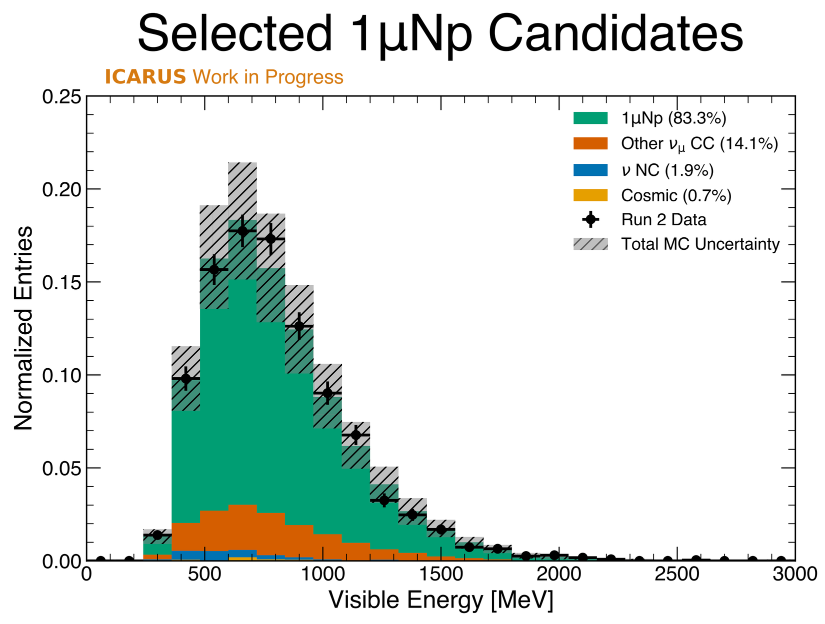

Figure 4. Reconstructed visible neutrino energy for $1\mu Np$ candidates.

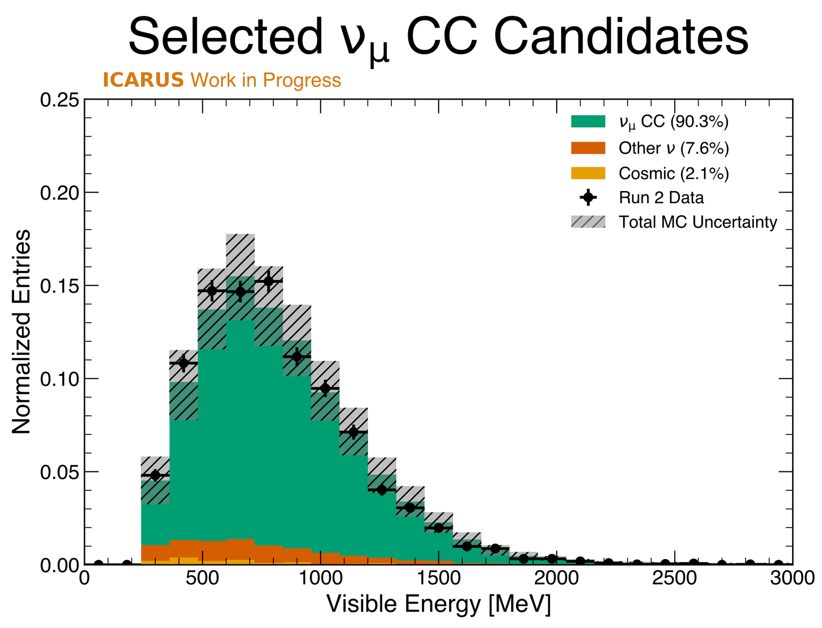

Figure 5. Reconstructed visible neutrino energy for ν_μ CC candidates.

Selection	Purity [%]	Efficiency [%]
$1\mu1p$	80.3	71.3
$1\mu Np$	83.3	75.4
ν_μ CC	90.4	83.3

Table 1. Selection performance for each channel.

Selection	$1\mu1p$	$1\mu Np$	ν_μ CC
Signal Events	12.2k	17.6k	35.4k

Table 2. Expected number of signal events for full ICARUS Run 2 dataset (1.9e20 POT).

Electromagnetic Shower Studies and $1\mu1\pi^0$ Selection

$1\mu1\pi^0$ is a subset of the ν_μ CC channel. Given the decay $\pi^0 \to \gamma\gamma$, the invariant diphoton mass is given by

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$

where E_1 and E_2 are the energies of the decay photons (reconstructed showers) and θ is the opening angle between them (calculated using reconstructed muon and shower start points).

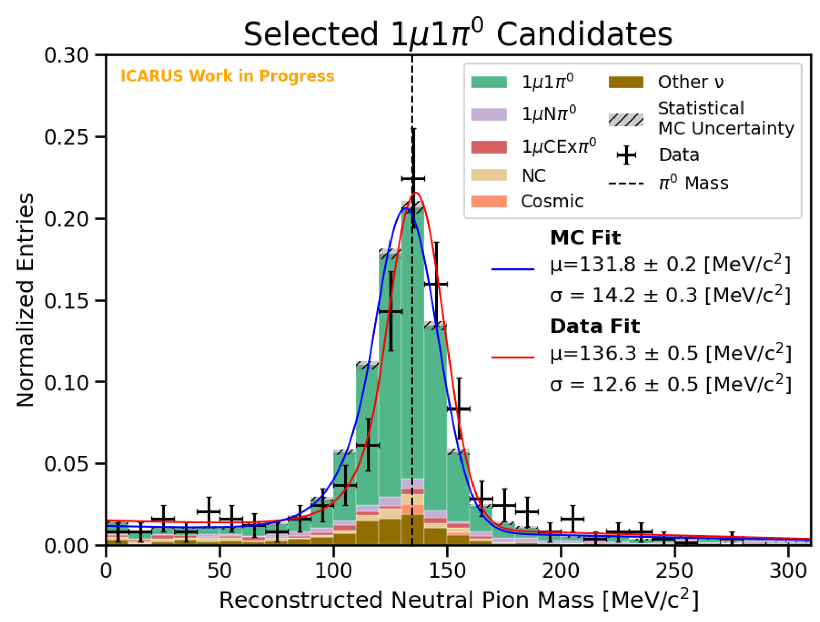

Figure 6. Reconstructed neutral pion mass, before calibrating shower energy scale to match true π^0 mass.

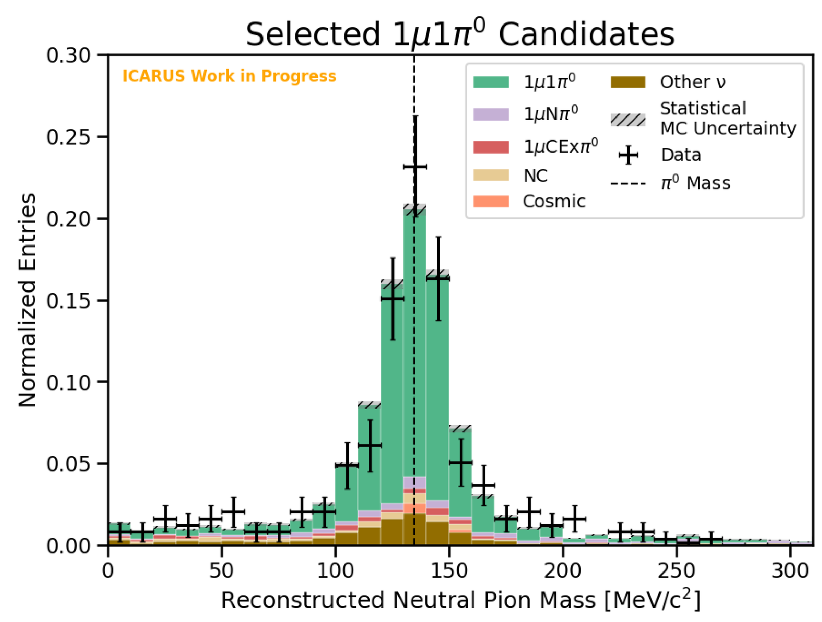

Figure 7. Reconstructed neutral pion mass, after calibrating shower energy scale to match true π^0 mass.

Crystal Ball fits to π^0 mass distributions show small EM shower energy scale bias (~3%) and excellent EM shower energy resolution (~10%).

References

[1] Hesla, Leah. "ICARUS Neutrino Detector Installed in New Fermilab Home," https://news.fnal.gov/2018/08/icarus-neutrino-detector-installed-in-new-fermilab-home/

[2] F. Drielsma, K. Terao, L. Dominé, D. Koh, "Scalable, End-to-End, Deep-Learning-Based Data Reconstruction Chain for Particle Imaging Detectors," arXiv:2102.01033

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