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).

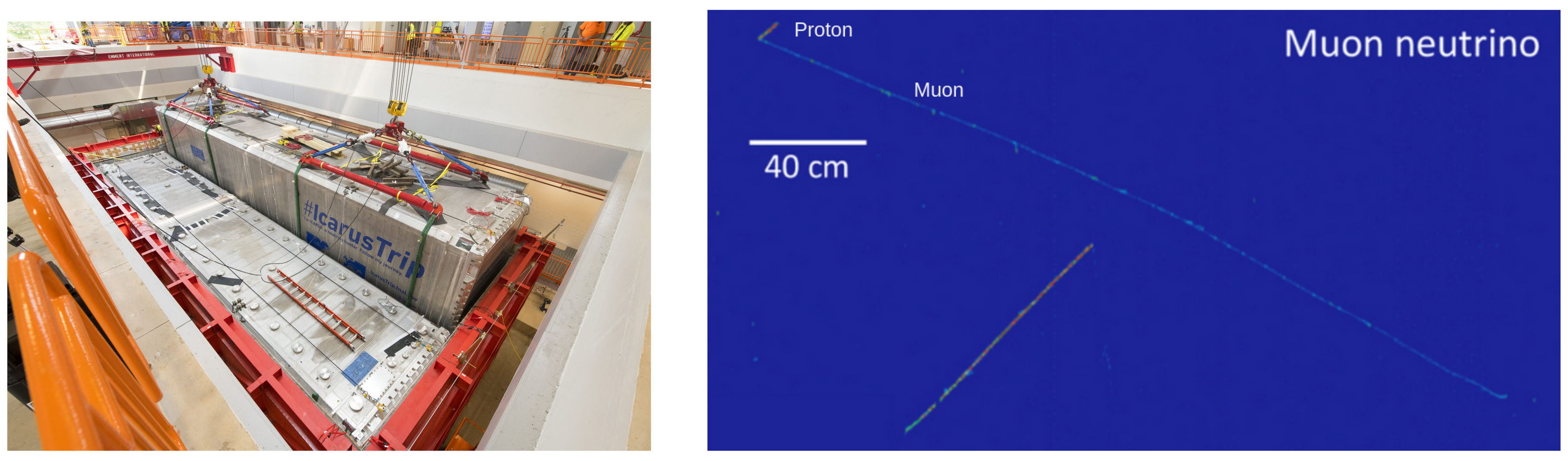

Figure 1. Left: ICARUS at Fermilab [1]. Right: An example muon neutrino interaction imaged by ICARUS.

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:**

- $\boldsymbol{1\mu 1p}$ (1 muon, 1 proton)
- $\boldsymbol{1\mu \mathrm{N}p}$ (1 muon, 1 or more protons)
- $\boldsymbol{\nu_\mu}$ **CC** (1 muon, inclusive)
  - ⇒ Including $\boldsymbol{1\mu 1\pi^0}$ (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].

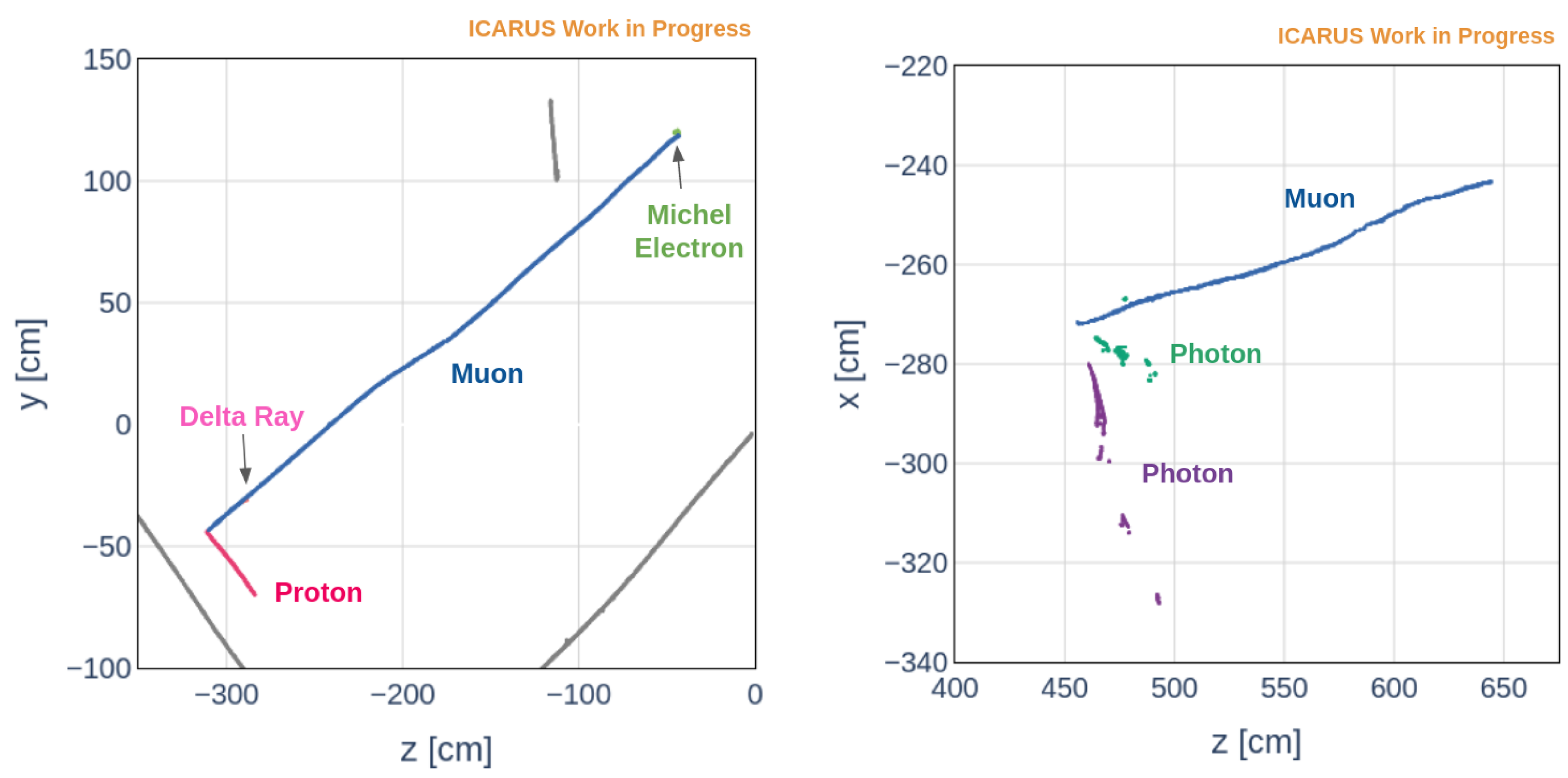

Figure 2. Left: Example of a reconstructed $1\mu 1p$ interaction in data. Right: Example of a reconstructed $1\mu 1\pi^0$ interaction in data. Photons originate from a $\pi^0 \to \gamma\gamma$ decay.

Selection Preface

Sample Composition

Data:

- On-beam data collected from BNB in 2022/2023
- Off-beam data used to estimate in-time cosmic background

Simulation: Monte Carlo simulation consisting of BNB neutrinos and out-of-time cosmics

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$1\mu 1p$ / $1\mu \mathrm{N}p$ / ν_μ CC Selections

$\boldsymbol{1\mu 1p}$ / $\boldsymbol{1\mu \mathrm{N}p}$: Simple final states, striaghtforward neutrino energy reconstruction

$\boldsymbol{\nu_\mu}$ **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.

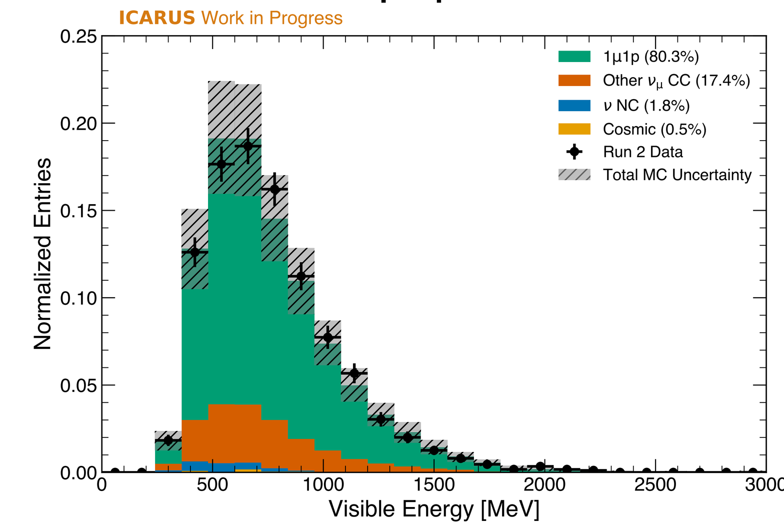

Figure 3. Reconstructed visible neutrino energy for $1\mu 1p$ candidates.

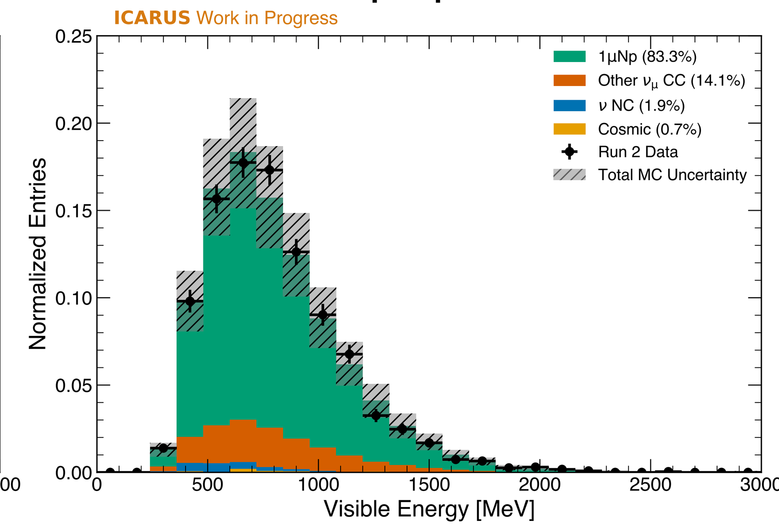

Figure 4. Reconstructed visible neutrino energy for $1\mu \mathrm{N}p$ candidates.

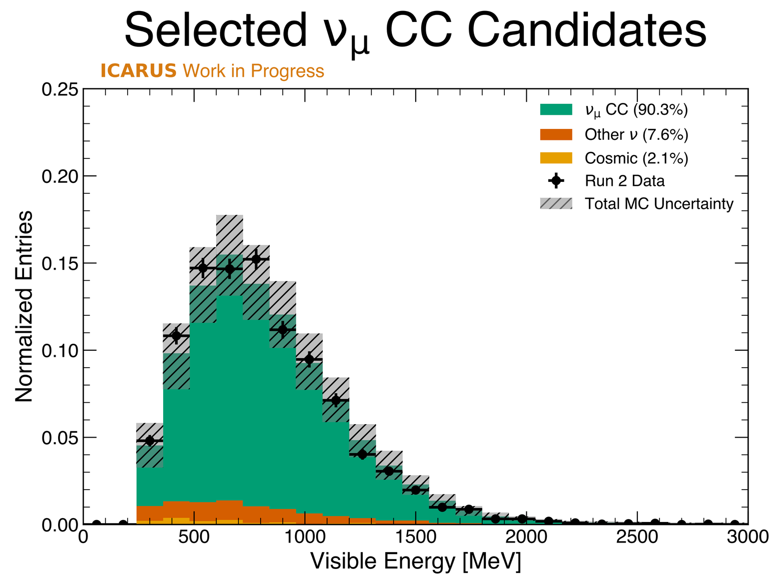

Figure 5. Reconstructed visible neutrino energy for ν_μ CC candidates.

Selection	Purity [%]	Efficiency [%]
$1\mu 1p$	80.3	71.3
$1\mu \mathrm{N}p$	83.3	75.4
ν_μ CC	90.4	83.3

Table 1. Selection performance for each channel.

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

$1\mu 1\pi^0$ 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).

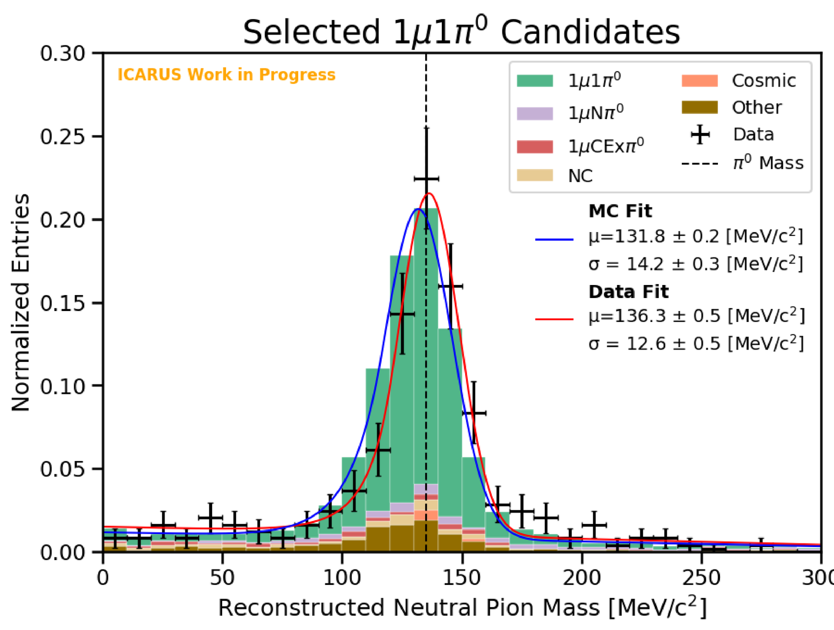

Figure 6. Reconstructed neutral pion mass, before calibrating shower energy scale to match true pi0 mass.

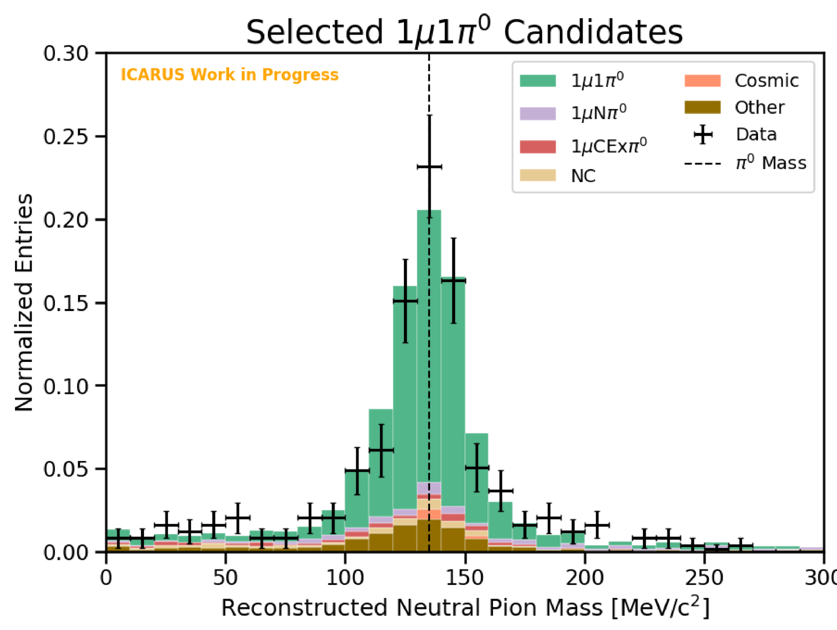

Figure 7. Reconstructed neutral pion mass, after calibrating shower energy scale to match true pi0 mass.

Crystal Ball fit to π^0 mass distributions shows small EM shower energy scale bias (∼3%) and excellent photon 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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