Prospects of Neutrino Cross Section Measurements Using the NuMI off axis at ICARUS

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Introduction

Proper modeling of nuclear effects in neutrino interactions, e.g.

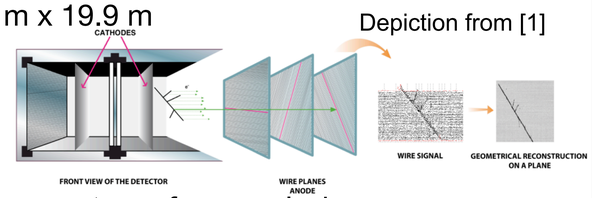
- initial state Fermi momentum and multinucleon effects
- final state interactions

is crucial to understanding neutrino energy reconstruction and calculation of signal efficiencies in oscillation probability measurements. Cross section measurements in liquid argon (LAr) in ICARUS using NuMI off-axis will cover the **second oscillation maximum** and **extend into** the region of **the first oscillation maximum** in DUNE.

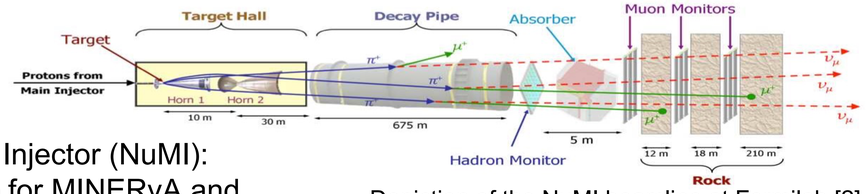
ICARUS Experiment

- 2 cyrostats, each approximately 3.6 m x 3.9 m x 19.9 m
- Each has 2 LAr time-projection chambers (TPC) with cathode in the middle
- 3 wire planes per TPC measure ionization charge (2 induction, 1 collection)
- Reconstruction pieces together tracks and showers to perform analysis

Depiction from [1]



Neutrino Interactions from NuMI off-axis



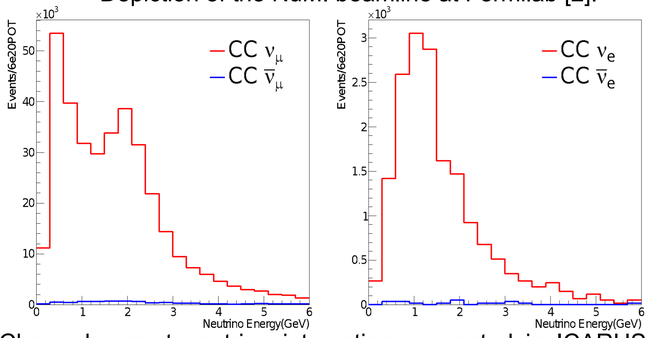
Depiction of the NuMI beamline at Fermilab [2].

Neutrinos at the Main Injector (NuMI):

- ν beam at Fermilab for MINERvA and long-baseline oscillation program
- 120 GeV protons onto (mostly) graphite target
- Decays of interaction products (and subsequent decays) produce mostly ν_μ beam with some ν_e

ICARUS **~800m** from target, **~6° off-axis**.

Wealth of ν_μ and ν_e events for important cross-section measurements:



Charged-current neutrino interactions expected in ICARUS per year, assuming 6×10^{20} POT per year. A wealth of events in the $\gtrsim$1 GeV range are expected.

- lower part of the spectrum (esp. ν_e CC) useful cross-check related to SBN sterile search
- ν_μ and ν_e at $\gtrsim$1 GeV provide important studies of nuclear effects relevant for DUNE

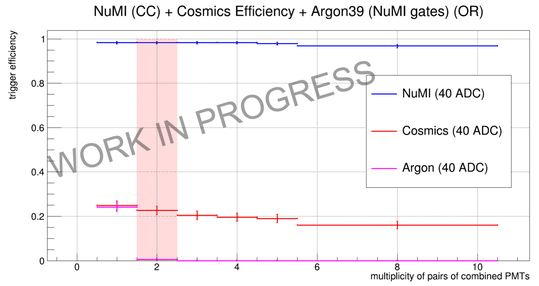
Trigger System & Simulation Studies

The trigger system is designed to maximize the amount of neutrino events recorded, while keeping the overall event rate below 1 Hz. 180 photomultiplier tubes (PMTs) per cryostat send paired discriminated waveforms as inputs to the trigger hardware.

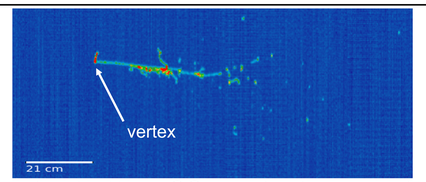
Cosmic rays are the largest contributor to event rates due to ICARUS' position at ground level.

Preliminary optimal hardware requirements for a trigger signal are:

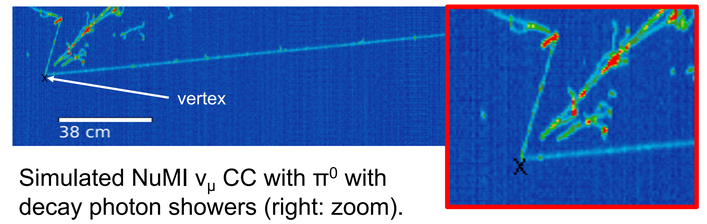
- **40 ADC** waveform threshold
- **2 PMT pair** multiplicity
- **OR** PMT pair combination logic



Maximal simulated trigger efficiency settings shown in red highlight.



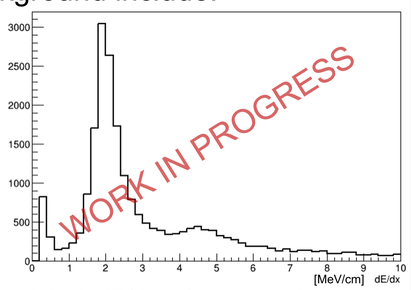
Simulated NuMI ν_e CC event with an electron shower extending from the interaction vertex.



Simulated NuMI ν_μ CC with π^0 with decay photon showers (right: zoom).

ν_e Reconstruction & Selection

- Uses LArSoft [3] with the Pandora framework [4]
  - Uses Tool-based Reconstruction Algorithm for Characterizing Showers (TRACS)
- ν_e CC have a shower from final-state electron. Backgrounds include cosmics & events with photons (π^0). Handles to tell signal from background include:
  - Matching scintillation and tracks – cosmic rejection
  - Gap between interaction vertex and start of electro-magnetic shower
  - Initial dE/dx of shower (e: 1 MIP, ɣ: 2 [pair-production
- Vertex and shower reconstruction incredibly important
  - Split showers or wrong vertex can lead to seemingly detached shower, misleading dE/dx measurement
- Work is ongoing to improve vertex reconstruction, and improvement expected by tuning shower characterization.



Initial dE/dx of a reco shower in simulated NuMI ν_e under certain criteria. Peak is ~1 MIP in LAr. Reco improvements are planned.

References

[1] C. Rubbia et al. Underground operation of the ICARUS T600 LAr-TPC: first results. JINST 6, P07011, 2011 arxiv: 1106.0975

[2] P. Adamson et al. The NuMI Neutrino Beam. NIM A, 806:279–306, 2016. arxiv: 1507.06690

[3] LArSoft [Software for LArTPCs]. (2016). https://larsoft.org/, https://github.com/LArSoft/larsoft

[4] Pandora [Multi-Algorithm Pattern Recognition Software]. (2013). https://github.com/PandoraPFA

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