Measurement of Muon neutrino Charged-Current Neutral Pion Production at ICARUS

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Abstract

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1 Introduction

Serving as the far detector for the Short-Baseline Neutrino (SBN) Program, ICARUS is poised to address anomalous results from the LSND and MiniBooNE experiments, where excesses of electron-like events could possibly be interpreted as originating from light sterile neutrinos. One key to resolving these anomalies is the search for electron neutrinos in a predominantly muon neutrino beam, for which ICARUS and other detectors in the SBN suite rely on liquid-argon time projection chamber (LArTPC) technology. With excellent calorimetry and fine-grained spatial resolution, LArTPCs enable ICARUS to make precise measurements of electron neutrino interactions as part of a robust neutrino oscillation program.

Equally important to the success of ICARUS is characterization of backgrounds that can mimic the electron neutrino appearance signal. Primary among these backgrounds is the production of neutral pions, or π^0s, which decay electromagnetically to photons. π^0 production is mostly attributed to baryon resonance (RES) in neutrino-nucleon interactions that occur at few-GeV scale, which is also the energy at which the upcoming Deep Underground Neutrino Experiment (DUNE) neutrino beam peaks at. An ICARUS analysis centered around neutral pions therefore not only informs us about the SBN Program's most significant background, but also provides a probe for the types of neutrino interactions expected at next-generation oscillation experiments.

1.1 Measurement

In this document, we report the flux-averaged differential cross section measurement of muon neutrino charged-current interactions with a single π^0 in the final state on argon, hereafter referred to as ν_μ CC π^0 interactions:

$$\nu_\mu + Ar \rightarrow \mu^- + \pi^0 + 0\pi^\pm + X. \tag{1}$$

Here, X represents any final state particles that are not muons or charged pions. The ommitance of charged pions in the final state aims to exclude charged-current coherent pion production from the analysis, therefore allowing the cross section measurement to probe the resonant production mode that is more relevant to the SBN Program.

Few charged-current π^0 measurements exist on liquid argon, and a high statistics cross section measurment of this channel at ICARUS will help constrain uncertainties in modeling resonant neutrino-nucleuon interactions. We present the ν_μ CC π^0 differential cross section measurement as a function of muon and neutral pion kinematic variables, with event selection being carried out by a novel machine-learning reconstruction pipeline. Benefiting from high purity and excellent resolution in reconstructed variables, the extraction of a precise, finely-binned differential cross section is made possible.

1.2 Data and Monte Carlo Samples

This analysis utilizes ICARUS data collected from the Booster Neutrino Beam (BNB) between winter 2022 and spring 2023 (ICARUS Run 2). This collection period corresponds to approximately 2.05×10^{20} protons on target (POT). The analysis can be easily extended to the Neutrinos at the Main Injector (NuMI) beam, and will be in the future as data processing and treatment of systematic uncertanties allows. Data is processed through the ICARUS reconstuction chain (see Appendices A & B) with *icaruscode* software version v09_89_01_01.

Monte Carlo simulation consisting of BNB neutrinos (produced with GENIE) and cosmics (produced with CORSIKA) is used to assess selection performance. This Monte Carlo sample corresponds to 1.74×10^{10} POT. To evaluate the impact from cosmic activity that occurs within the 9.6 μs BNB beam gate, off-beam data is used (To-do). A summary of production files uses in this analysis is shown in Table 1.

Table 1: Data/Simulation Productions used for ν_μ CC π^0 analysis.

	Production	POT
Data (on-beam)	BNB Run 2 On-Beam Majority Trigger	2.05×10^{20}
Data (off-beam)	BNB Run 2 Off-Beam Majority Trigger	N/A
Simulation	BNB ν + Cosmics	1.74×10^{20}

1.2.1 Data Quality Cuts

To ensure the data used in this analysis is of physics quality, a number of data quality cuts are enforced. Namely, any data collection runs that were subject to DAQ issues or happened during detector hardware updates are removed from consideration. Additionally, cuts are made to avoid detector features that are yet to be modeled in simulation, including a field cage short in the EE TPC and a cable hanging in the active volume of the WW TPC. A full description of all data quality cuts used in this analysis can be found in Appendix A.

1.2.2 Unblinding Strategy

The official blinding policy of the ICARUS collaboration (doc-db 34523) states that 90 percent of data is to remain blinded until any analysis is finalized. To comply with this policy, all analysis toward the ν_μ CC π^0 cross section measurement shown in this document only uses the 10 percent of Run 2 data that has been unblinded. An exception has been made for data collection run 9435, which has been completely unblinded for the purpose of visual scanning.

Pending approval from the physics coordinators and event selection working group, we request access to...(To-do)

2 ν_μ CC π^0 Selection

2.1 Signal Definition

The ν_μ CC π^0 signal definition encompasses charged-current neutrino interactions occuring within the fiducial volume of the detector and containing

- exactly one primary muon
- exactly zero charged pions
- exactly one neutral pion
- any number of particles that are not muons or pions.

This signal definition applies to final state particles, or particles exiting the target nucleus post-final state interactions (FSI). The fiducial volume requirement applies to the neutrino interaction vertex, which must be 25 cm from detector boundaries in the drift and vertical directions, 30 cm from the upstream detector face, and 50 cm from the downstream face.

Additional requirements are placed on the signal definition to ensure tracking thresholds are met and selection purity and efficiency are optimized. These are referred to as phase space constraints and include:

- $p_\mu \geq 226$ MeV/c
- $p_{\pi^0} \geq 100$ MeV/c.

2.2 Selection Cuts

When selecting ν_μ CC π^0 interactions, cuts are made on various reconstructed outputs to narrow the list of candidate interactions. Included are cuts on:

- <u>Fiducial volume</u>: Reconstructed vertex is required to be inside fiducial volume (defined in signal definition).

- Topology: Interaction contains exactly one primary muon, zero primary charged pions, and two or three primary photons as reported by the machine-learning reconstruction chain's primary particle classification and particle identification algorithms. Particles also meet phase space requirements of the signal definition. In the case of three photons, the pair of photons with reconstructed invariant mass closest to m_{π^0} is chosen to represent the neutral pion candidate.
- Neutral pion mass: Invariant diphoton mass < 400 MeV in order to reject η mesons.
- Flash time: Interaction is associated with an optical flash that is in-time with BNB beam gate, as determined by the OpT0Finder algorithm.

2.3 Selection Performance

Selection performance is assessed using the BNB ν + Cosmic MC sample and off-beam BNB Run 2 data. The metrics that have been evaulated are efficiency - the fraction of true signal interactions that are matched to selected interactions, and purity - the fraction of selected interactions that are matched to true signal interactions. Figure 1 shows the selection efficiency for ν_μ CC π^0 events before muon and neutral pion momentum thresholds are applied. The sharp drop-offs at 226 MeV/c and 100 MeV/c for the muon and neutral pion distributions, respectively, motivate the phase space constraints of the signal definition.

Figure 1: A missing figure.

Overall, the selection acheives an efficiency of 80% and a purity of 80%. Efficiency and purity for each selection cut are shown in Table 2. Signal inefficicies are further characterized in the confusion matrix shown in Figure 2, while the backgrounds that lead to impurities are seen in Section 2.4.

Table 2: Purity and efficiency for ν_μ CC π^0 Selection Cuts

Selection Cut	Purity [%]	Efficiency [%]
No Cut	xx	xx
Fiducial Volume	xx	xx
Final State Topology	xx	xx

Figure 2: A missing figure.

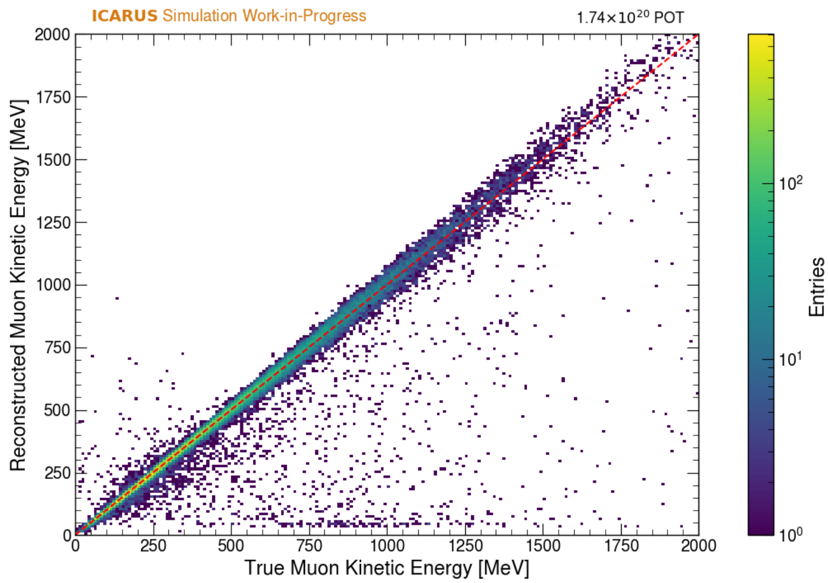
2.4 Variables of Interest

In this section, the kinematic observables used in the single differential cross section measurement are discussed. Included are the momenta of the final state muon and neutral pion, as well as the angles these particles make with the NuMI beam. An additional variable, the invariant diphoton mass, is examined as it serves as a useful standard candle in the calibration of the electromagnetic shower energy scale. First, however, the methods used to estimate the energy (and momentum) of the reconstructed particles of interest is detailed.

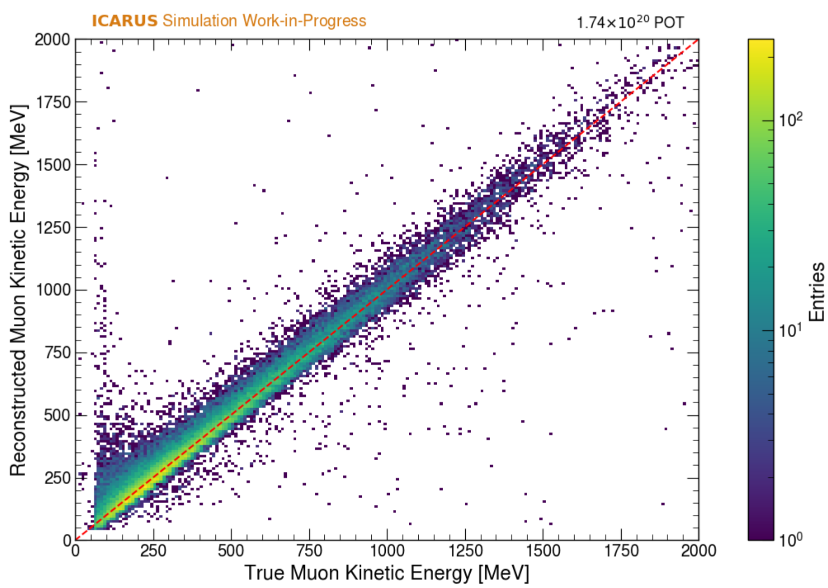
2.4.1 Energy Reconstruction

To estimate the momentum of the reconstructed muon, it is first necessary to reconstruct its energy, for which a “best estimate” approach is taken. For muons contained within the active detector volume, momentum is calculated using the

Continous Slowing Down Approximation (CSDA) that relates a particle's kinetic energy to its range in a material. For momentum estimation of exiting muons, the degree of multiple coulomb scattering (MCS) along the track is instead used. Figure 3 shows how each muon momentum estimate compares with true muon momentum in simulation.



(a) Reconstructed energy is calculated using range-based method.



(b) Reconstructed energy is calculated using information from multiple coulomb scattering.

Figure 3: Comparisons of reconstructed and true muon kinetic energy for a selection of contained muons in ICARUS simulation.

Unlike muons, neutral pions do not directly ionize the detector medium. The neutral pion momentum must therefore be inferred from the electromagnetic showers instigated by the photons it decays to. Shower energy (and momentum) is estimated calorimetrically by summing charge depositions belonging to the shower and accounting for various detector effects:

$$E_{shower} = W_i[\frac{MeV}{e^-}] \cdot C_{cal}[\frac{e^-}{ADC}] \cdot C_{adj} \cdot \frac{1}{R} \cdot \sum_{dep} e^{\frac{t_{drift}}{\tau}} \cdot dep[ADC], \qquad (2)$$

where

W_i is the work function for argon

C_{cal} converts charge units from ADC to electrons

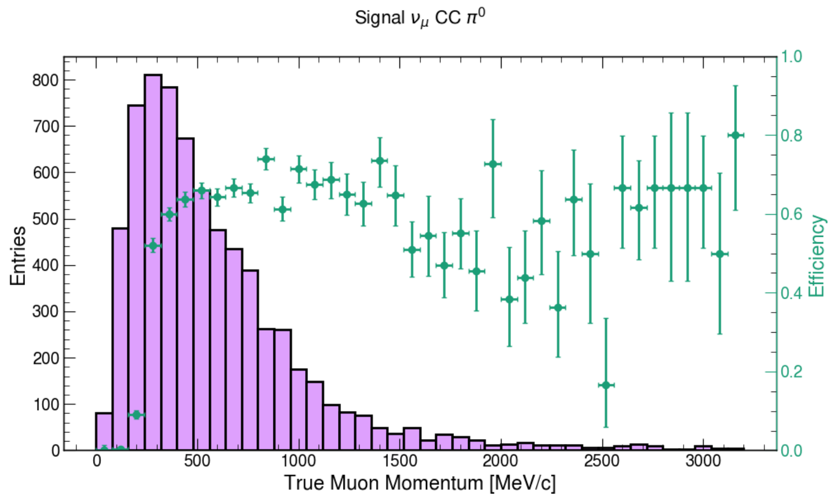
C_{adj} accounts for missing energy due to subthreshold charge and clustering effects in reconstruction

R is the recombination factor

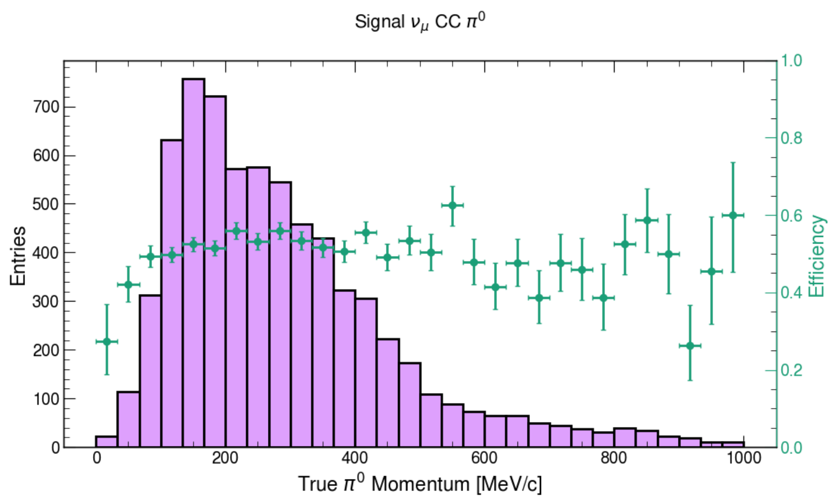
τ is the electron lifetime

dep is charge in units of ADC.

As the signal definition for this analysis does not require showers to be contained, an additional correction factor is needed to correct for missing energy in exiting showers. A study for deriving this factor is ongoing with results expected soon.



(a) Muon



(b) Pion

Figure 4: Comparisons of reconstructed and true muon kinetic energy for a selection of contained muons in ICARUS simulation.

2.4.2 Muon Observables

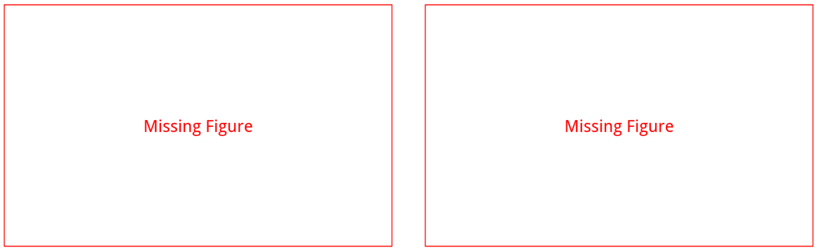


Figure 5: A missing figure.

2.4.3 Photon Observables

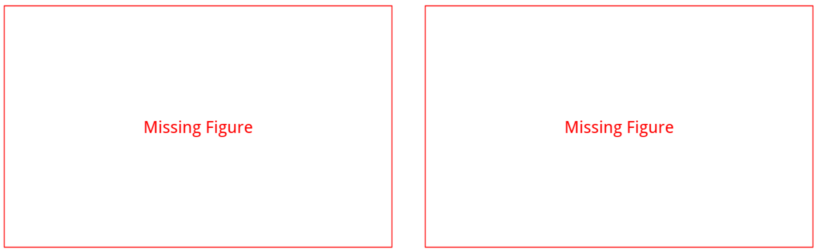


Figure 6: A missing figure.

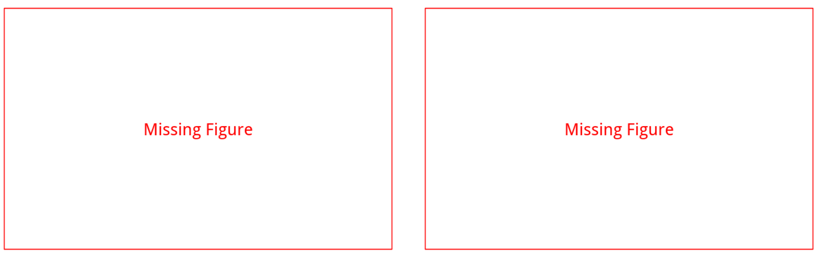


Figure 7: A missing figure.

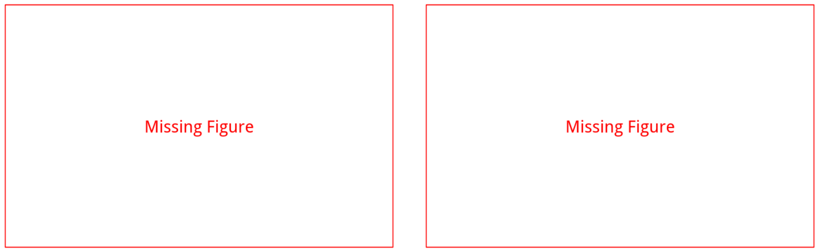


Figure 8: A missing figure.

2.4.4 Neutral Pion Observables

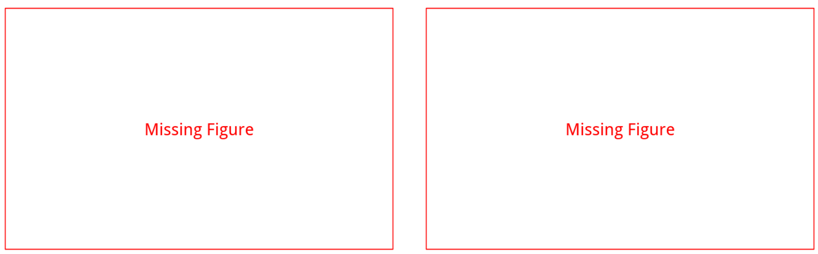


Figure 9: A missing figure.

Figure 10: A missing figure.

3 Systematic Uncertainties

3.1 Flux Uncertainties

3.2 Cross Section Uncertainties

3.3 Detector Uncertainties

4 Data/Monte Carlo Comparisons

5 Cross Section Measurement

5.1 Cross Section Extraction Procedure

5.2 Results

6 Conclusions

References

[1] F. Drielsma, K. Terao, and L. D. andDae Heun Koh, "Scalable, end-to-end, deep-learning-based data reconstruction chain for particle imaging detectors", (2021).

Appendices

A Data Quality Cuts

B Raw Signal Processing and Calibration

C Machine Learning Reconstruction

In this section, neutrino event reconstruction is discussed. For information on raw signal processing and calibration, see Appendix B. Reconstruction of neutrino events is handled by the end-to-end, machine-learning based reconstruction chain known as SPINE (Scalable Particle Imaging with Neural Embeddings) [1]. As input, SPINE takes an image of 3D charge depositions within the detector, which is then operated on by a series of neural networks to carry out point classification and formation of particle and interaction objects.

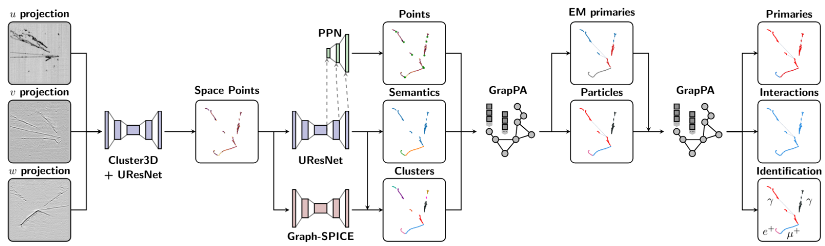


Figure 11: The SPINE reconstruction chain.

C.1 Point Classification

Point classification refers to the classification of 3D space points into abstract particle classes and the identification of points of interest. Convolution neural networks (CNNs) are used for these tasks, beginning with the removal of tomographic reconstruction artifacts by the

C.2 Formation of Particles and Interactions

C.3 Post-Processors