Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

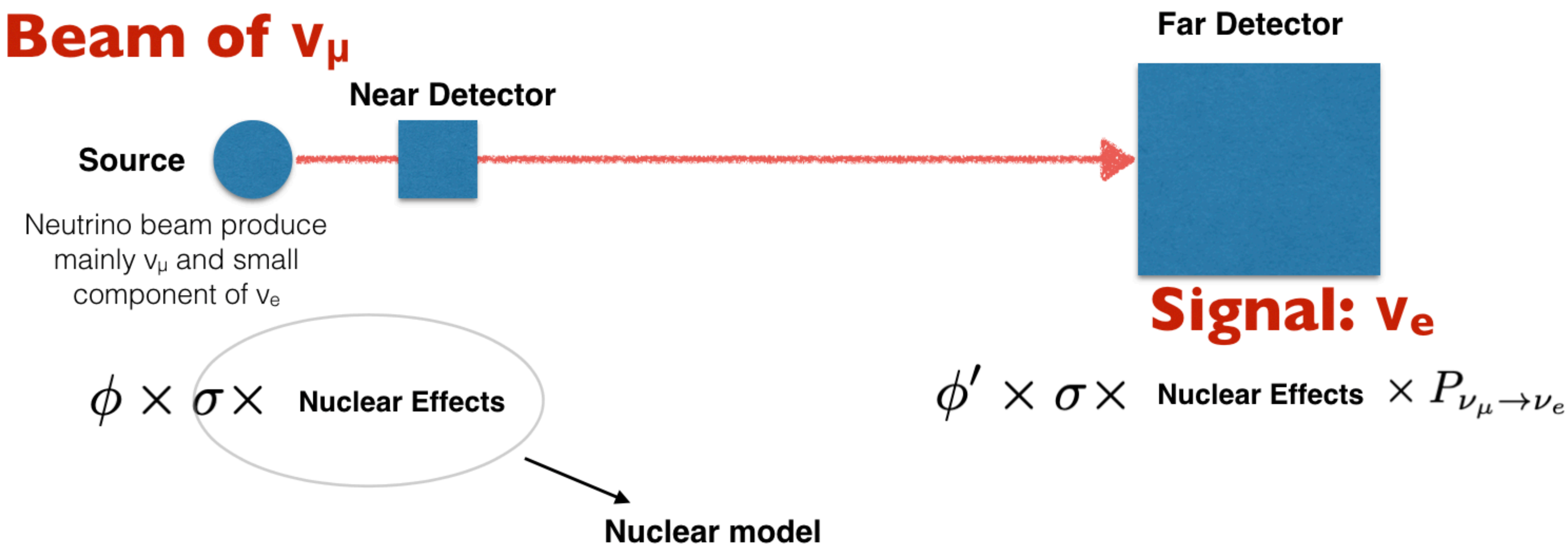
Cross Section Measurements with MINERvA and Prospects with ICARUS

Minerba Betancourt, Fermilab

August 02 2022

Motivation

- Measure CP violation in the lepton sector $P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e]$?
- Oscillation experiments use near and far detectors



- To get the oscillation probability from event rates, we must reconstruct the neutrino energy precisely and must know flux, cross section and nuclear effects

$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{E_\nu})$$

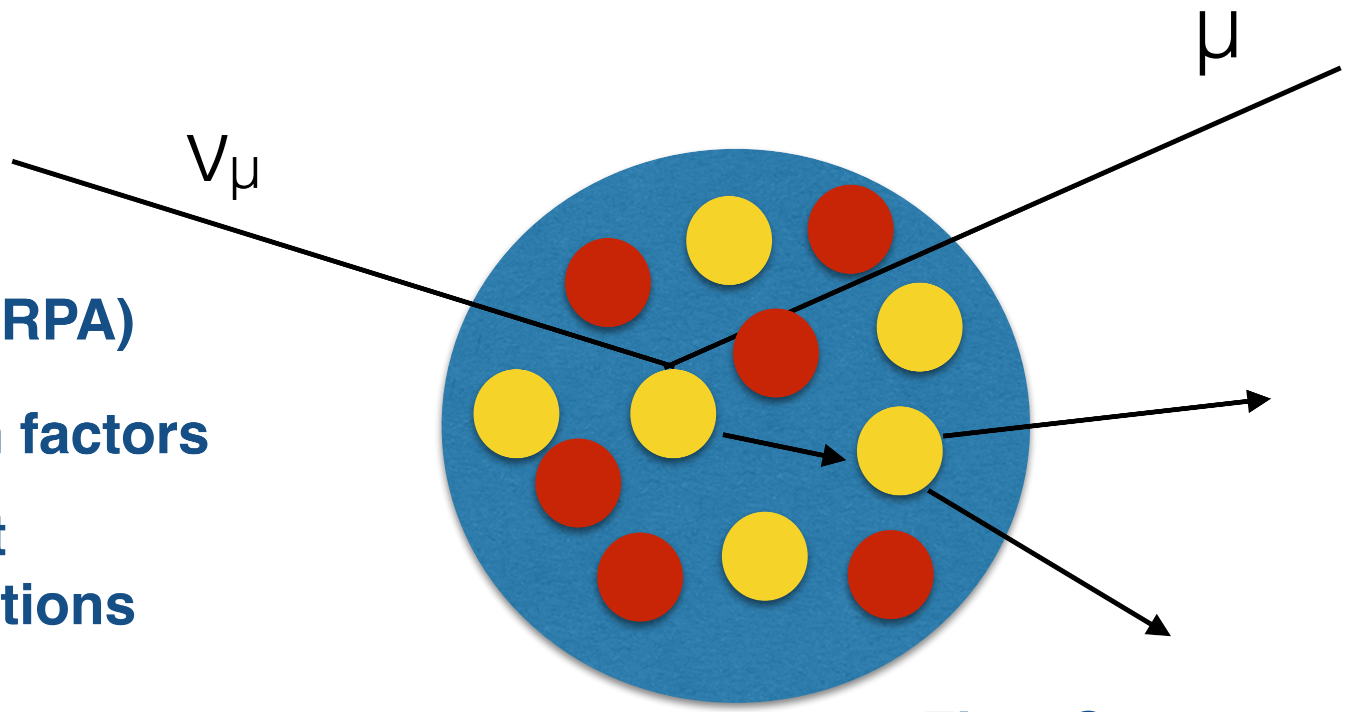
Neutrino Scattering

- Understanding neutrino interactions is challenging
- Modeling the interactions and measuring them present different types of challenges

Nuclear long range correlations (RPA)

Nucleon form factors

Nuclear short range correlations

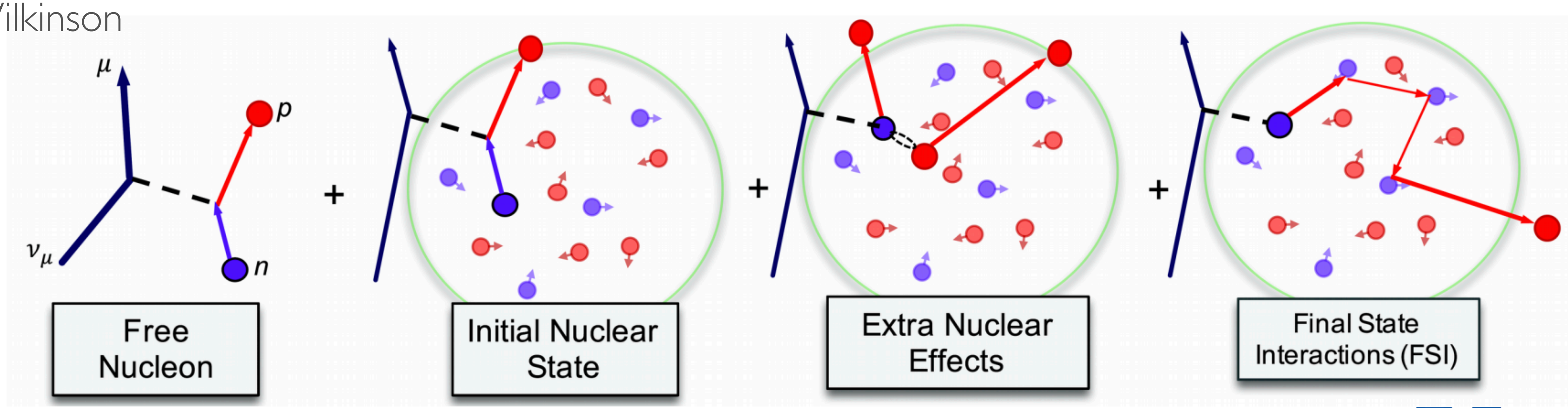


Fermi motion
Pauli blocking
Removal Energy

Final State Interactions

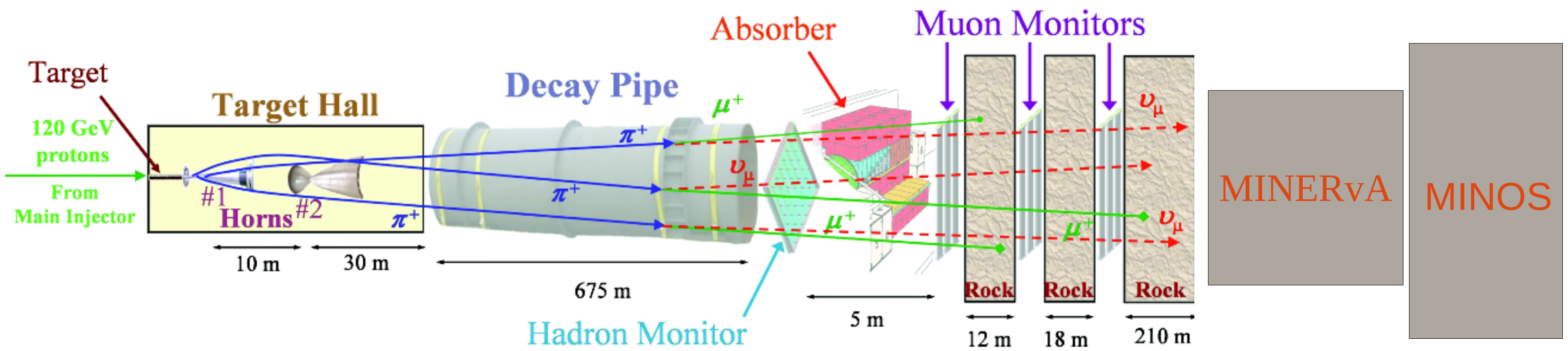
Meson Exchange Currents (MEC=2p2h)

C. Wilkinson

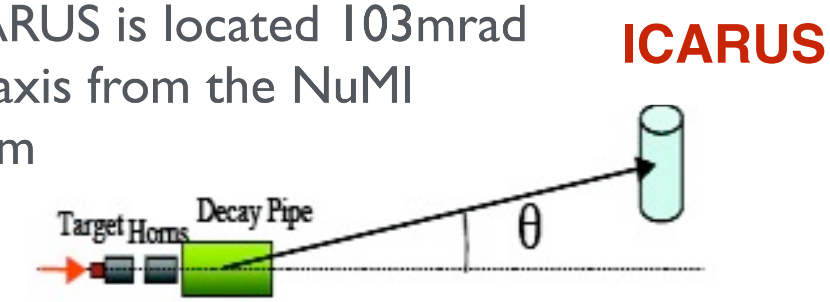


NuMI Neutrino Beam

- A beam of protons interact with a target and produce pions and kaons



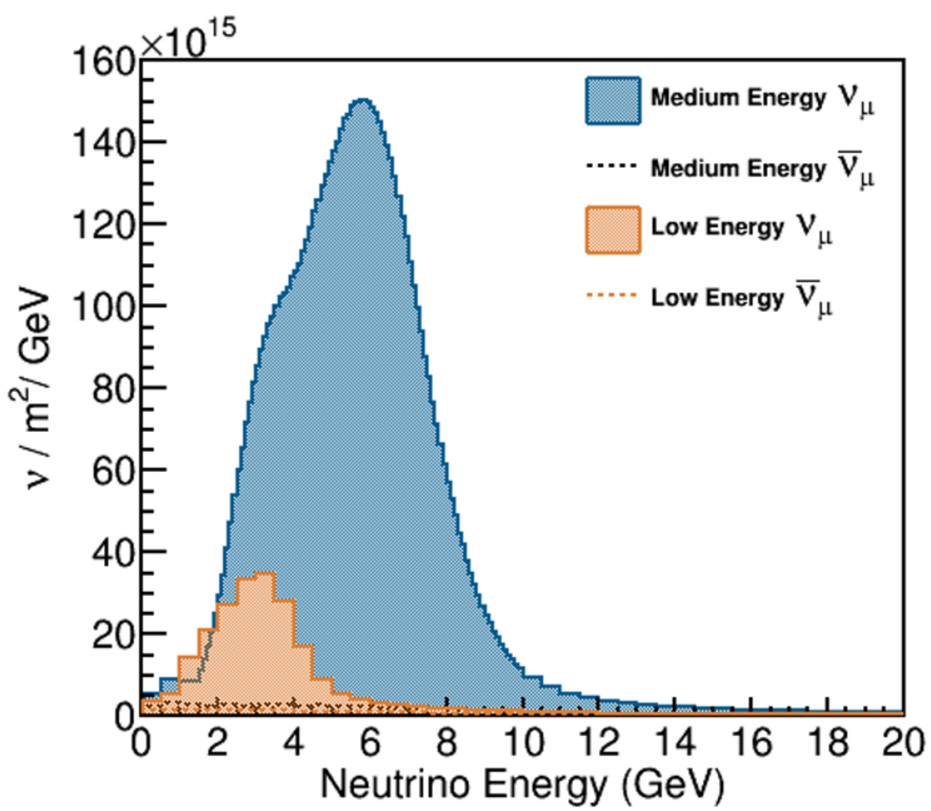
ICARUS is located 103mrad off axis from the NuMI beam



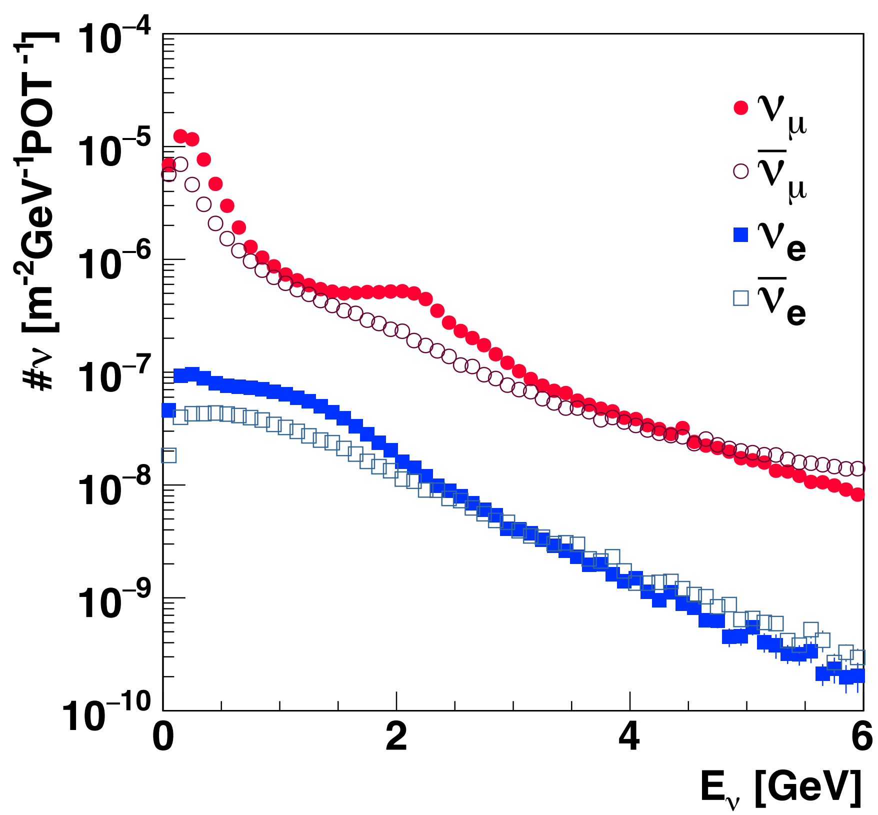
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

- The target and second magnetic horn can be moved relative to the first horn to produce different energy spectra

NuMI on axis

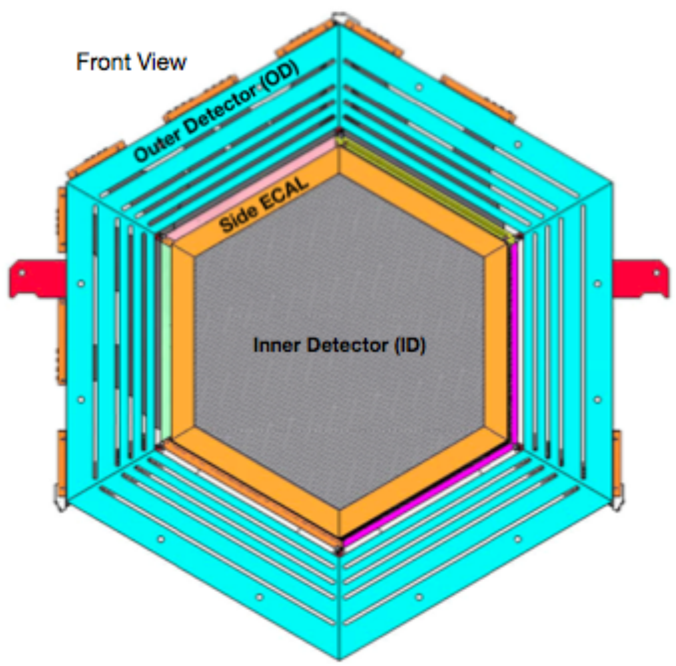


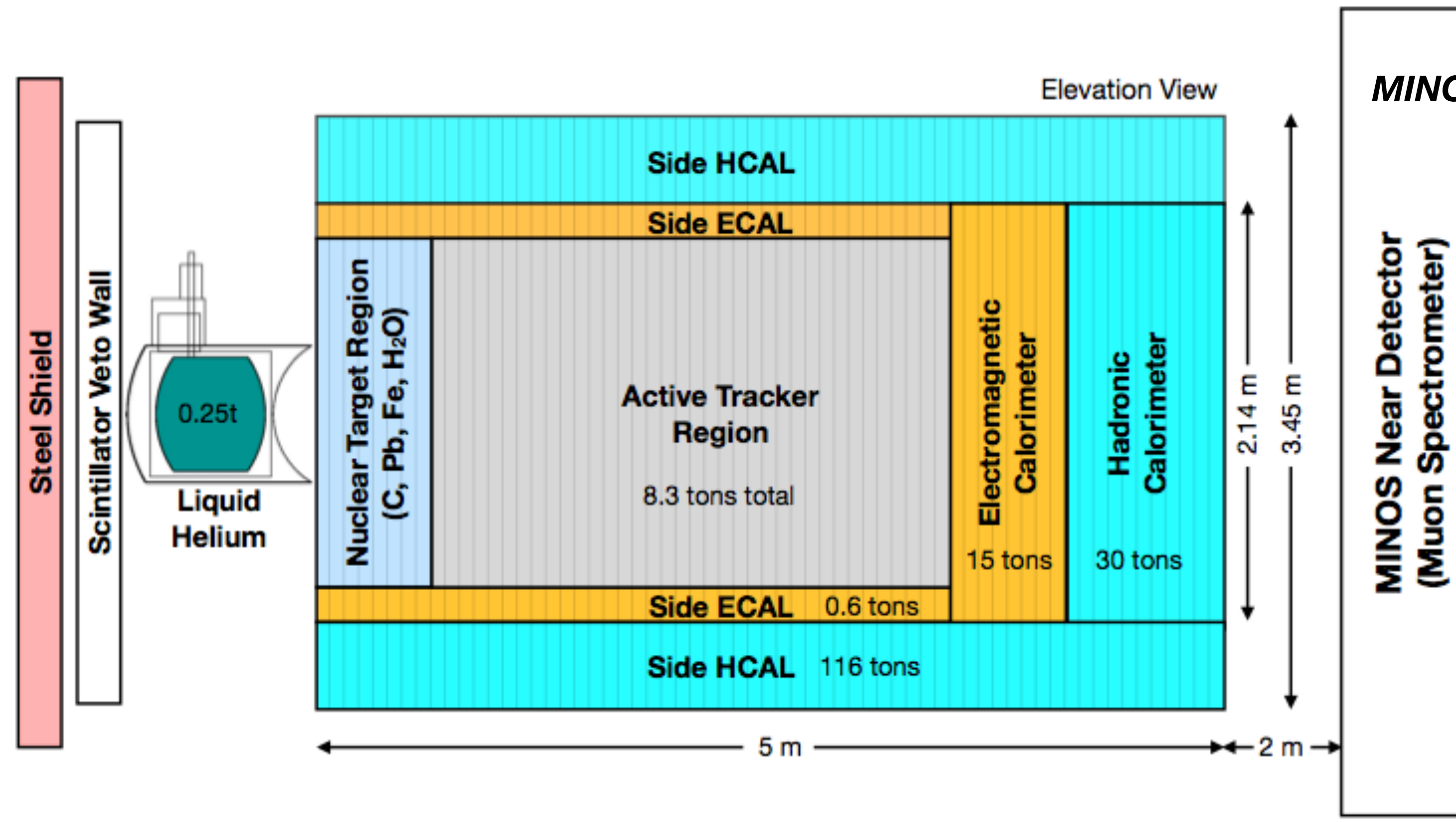
NuMI off axis



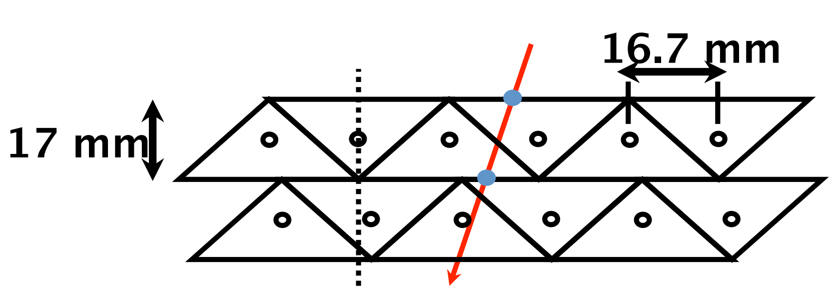
MINERvA Experiment

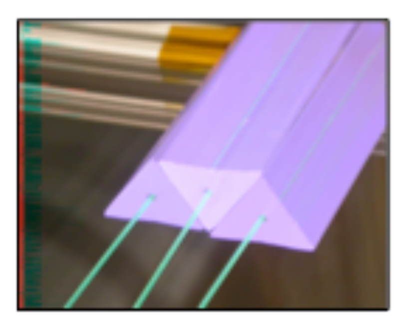
- Designed to make precision measurements of neutrino interaction cross sections
- Fine-grained scintillator tracker surrounded by calorimeters
- MINERvA has different nuclear targets: iron, lead, carbon, helium, and water





Thanks to MINOS





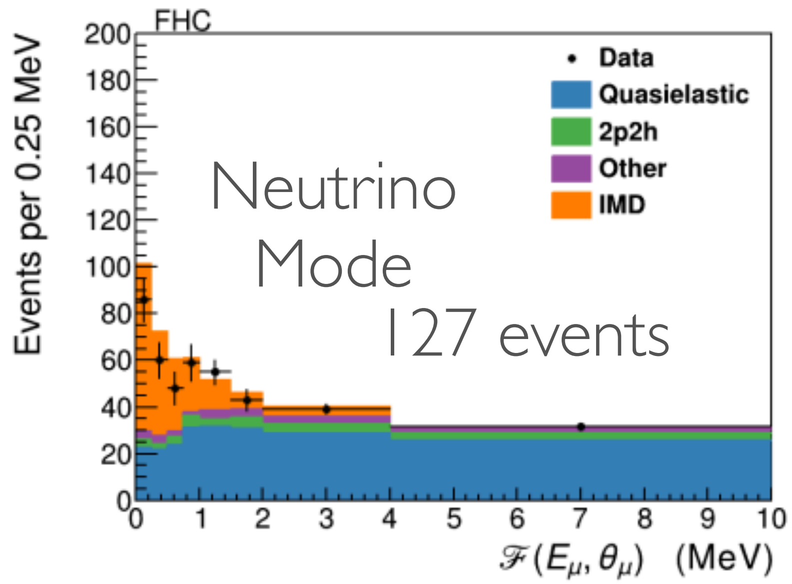
Three views of scintillator bars give unambiguous 3D track reconstruction

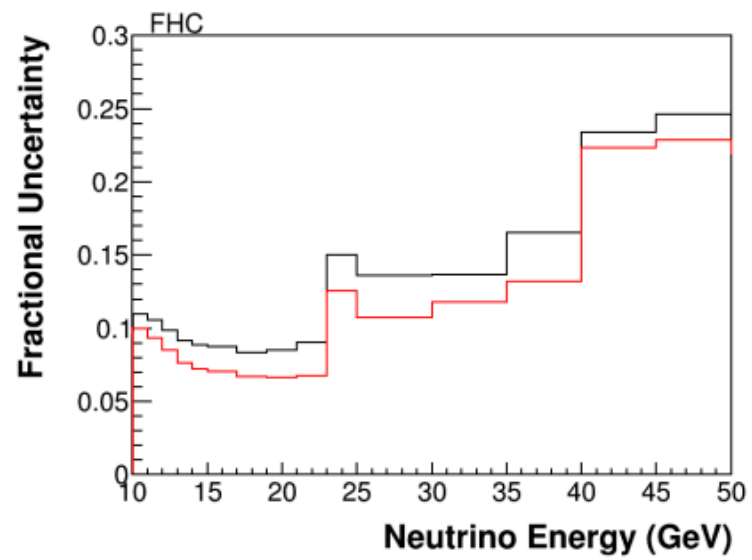
Design, calibration, and performance of the MINERvA detector

Nuclear Inst. and Methods in Physics Research, A, Volume 743, 11 April 2014, Pages 130-159

Flux Measurements

- MINERvA has used inverse muon decay as a standard candle to measure the NuMI

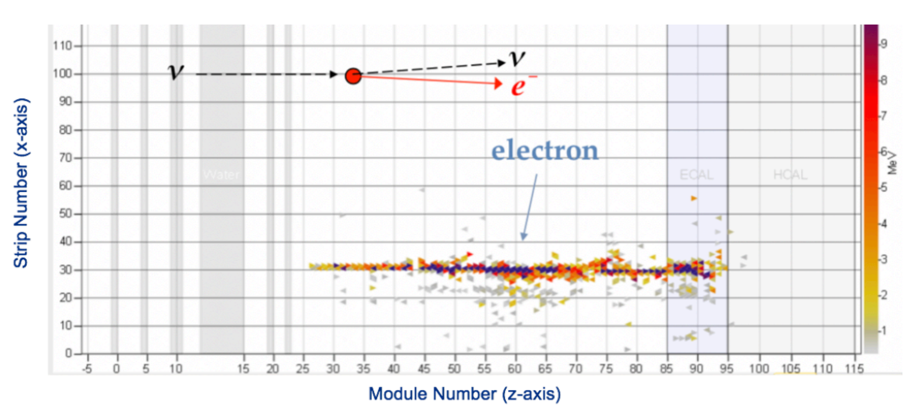


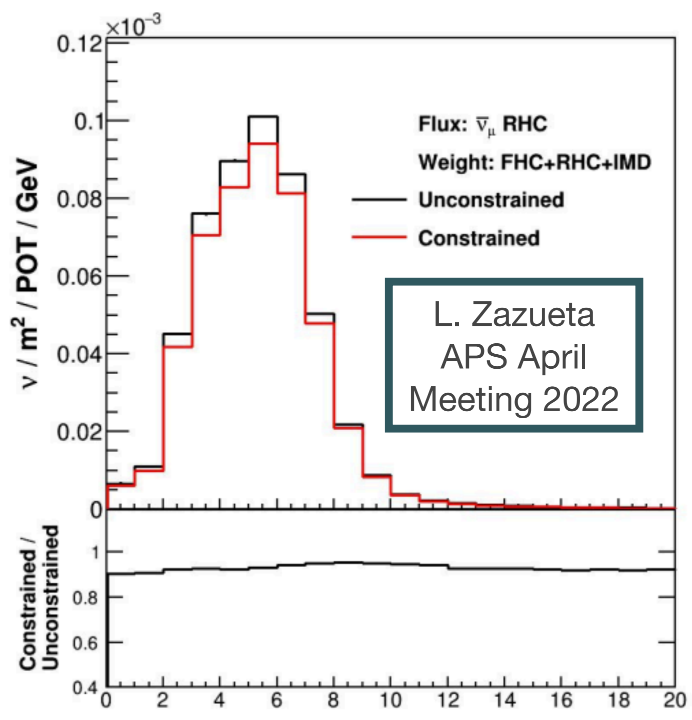


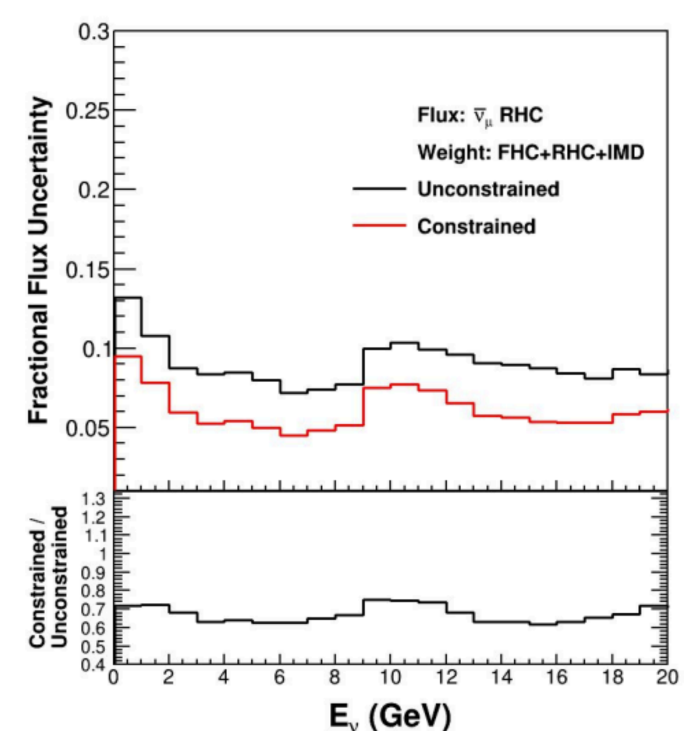
  - Constrains flux in high energy tail

Phys. Rev. D 104, 092010 (2021)

- MINERvA used neutrino scattering on electrons to measure flux in both neutrino and antineutrino mode
  - Combining all flux constrains:
    - 3.3% uncertainty in neutrino
    - 4.7% uncertainty in antineutrino



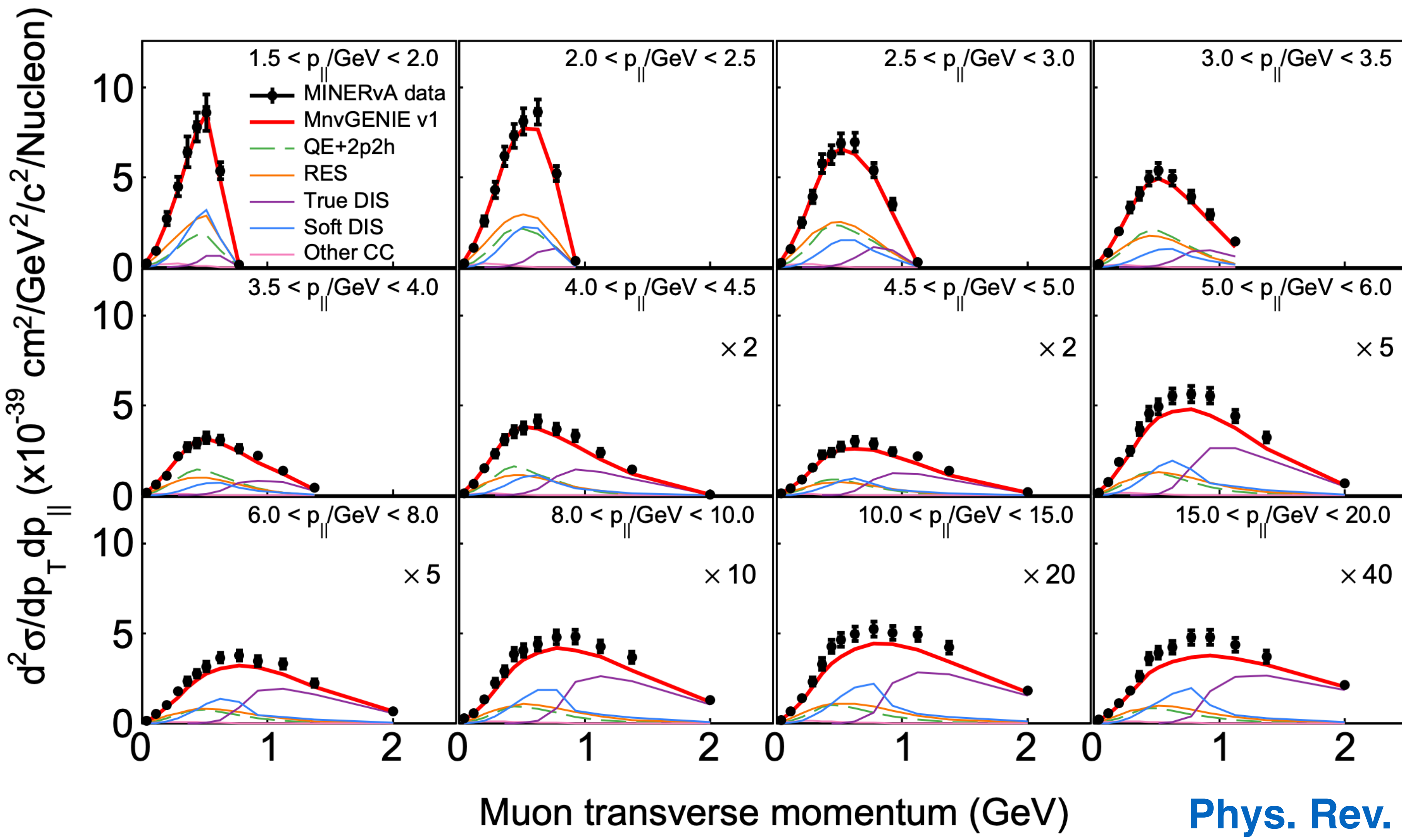




Fermilab

Neutrino Inclusive Cross section in CH

- Inclusive charged current ν_μ cross section as a function of muon longitudinal and transverse momentum
- Agreement with simulation is not perfect, underproduction around p_t peak for values $p_{||}$> 3GeV and overproduction for low values of pt
- Illustrates that MINERvA covers the full QE+RES+DIS range

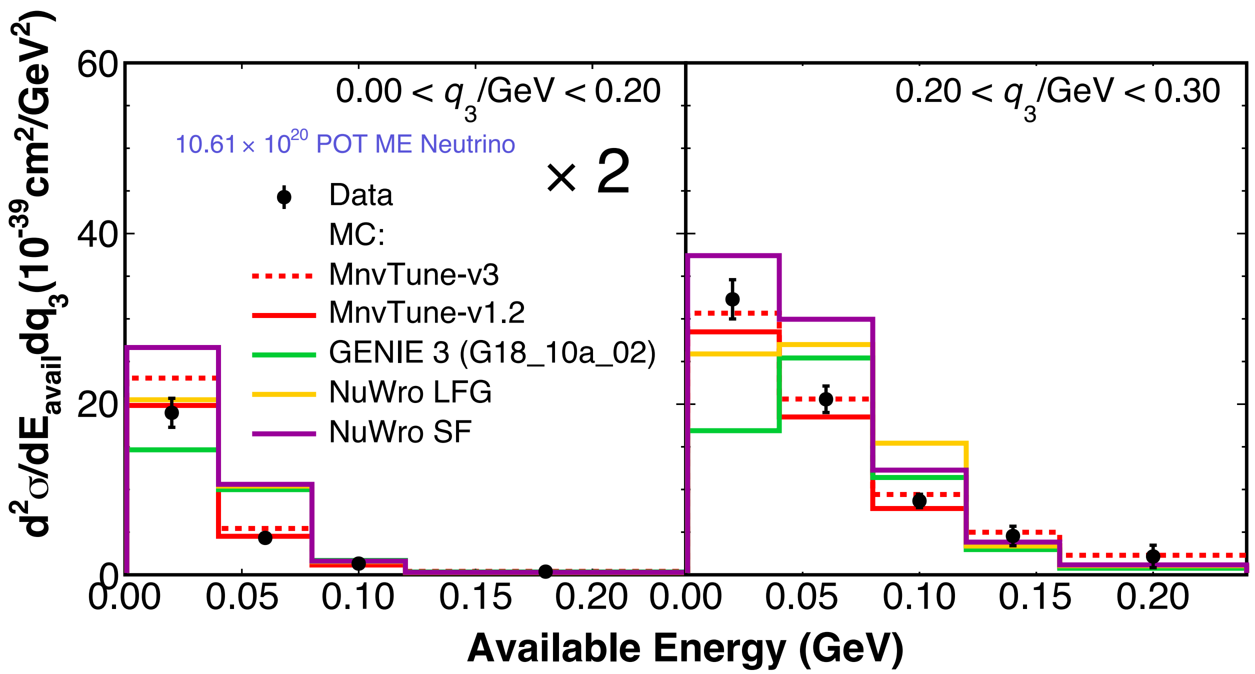


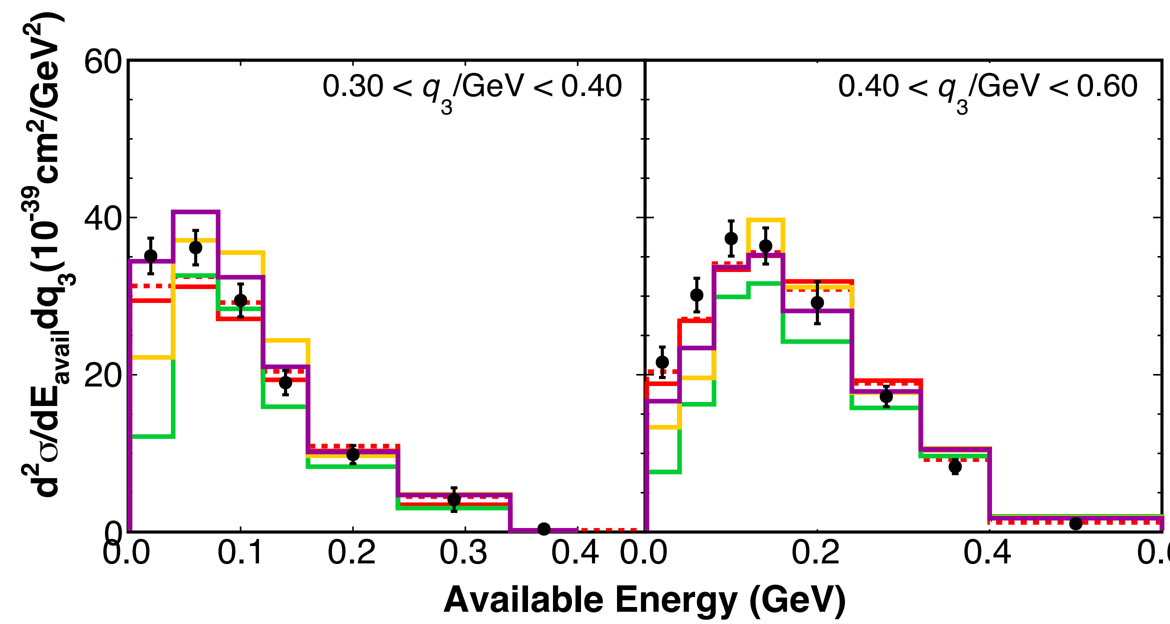
Phys. Rev. D 101, 11 (2020)

Low Recoil Measurements with the Medium Energy

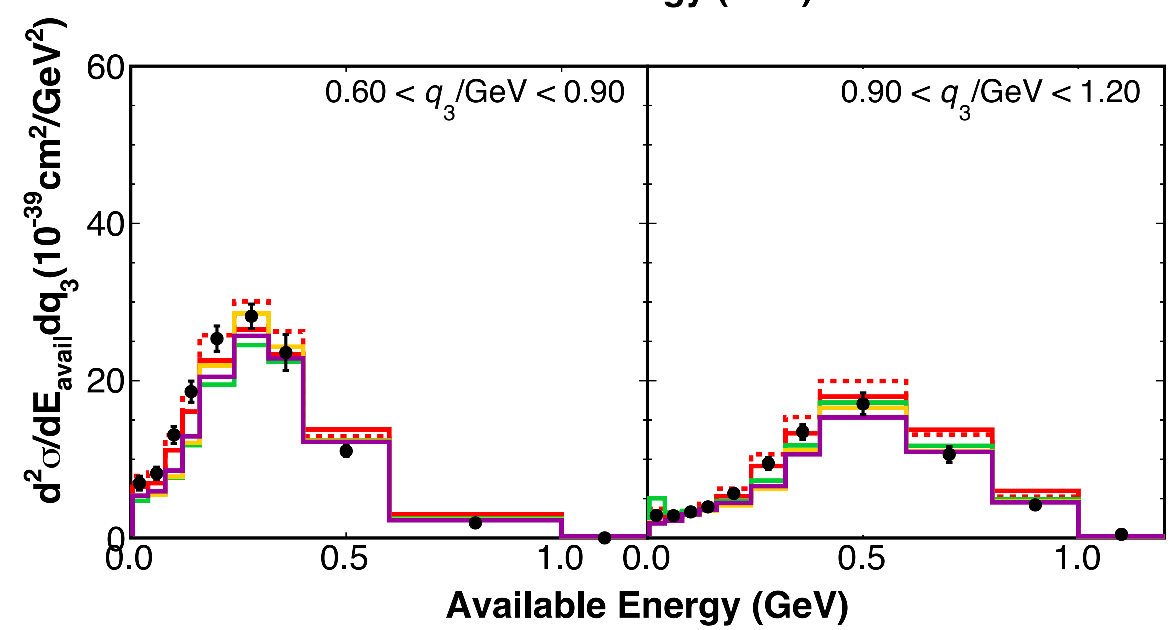
- Inclusive charged current double differential cross section as a function of available energy and three momentum transfer $q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$
- We use available energy

$$E_{avail} \coloneqq \sum T_p + \sum T_{\pi^\pm} + \sum E_{\text{other particles}} \quad \text{(neutrons not included!)}$$





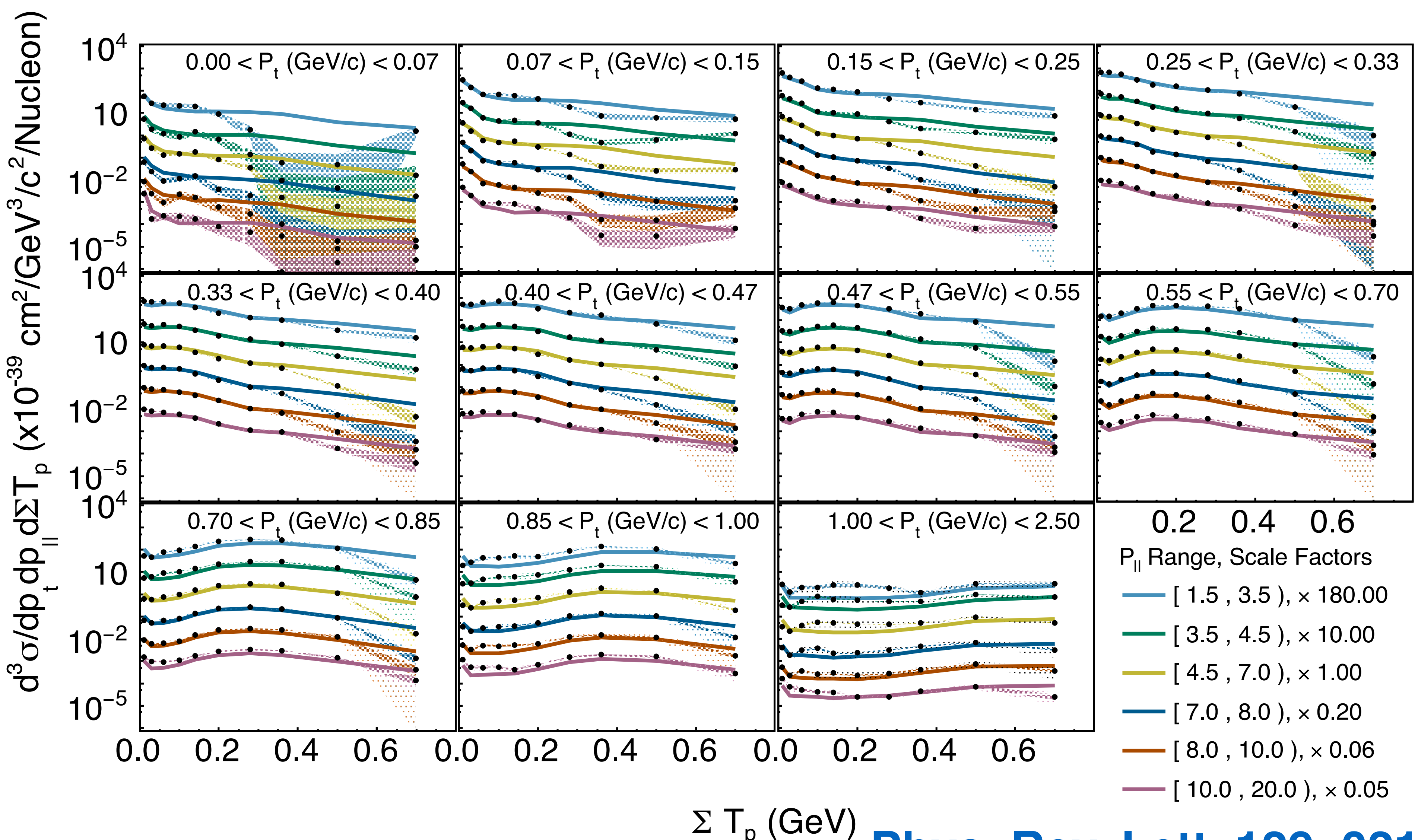
- Agreement with the different event generators varies, some disagreement in the QE-enriched regions and middle $0.3<q_3/\text{GeV}<0.6$ and better agreement at $q_3/\text{GeV}>0.6$



Phys. Rev. D 106, 032001, Aug 2022

Massive CCQE-Like Statistics

- QE-like measurements on scintillator in 3D, as a function of total proton kinetic energy, transverse and longitudinal momentum
- Excellent statistics, 3,390,718 events
- Modeling $p_{||}$ well: same trend across all T_p and p_T bins

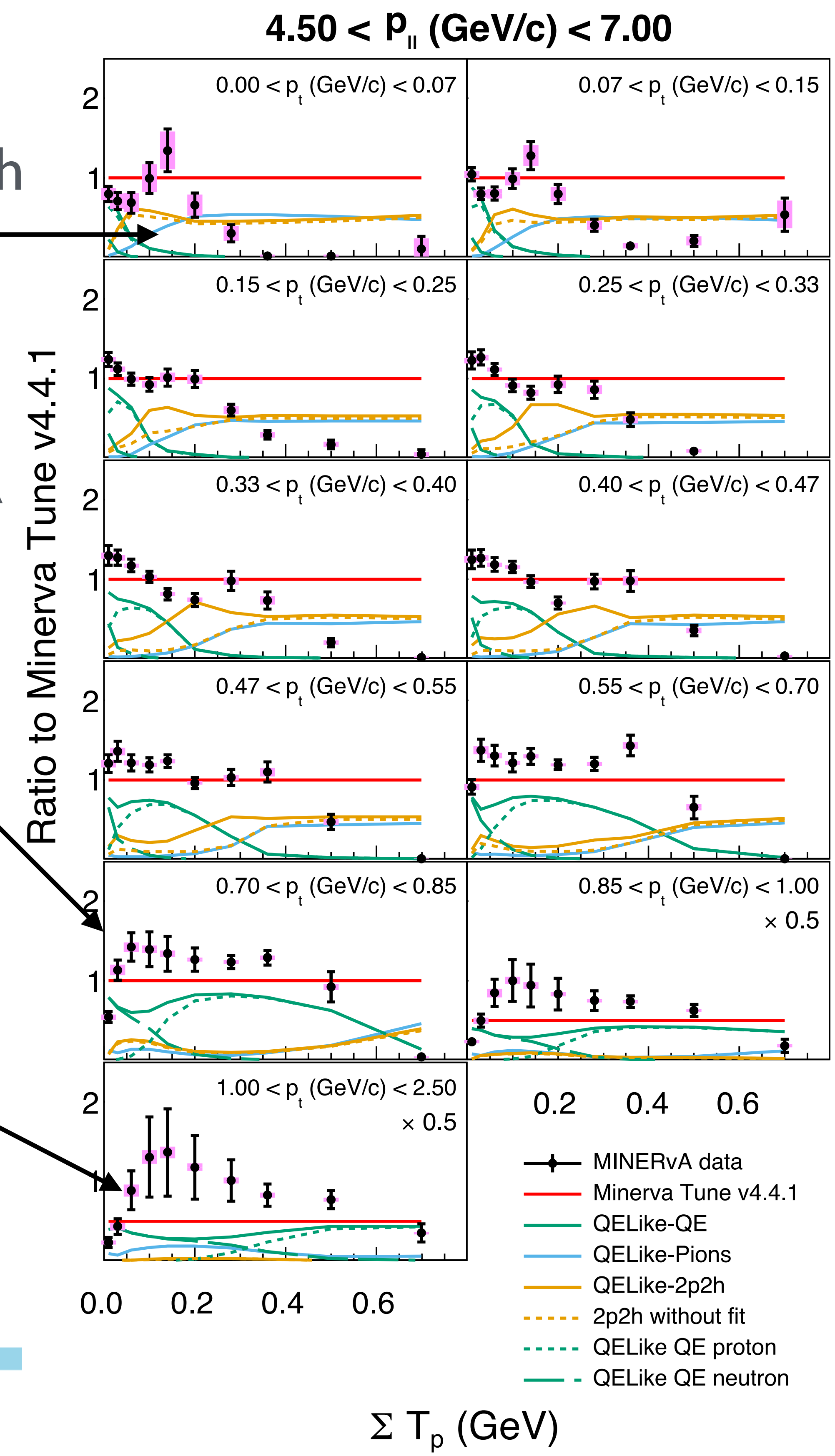


Phys. Rev. Lett. 129, 021803, July 2022

Colored band show data uncertainties

Massive CCQE-Like Statistics

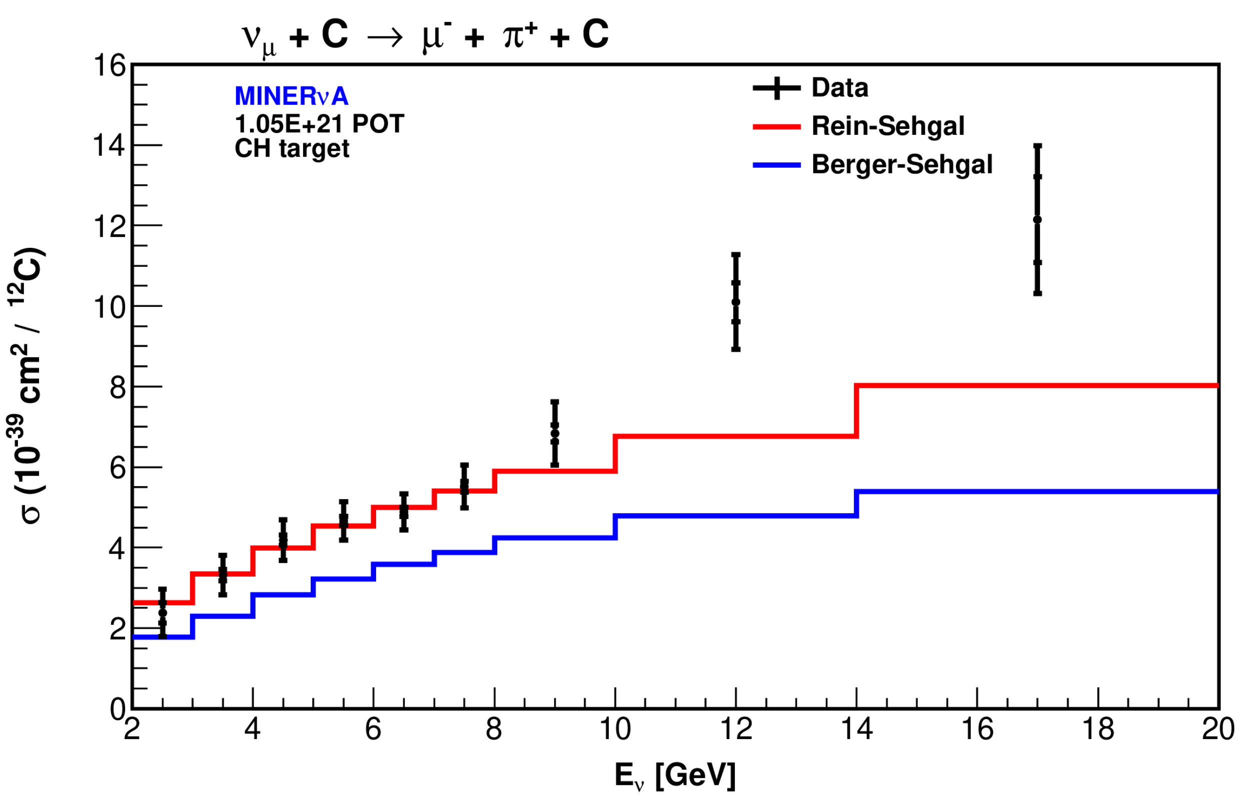
- Low muon p_T, high proton kinetic energy
  - Few events in data where simulation predicts 2p2h resonant + pion absorption
- Proton kinetic energy near 0.2 GeV
  - Low p_T: relatively good agreement with MINERvA tune
  - High p_T: Tune not sufficient at high pT
- High PT, low Tp:
  - Over prediction in data in a region dominated by QE with FSI

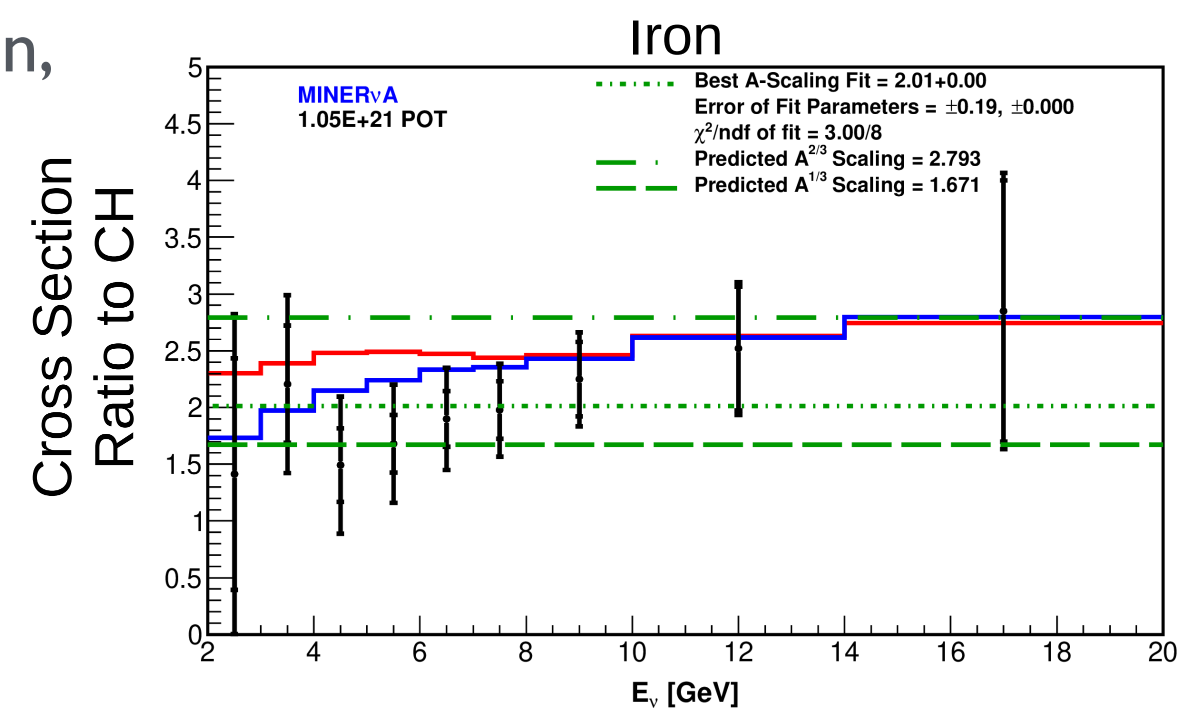


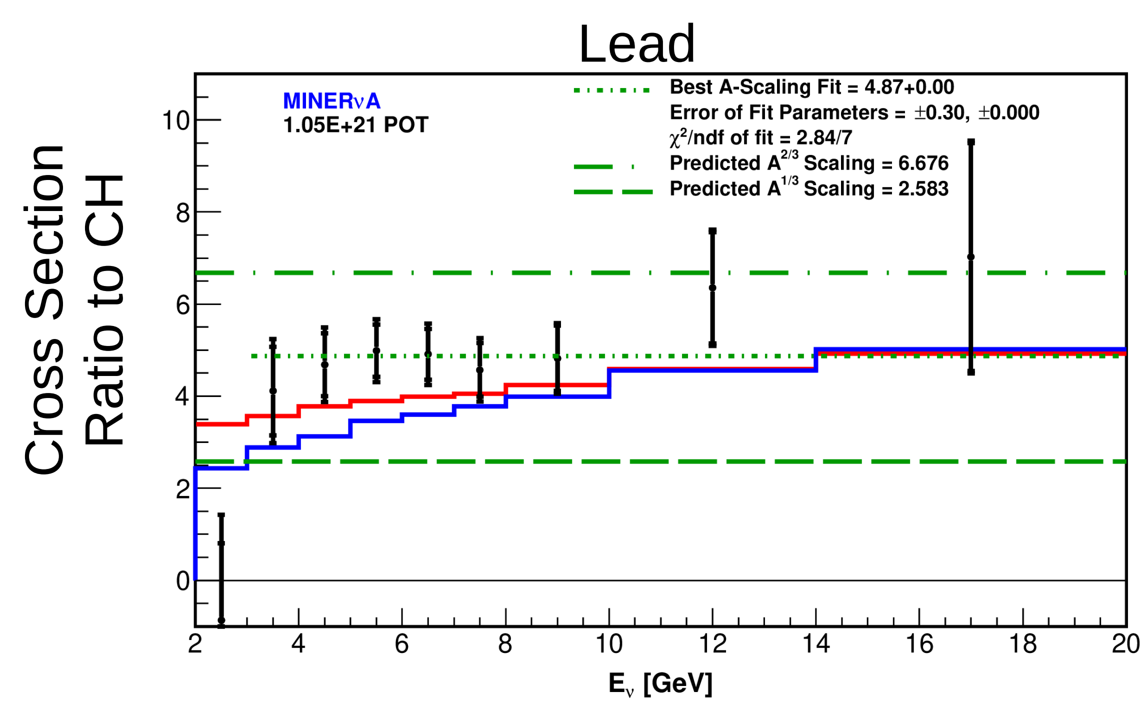
Phys. Rev. Lett. 129, 021803, July 2022

Coherent Pion Production

- Coherent: neutrino interacts of whole nucleus
- Models related to NC coherent pi0 production, important for electron neutrino background
- A-scaling is prime model test
- First ME energy nuclear targets result
- Fe/CH and Pb/CH neither model does a good job description





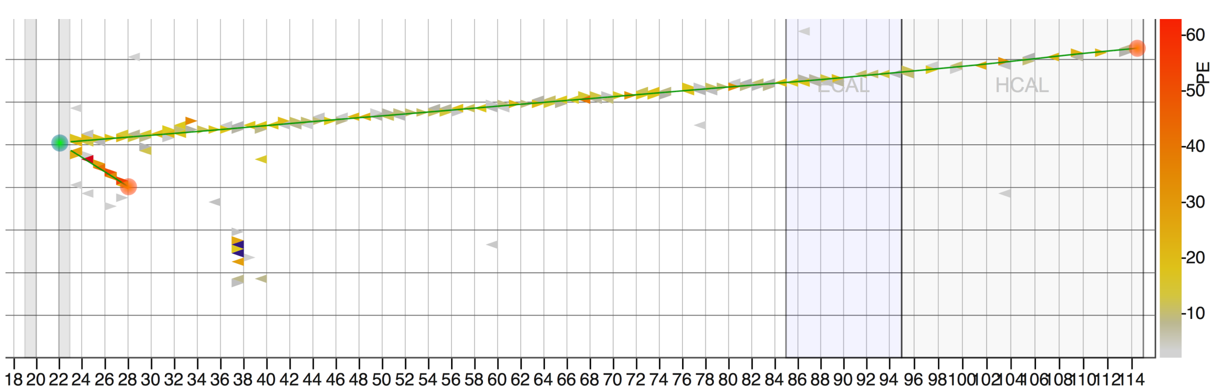


Alejandro Ramirez Fermilab W&C Seminar, June 10, 2022

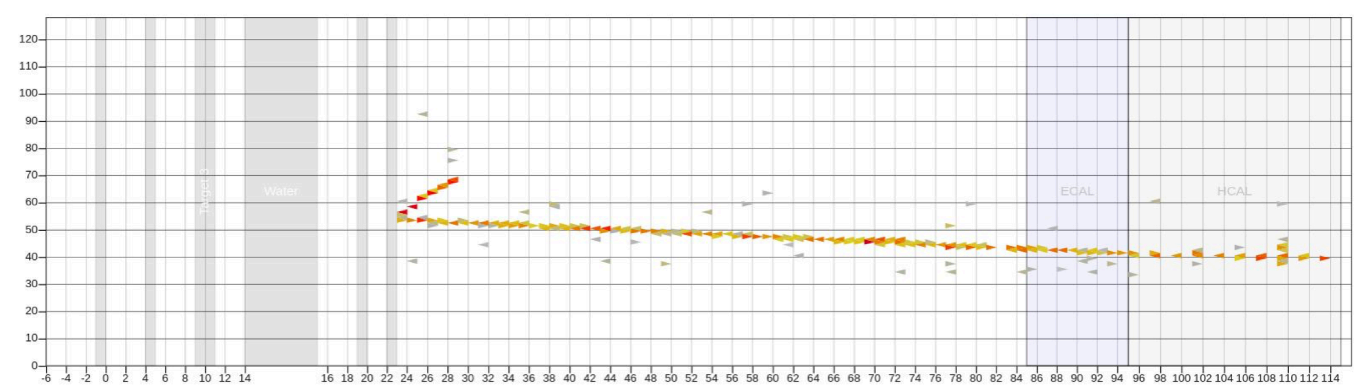
Coming Soon

- Many measurements in preparation using the medium energy on different targets
  - Neutrino QE-like measurements in the nuclear targets: Carbon, Water, Iron and Lead
    - Cross section in initial struck neutron momentum, transverse kinematic imbalances observable and muon observables
  - Neutrino π^+ and π^0 in the nuclear targets
    - Cross sections as a function of muon transverse momentum
  - Antineutrino CCQE on hydrogen
    - Differential cross section as a function of Q^2

CCQE-like

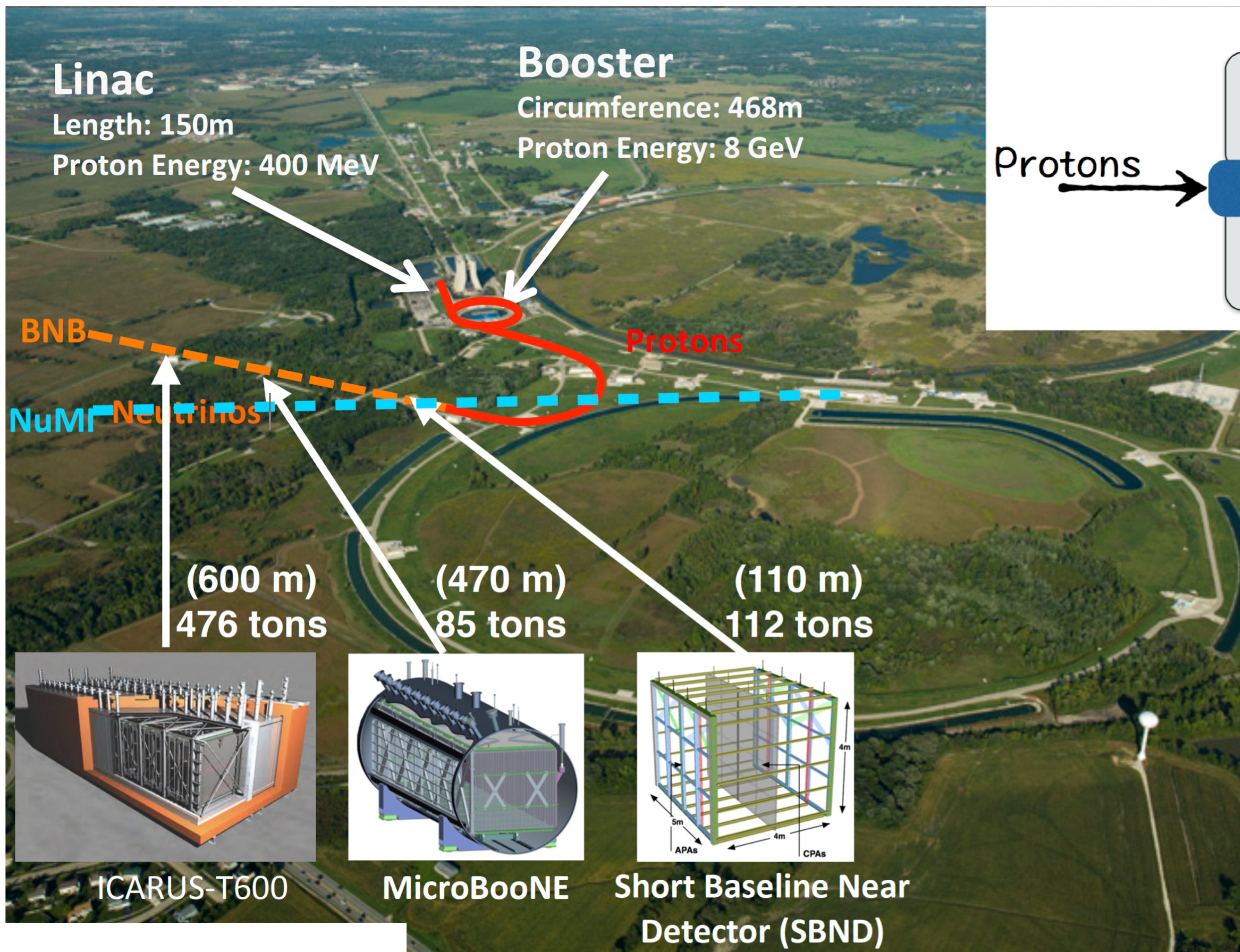


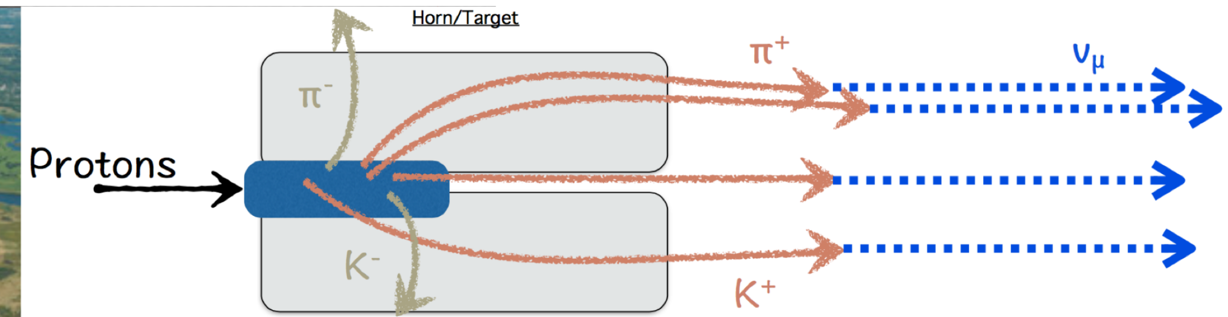
CC π^+



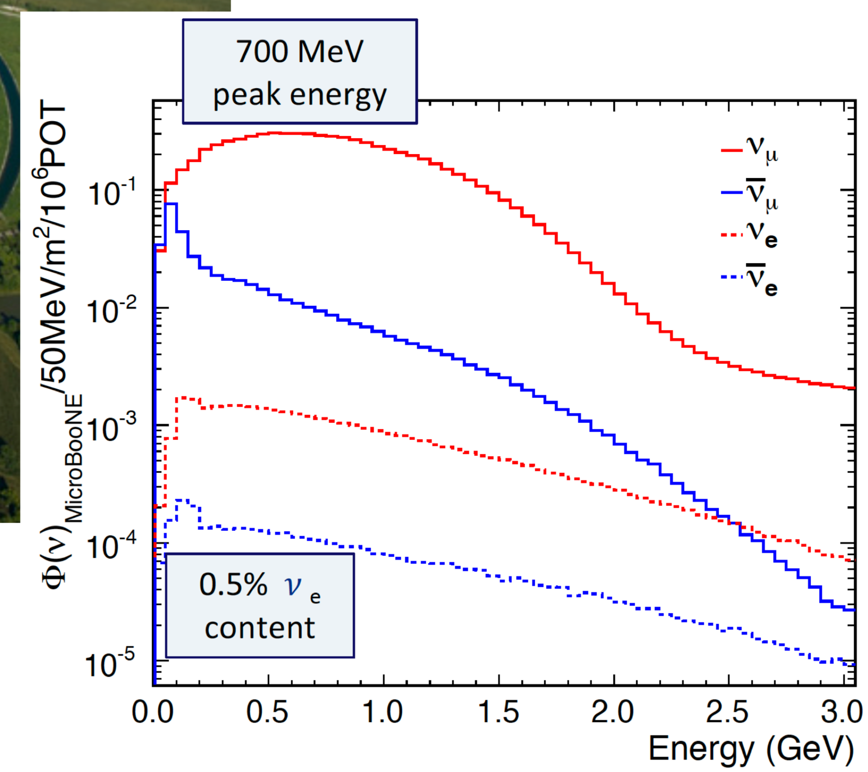
Short Baseline Program

- Three argon Time Projection chambers (TPC) detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations
  - Measuring both appearance and disappearance channels

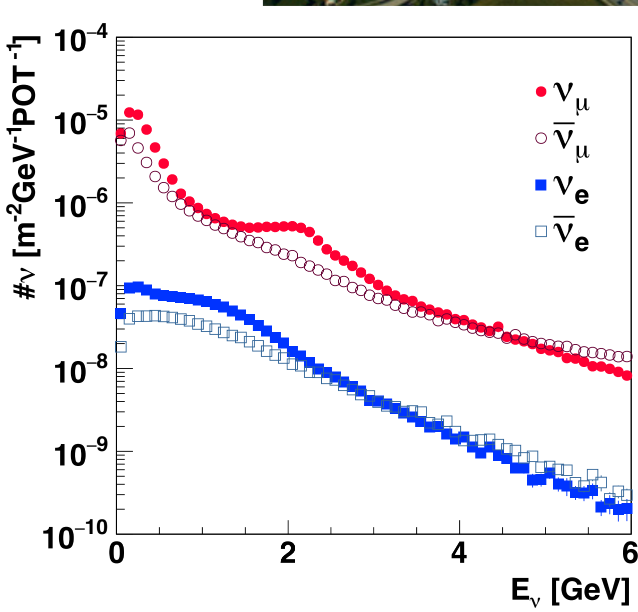




Neutrinos from Booster



Neutrinos from NuMI

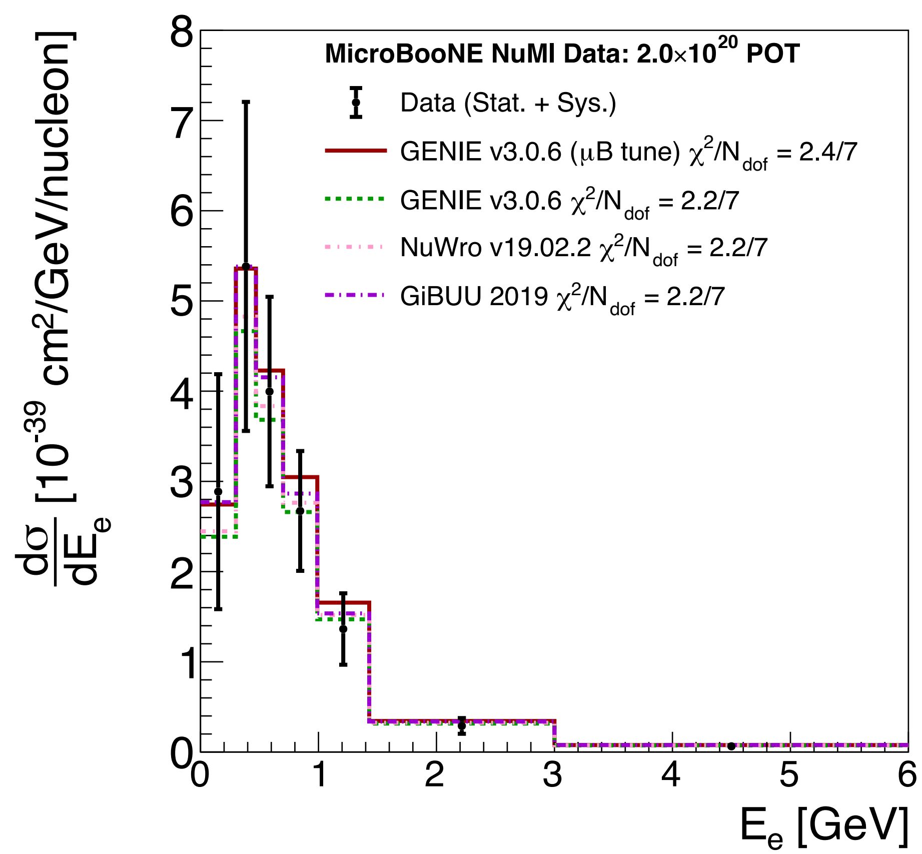


More details at Biswaranjan Behera's talk

What could we do with ν from the NuMI off axis?

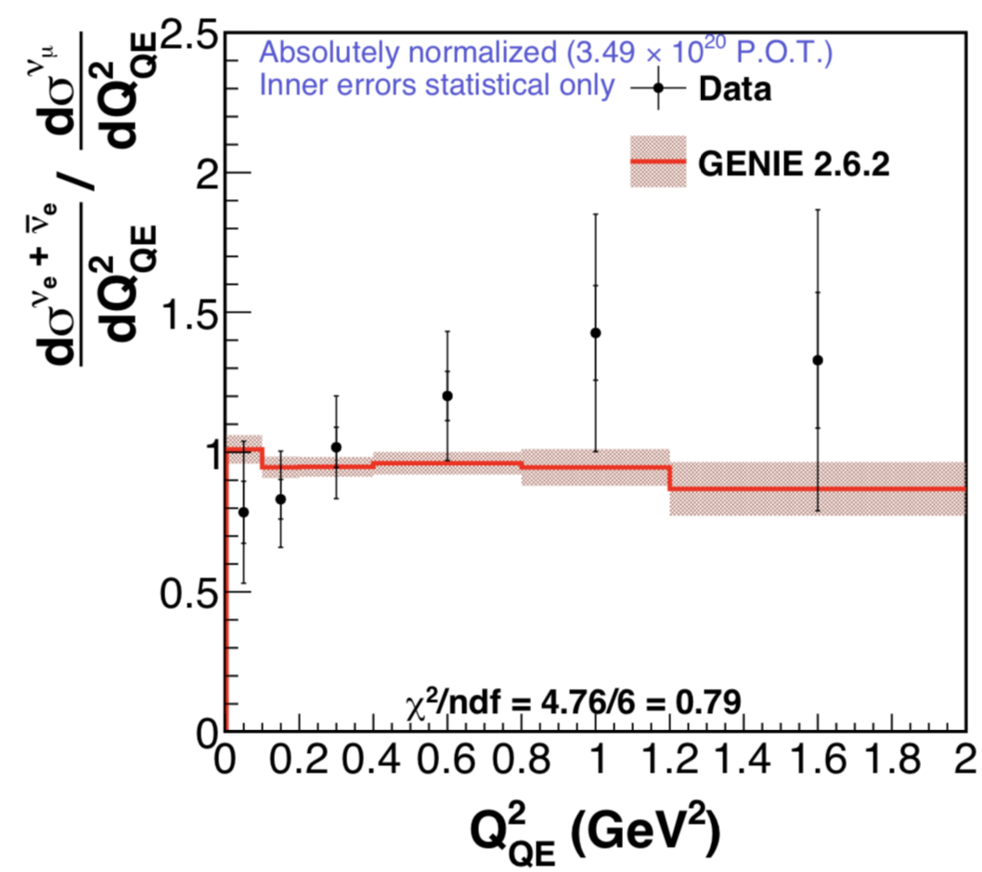
- No high statistics measurements of electron neutrino cross section on liquid argon at DUNE energies
- Electron neutrino spectrum from NuMI at ICARUS covers the first oscillation peak and the tail covers the high statistics peak from DUNE
- Excellent statistics from muon neutrino to measure exclusive channels: quasi-elastic and pion production

New electron neutrino measurement from MicroBooNE



243 events with 72% purity, https://arxiv.org/pdf/2109.06832.pdf

Electron to muon neutrino quasi elastic from MINERvA

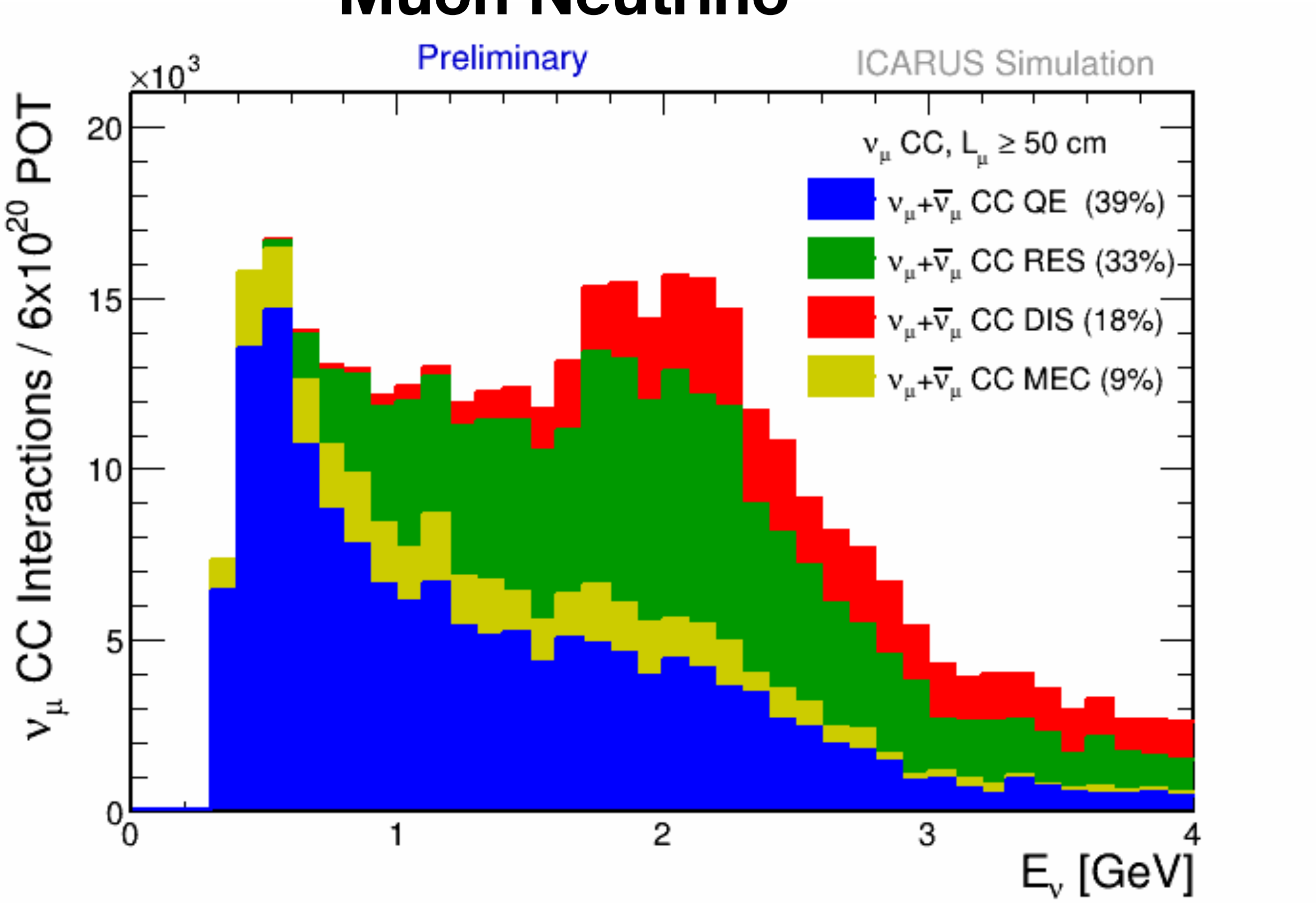


Phys.Rev.Lett. 116 (2016) no.8, 081802

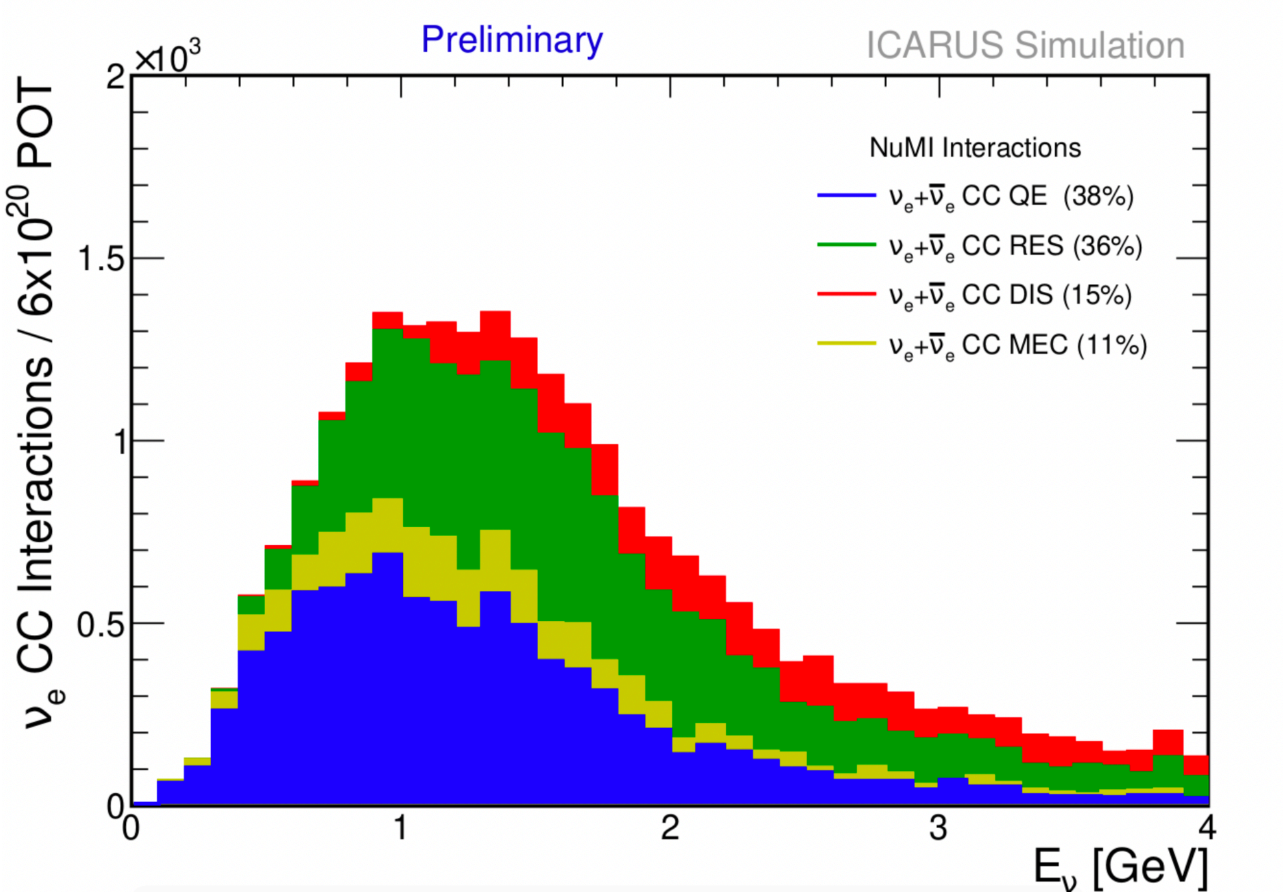
Neutrino Interactions from NuMI off axis

- Main channels are quasi-elastic and resonance interactions
- Excellent statistics to make cross section measurements for quasi-elastic and pion production scattering, for both electron and muon neutrinos

Muon Neutrino



Electron Neutrino



Expected event rates for 1 year

Muon neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	186400	40262	142780	77060
Electron neutrino	CCQE	CCMEC	CCRES	CCDIS
6E20 POT	8256	2000	7905	3678

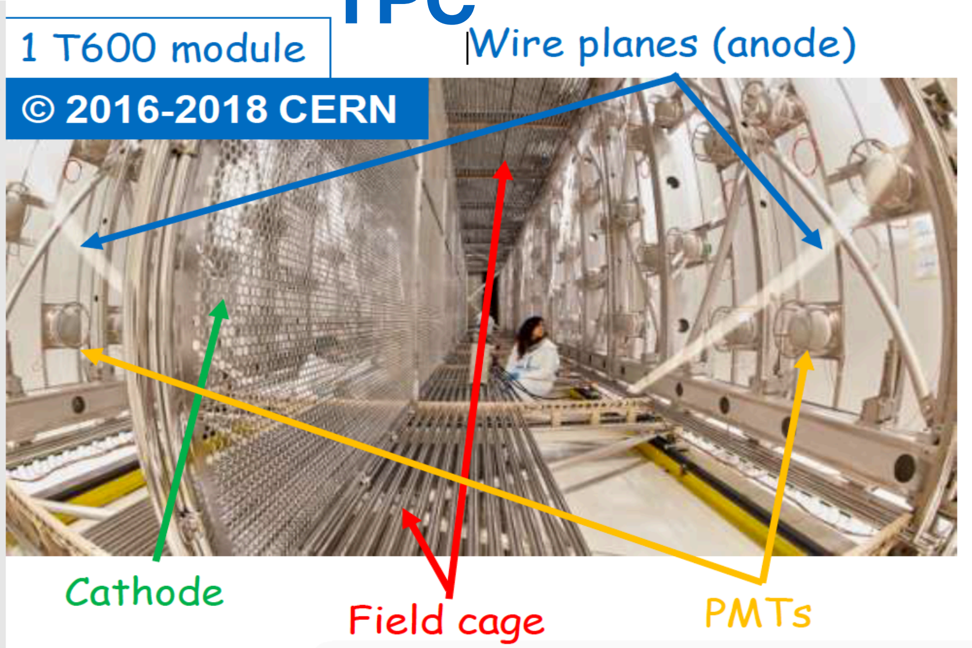
Fermilab

ICARUS at FNAL

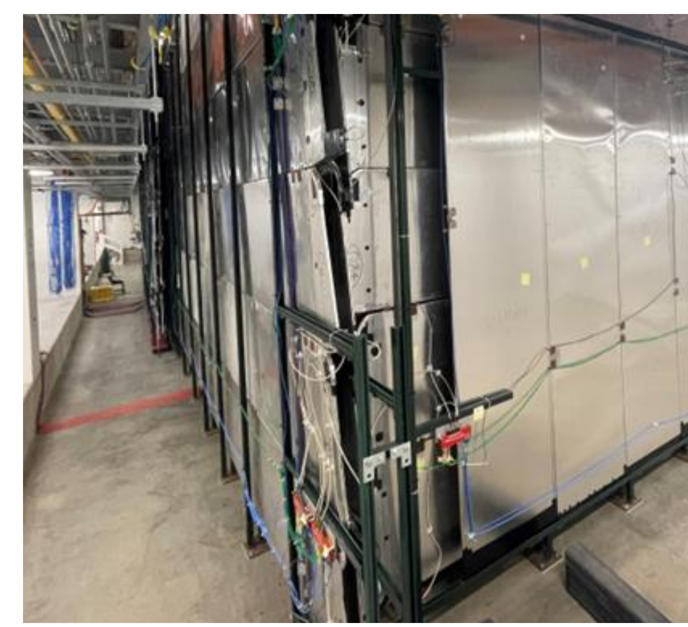
- Several technology improvements were introduced, aiming to further improve the achieved performance ICARUS previous runs: new cold vessels, improvement of the cathode planarity, higher performance read-out electronics and upgrade of the PMT system
- 2 TPCs per module with central cathode, 1.5 m drift, E_D=0.5 kV/cm, 3 mm wire pitch
- 3 readout wire planes (2induction+collection) per TPC, ~54000 wires at 0, 60 degrees
- 360 PMTs 8”
- Cosmic ray tagger: scintillator strips read out by SiPMs

Top CRT

TPC



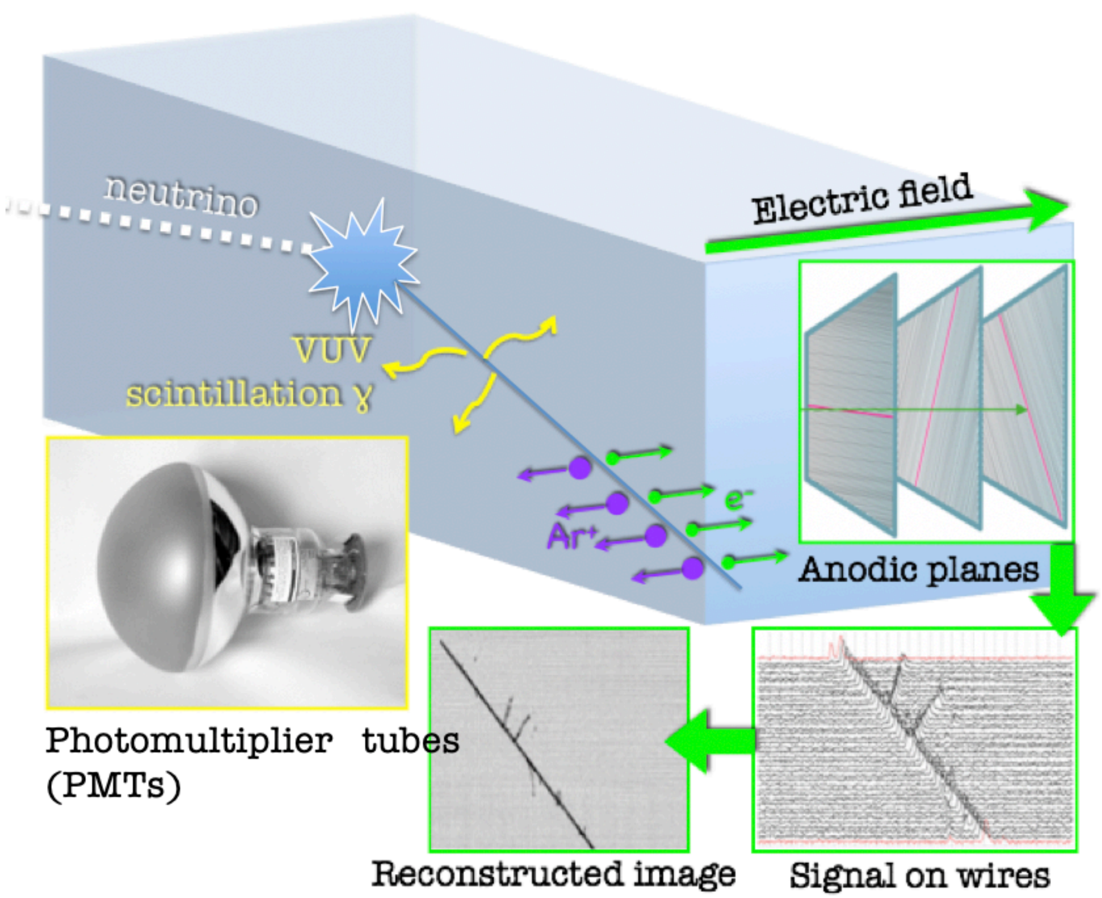
PMT



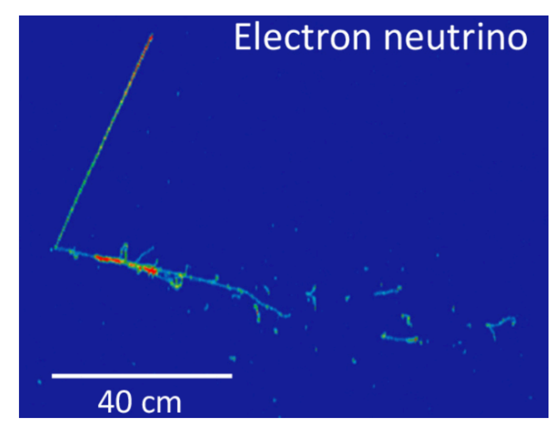
side CRT

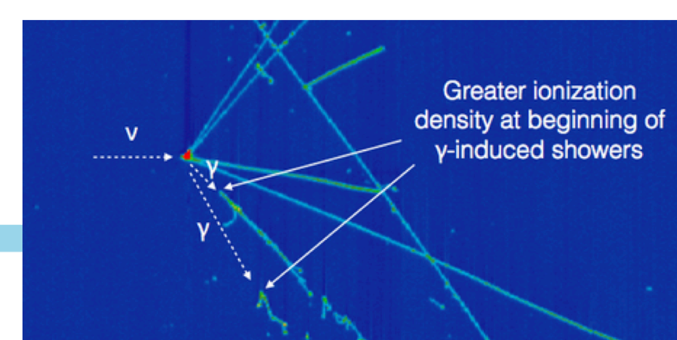
Liquid Argon TPC Detection Technique

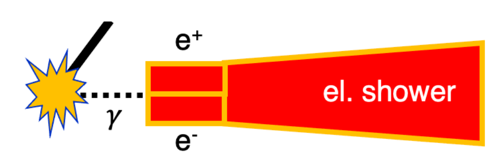
- Tracking device: precise 3D event topology with ~mm³ resolution for ionizing particle
- Scintillation light detected by PMTs to provide event time and trigger
- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires



- Powerful particle identification by dE/dx vs range
- Remarkable e/γ separation: calorimetric capabilities can distinguish e from γ at the shower start

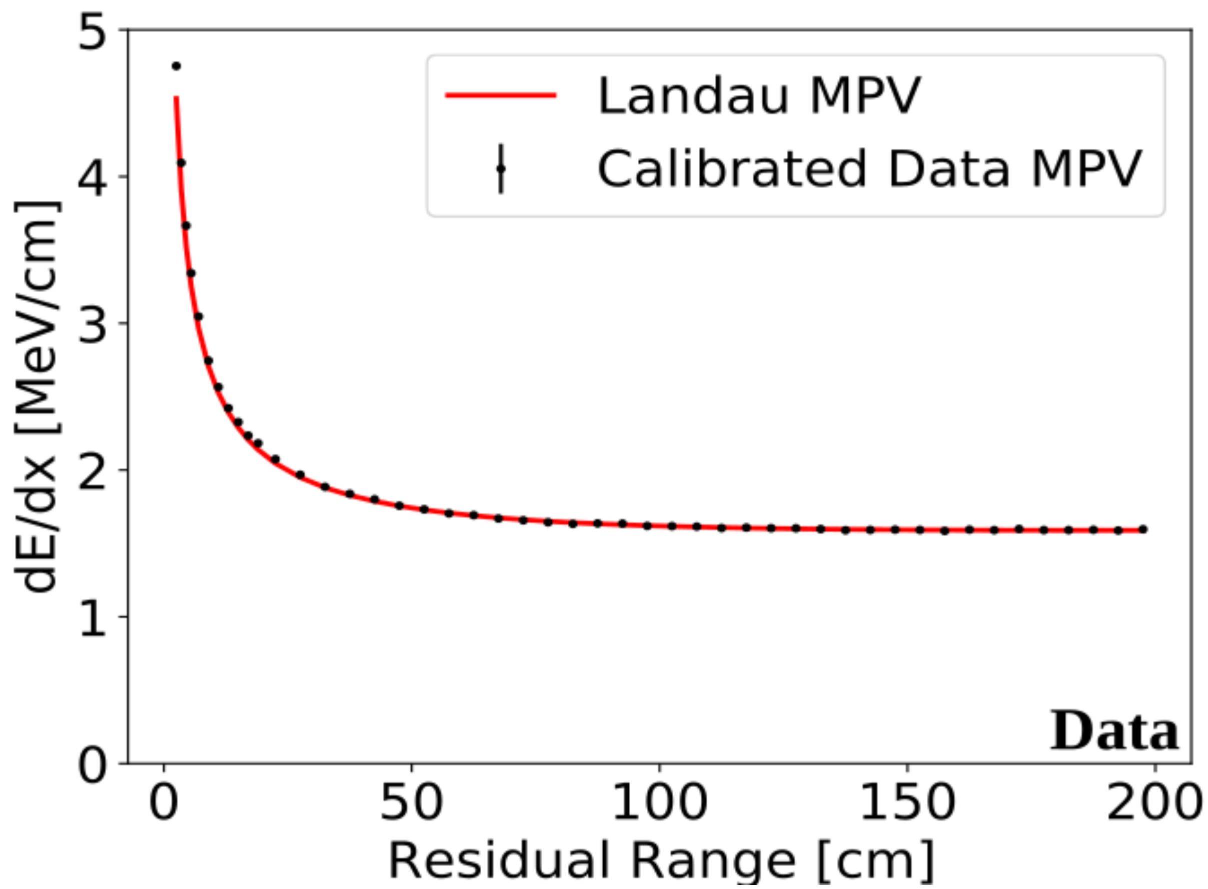


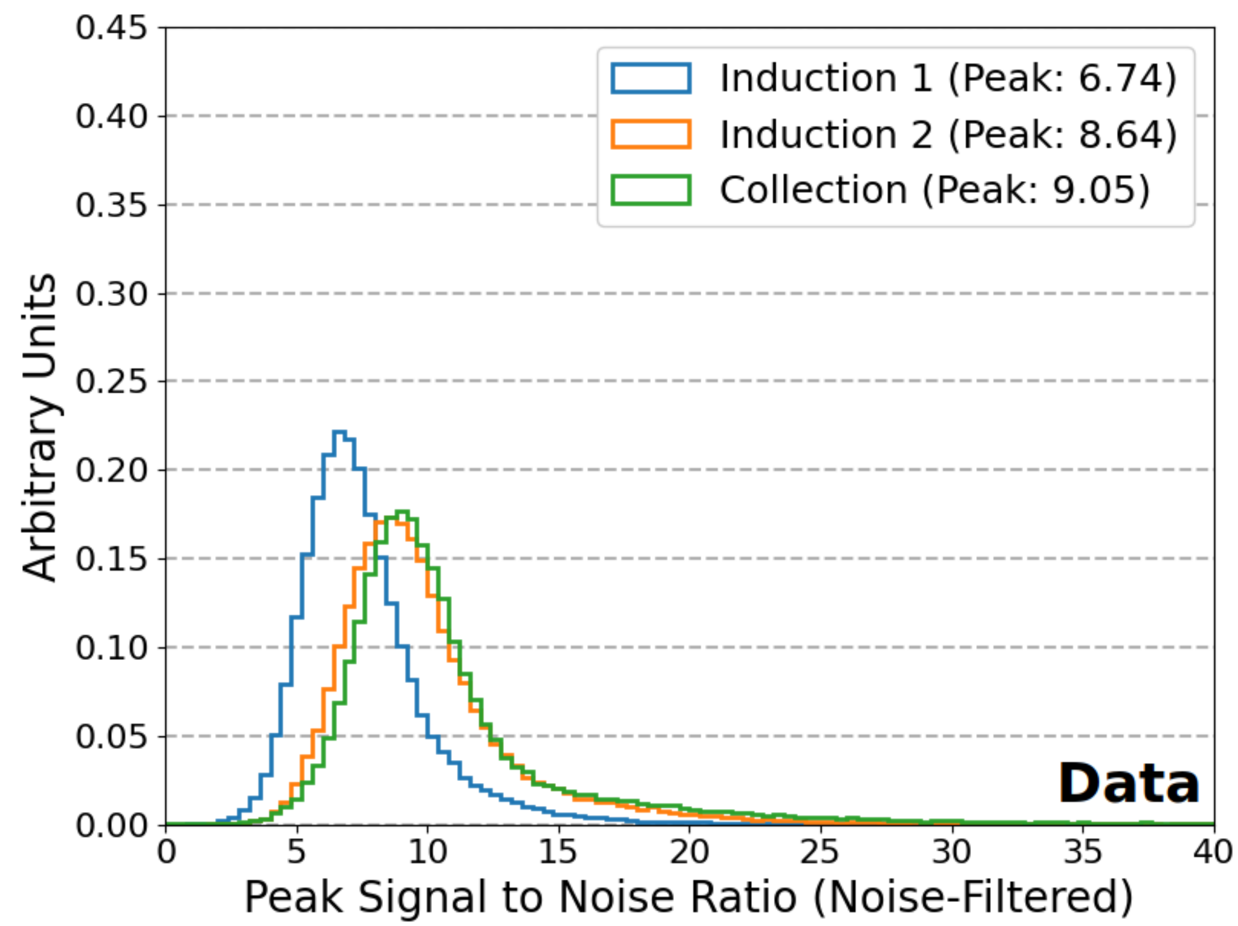




Commissioning

- ICARUS has been collecting cosmic data since summer 2020
- Studying detector performance with a sample of cathode-crossing stopping cosmic muon, dE/dx versus residual range
- The signal-to-noise ratio was extracted from a sample of almost-vertical anode-to-cathode crossing cosmic muons

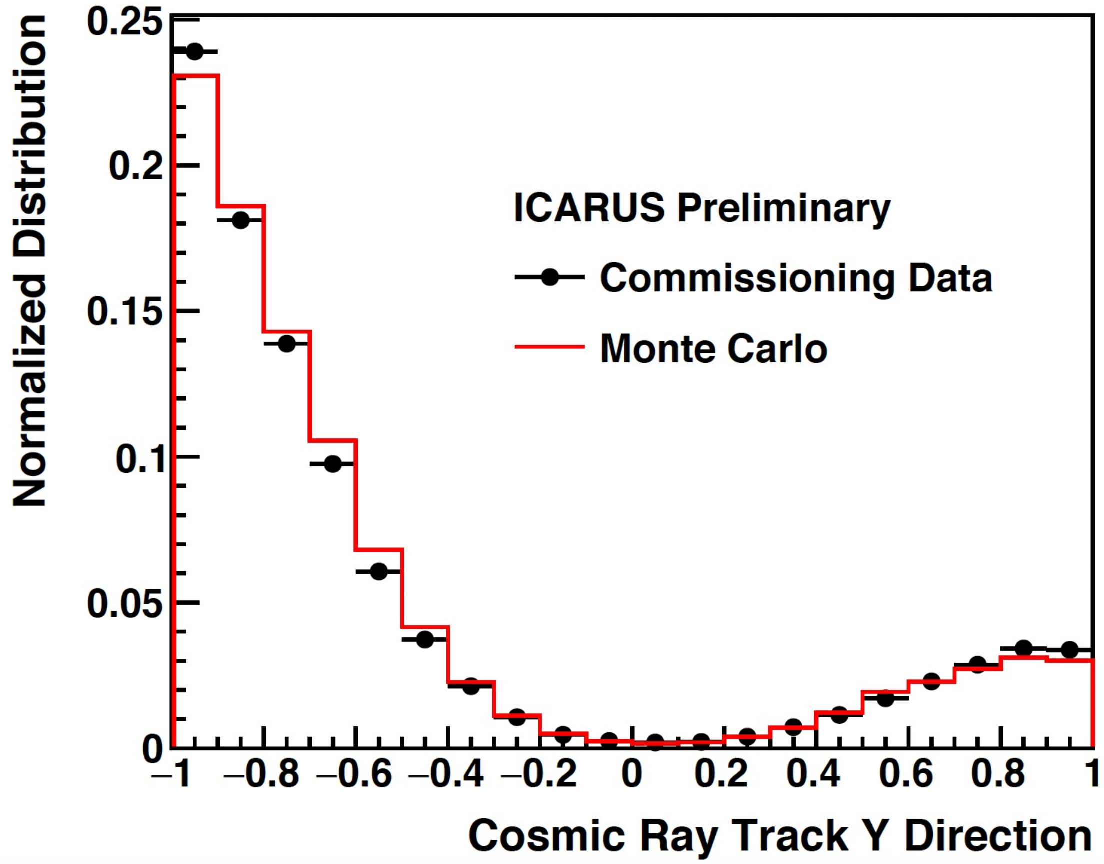


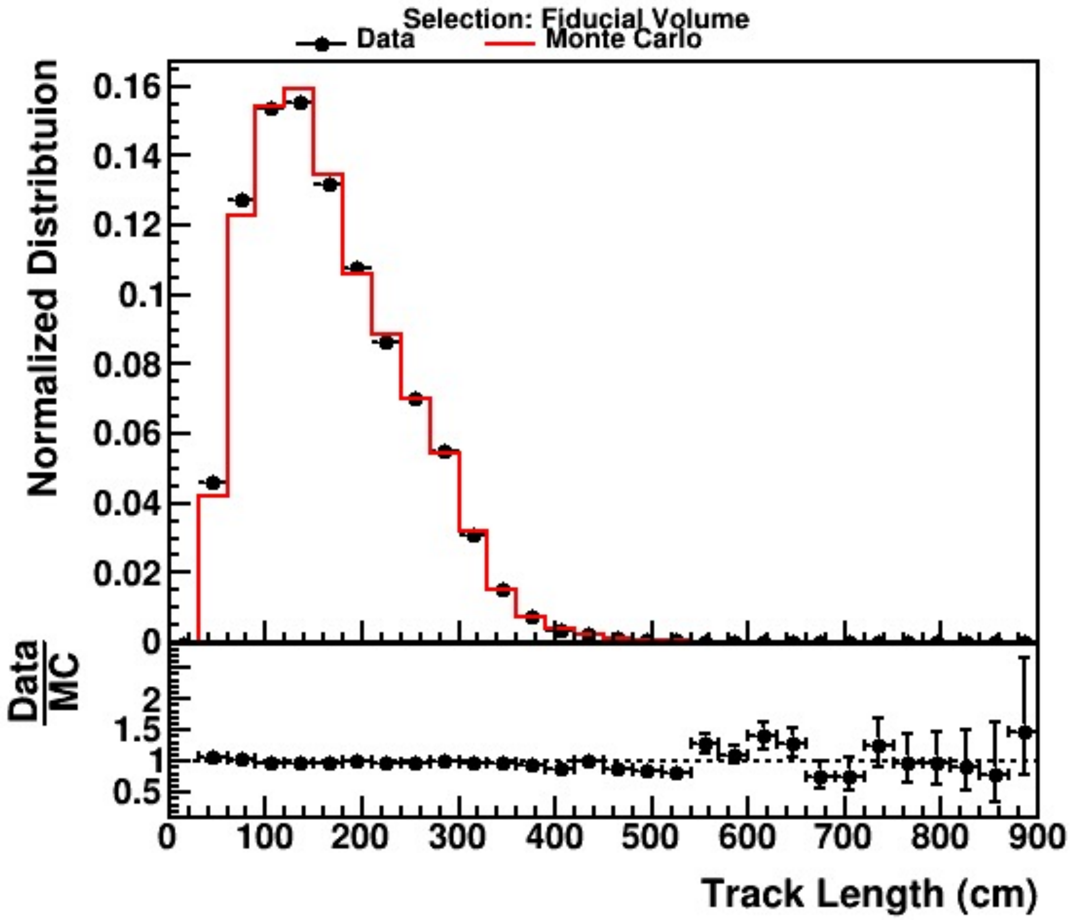


More details about calibration at Gray Putnam's talk

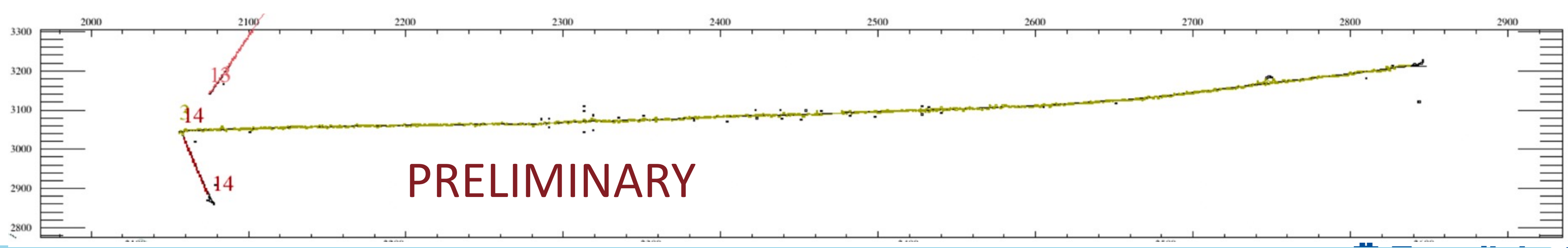
Track Reconstruction

- Comparison of cosmic events reconstructed in data and simulation





- Neutrino events found from hand scanning useful to investigate and test the automated software tools and compare performance between data and MC



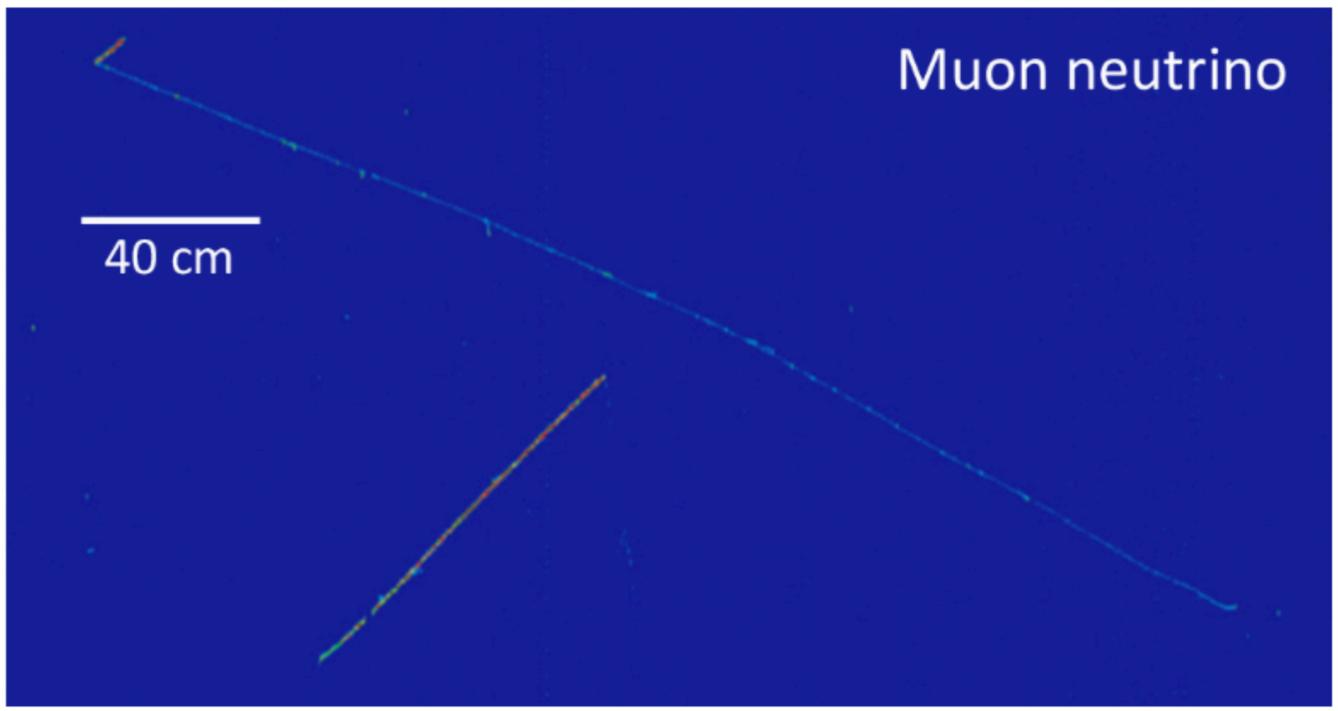
Using Pandora reconstruction, https://github.com/PandoraPFA

Fermilab

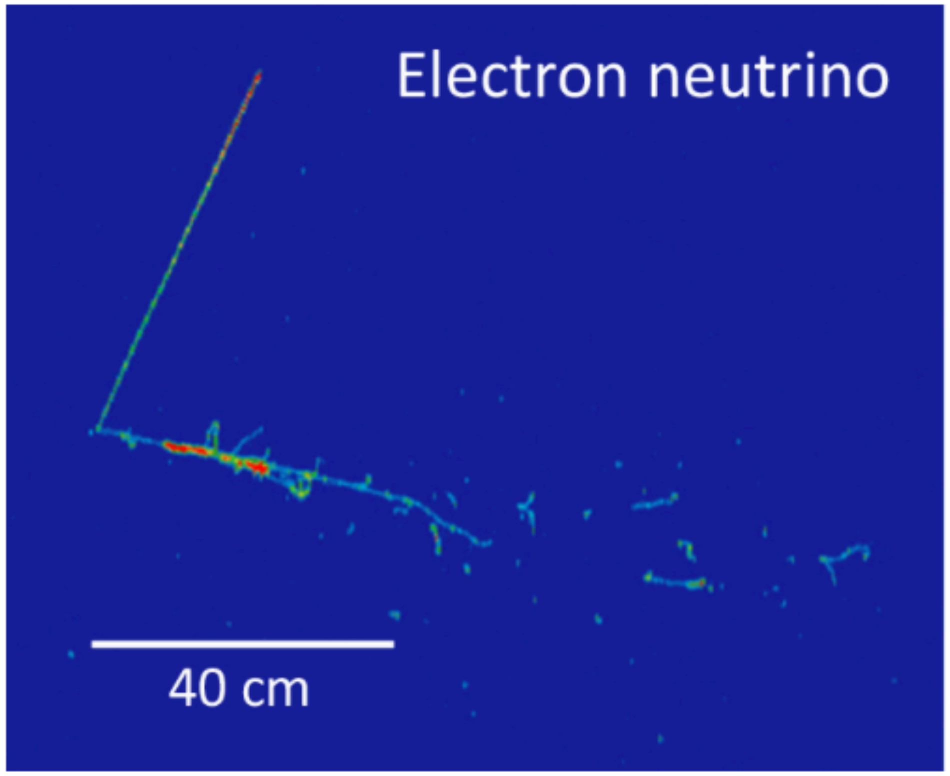
ICARUS Commissioning Status

- Collecting neutrino data from Booster and NuMI neutrino beams
- ICARUS started to take neutrino data from Booster and NuMI last year June 2021

Muon Neutrino candidate from data



Electron Neutrino candidate

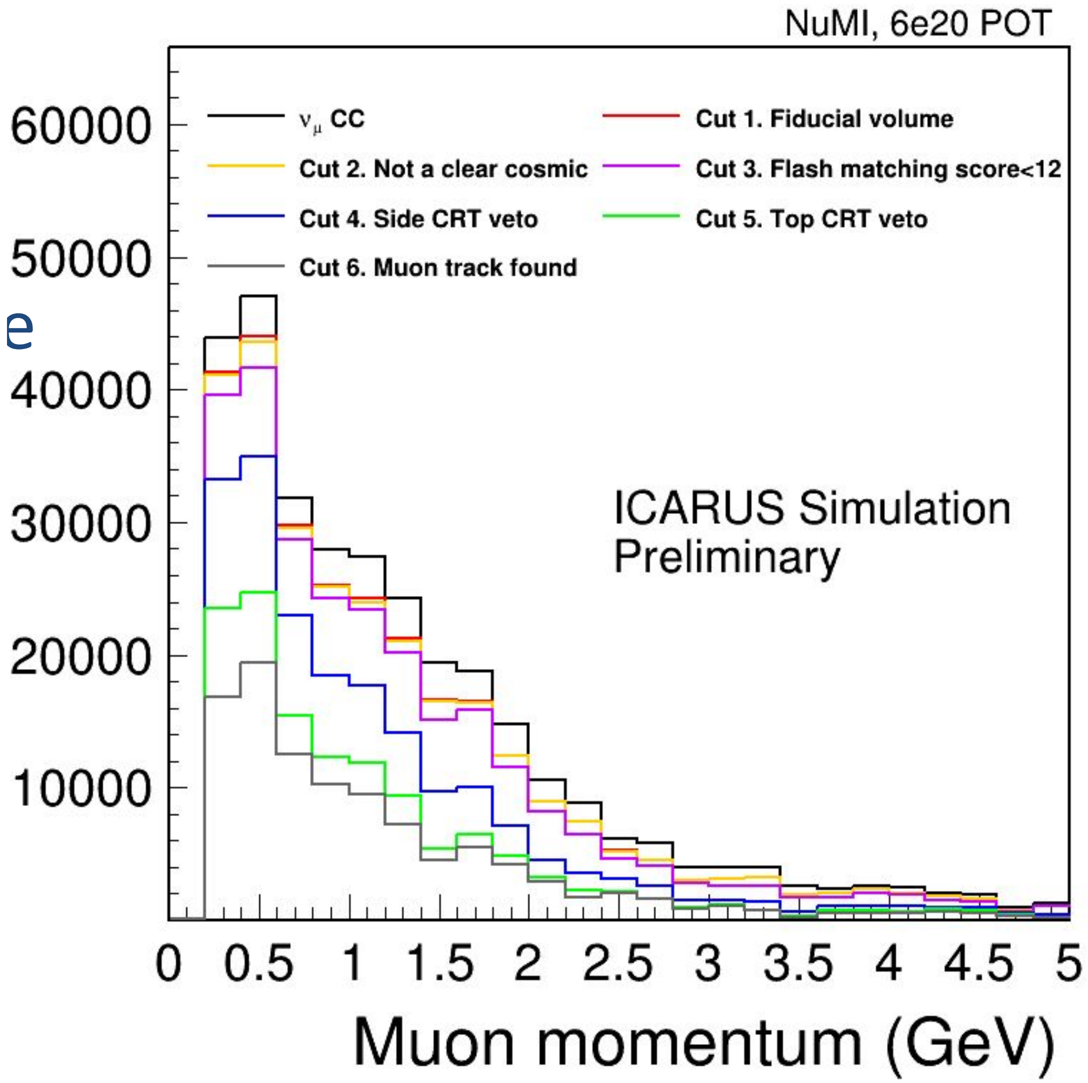


- Final stages of the trigger system and installation of the overburden was completed last May 2022
- Finalized the commissioning and started the data physics taken in June 2022

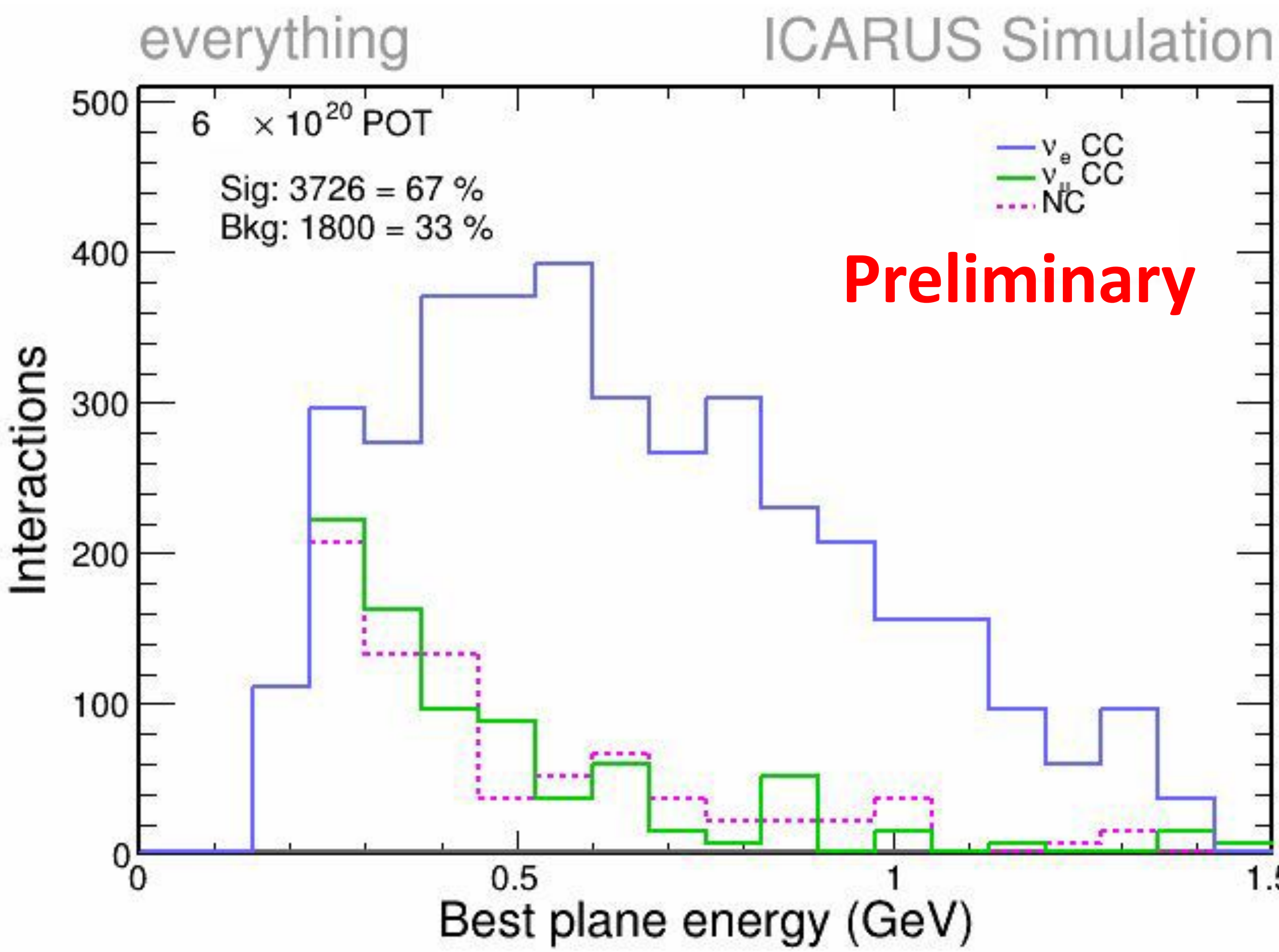
Starting with Event selections

- Selection uses reconstructed output from TPC, PMT and CRT systems and looks for neutrino-like interactions with a muon-like track or electron-like shower

Selection for Muon Neutrino



Selection for Electron Neutrino

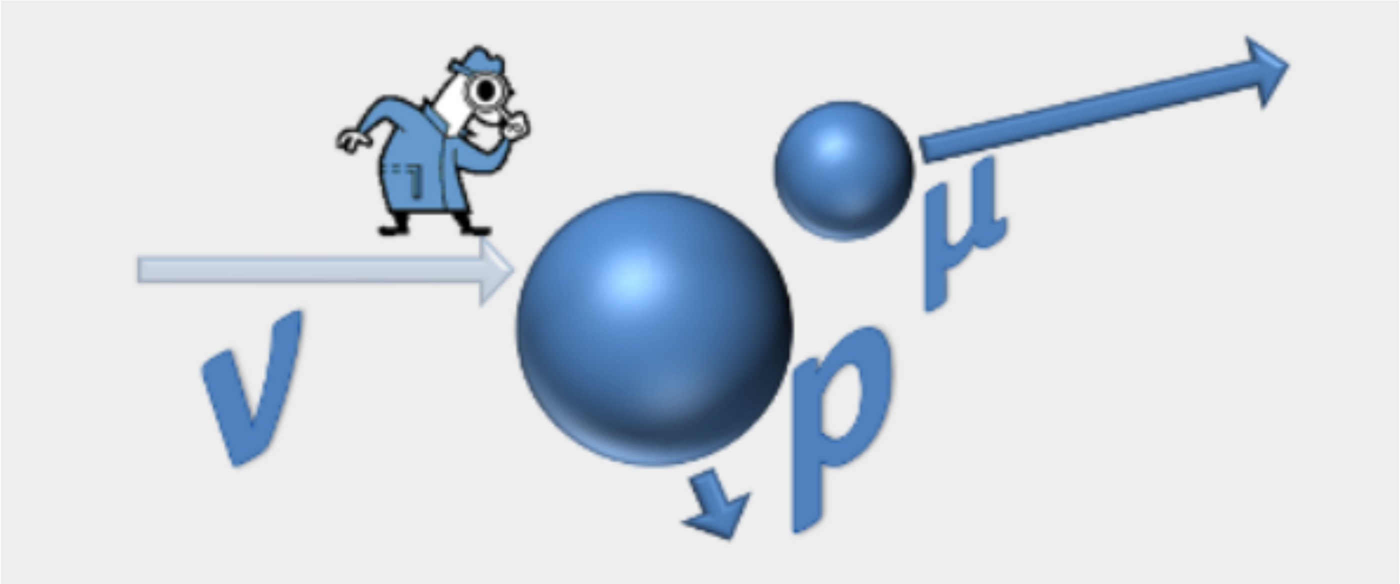


Fermilab

Summary

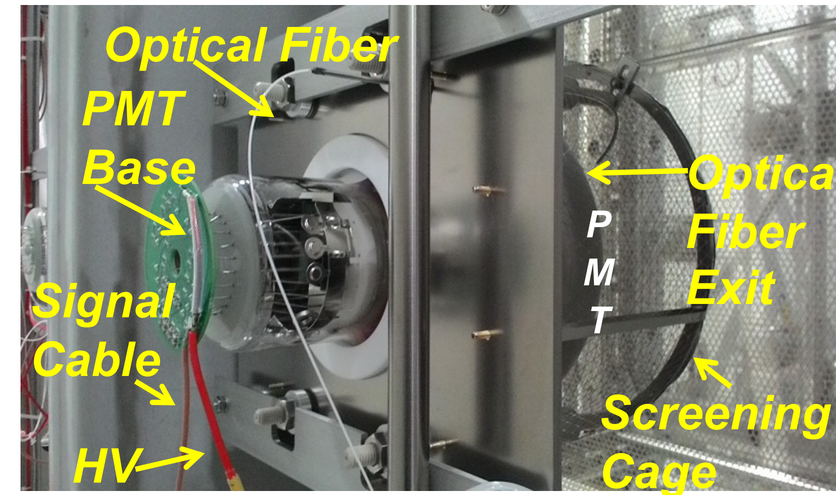
- Oscillation experiments depend on modeling nuclear effects correctly and knowledge of cross sections to a few percent for precision oscillation measurements
- MINERvA is building a rich data set of results for the oscillation experiments
  - More observables with a rich statistics
  - More nuclear dependence (Carbon, Iron, Lead, Water and Helium)
- ICARUS will collect good statistics of neutrino interactions from NuMI of axis to perform cross section measurements
  - Muon neutrinos, electron neutrinos and ratio muon to electrons
  - Excellent statistics to measure similar observables from MINERvA to constrain initial and final state interactions for DUNE
- ICARUS operated steadily since summer 2020, data collected with cosmics and neutrinos are used for calibration and tuning of the simulation and reconstruction
- ICARUS has begun first physics run in June 2022

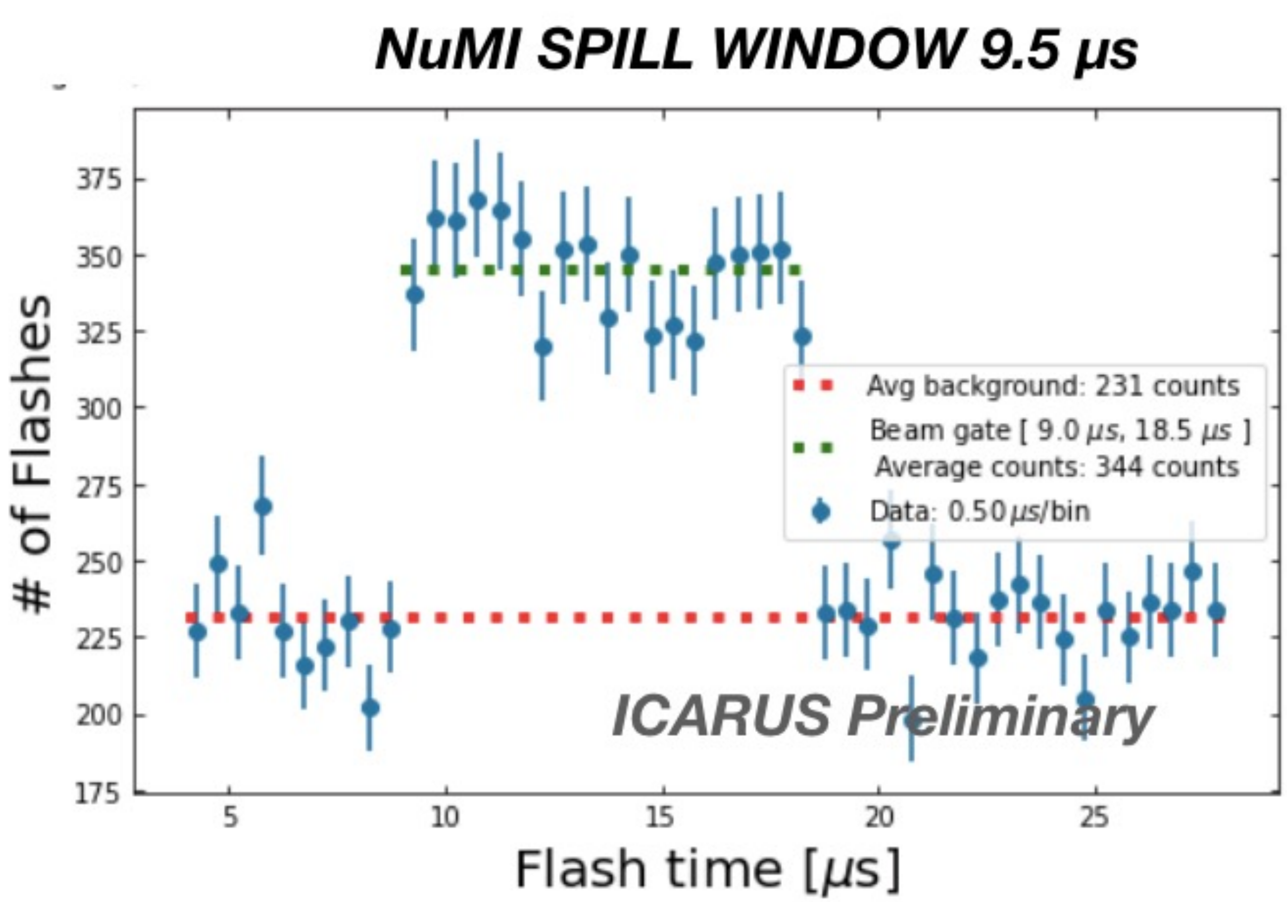
Back Up Slides



Light Collection System Upgrade (PMT)

- ICARUS at SBN has 360 PMTs 8” (5% photocathode coverage of TPC wire area, 15 phe/MeV) that provides:
  - Precisely identify the time of occurrence of any ionizing event in TPC with ns resolution
  - Localize events with <50 cm spatial resolution
  - Give event topology for selection purposes
    - Sensitivity to low energy events (~100 MeV)
- The system was completed in 2019
- Commissioning of the system started in 2020

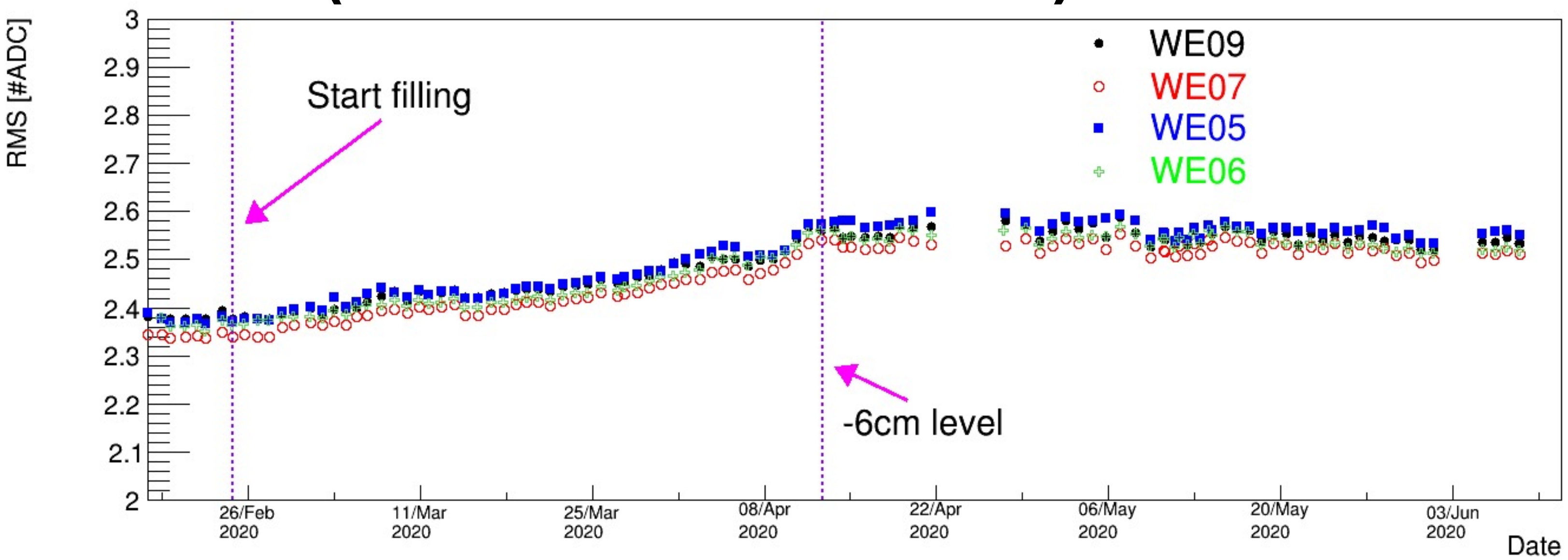




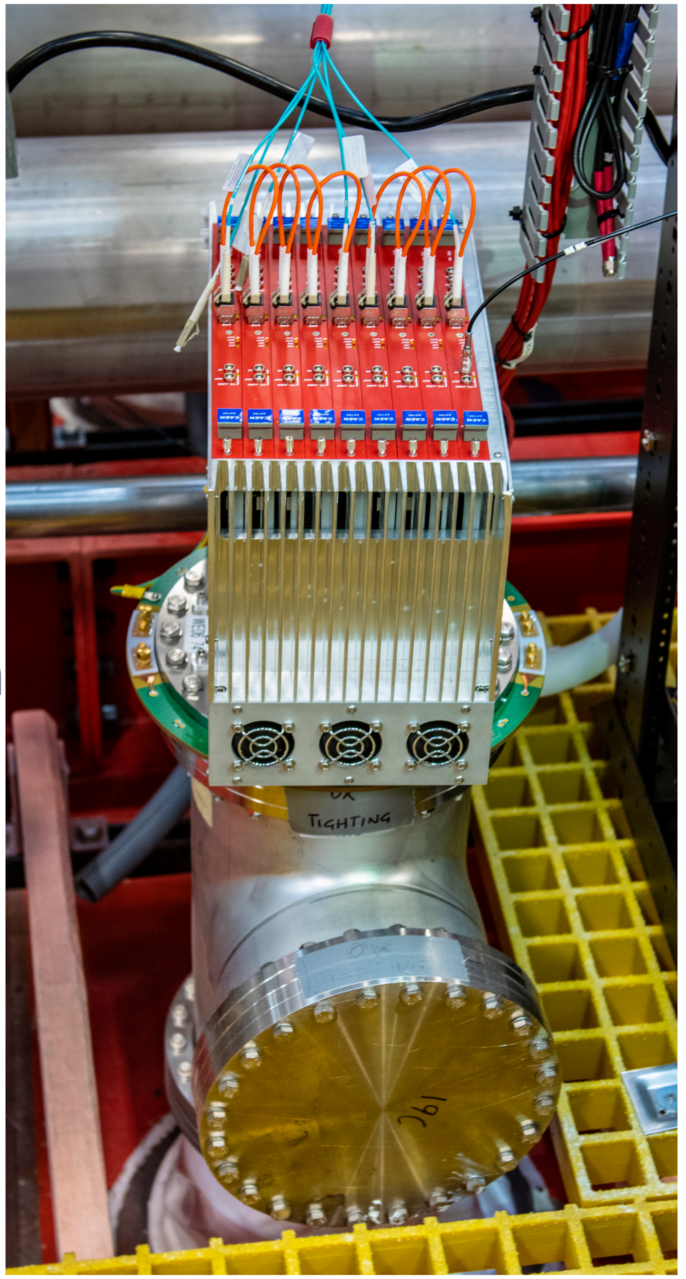
TPC Readout Electronics Upgrade

- New TPC readout electronics
  - A front-end based on analogue low noise/charge sensitive pre-amplifier
  - More compact layout: both analog+digital electronics in a single flange
  - Lower noise ~1200 e- equivalent (~20% S/N improvement w.r.t LNGS)
  - Shorter shaping time ~1.5 µs matching e- transit time between wire planes providing a better hit position separation
-

TPC Noise (coherent noise removed)



Reside outside the cryostat



New Cosmic Ray Tagging System (CRT)

- CRT surrounds the cryostat with two layers of plastic scintillators (~1100 m^2)
- Provides spatial and timing coordinates of the track entry point
- Few ns time resolution allows measuring direction of incoming/outgoing particle propagation via time of flight
- Three subsystems providing ~95% tagging efficiency:
  - Bottom, side and top CRT

Top CRT: installed

Side CRT: installed

Fermilab