Toward Muon Neutrino Charged-Current Neutral Pion Cross Section Measurements at ICARUS

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FERMILAB-POSTER-26-0102-V

ICARUS and the SBN Program

ICARUS is the far detector for the Short-Baseline Neutrino (SBN) Program at Fermilab.

- 470-ton liquid argon time projection chamber (LArTPC)
- Images neutrinos from Booster Neutrino Beam (BNB)

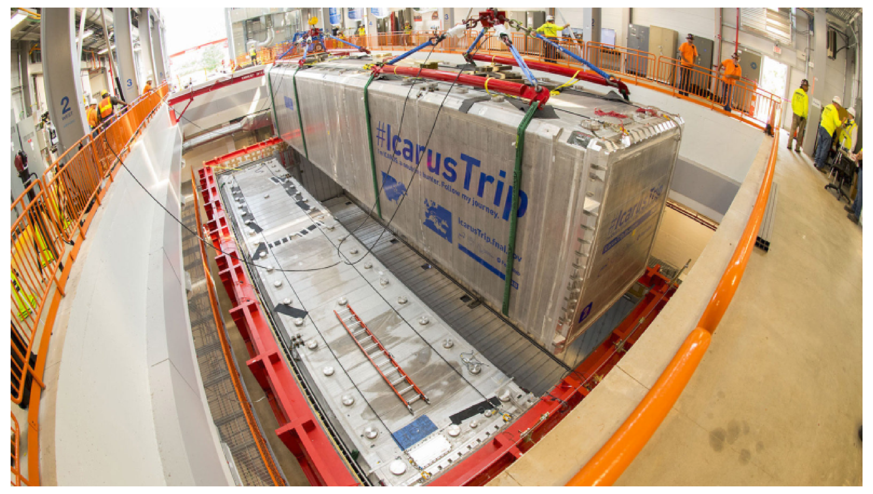

Figure 1: ICARUS at Fermilab.

Signal Definition

ν_μ CC π^0 : Muon neutrino charged-current interaction characterized by the presence of the following final state particles:

- 1 muon (length > 50 cm → KE > 143.425 MeV)
- 0 charged pions
- 1 neutral pion

→ Offers a probe for resonance interactions relevant to all accelerator-based neutrino experiments.

Sample Composition

Data: BNB 2022/2023 (1.60e20 POT). Off-beam for cosmic background.

Simulation: GENIE (neutrinos) and CORSIKA (cosmics).

Table 1: Summary of the GENIE interaction model employed for sample production in the ν_μ CC π^0 analysis.

Interaction	Model
Nuclear	Correlated Local Fermi Gas
Quasielastic Scattering	Valencia
2p2h	SuSAv2
Resonance	Berger-Sehgal
Coherent Pion Production	Berger-Sehgal
Deep Inelastic Scattering	Bodek-Yang
Hadronization	AGKY
Final State Interactions	INTRANUKE hA

Machine Learning Reconstruction

SPINE (Scalable Particle Imaging with Neural Embeddings) extracts particle identification and classification in 3D by combining 2D projections.

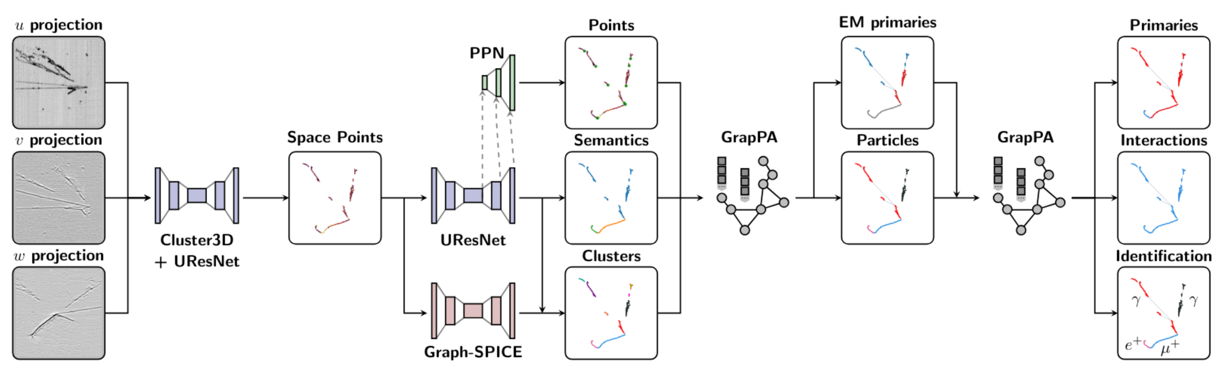

Figure 2: Schematic architecture of SPINEs end-to-end, machine-learning-based reconstruction chain for LArTPCs [1].

Event Selection

Selection criteria for ν_μ CC π^0 interactions:

- 1 primary muon (length > 50 cm → KE > 143.425 MeV)
- 0 primary muons (KE > 25 MeV)
- 0 primary charged pions (KE > 25 MeV)
- 2 primary photons (KE > 25 MeV)

Additionally, selected interactions are required to be in-time with the BNB and have a vertex reconstructed within the ICARUS fiducial volume.

Selection performance is evaluated with Monte Carlo simulation.

Efficiency: 66% **Purity:** 89%

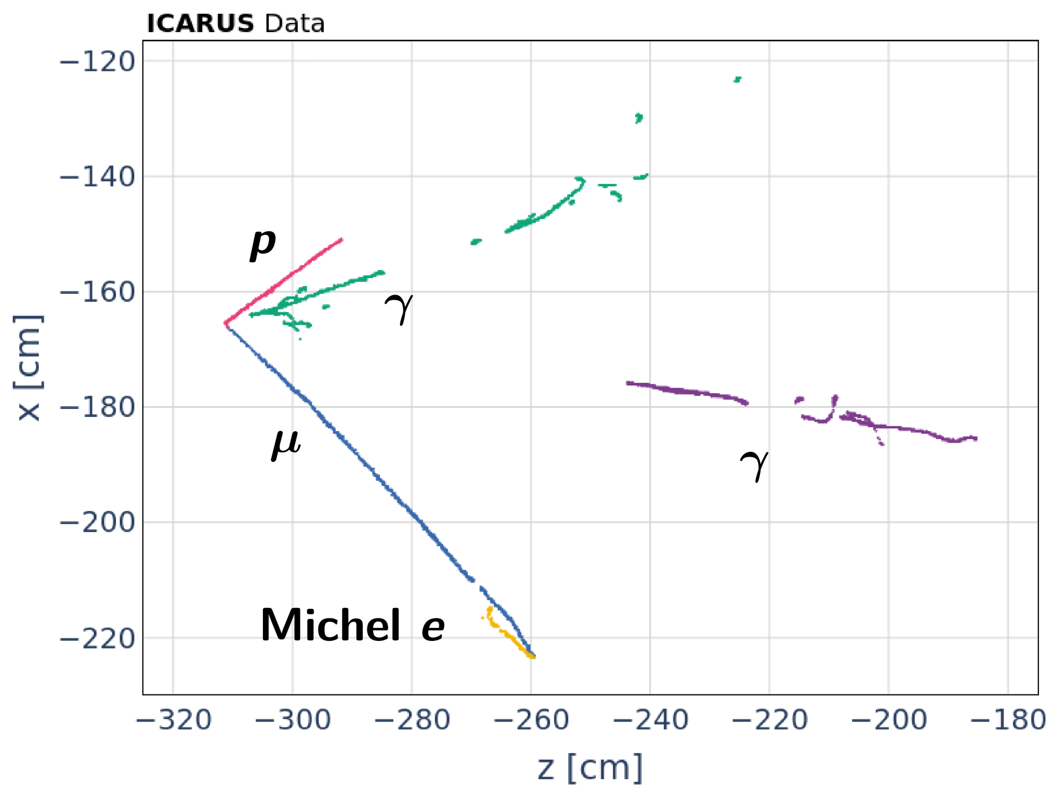

Figure 3: An ν_μ CC π^0 interaction from ICARUS data that has been reconstructed with SPINE. Different colors represent distinct particle instances predicted by SPINE's neural networks.

EM Shower Energy Studies

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).

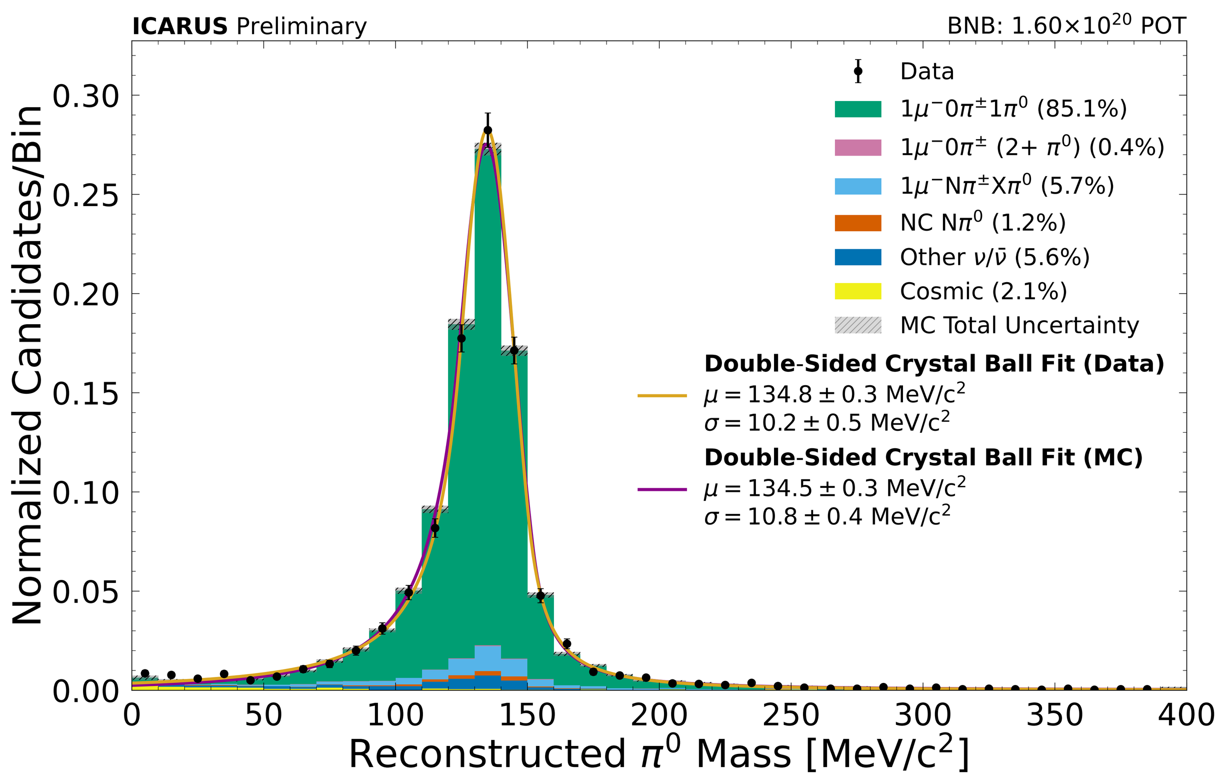

Figure 4: Unit-normalized reconstructed neutral pion mass for selected ν_μ CC π^0 interactions with BNB neutrino data and ICARUS simulation. A subset of fit parameters are reported for double-sided Crystal Ball fits to each distribution.

Crystal Ball fits to π^0 mass distribution show excellent EM shower energy resolution →Ultimately allows finer binning for cross section observables.

Cross Section Observables

Differential cross sections are to be measured in bins of muon and neutral pion kinematics:

- Momentum
- Angle with respect to the neutrino beam direction

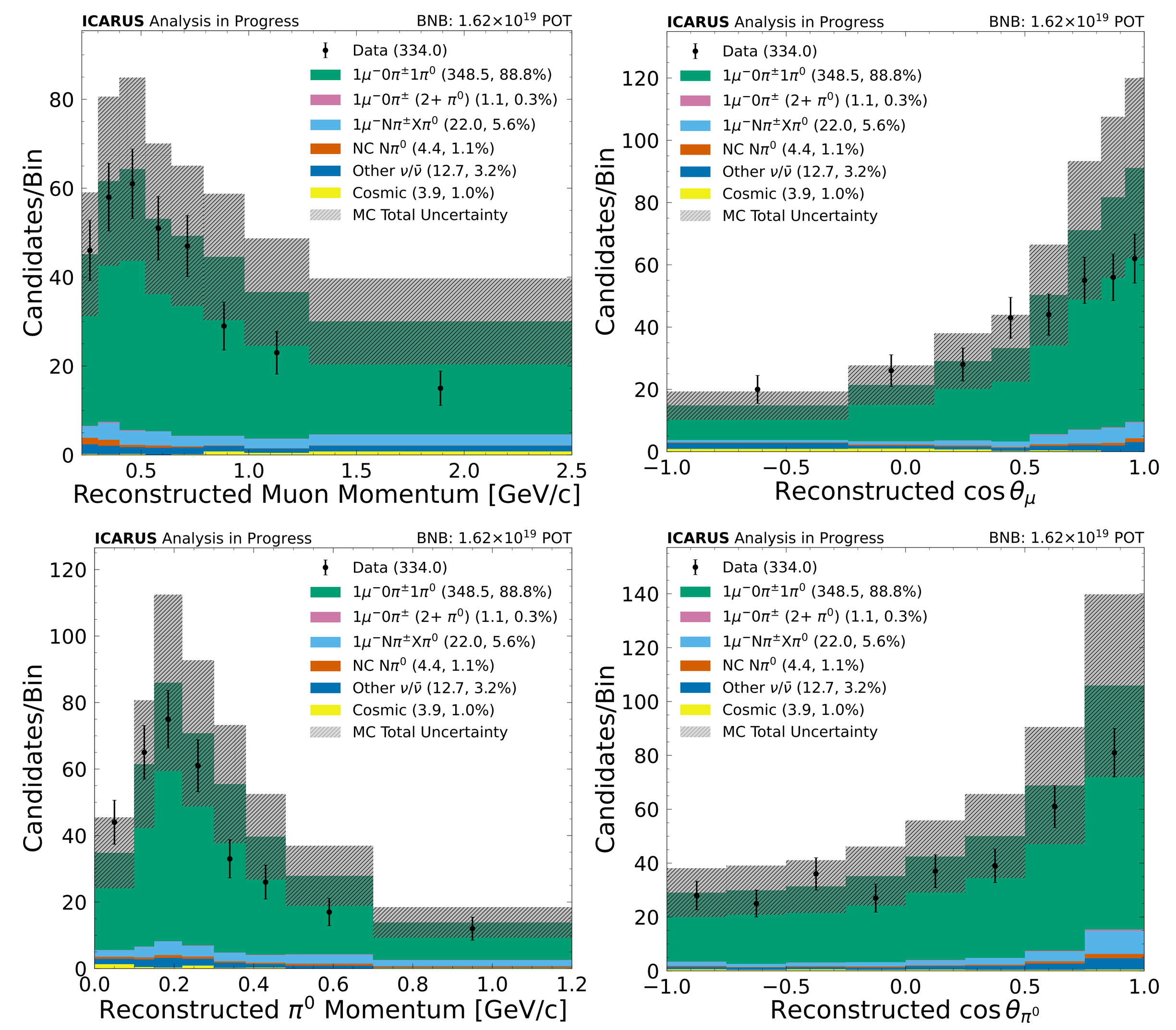

Figure 5: Reconstructed cross section observables for selected ν_μ CC π^0 interactions in simulation and the unblinded 10% of ICARUS BNB Run 2 data. Muon momentum and angle with respect to the BNB direction are shown in the top row, while the same quantities are shown for the neutral pion in the bottom row.

Systematic Uncertainties

Uncertainties on selected ν_μ CC π^0 event counts have been assessed for the following sources:

- Beam flux model
- ν-Ar interaction model
- Detector model

ν-Ar interaction model uncertainties on signal events dominate, with leading contributions stemming from parameters associated with resonance production and final state interactions (FSI).

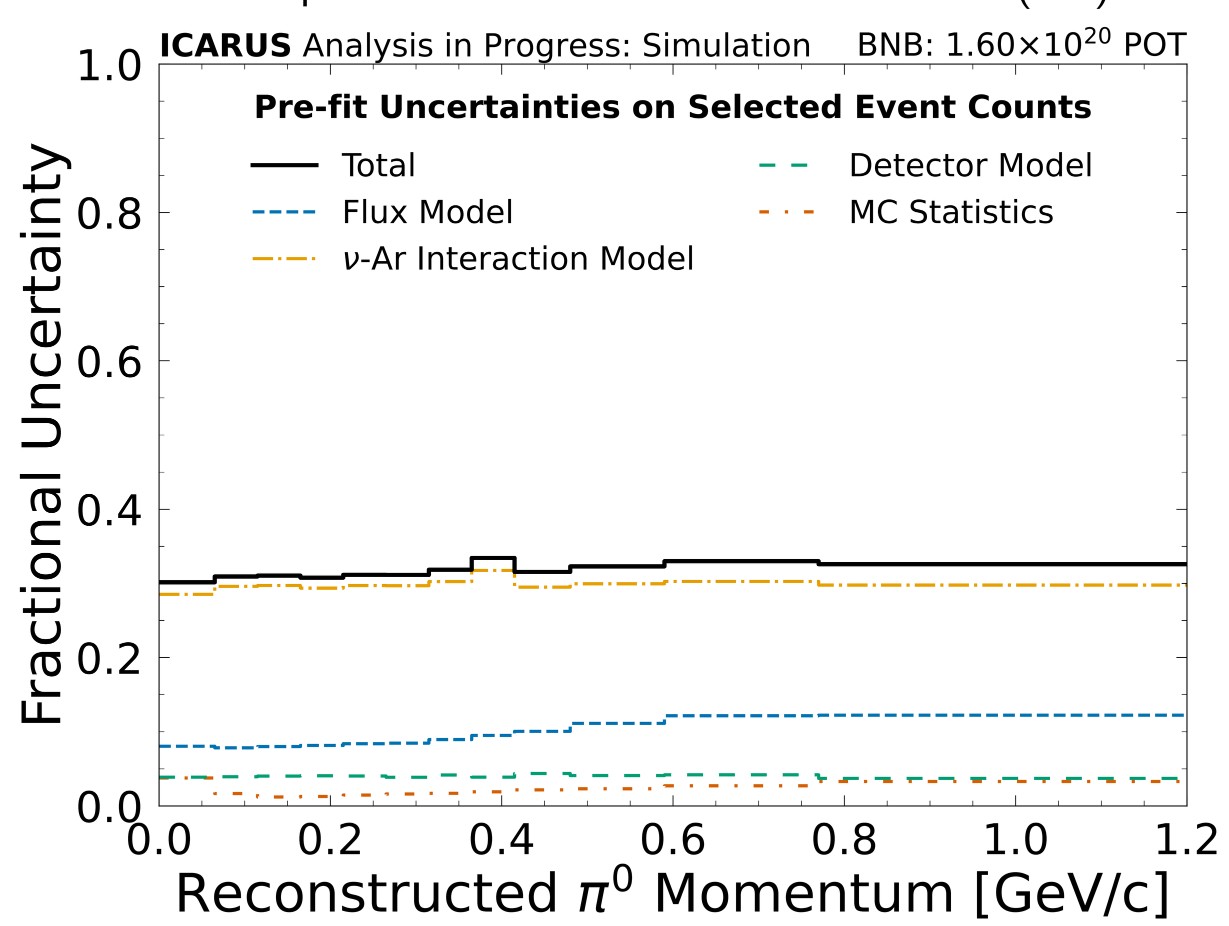

Figure 6: Fractional uncertainties on the number of selected ν_μ CC π^0 interactions as a function of reconstructed neutral pion momentum.

Cross Section Extraction Procedure

The cross section in true bin i of kinematic variable X is given by:

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}X}\right|_i = \frac{N^{\text{sig}}_{i,\text{unfolded}}}{\Phi\, N_{\text{targets}}} \frac{1}{\Delta X_i}. \tag{1}$$

where Φ is the integrated neutrino flux and N_{targets} is the number of nuclear targets.

The efficiency-corrected, unfolded number of signal events $N^{\text{sig}}_{i,\text{unfolded}}$ is determined from negative log-likelihood minimization with the GUNDAM fitting framework [2]:

$$-2\ln\mathcal{L} = -2\ln\mathcal{L}_{\text{stat}} - 2\ln\mathcal{L}_{\text{syst}}. \tag{2}$$

Mock Data Studies

Mock data studies are carried out before cross sections are extracted with real neutrino data:

- Asimov dataset
- Systematic/statistical throws
- Out-of-model variations (low-Q^2 suppression, alternative FSI models, etc.)

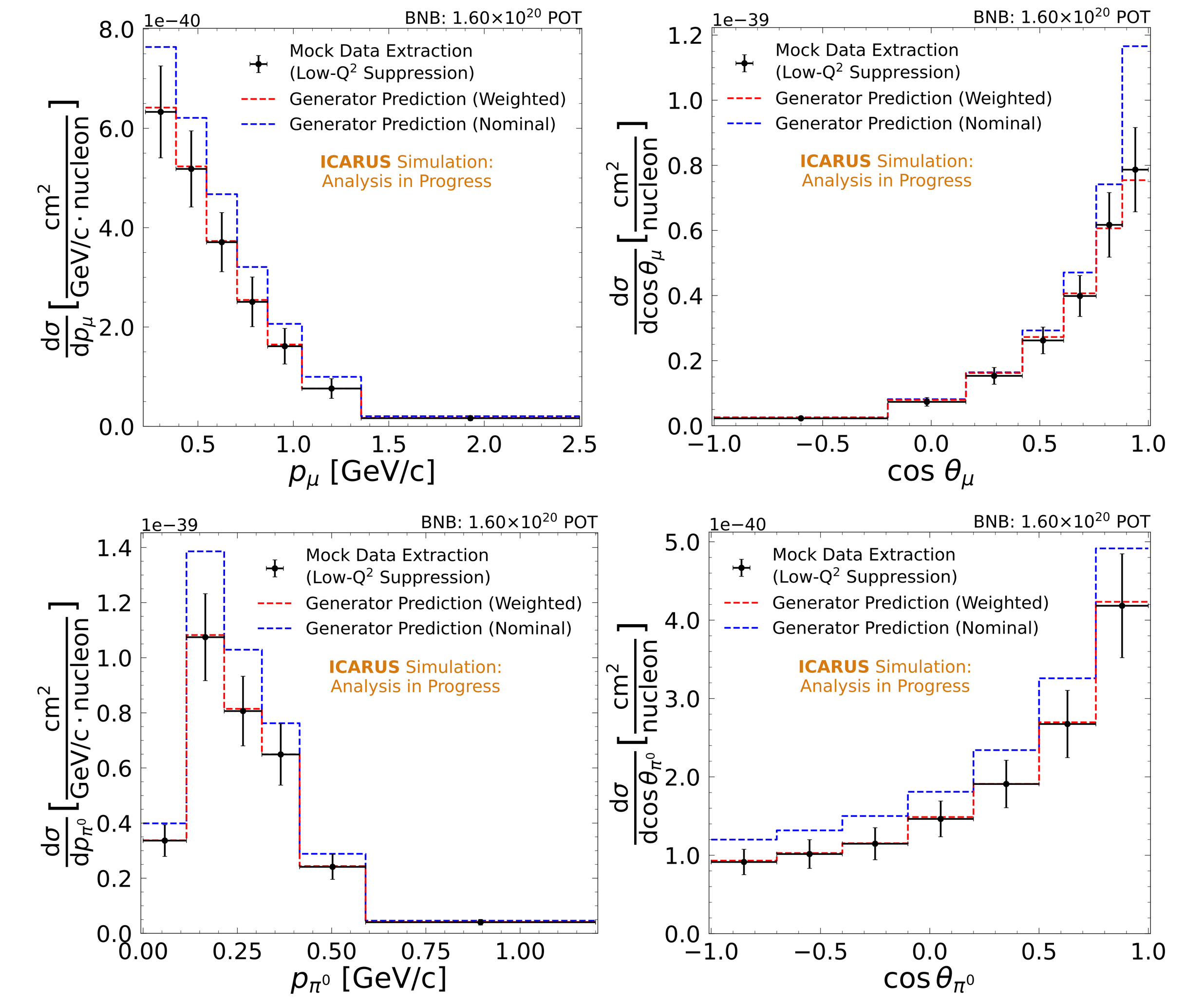

Figure 7: Extracted cross sections, where mock datasets have been created from the nominal ICARUS simulation with low-Q^2 suppression for signal events.

Thus far, all studies point to a *well-behaved fit parameter space and a comprehensive systematic uncertainty model.*

→Stay tuned for cross section extraction with BNB data!

References

[1] Scalable Particle Imaging with Neural Embeddings (SPINE), https://github.com/DeepLearnPhysics/SPINE.

[2] GUNDAM Organization, https://github.com/gundam-organization/gundam

Acknowledgements: This work is supported by the United States Department of Energy under Grant Nos. DE-SC0017740 and DE-SC0021191. This document was prepared by the ICARUS Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

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