Fermilab

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

# Status and Plans for Measurements of $\nu$-Ar Interactions at ICARUS

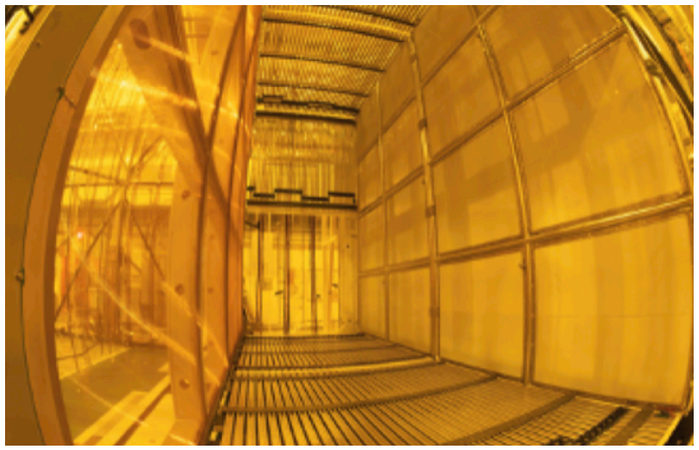
Minerba Betancourt (Fermilab) on behalf of the ICARUS collaboration

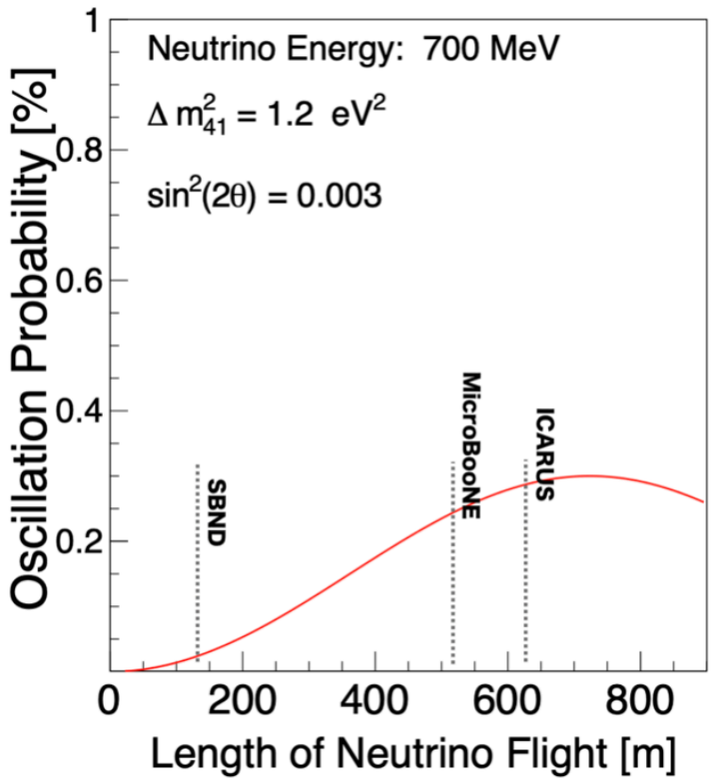
17 April 2024

Nuint 2024

# Short Baseline Science Program

## Near detector (SBND)



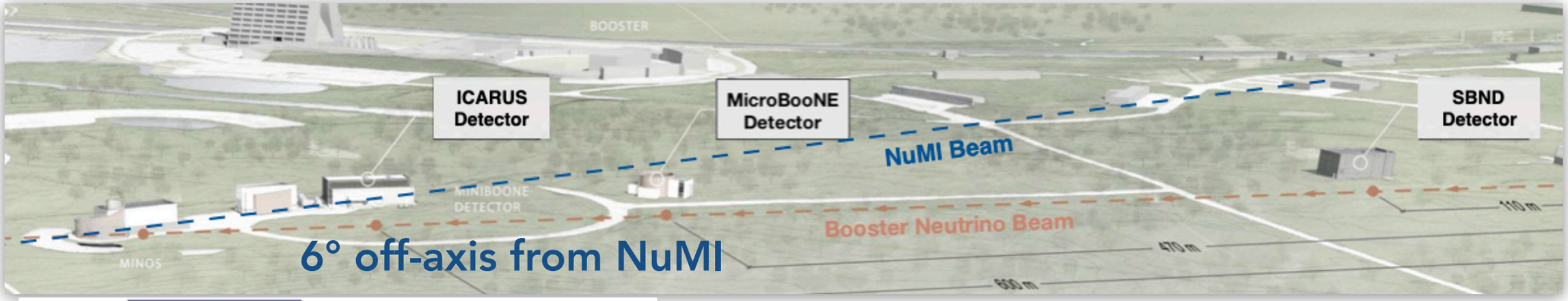


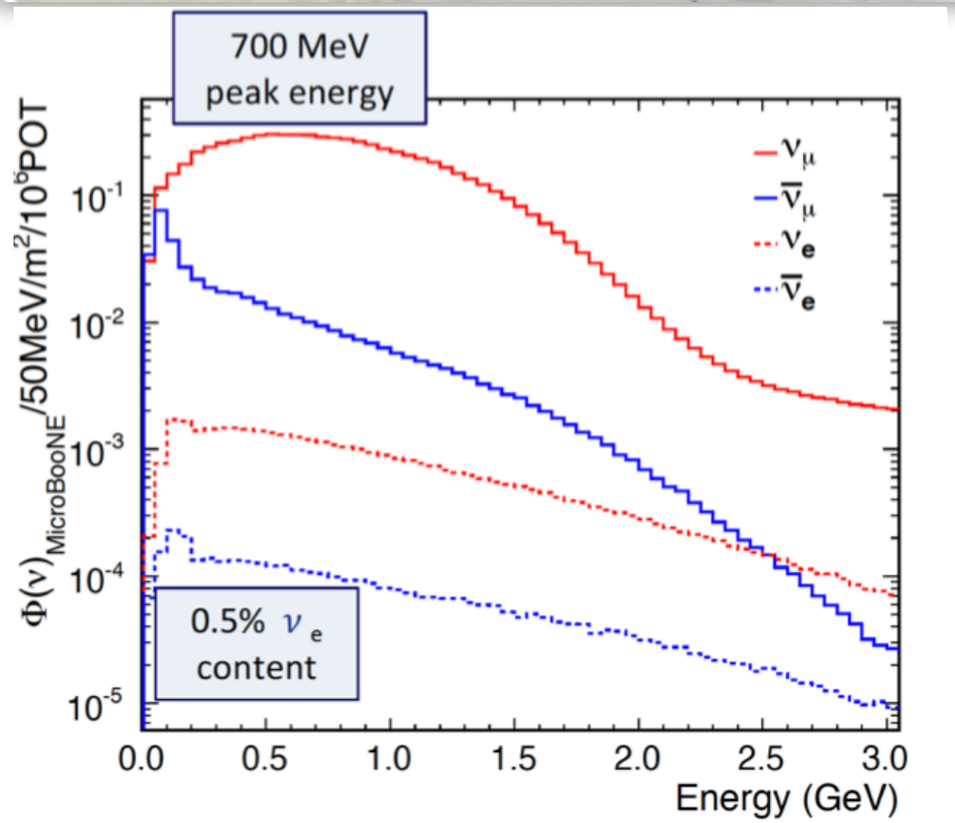

## Far detector (ICARUS)

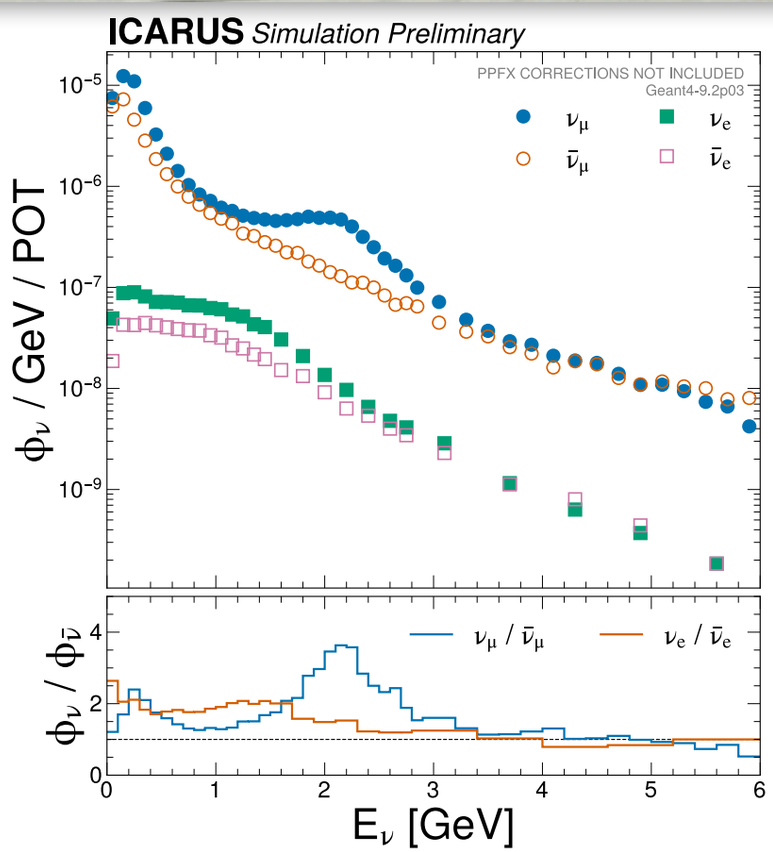
- Search for Sterile Neutrinos
  - $\nu_\mu$ disappearance, $\nu_e$ appearance and $\nu_e$ disappearance
- Neutrino cross section measurements
  - Millions of neutrino interactions for $\nu_\mu$ and high statistics for $\nu_e$
- Search for Beyond Standard Model physics, detector locations and technology will enable many searches
  - Dark neutrinos, light dark matter, axion-like particles, heavy neutral leptons, higgs portal scalar, transition magnetic moment and millicharged particles

# ICARUS at FNAL

- The ICARUS detector is located on-axis from the Booster beam and 5.75° off-axis from the NuMI beam



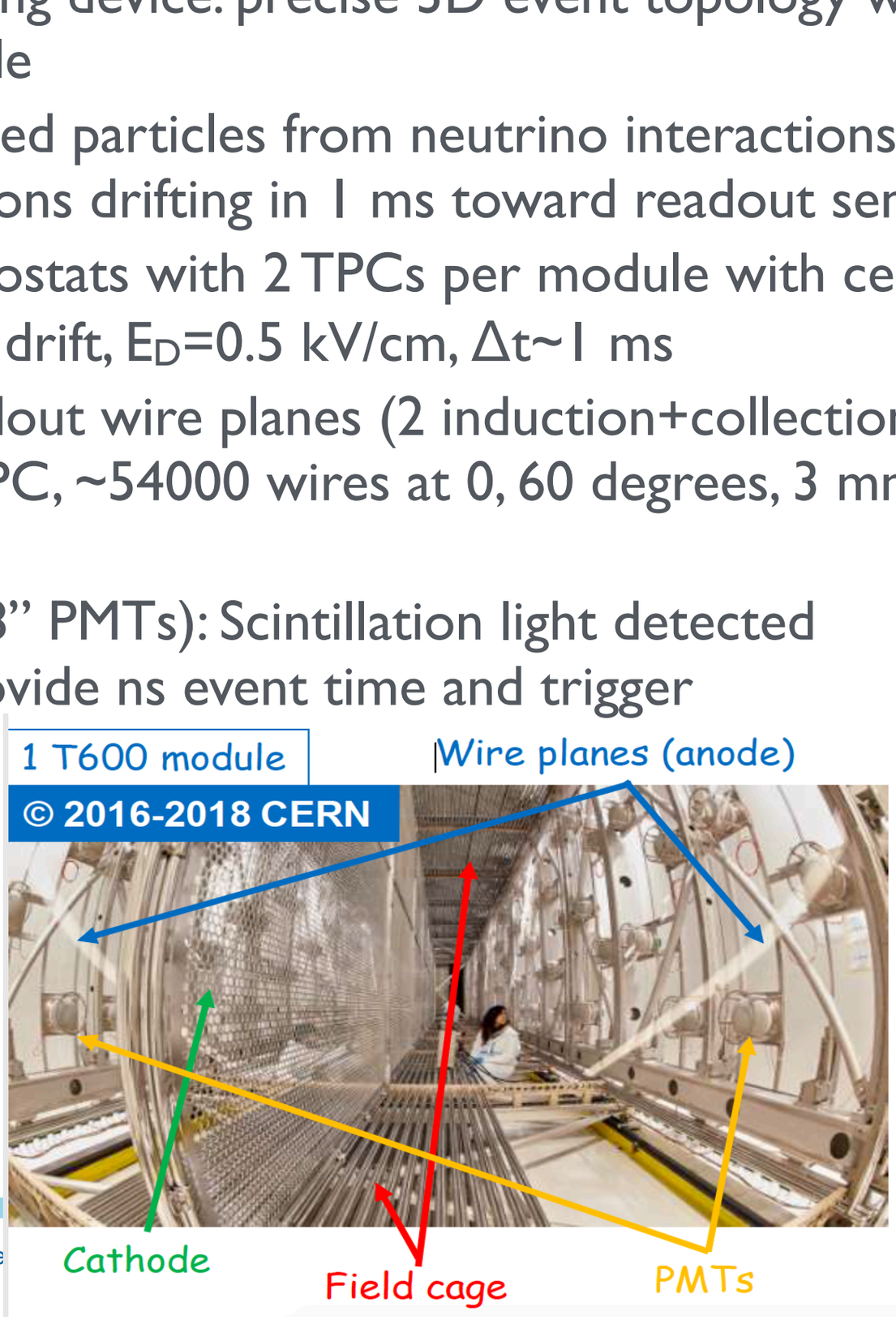



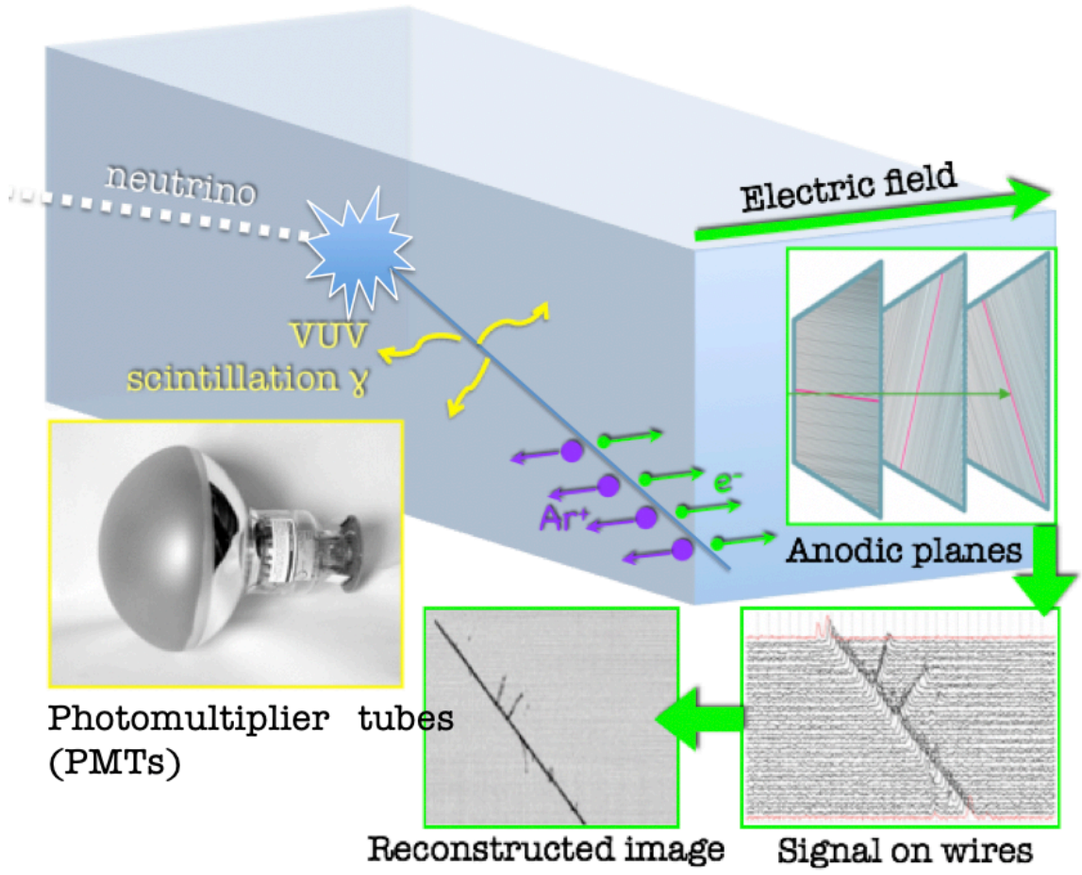




Great opportunity to probe interactions in DUNE's neutrino energy range before DUNE turns on

# ICARUS (Imaging Cosmic And Rare Underground Signals)

- Tracking device: precise 3D event topology with ~mm$^3$ resolution for ionizing particle
- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires
- 2 Cryostats with 2 TPCs per module with central cathode, 1.5 m drift, $E_D$=0.5 kV/cm, $\Delta t$~1 ms
- 3 readout wire planes (2 induction+collection) per TPC, ~54000 wires at 0, 60 degrees, 3 mm pitch
- 360 (8" PMTs): Scintillation light detected to provide ns event time and trigger



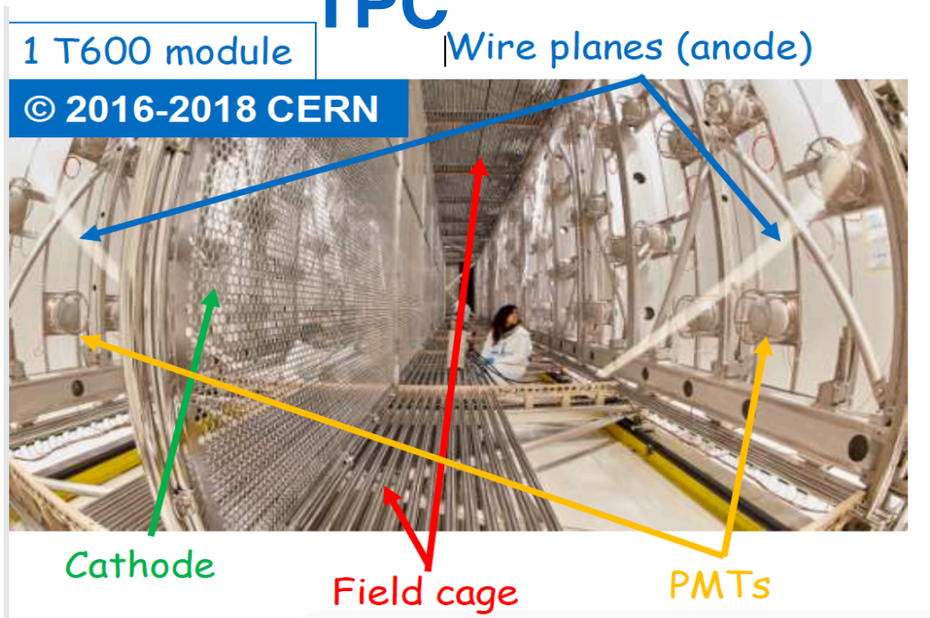



Fermilab

# 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
- ICARUS is located on the surface, a cosmic tagger and overburden has been installed to reduce and tag the abundant cosmic background events

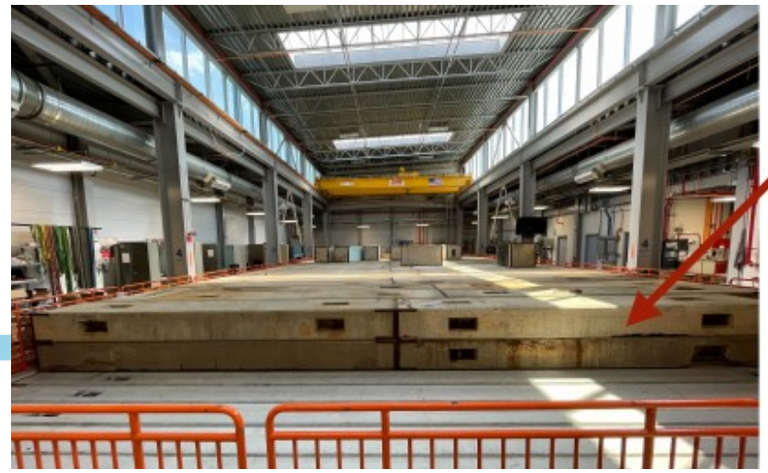
**TPC**




**PMT**

**side CRT**

**Top CRT**

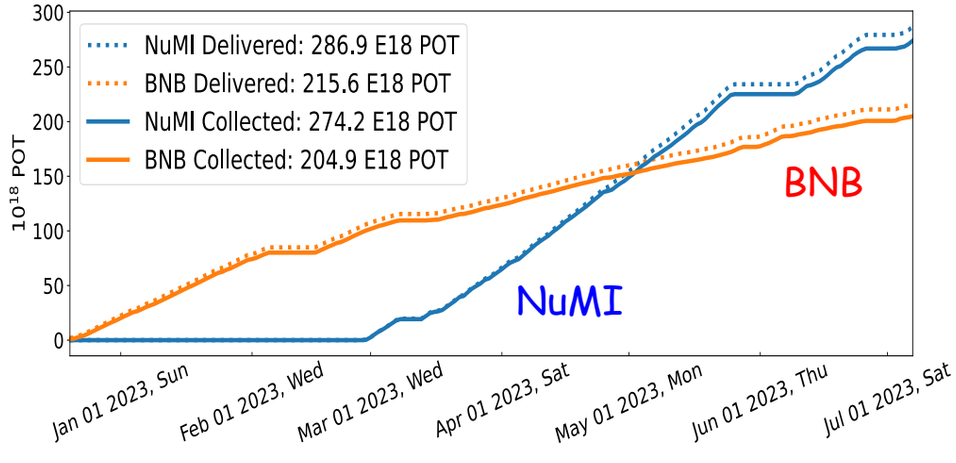


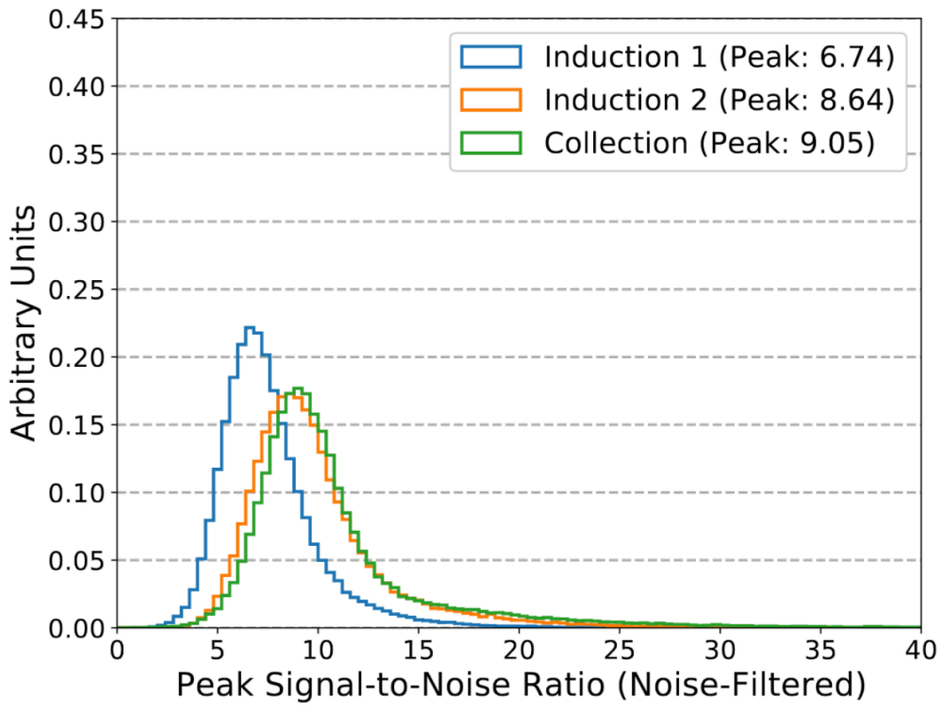
**3m concrete overburden**

**Fermilab**

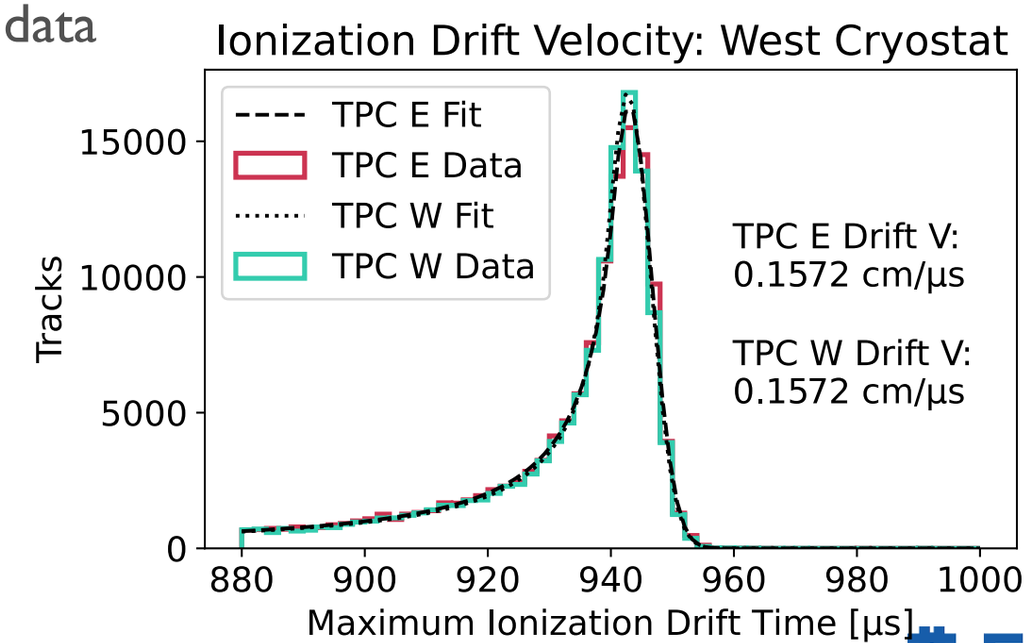
# ICARUS at FNAL

- ICARUS began commissioning in 2020 with cosmic data
- First ICARUS physics runs collected last June - December 2022 and spring 2023 from NuMI and Booster neutrino beams
- Commissioning and physics data have been used to perform the calibration, tune the reconstruction and start the first analyses with neutrino data
- The signal-to-noise ratio was extracted from a sample of anode-to-cathode crossing cosmic muons




Results of ionization drift velocity measurement using cosmic muon data

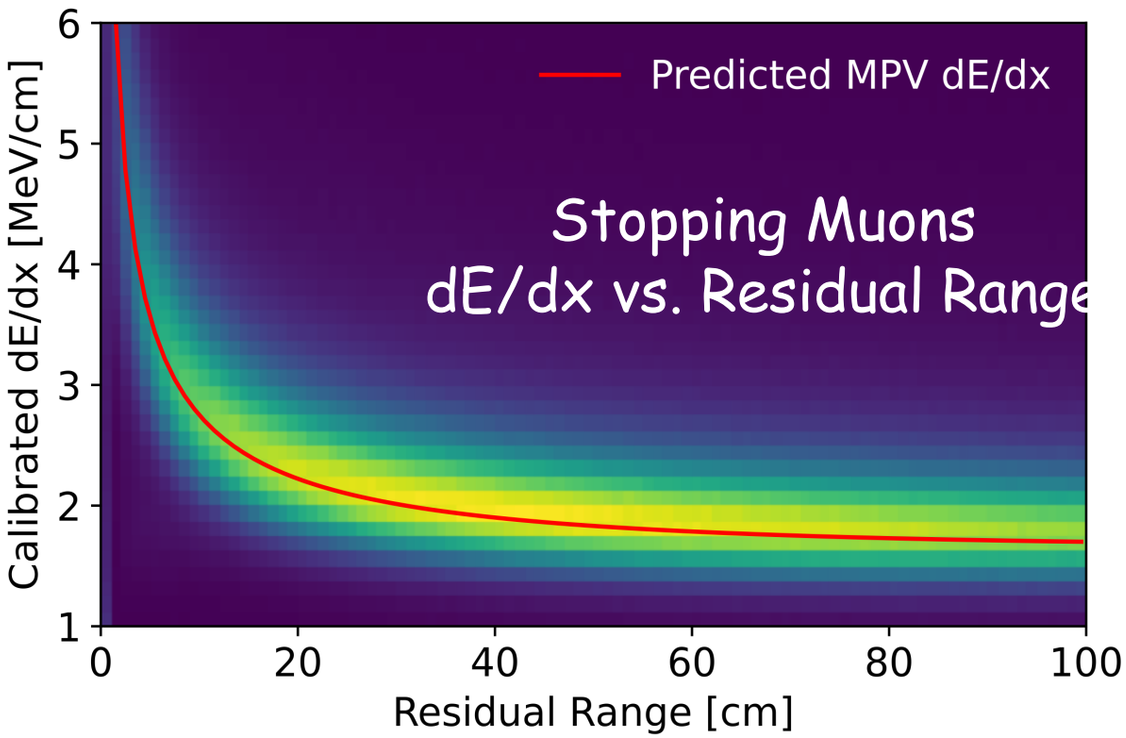


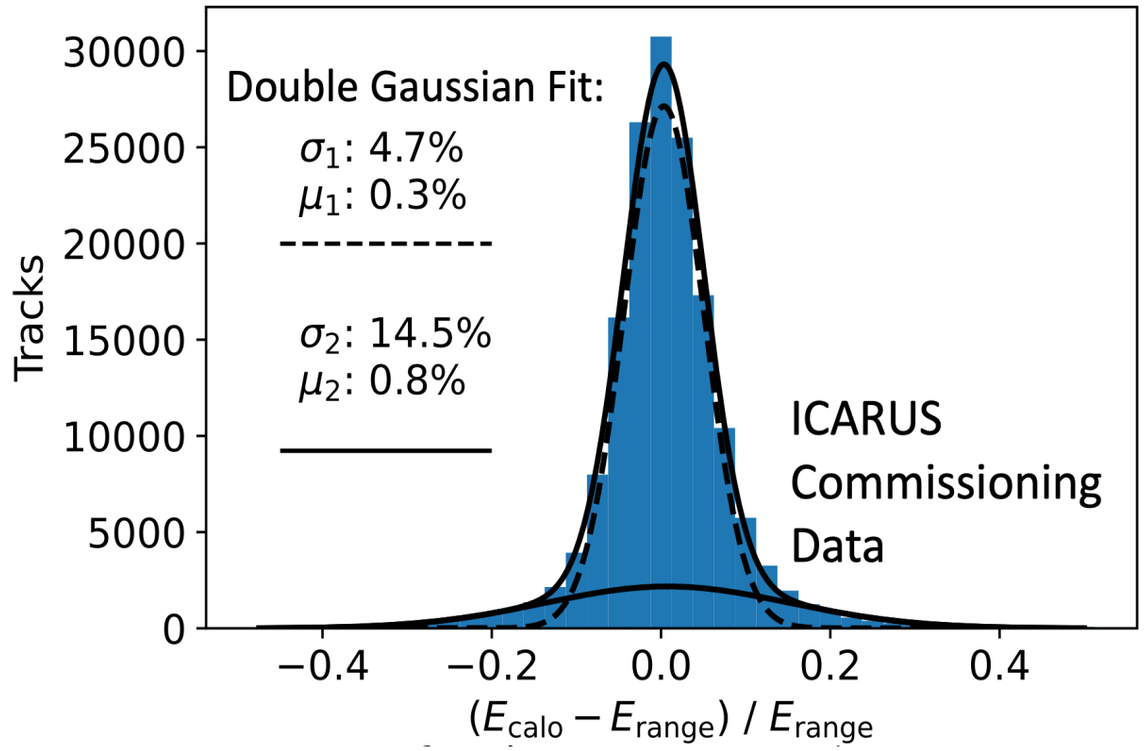



**P. Abratenko et al, Eur. Phys. Journal C 83, 467 (2023)**

# Calibration

- The full calibration has been developed, including: measurement of the drift velocity, equalization of electronic changes and detector response across the wire plane
- The measured ionization density dQ/dx is studied in bins of residual range, track angle and drift time for cosmic muon stopping/decaying in the LAr

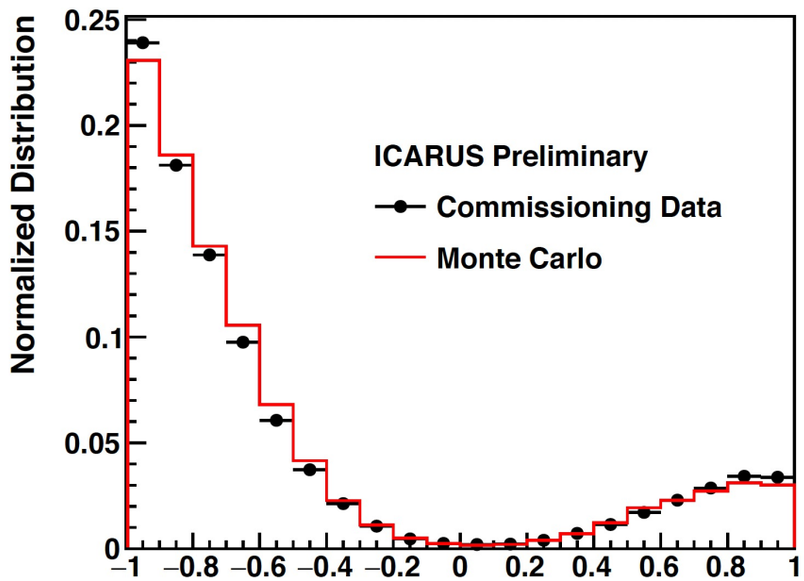


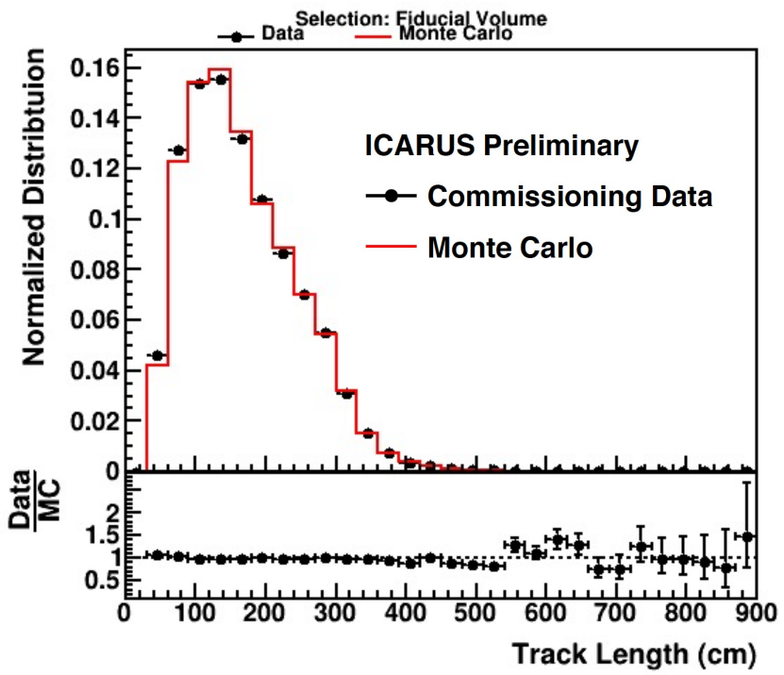




**P. Abratenko et al, Eur. Phys. Journal C 83, 467 (2023)**

# TPC Track Reconstruction

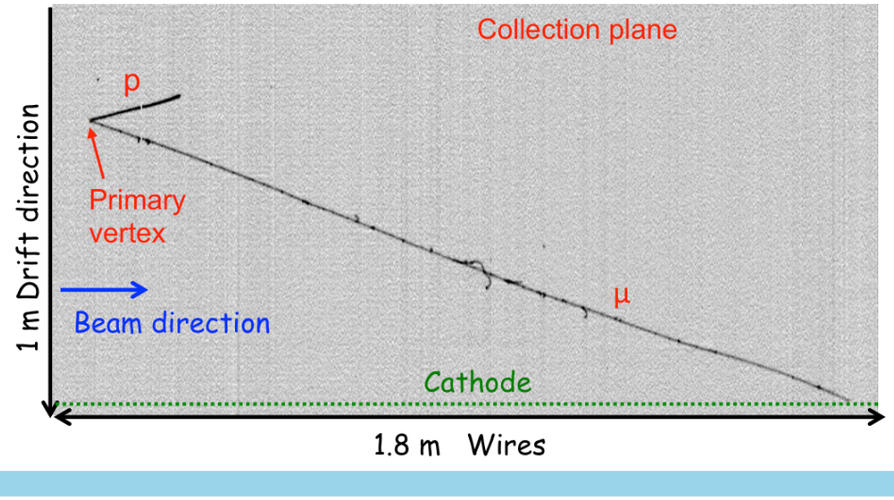
- Comparison of cosmic events reconstructed in data and simulation in TPC



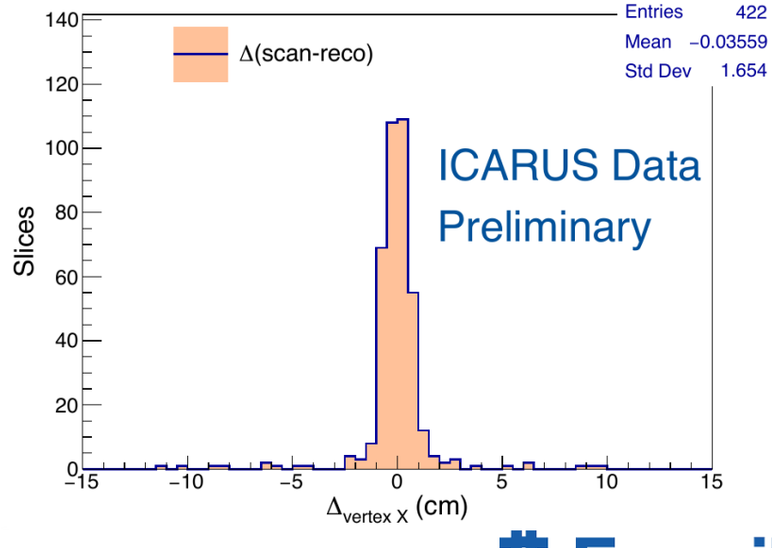

Using Pandora reconstruction, https://github.com/PandoraPFA

- Visual study of ~600 neutrino candidates from BNB




**Difference between the reconstructed and scanned x position**

**Preliminary**

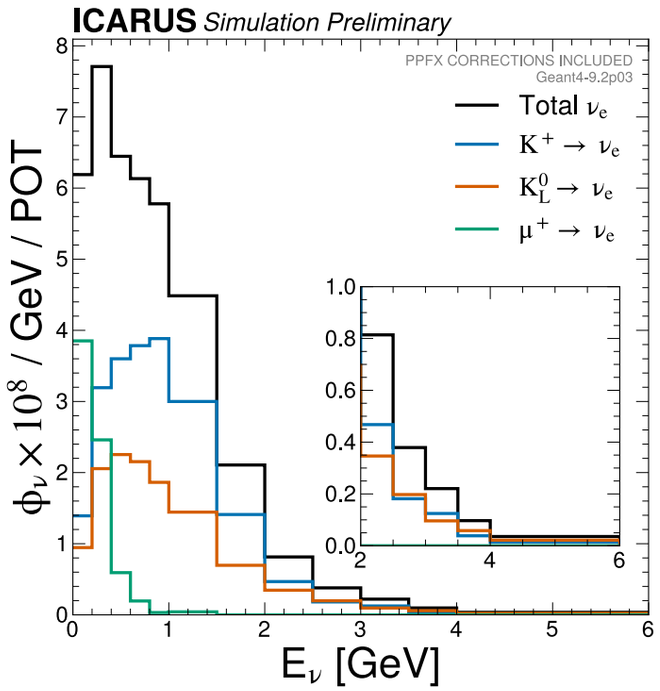


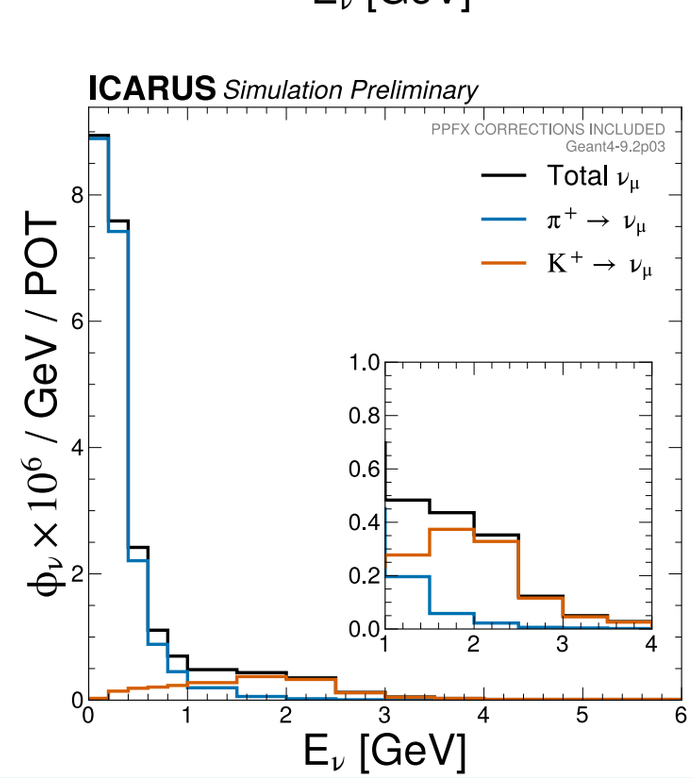



Fermilab

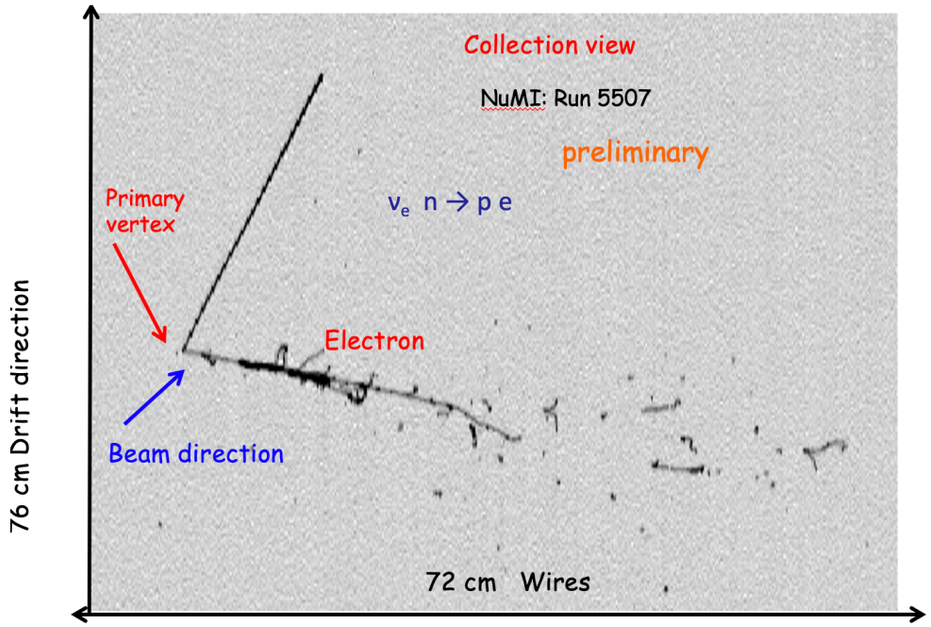
# NuMI off Axis at ICARUS

- The ICARUS detector is located 5.75° off-axis from the NuMI beam

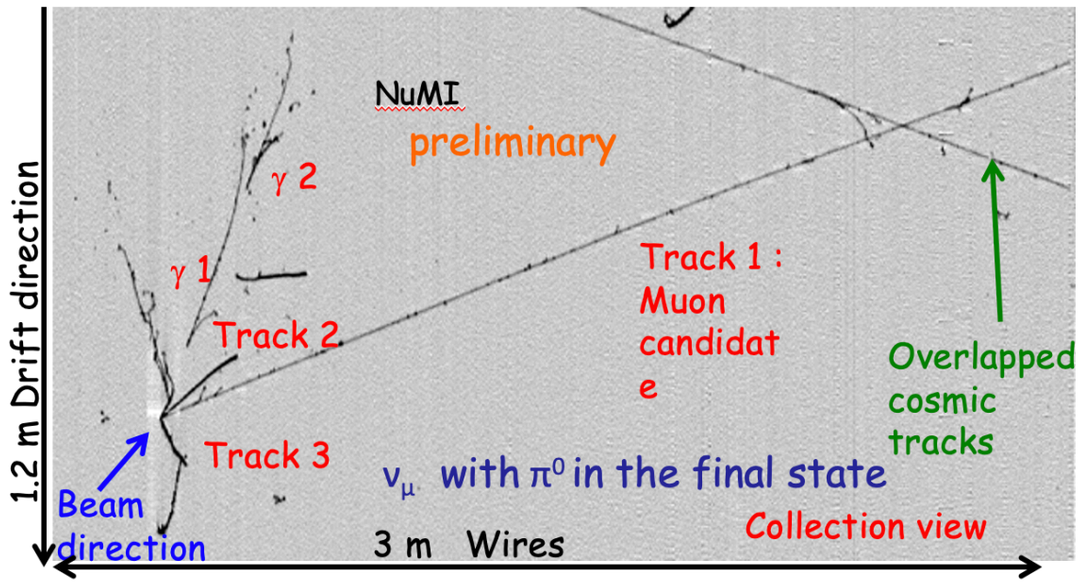



## Data events from NuMI off axis




**Electron neutrino candidate with electromagnetic shower $E_{dep}$=600 MeV**




**Muon neutrino candidate with muon candidate p~1.3 GeV/c and $\pi$0 candidate with photons of 200 and 240 MeV**

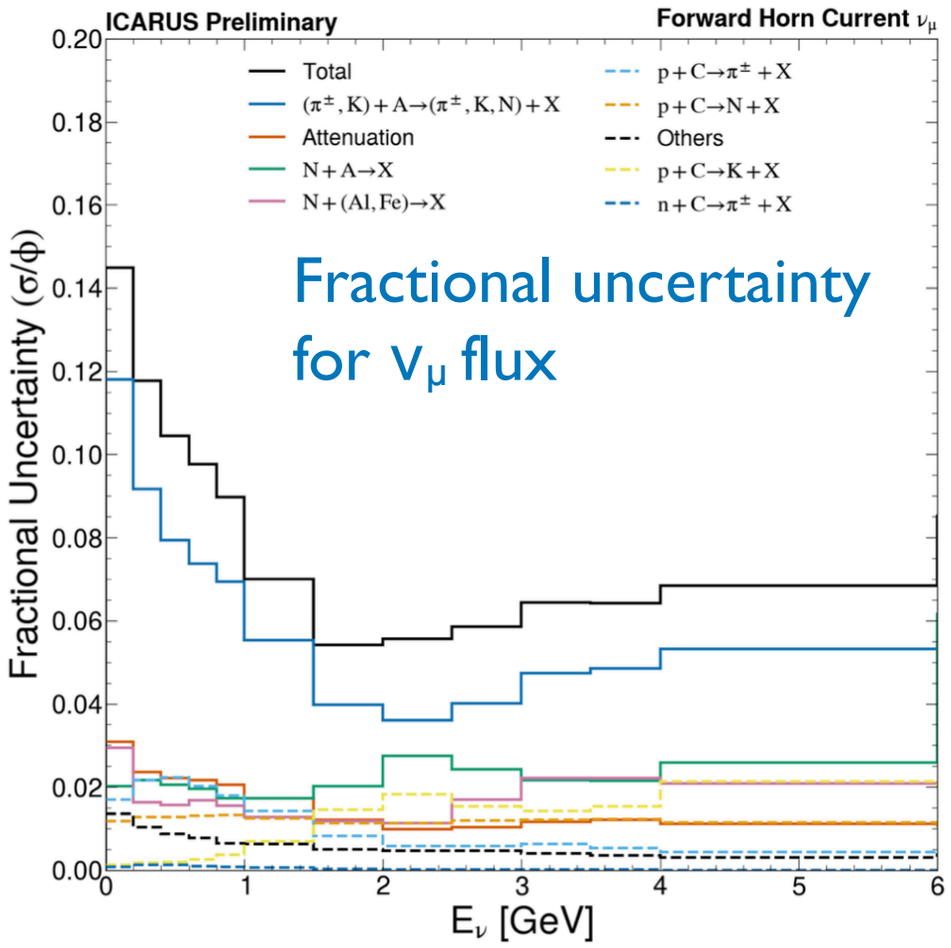


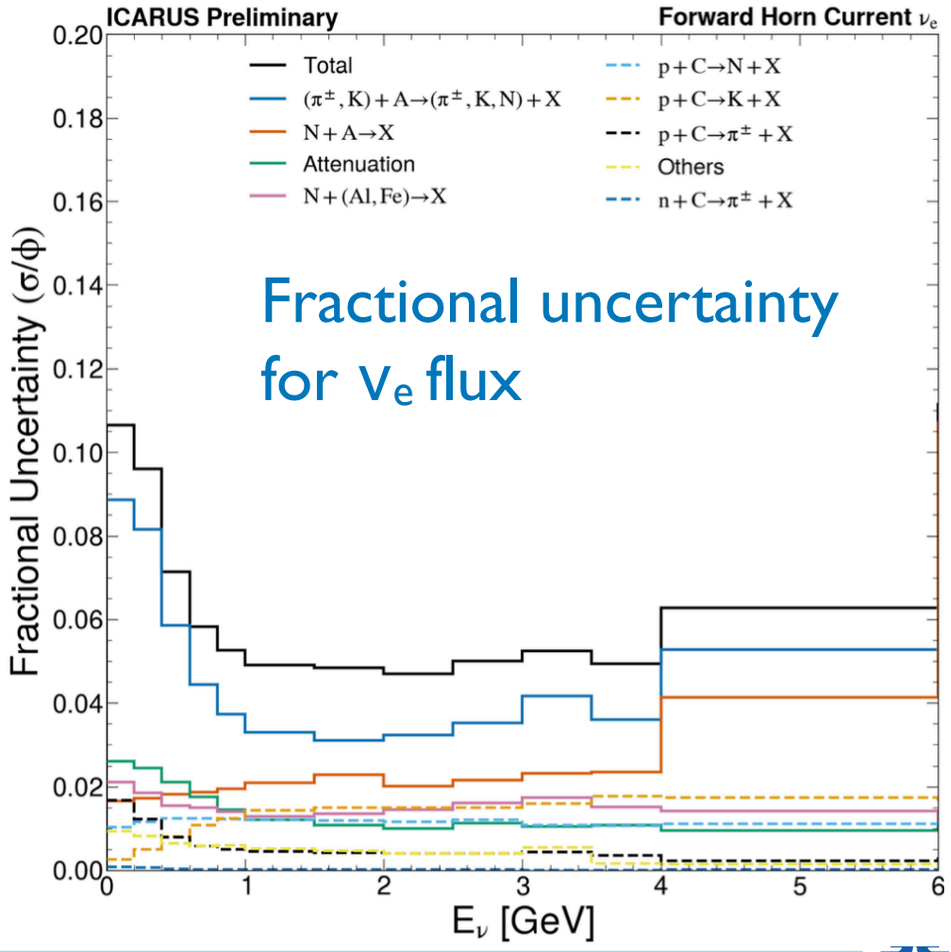
Fermilab

# NuMI off axis at ICARUS

- A detailed characterization of the NuMI flux at ICARUS has been made
- Using the NuMI flux files produced by NOvA, tuned to hadron production data using PPFX
- Error propagation using PPFX (HP) and alternate fluxes (Focusing) was studied extensively and validated at the 5.75° off-axis angle

## Hadron Production Uncertainties



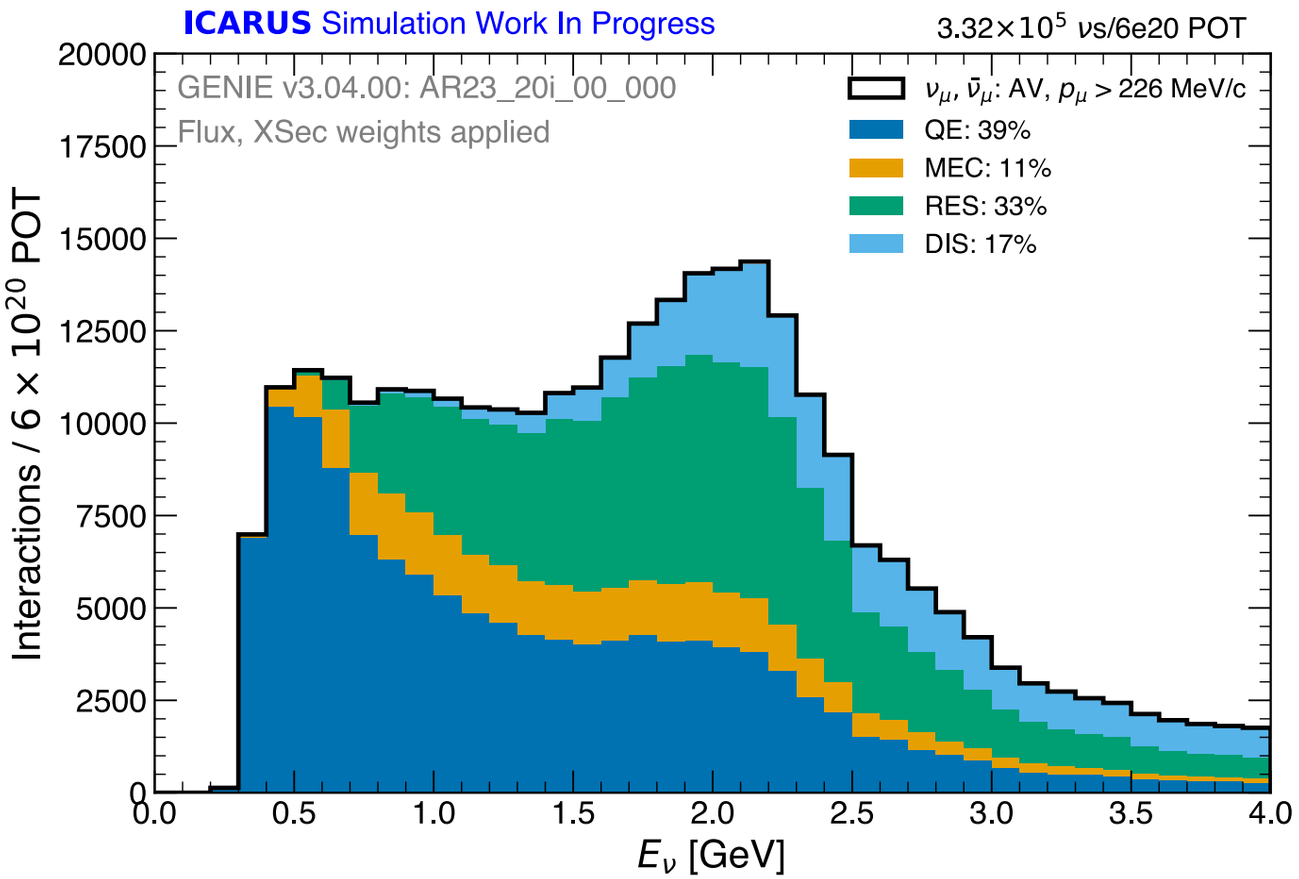



# Physics with NuMI off-axis beam

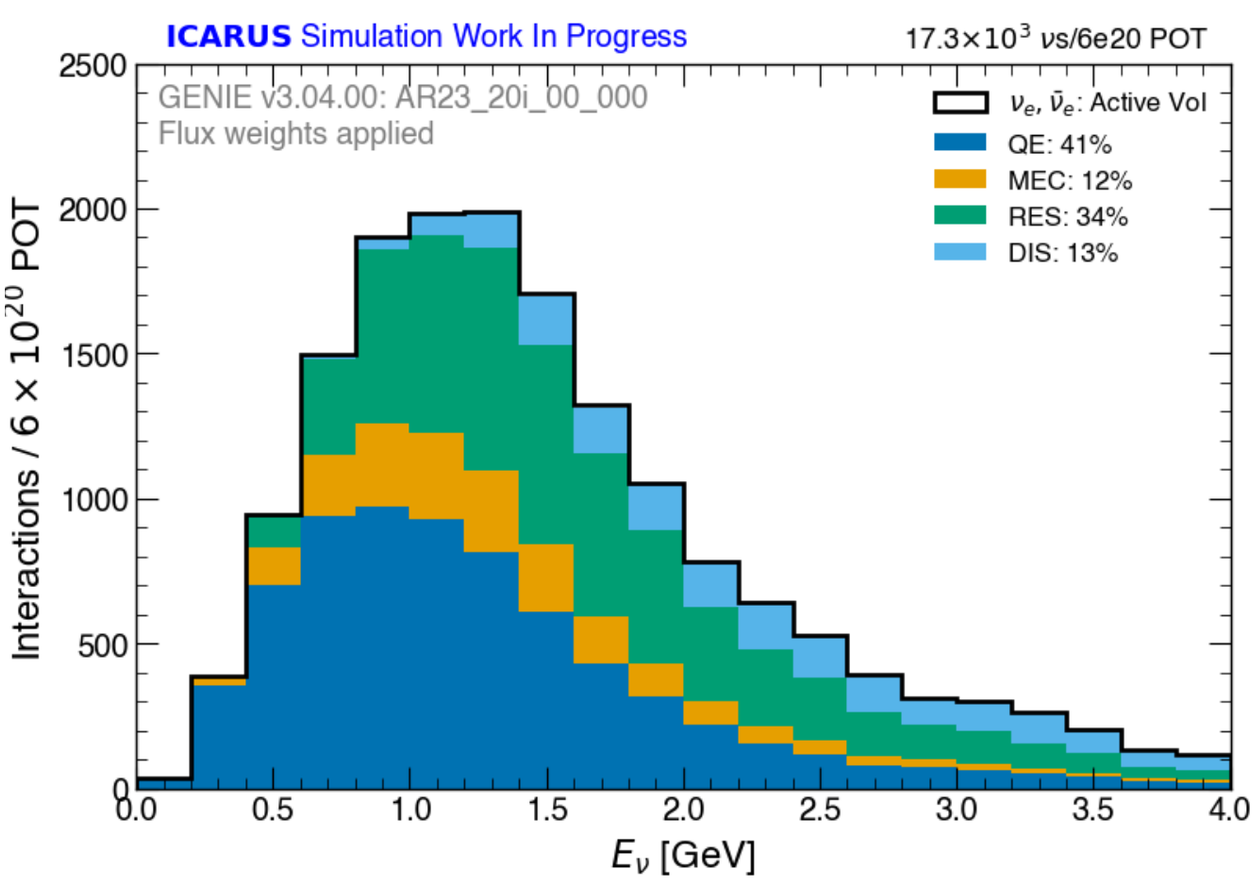
# Neutrino Interactions from NuMI off axis at ICARUS

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

## Muon Neutrino




## Electron Neutrino




CC Events/6E20: $\nu_\mu$ 332,000 and $\nu_e$ 17,000

- Pretty good statistics to study resonance and deep inelastic scattering
- Available data ~3E20POT for physics analysis now

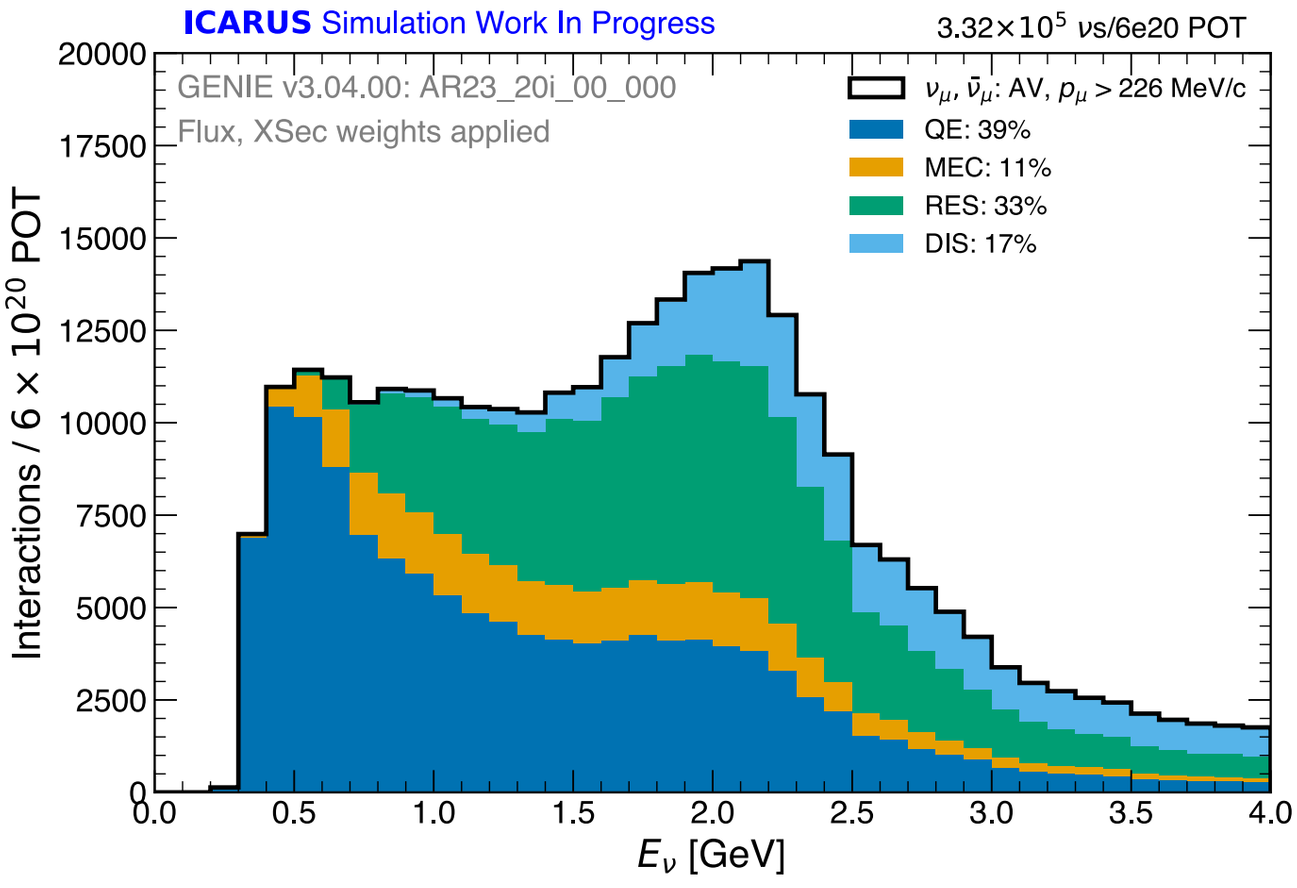


Fermilab

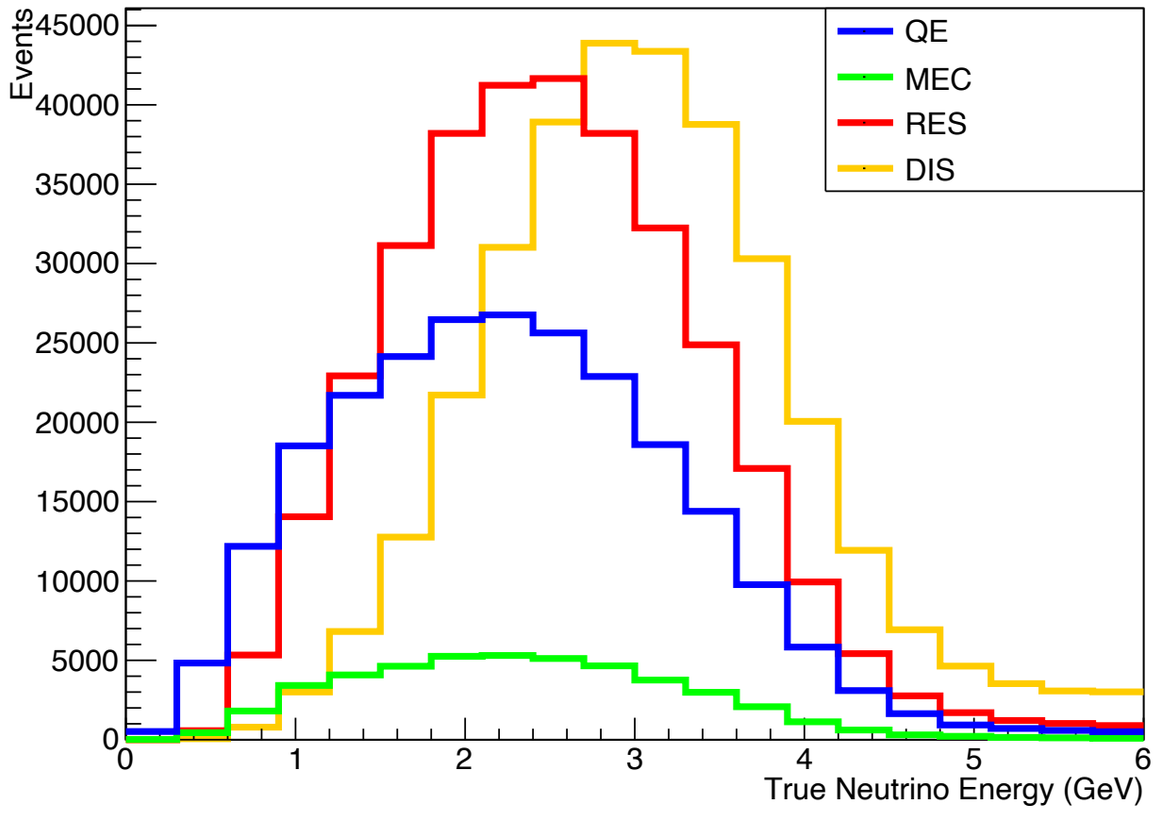
# Relevance for DUNE

- NuMI at ICARUS offers excellent coverage for $\nu_\mu$

## Muon Neutrinos from NuMI




## Spectrum at DUNE Near Detector



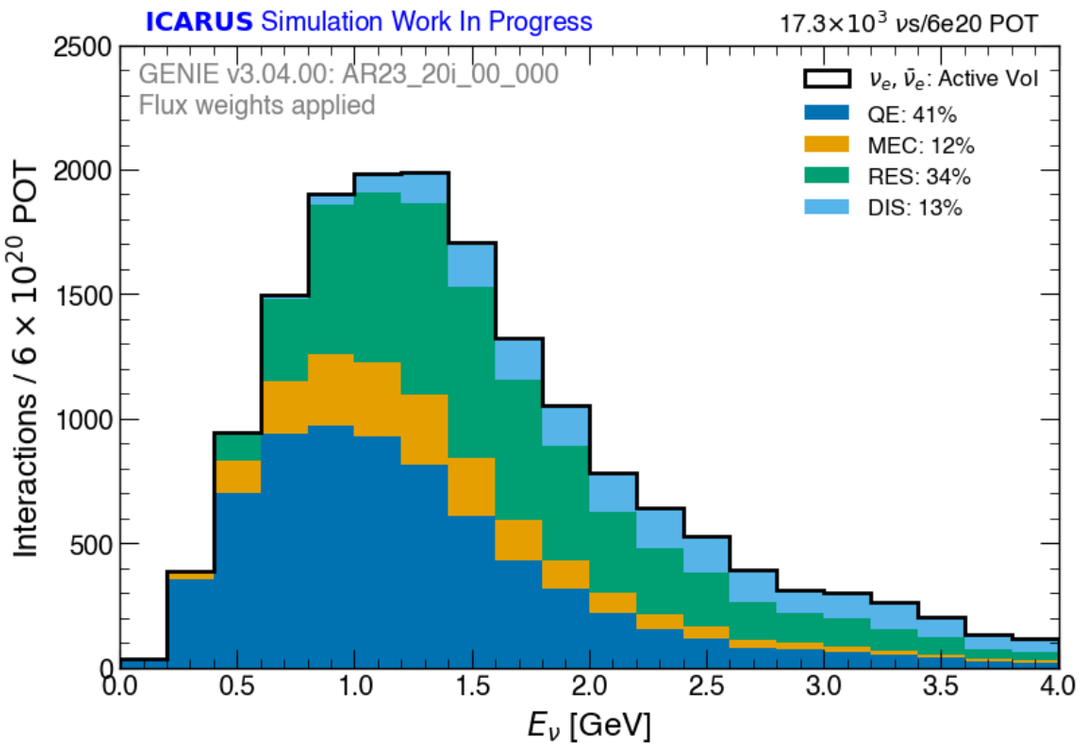



Fermilab

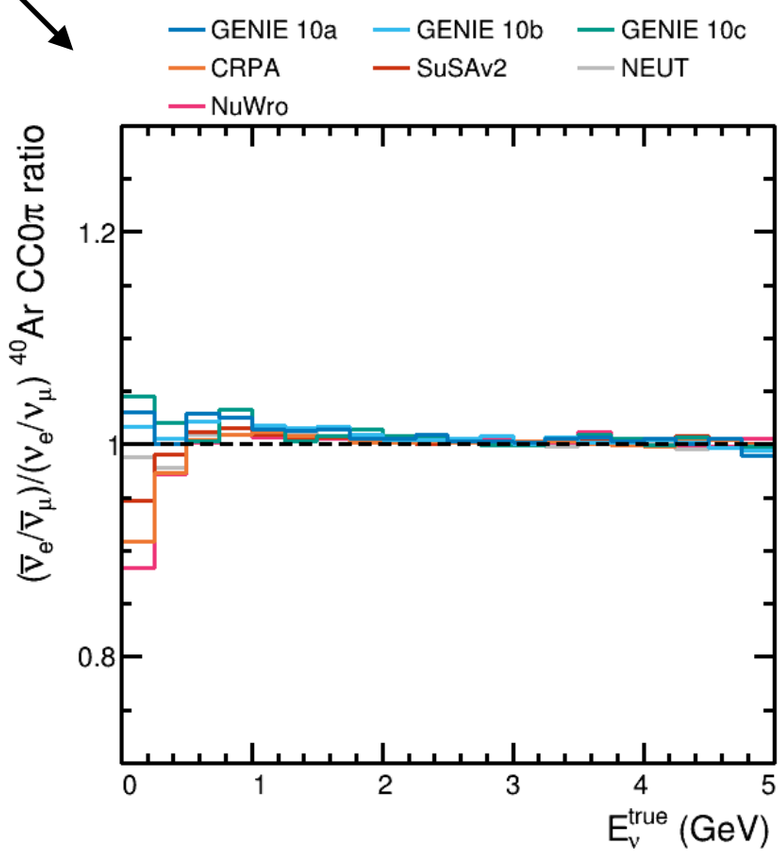
# Relevance for DUNE

- Electron neutrino spectrum from NuMI at ICARUS covers the first oscillation peak and good coverage of the relevant phase space for the DUNE experiment and where we expect to see model differences

**Electron Neutrinos from NuMI**




**Ratios of True energy with different event generators for CC0pi**



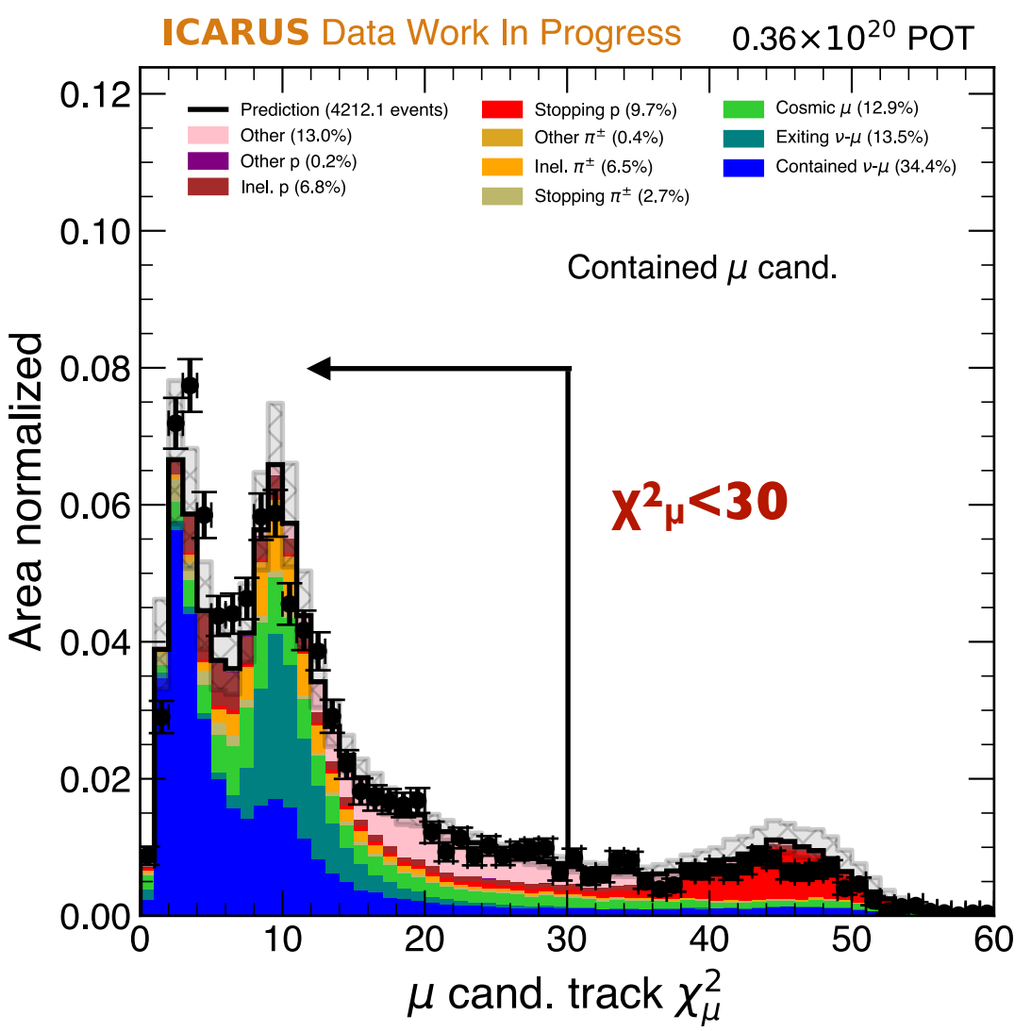

C. Wilkinson

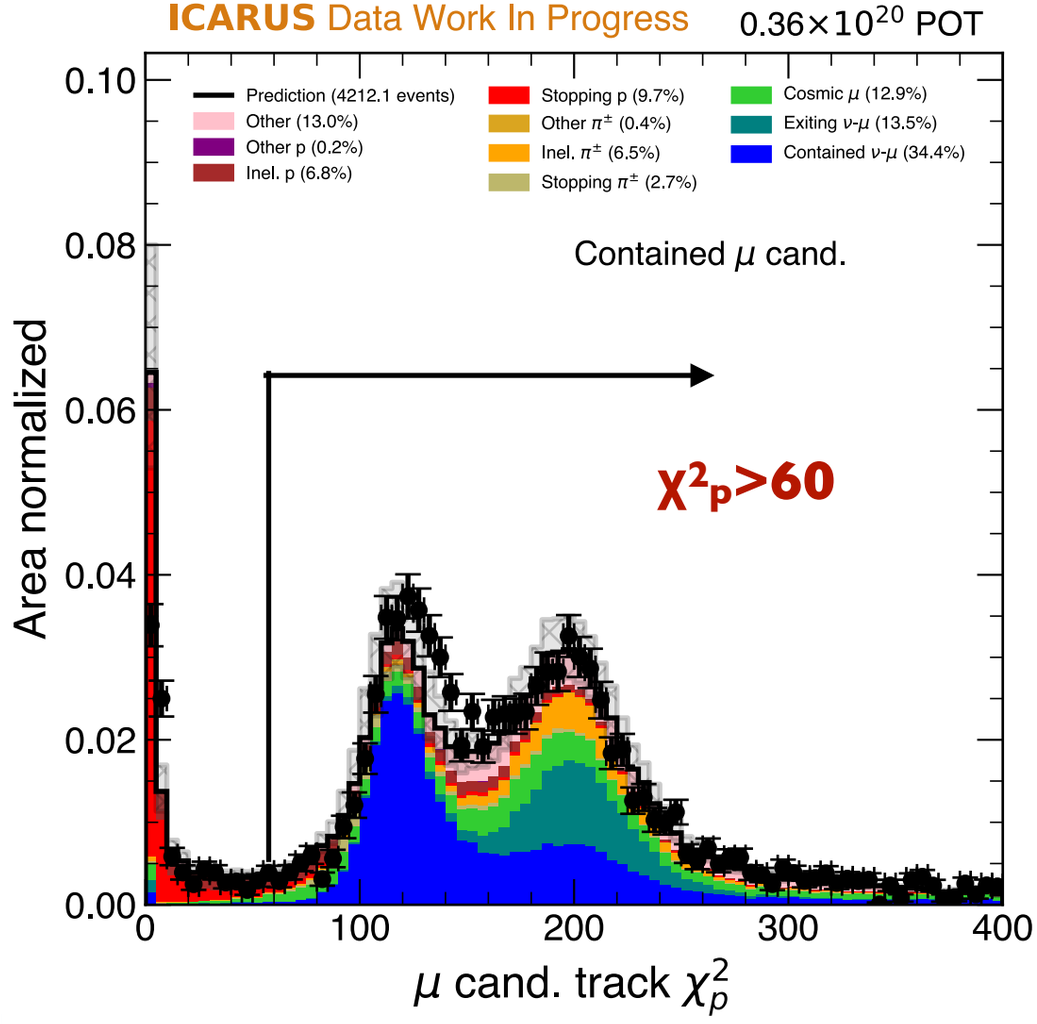
- $\nu_e$ flux is excellently distributed to probe regions of kinematic phase space in which we expect the largest $\nu_e/\nu_\mu$ differences (which is the dominant systematic for DUNE-CP violation measurements)
- Planning to understand and build properly uncertainties with ICARUS data for DUNE

# Selecting CC0$\pi$+Np Events

# CC 0$\pi$ Event selection

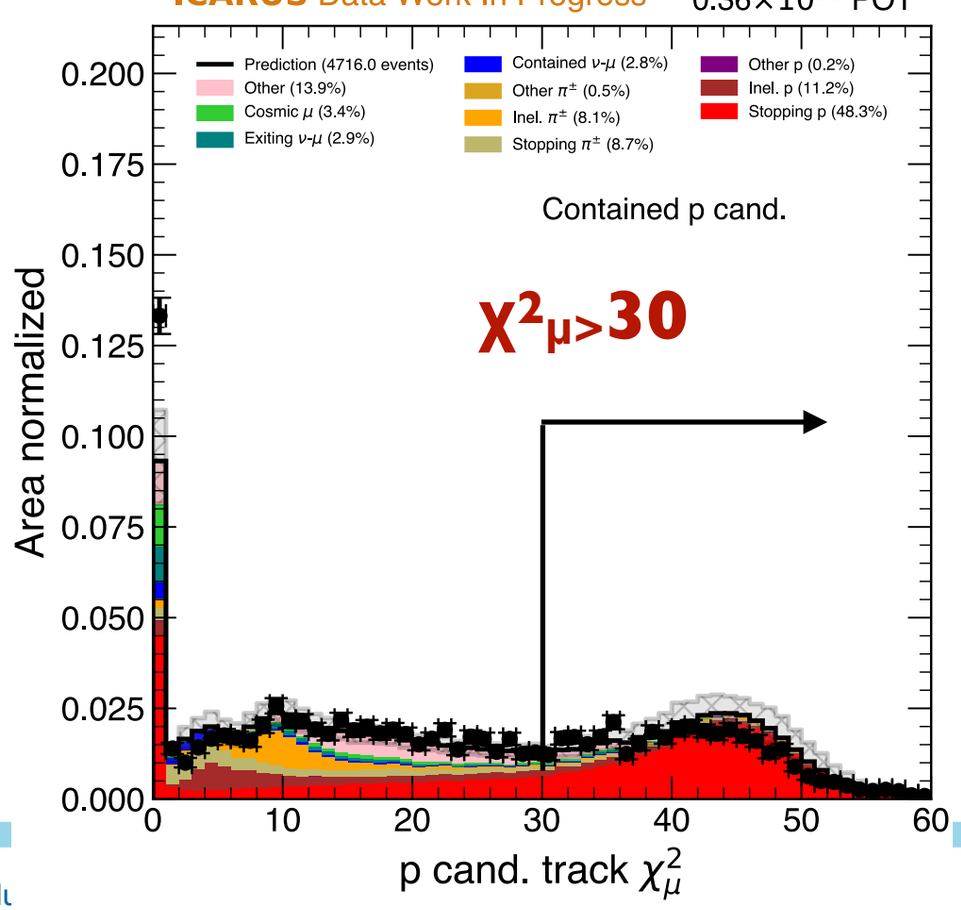
- Requiring the reconstructed vertex to be in fiducial volume (25 cm on sides and top/ bottom, 30 cm upstream and 50 cm downstream)
- Events tagged as clear cosmics by Pandora rejected
- At least two primary tracks
- Muon track, using calorimetric PID scores based on dE/dx profiles
  - $\chi^2_\mu$<30 and $\chi^2_p$>60, length > 50 cm and muon track-like from Pandora

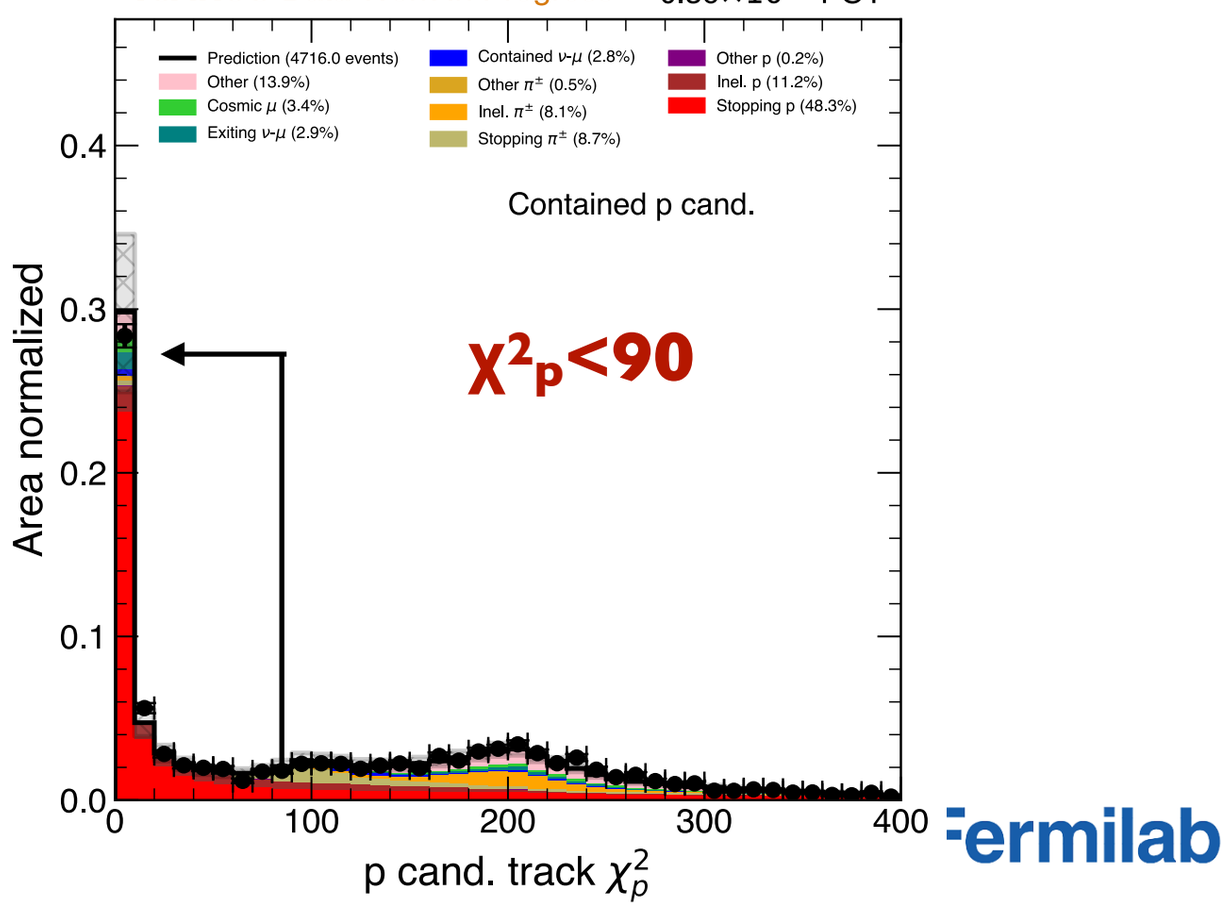


# Event selection

- Requiring the reconstructed vertex to be in fiducial volume (25 cm on sides and top/bottom, 30 cm upstream and 50 cm downstream)
- Events tagged as clear cosmics by Pandora rejected
- At least two primary tracks
- Muon track:
  - $\chi^2_\mu<30$ and $\chi^2_p>60$, length > 50 cm
- Proton track:
  - Contained, $\chi^2_\mu>30$ and $\chi^2_p<90$, proton momentum >0.4 GeV/c and < 1 GeV/c



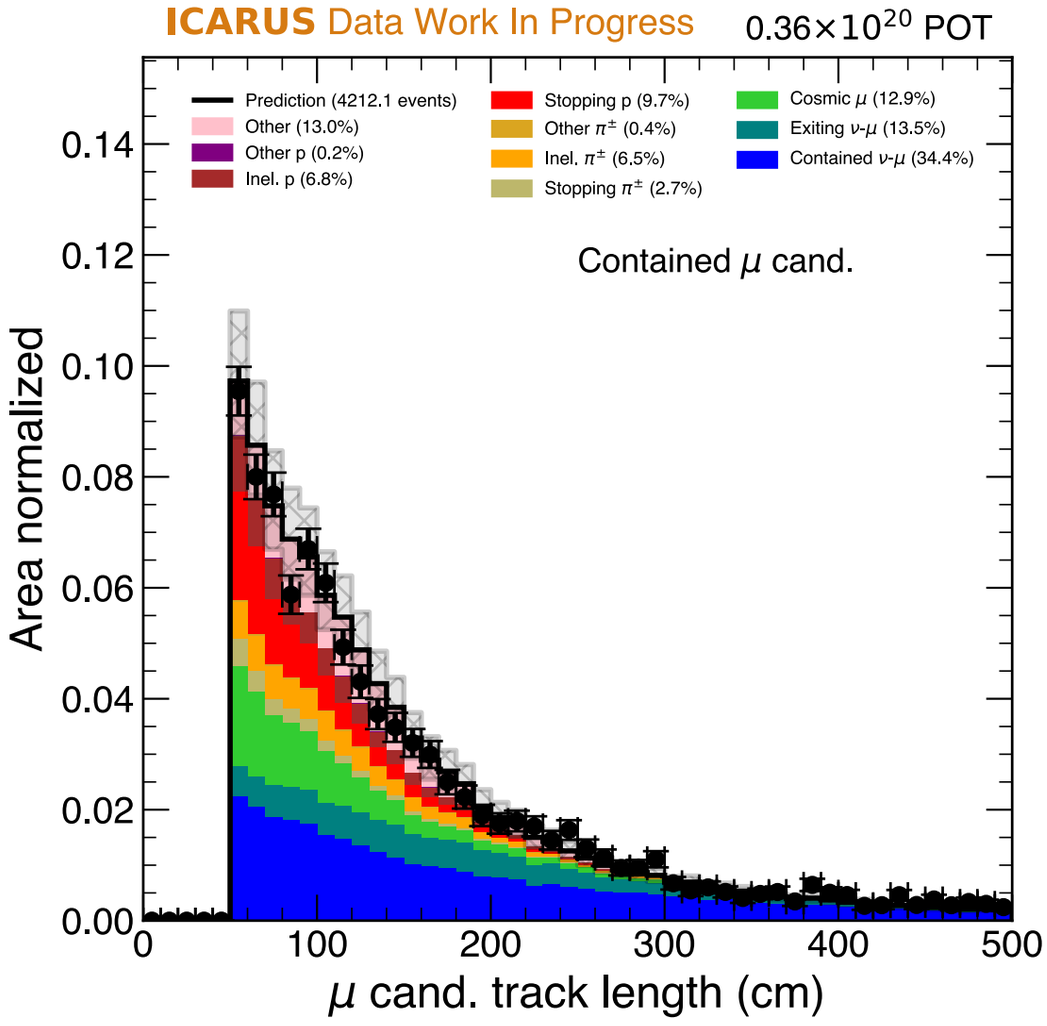



Fermilab

# Studies with Data

- Developing the cross section with small set of the data (15%)
- A selection targeting 1$\mu$+Nproton + anything with some differences in cuts with data samples to highlight cosmic rejection and selected beam events
- Using data taken outside of beam window to make the in time cosmic prediction
- Data versus MC studies ongoing: shown here some relaxed cuts, fairly reasonable comparisons
- Measuring backgrounds/sidebands for analysis (e.g. charged pions)
- Developing and evaluating systematic uncertainties, using GENIE v3.04.00 with the latest development shared from DUNE

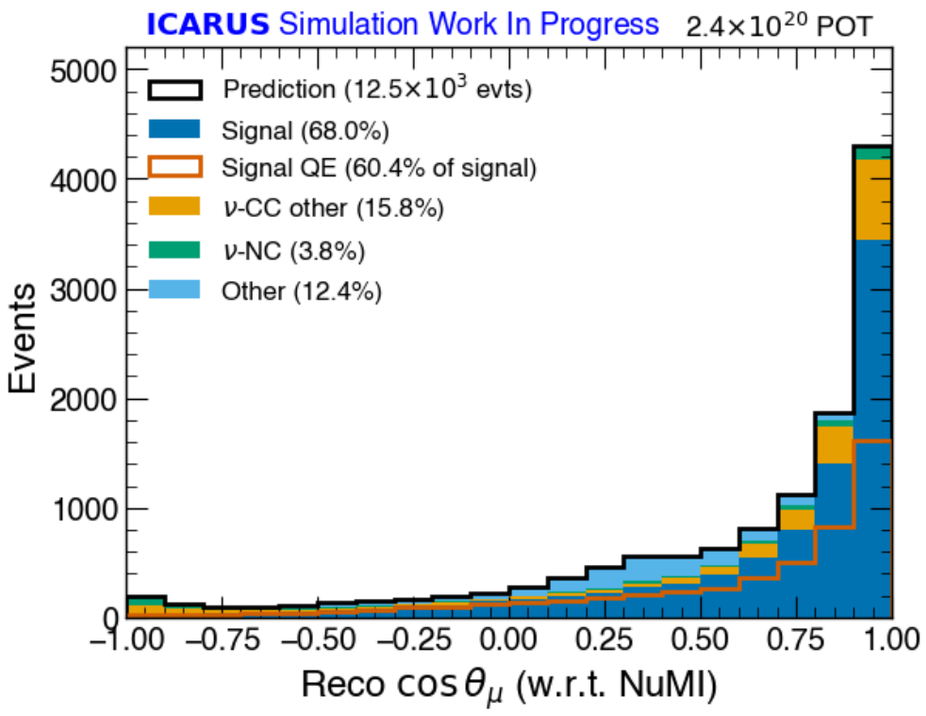
**15% of data**

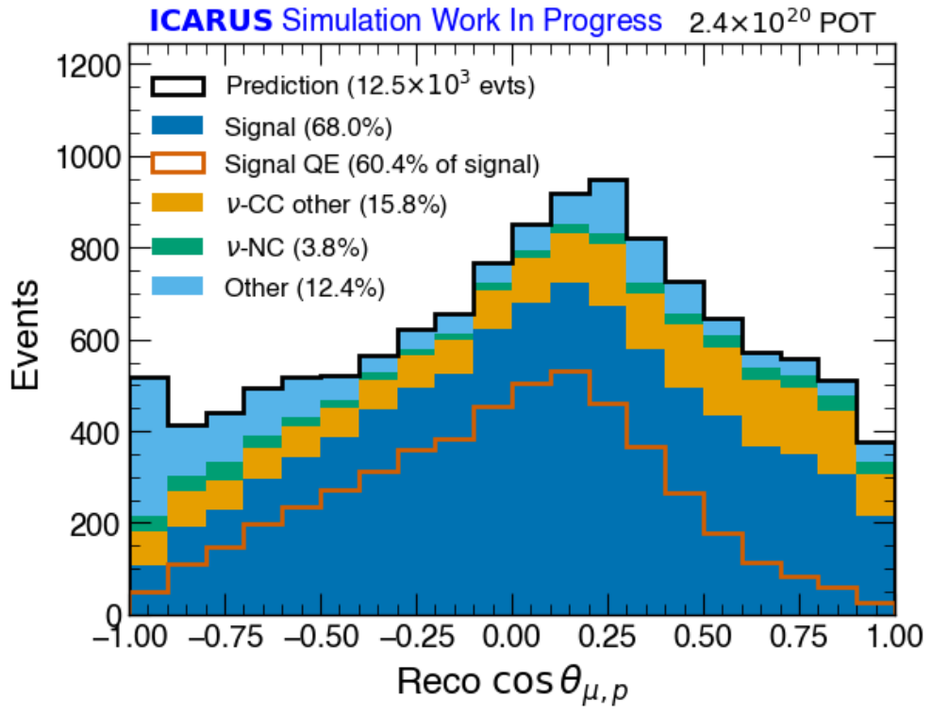


# CC0$\pi$+Np: Our first Cross-section Analysis

# CC 0$\pi$ Selected Sample

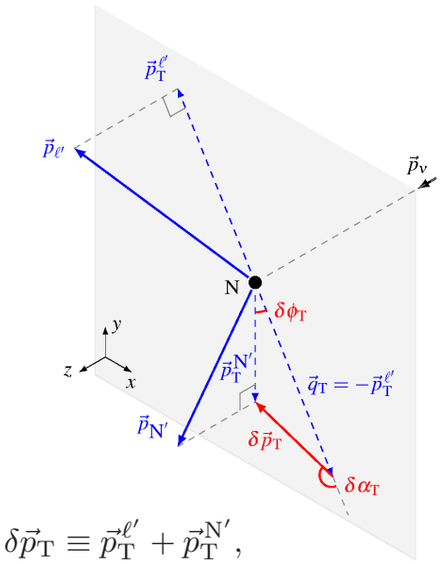
- First analysis targets 1$\mu$+Nproton+0$\pi$
  - 1$\mu$+Nproton+0$\pi$, N>0 enhanced in quasi-elastic and 2p2h interactions
- Building up cross-section analysis to conduct model investigations
- Angle between the muon candidate and leading proton candidate populates the phase space somewhat broadly and would be expected to encode information about FSI for all events
- Signal definition: One muon with momentum > 226 MeV/c, any proton with momentum between 400 MeV/c and 1 GeV/c, no charged or neutral pions in the final state
- Events with contained and exiting muons



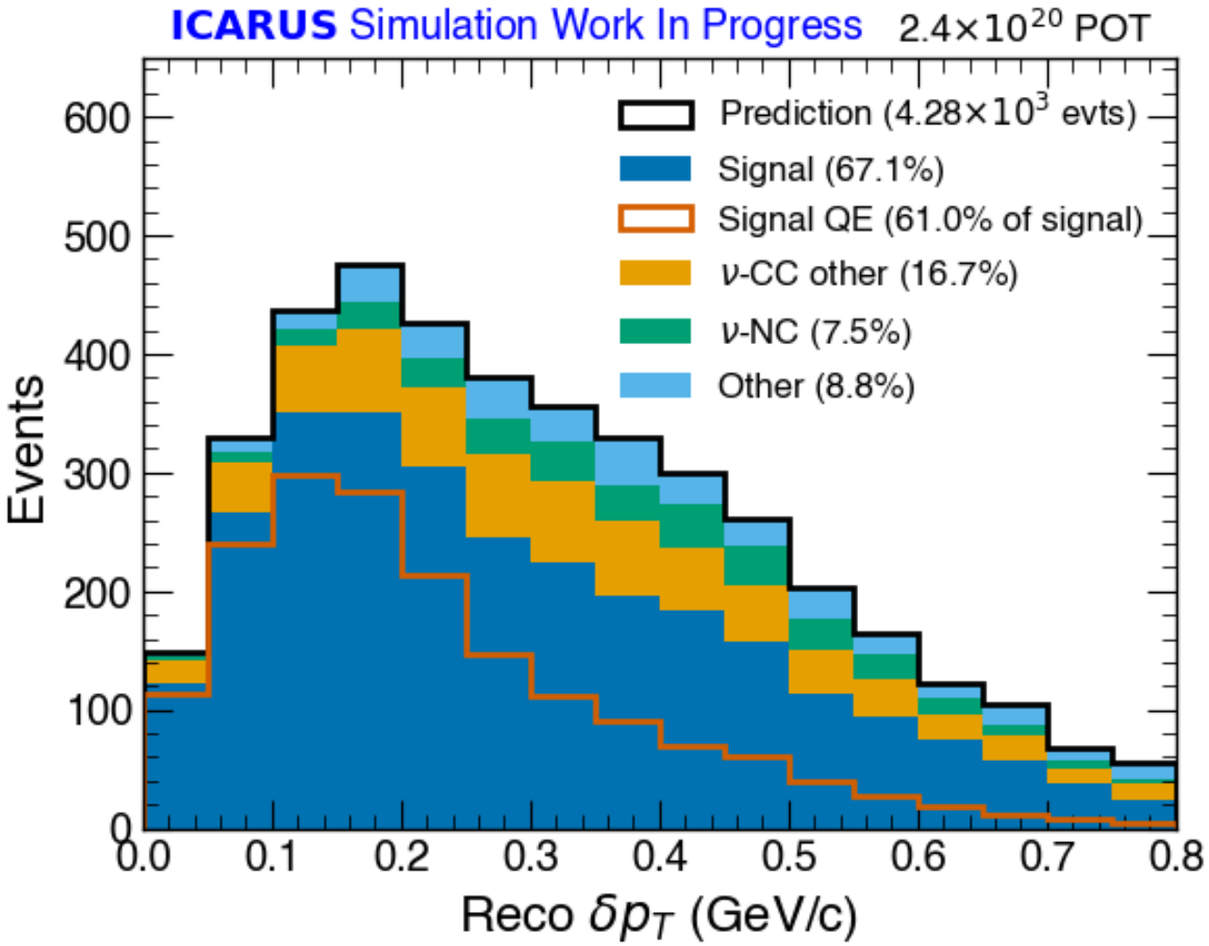
# CC 0$\pi$ Event Selection for fully contained Events

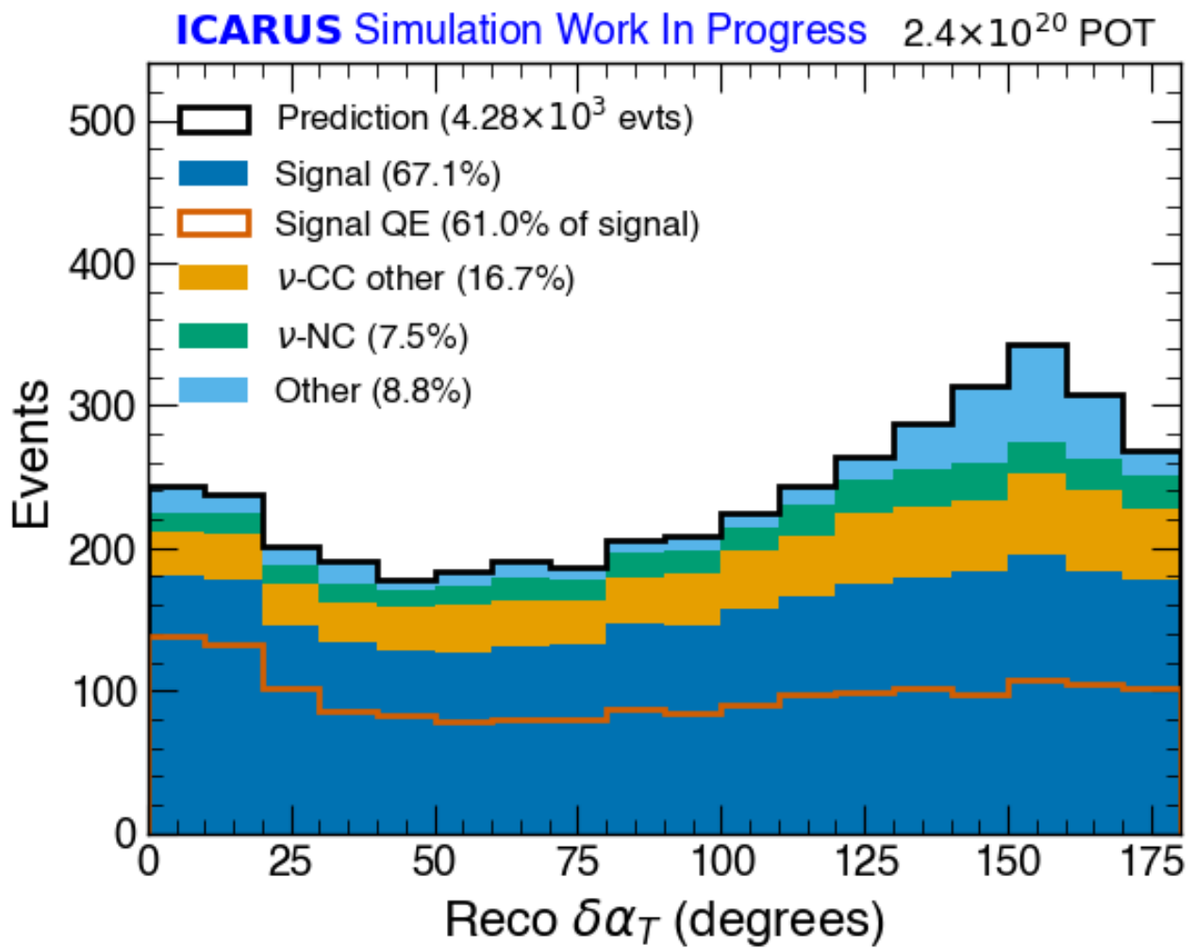
- Transverse kinematic imbalance observables $\delta P_T$ and $\delta\alpha_T$ for fully contained events, using the leading proton
  - Observables sensitive to initial and final state effects
- Events with contained muons and protons
- Main background is events with pions




$$\delta\vec{p}_T \equiv \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'},$$

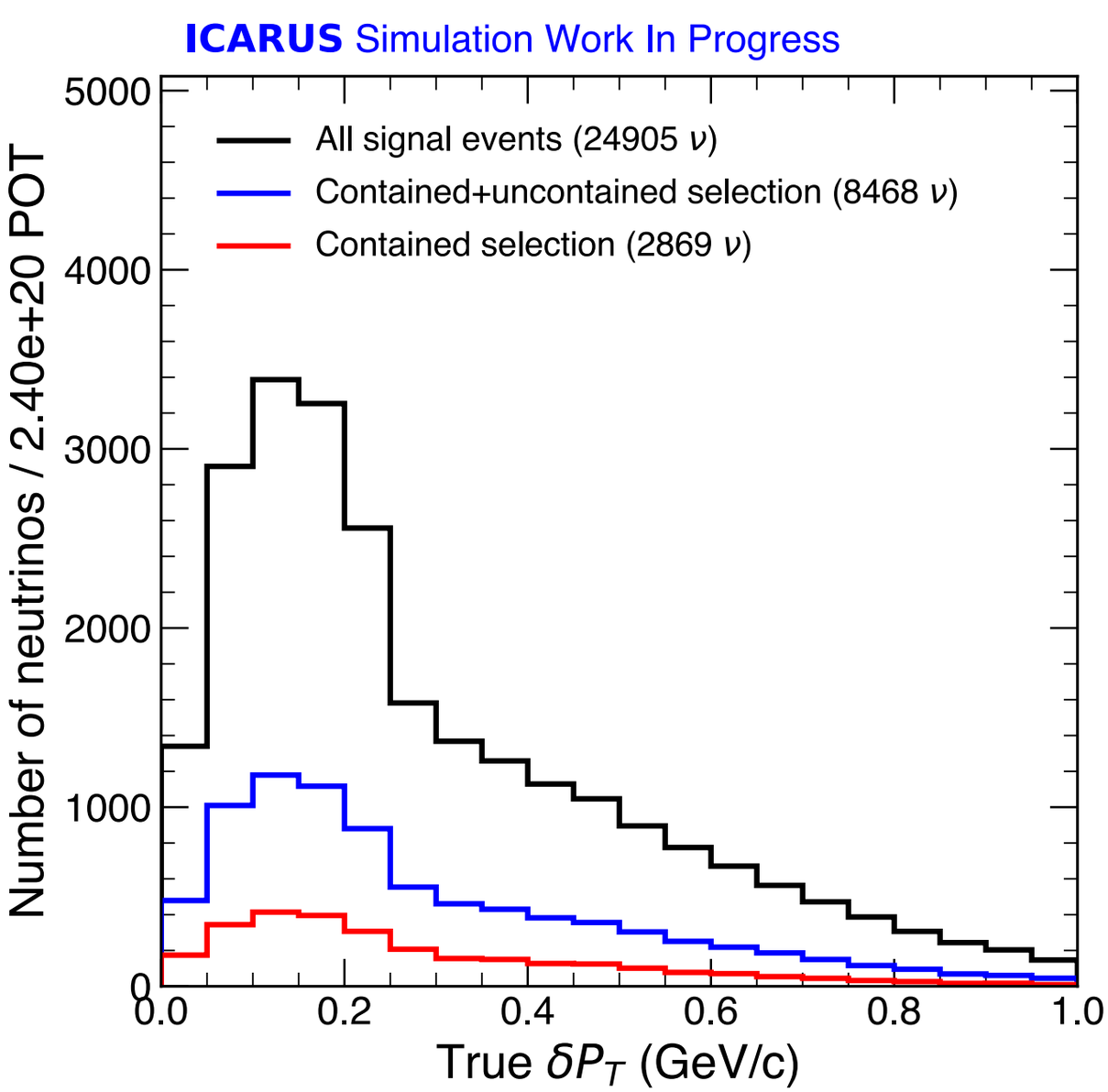
$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\delta p_T},$$

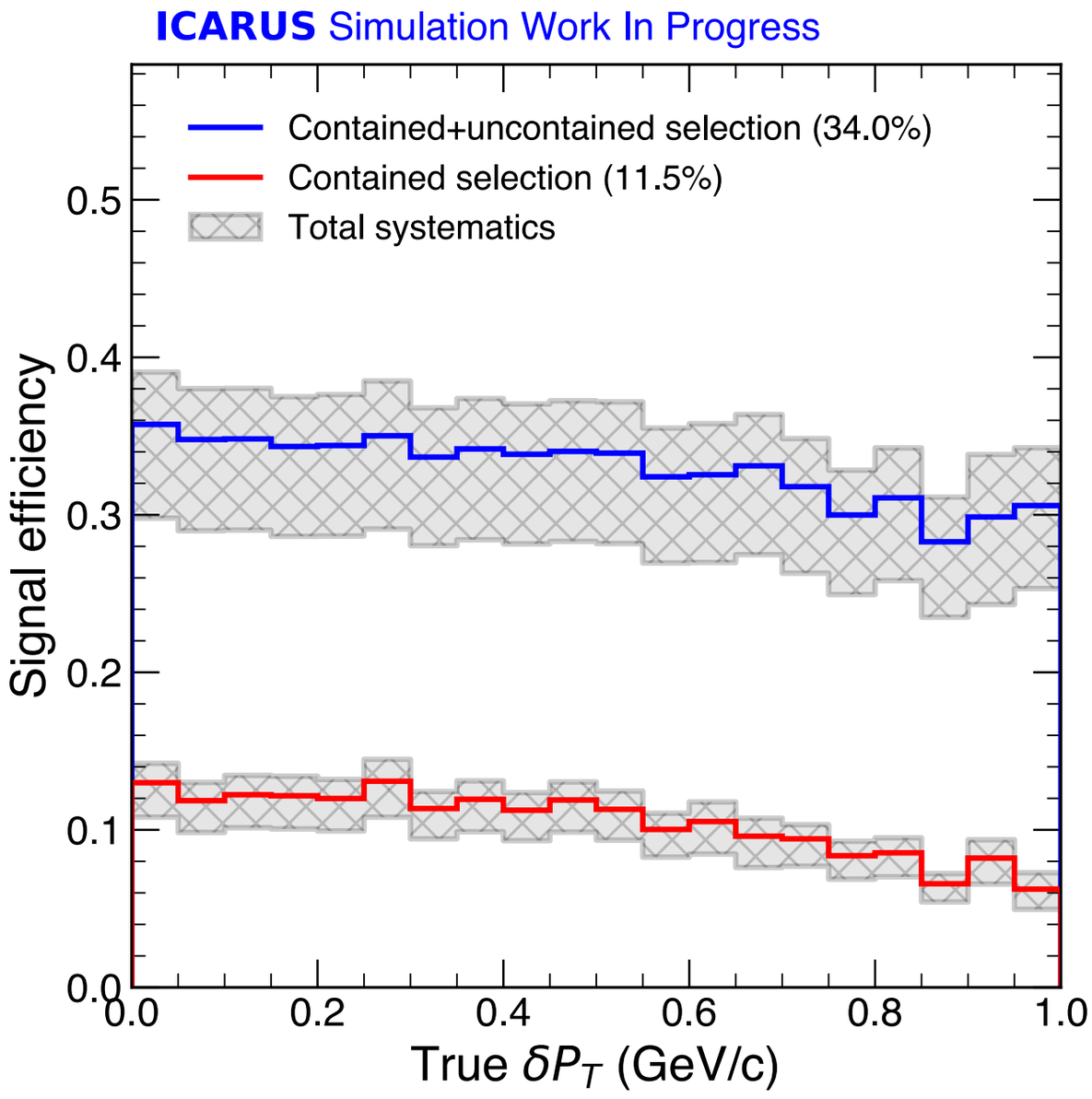


# Efficiencies

- Efficiencies for both samples: contained plus exiting muons and fully contained muons






Fermilab

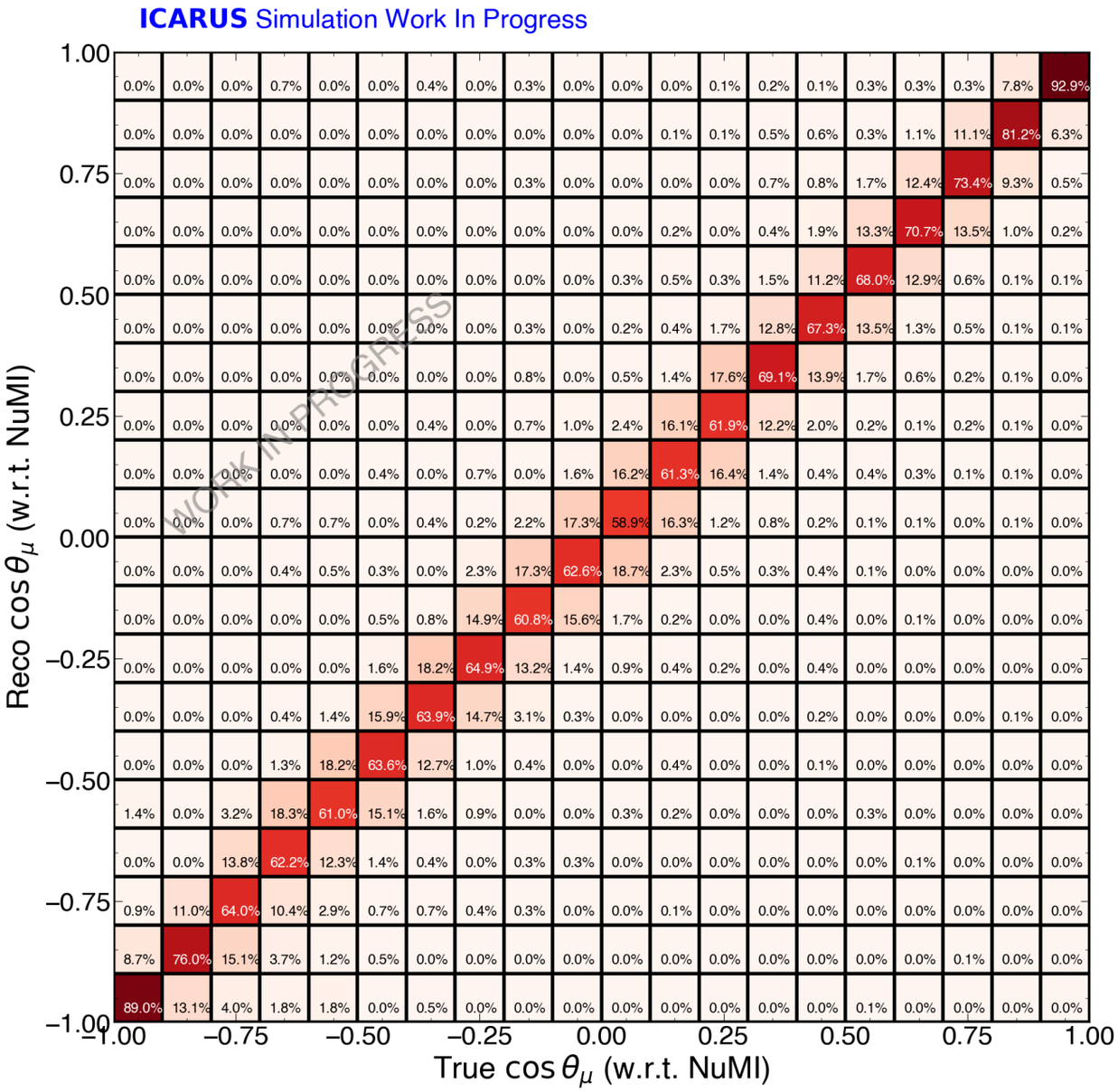
# CC 0$\pi$ Selected Sample

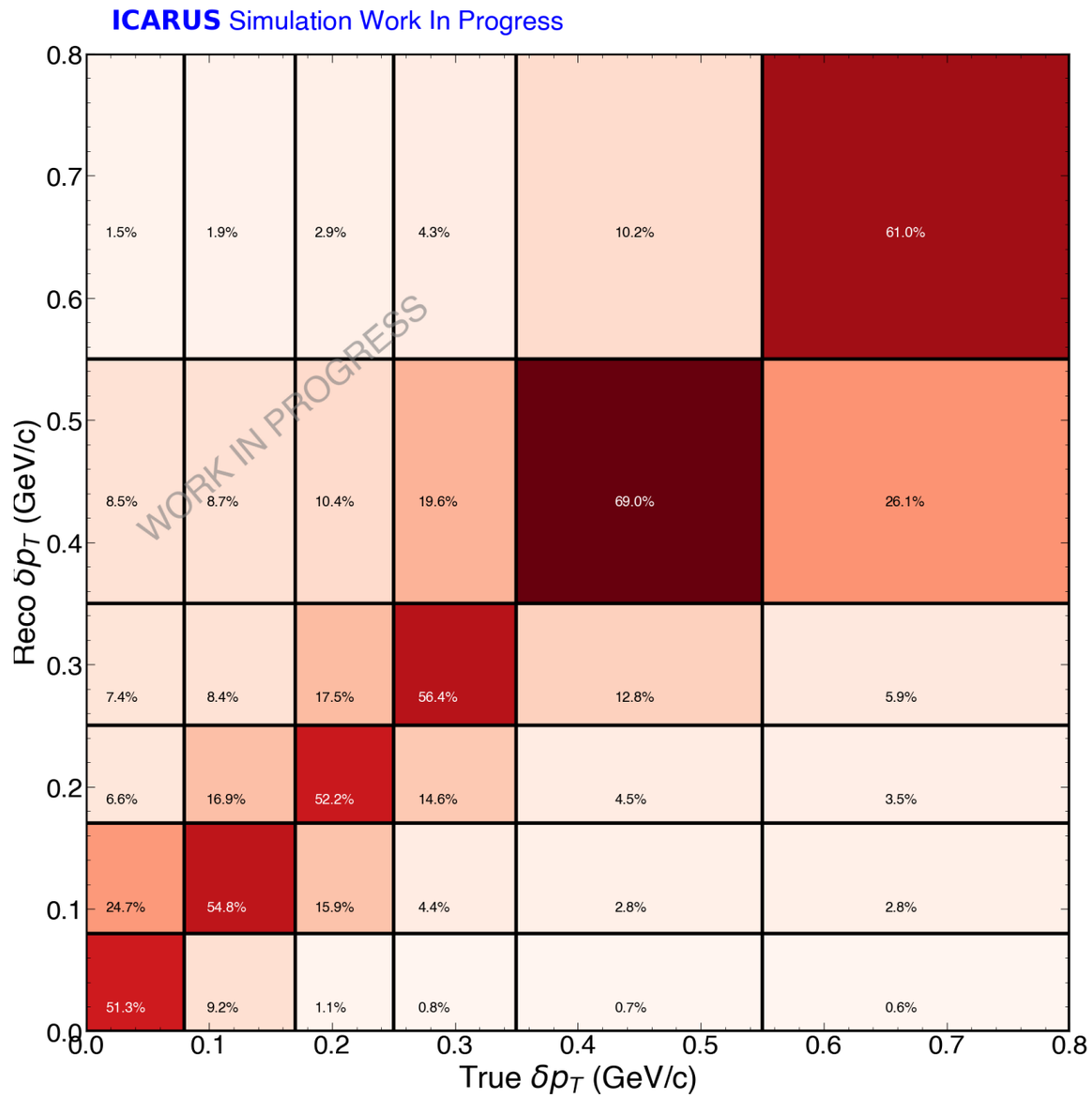
- The selected sample has ~12500 interactions with contained and exiting muons and ~4000 with fully contained muons in hand right now
- More data with antineutrino mode (RHC) is being collected now
- Efficiency for the uncontained sample: 34%
- Efficiency for the fully contained: 11%
- This measurement fills a crucial gap in CC0$\pi$+proton measurements: T2K: lower E CH, MINERvA: higher E CH, uBooNE: lower E Argon, ICARUS: higher E Argon
- Having these wide range of measurements helps lift degeneracies between nuclear effects (e.g. FSI and 2p2h have different A scaling)

# Migration Matrices

- Migration matrices for both samples as a function of cos$\theta\mu$ and $\delta P_T$

## Reconstructed versus True



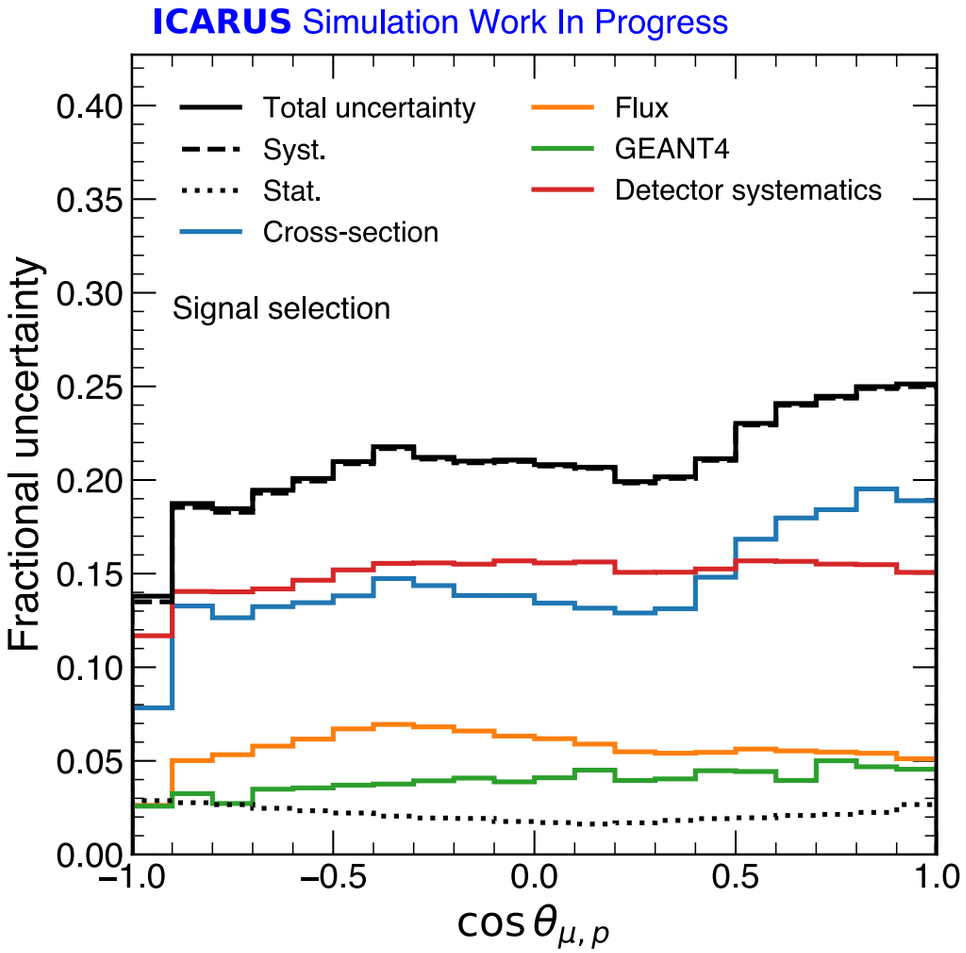

- Pretty good migration matrix to perform a cross measurement

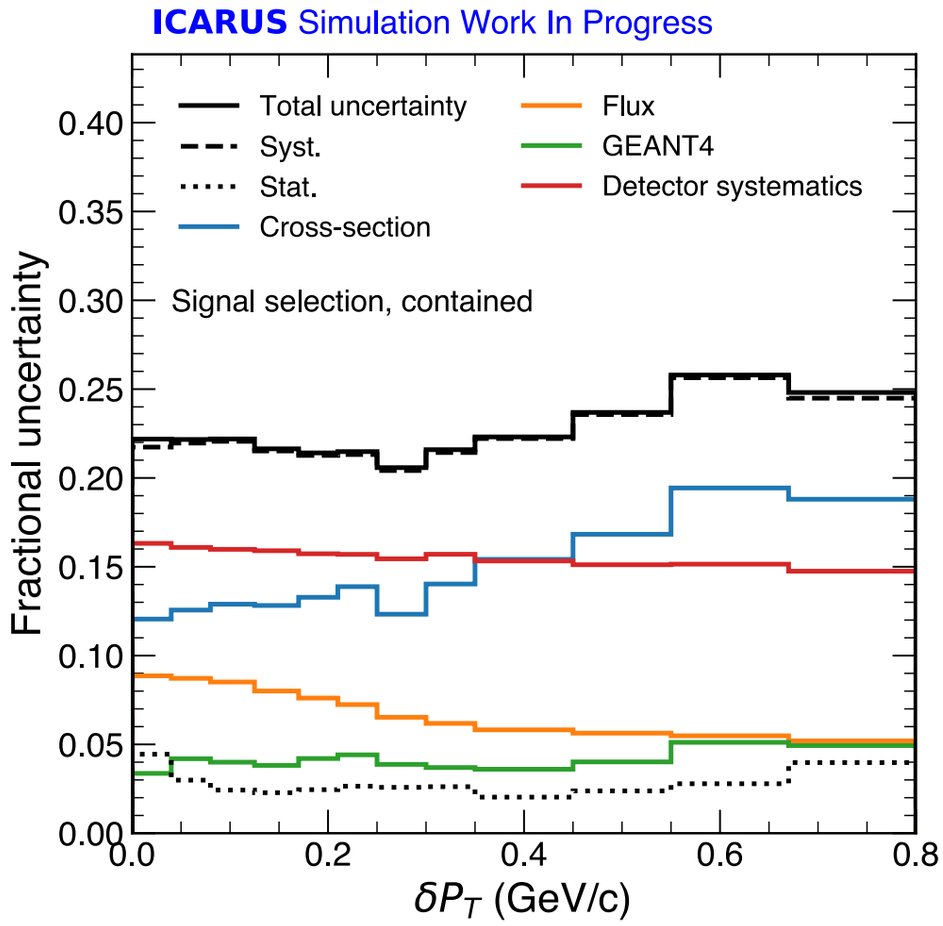


Fermilab

# Systematic Uncertainties

- Several systematics uncertainties have been evaluated: Flux systematics, GENIE, Geant4 and detector systematics
- Systematics from nuclear effects NuSystematics (DUNE) and remaining detector systematics will be evaluated soon
- Uncertainties on the reco-level distributions

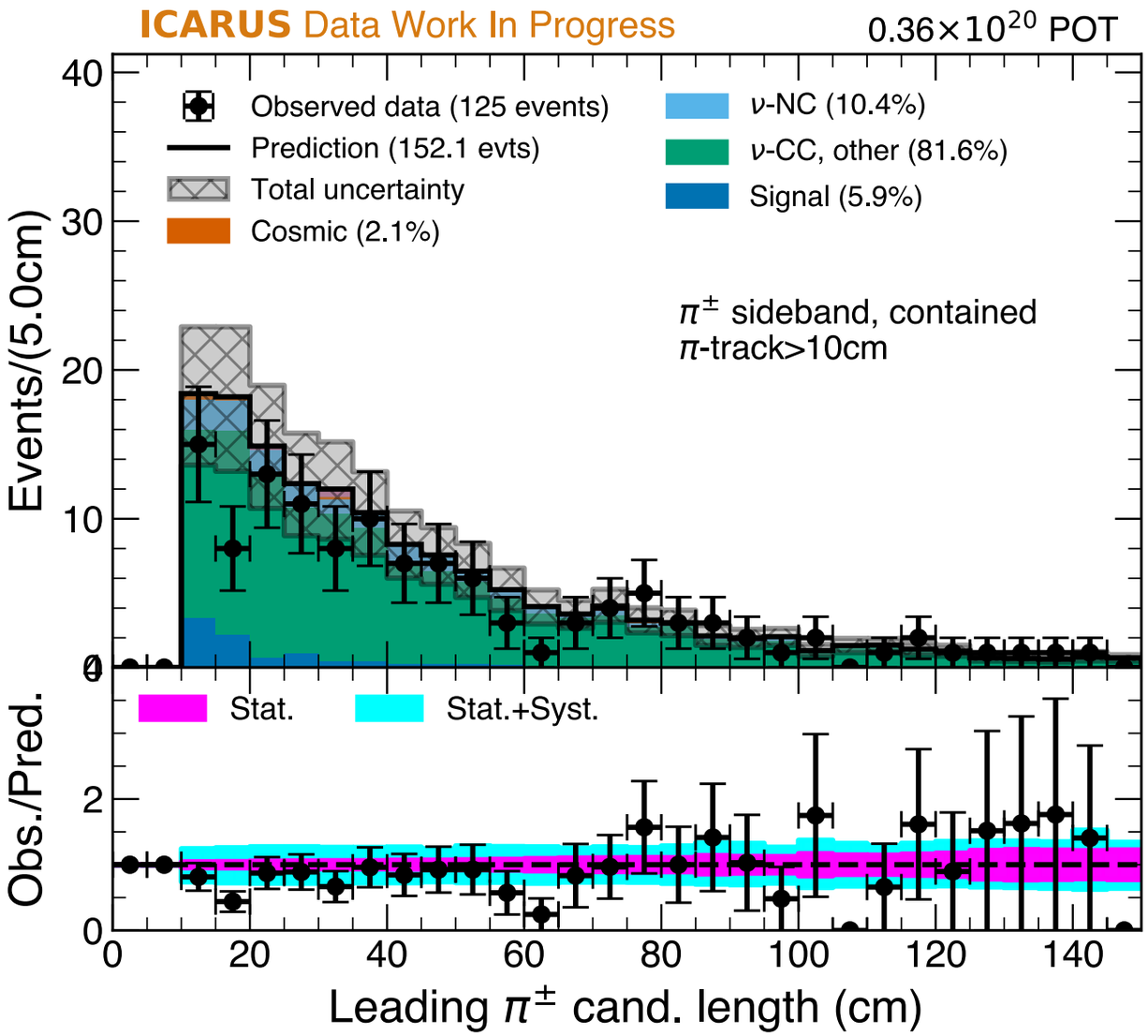


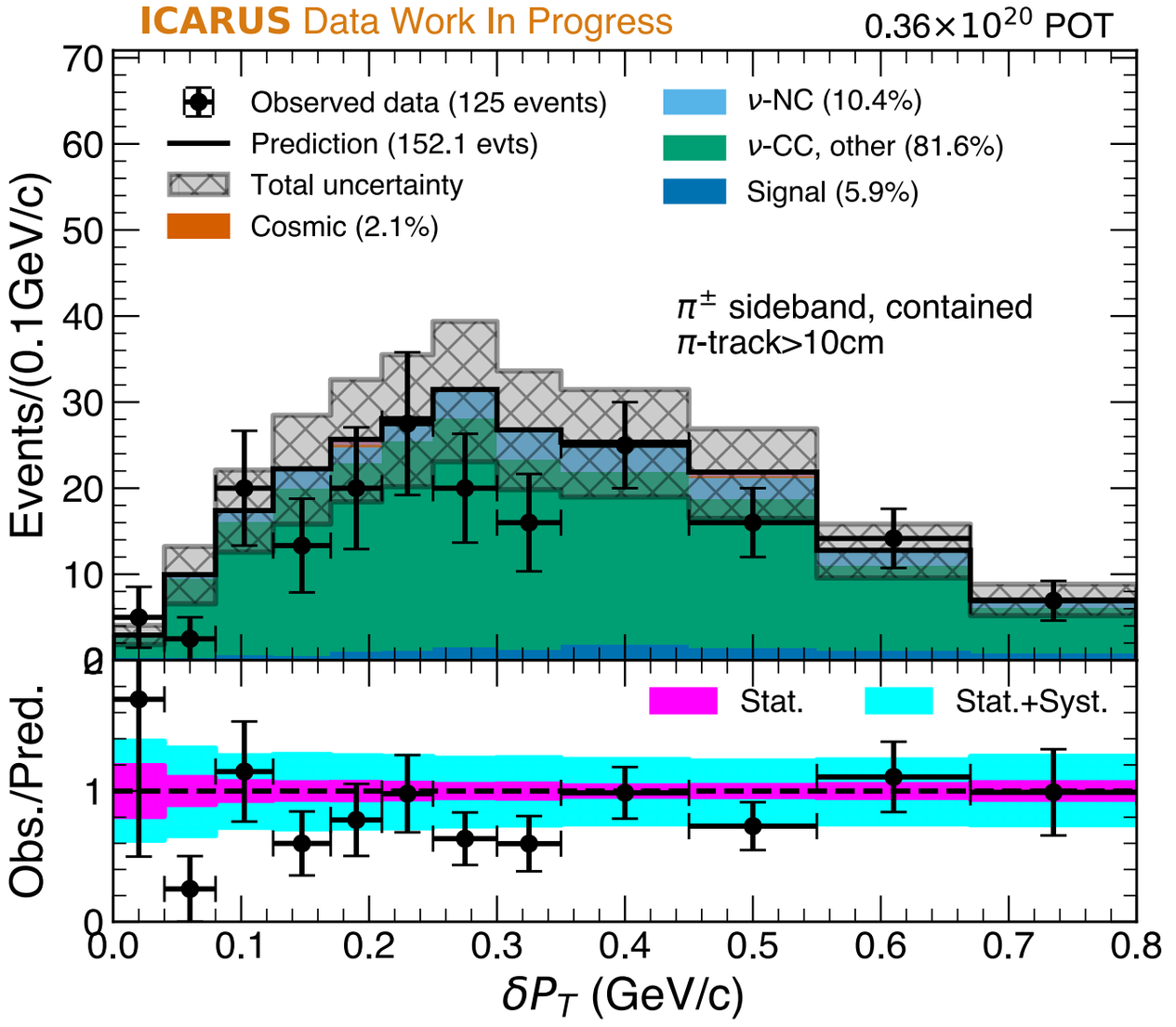



# Charged Current Pion Control Sample

**15% of data**

- Major background for the selected sample is events with pions
- Developed a control sample  with pion candidates (secondary muon-like track)



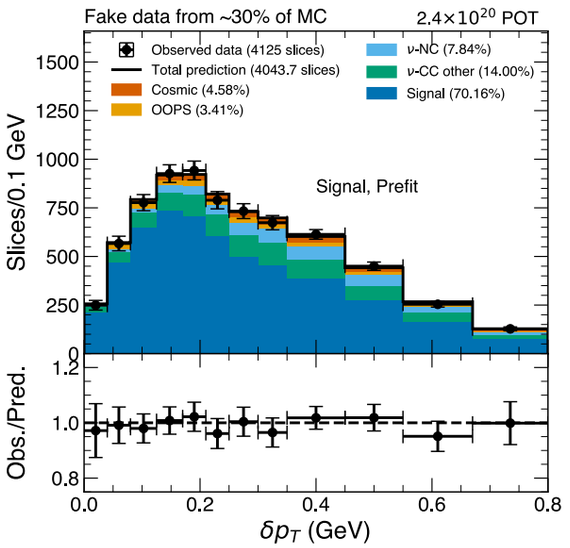

- Using external data sets from MINERvA to constrain the pions at low pion momentum and evaluate systematic uncertainties

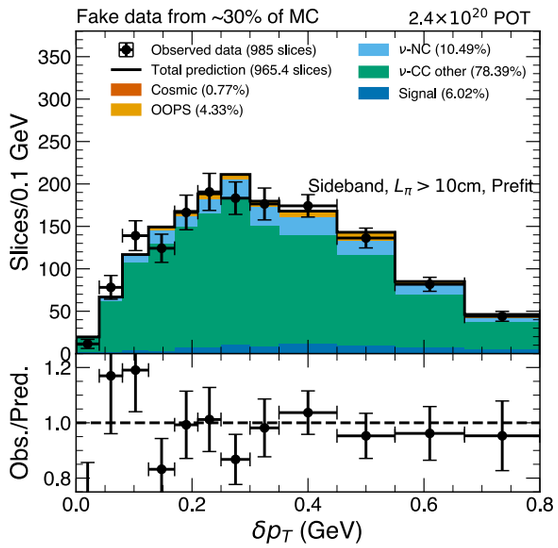


Fermilab

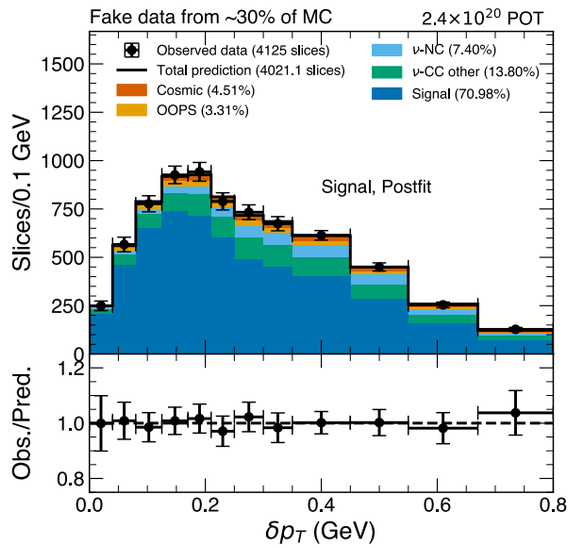
# Fitting

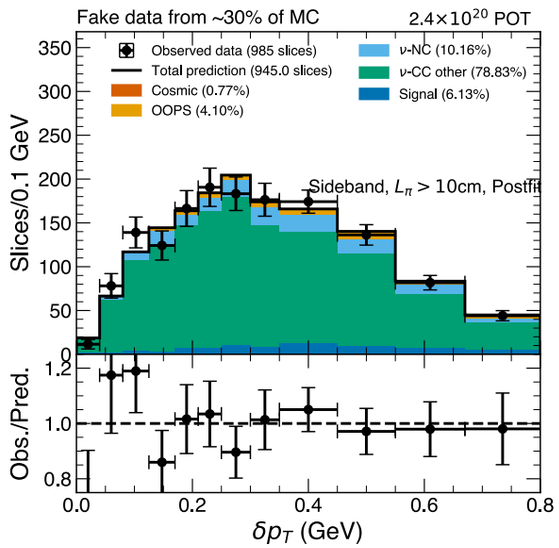
- Using the open-source GUNDAM fitting tool first developed within T2K
- Fake data studies with the fitter (before the extraction step):
- Asimov, fake data, pulled values, evaluating different GENIE models
- Example: Fake data from picking ~30% of existing MC




**Prefit**




**Postfit**

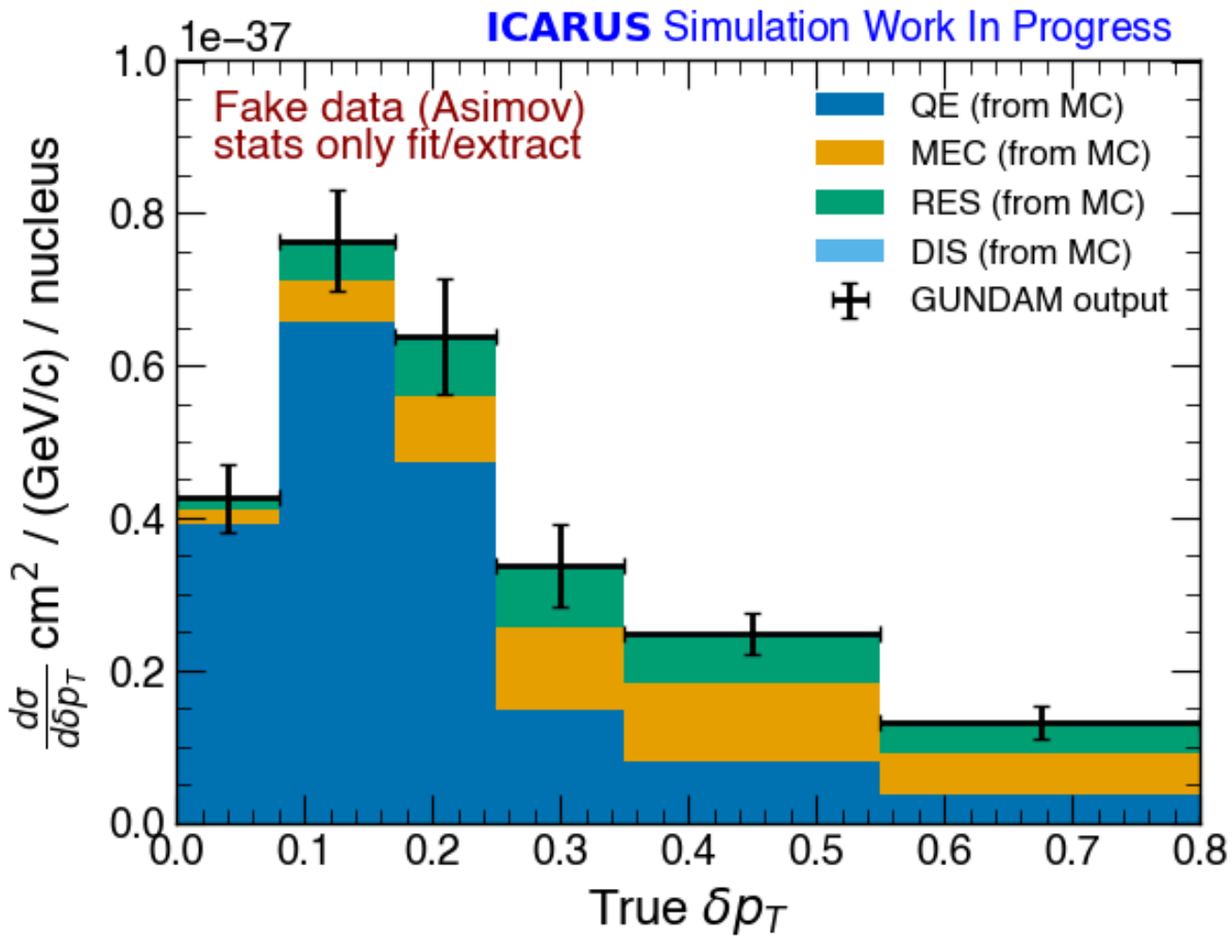
- Evaluate the fits with different fake data studies, pulling the systematics
- Changing normalization and flux

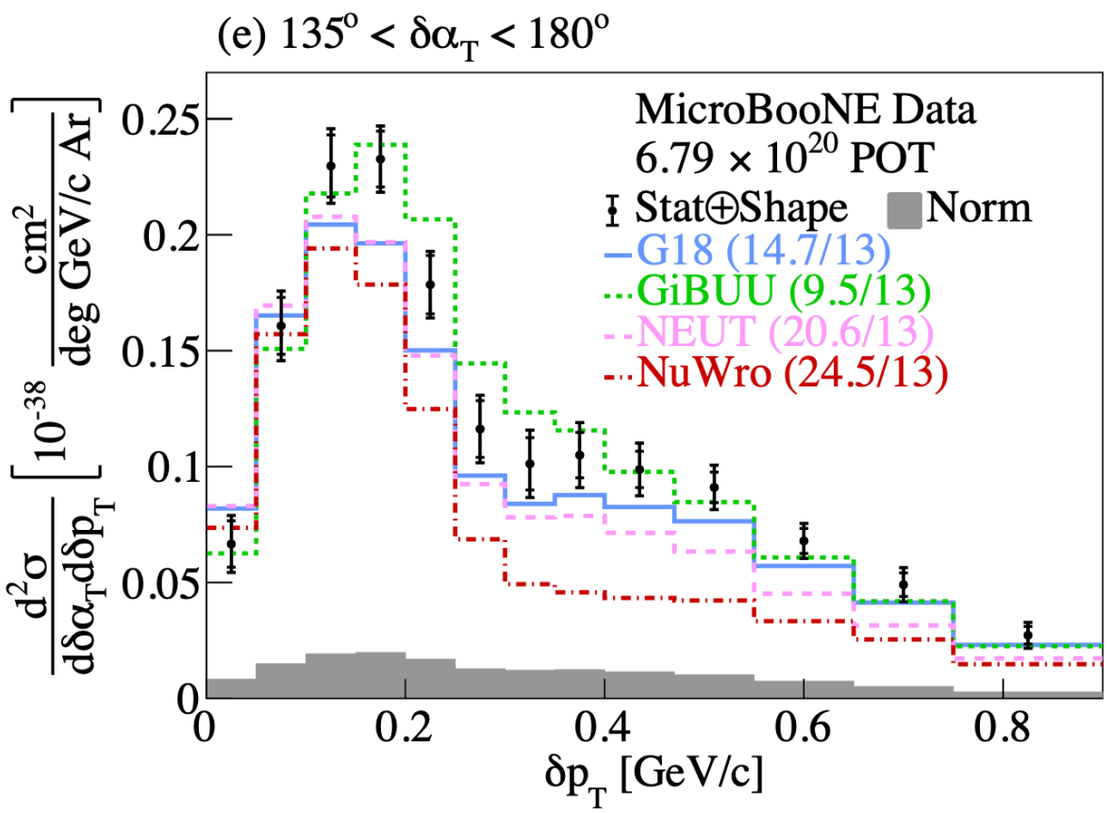


Fermilab

# Cross Section Extraction

- Many components in place to extract the cross section, including control sample to constrain the main background (pion), several systematic uncertainties evaluated, fitting and cross section extraction with closure test using fake data sets
- Fake data extracted single differential cross section with expected data ~3E20POT




Phys. Rev. D 108, 053002

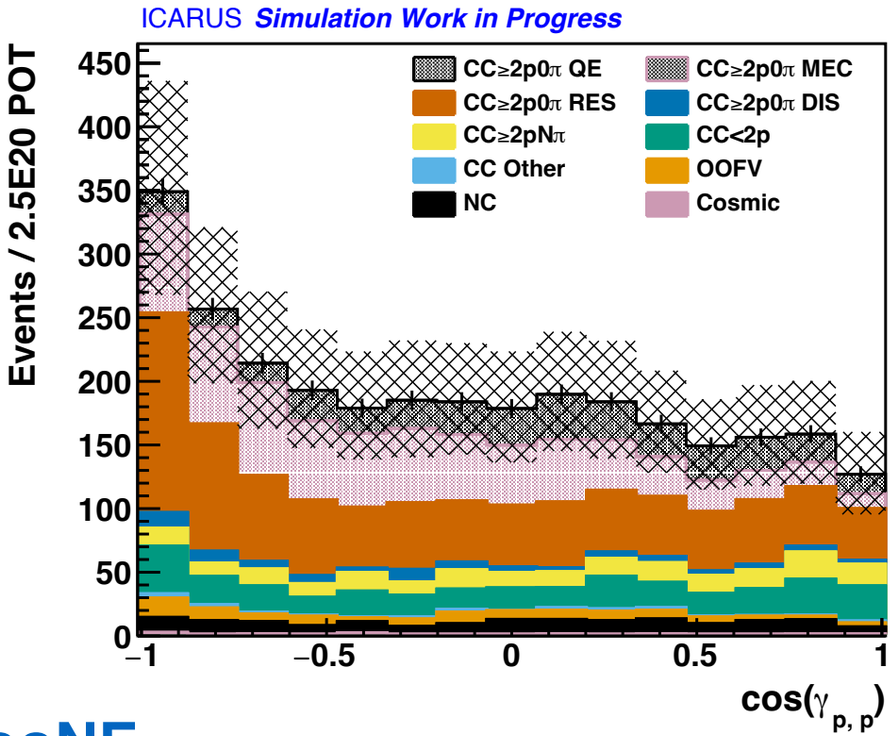


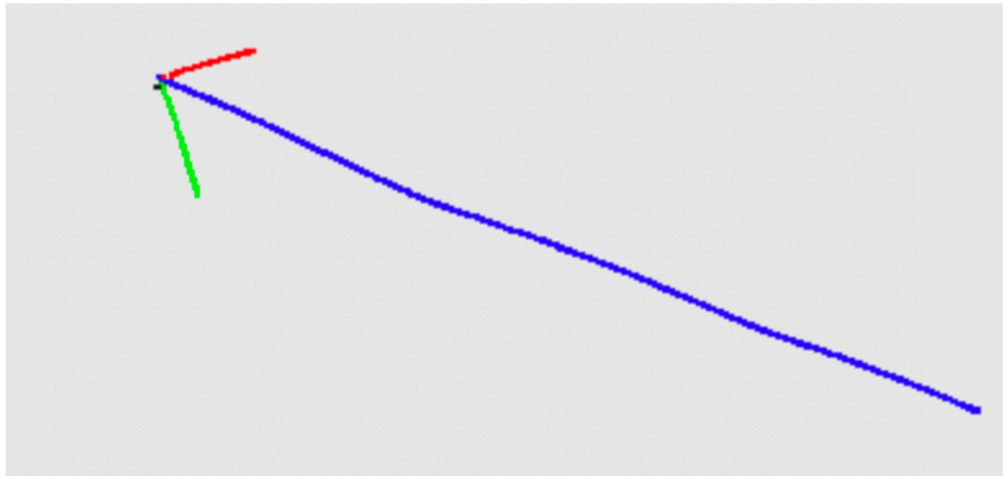
Fermilab

# Other Ongoing Analyses: CC0$\pi$>2p, CC Inclusive and CC Electron Neutrino

# Muon Neutrino 0$\pi$ with 2 protons in Progress

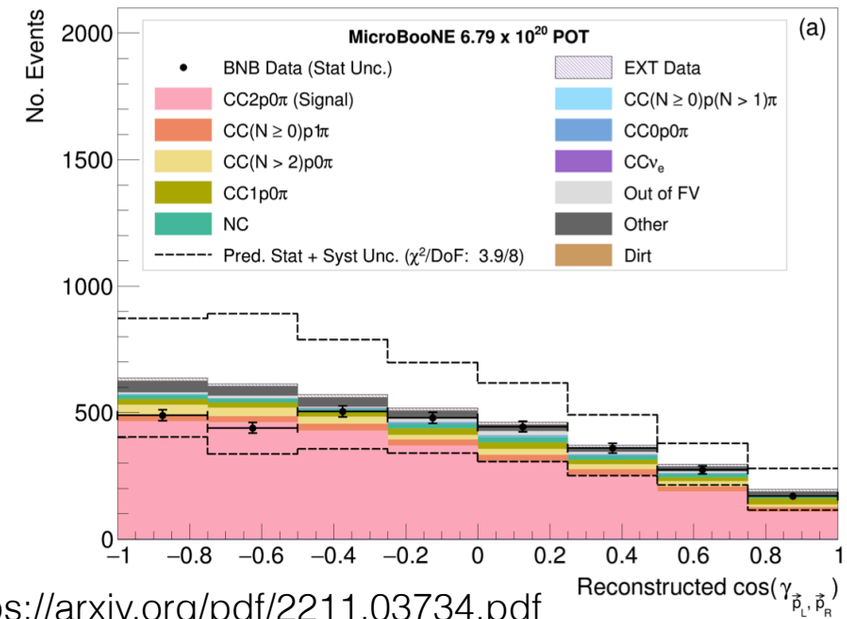
- CC 0$\pi$ with 2 protons, excellent sample to probe initial and final states effects



- Event selection for CC 0$\pi$ 2p uses:
  - Vertex in fiducial volume
  - Hadronic system is fully contained
  - Muon candidate and at least two proton candidates
  - No other primary tracks/showers longer than 10 cm

**MicroBooNE**



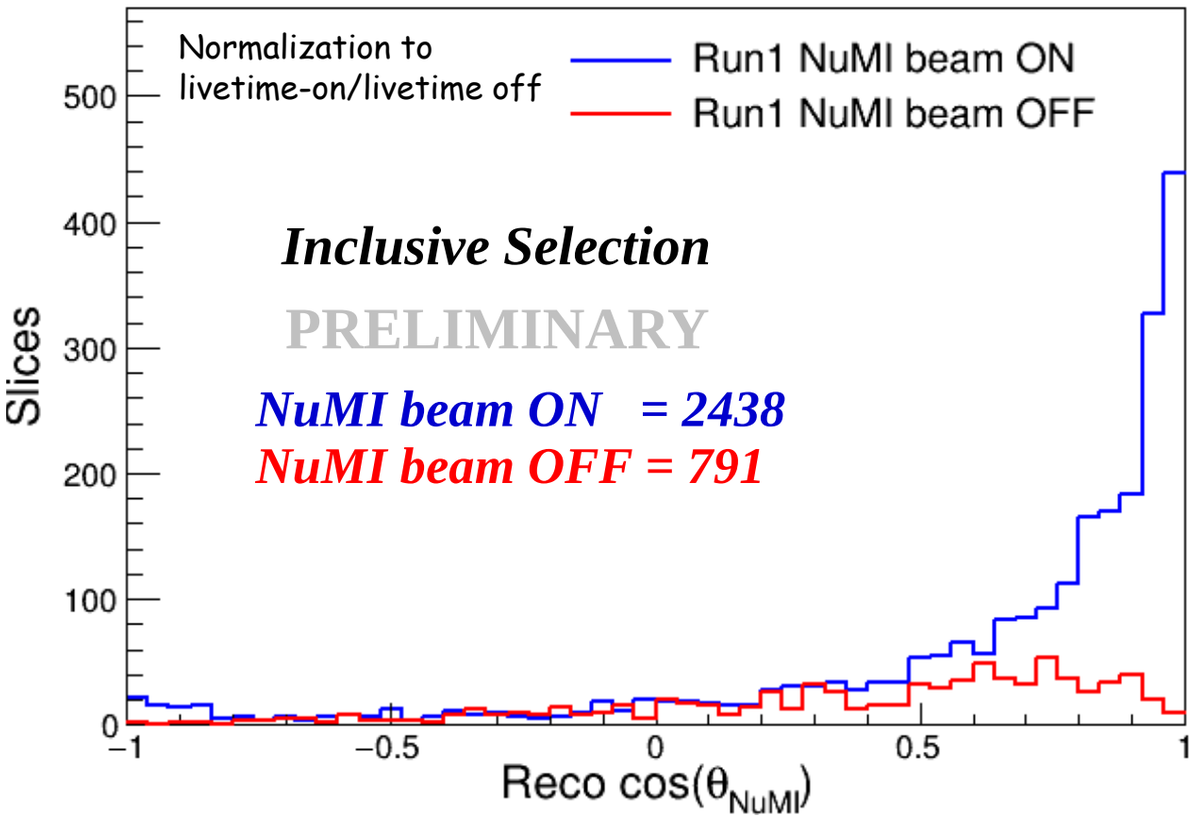

https://arxiv.org/pdf/2211.03734.pdf

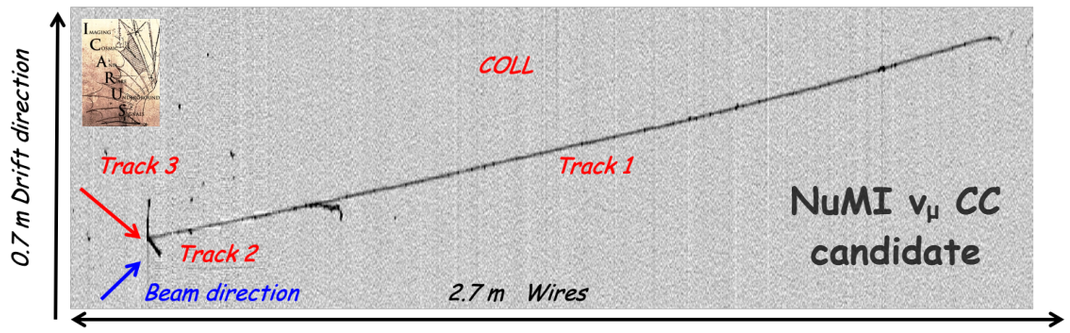


Fermilab

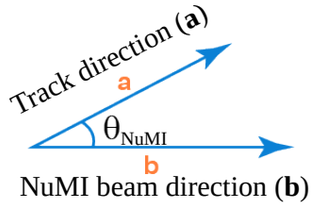
# Muon Neutrino CC Inclusive in Progress

- Analyses looking at muon information for different processes
- Charged current inclusive analysis



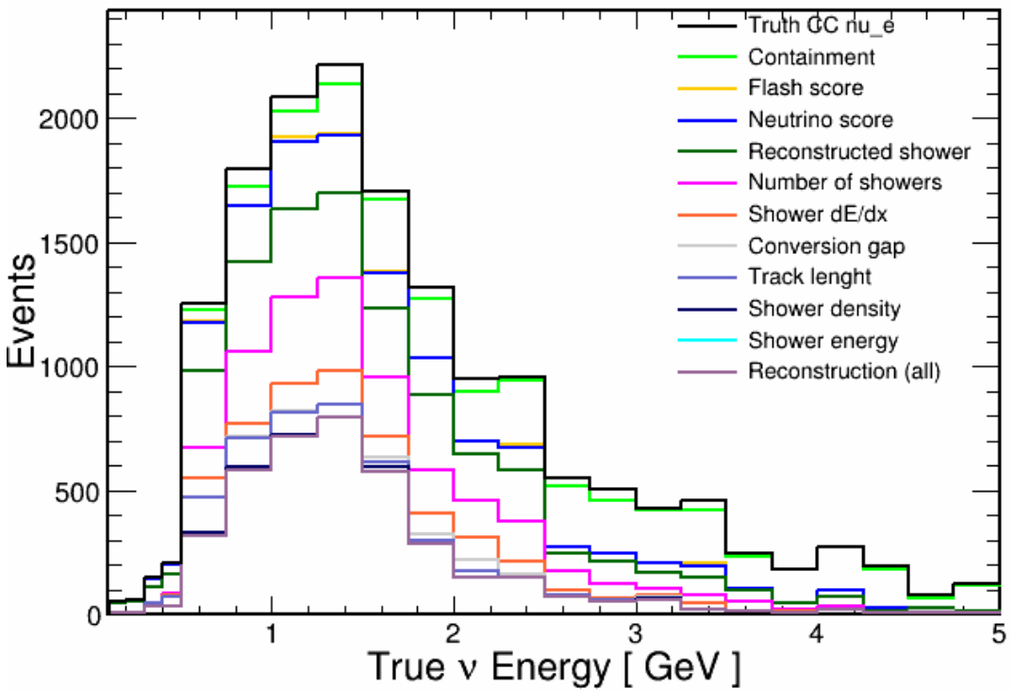

- Inclusive selection cuts
  - Vertex in fiducial volume
  - Reject vertical tracks with track information
  - Requiring PMT-TPC matching
  - Muon candidate

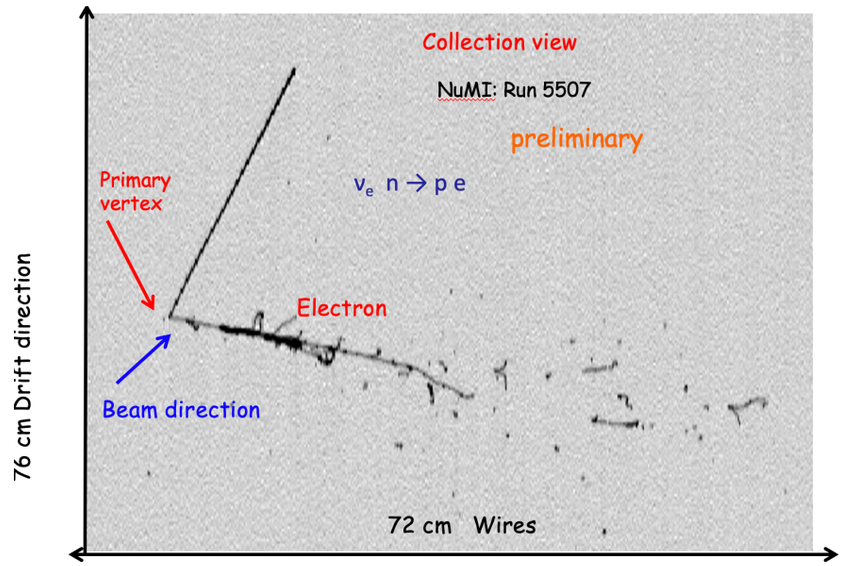



$$cos(\theta_{NuMI}) = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}||\vec{b}|}$$

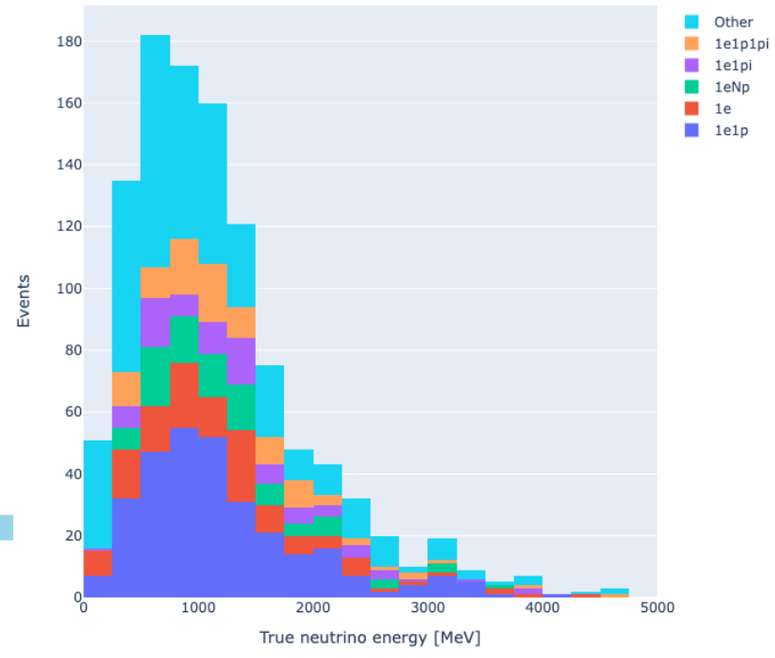
# Electron Neutrino Analyses in Progress

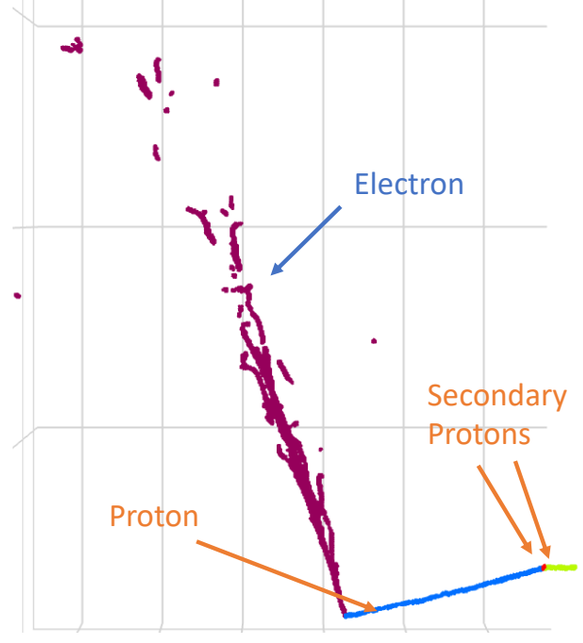
- CC Electron neutrino event selection using Pandora reconstruction




- CC 1e1p event selection using Machine Learning:
  - Efficiency 63%
  - Purity 78%






Fermilab

# Summary

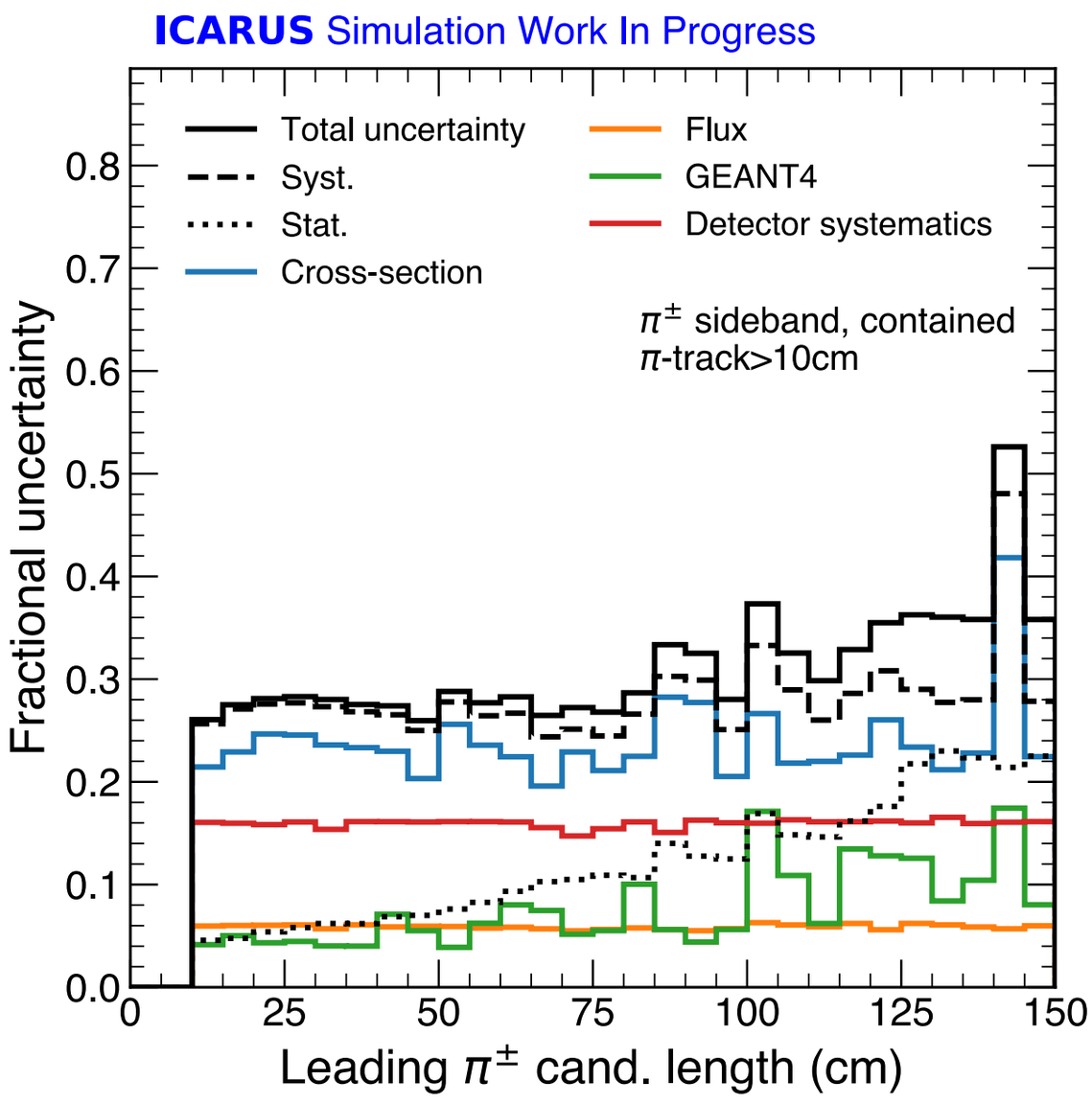
- ICARUS at Fermilab underwent a period of commissioning and first operations as captured in recent paper: P. Abratenko et al, Eur. Phys. Journal C 83, 467 (2023)
- Rich physics program of neutrino-argon scattering measurements using NuMI
- Actively developing cross section extraction with the data collected ~3E20 POT from NuMI
  - Mature analysis to conduct 1$\mu$+Nproton+0$\pi$ cross section
  - Several analyses with event selection in place: 1$\mu$+2proton+0$\pi$, CC Inclusive, 1e1p and CC $\nu$e
- Conducting neutrino cross-section and interaction measurements using neutrinos from NuMI beam in a similar kinematic regime as DUNE
  - Opportunity to test and constrains models for use in DUNE
- ICARUS results will be quantitatively useful when DUNE is building and tuning its interaction model for real data analysis

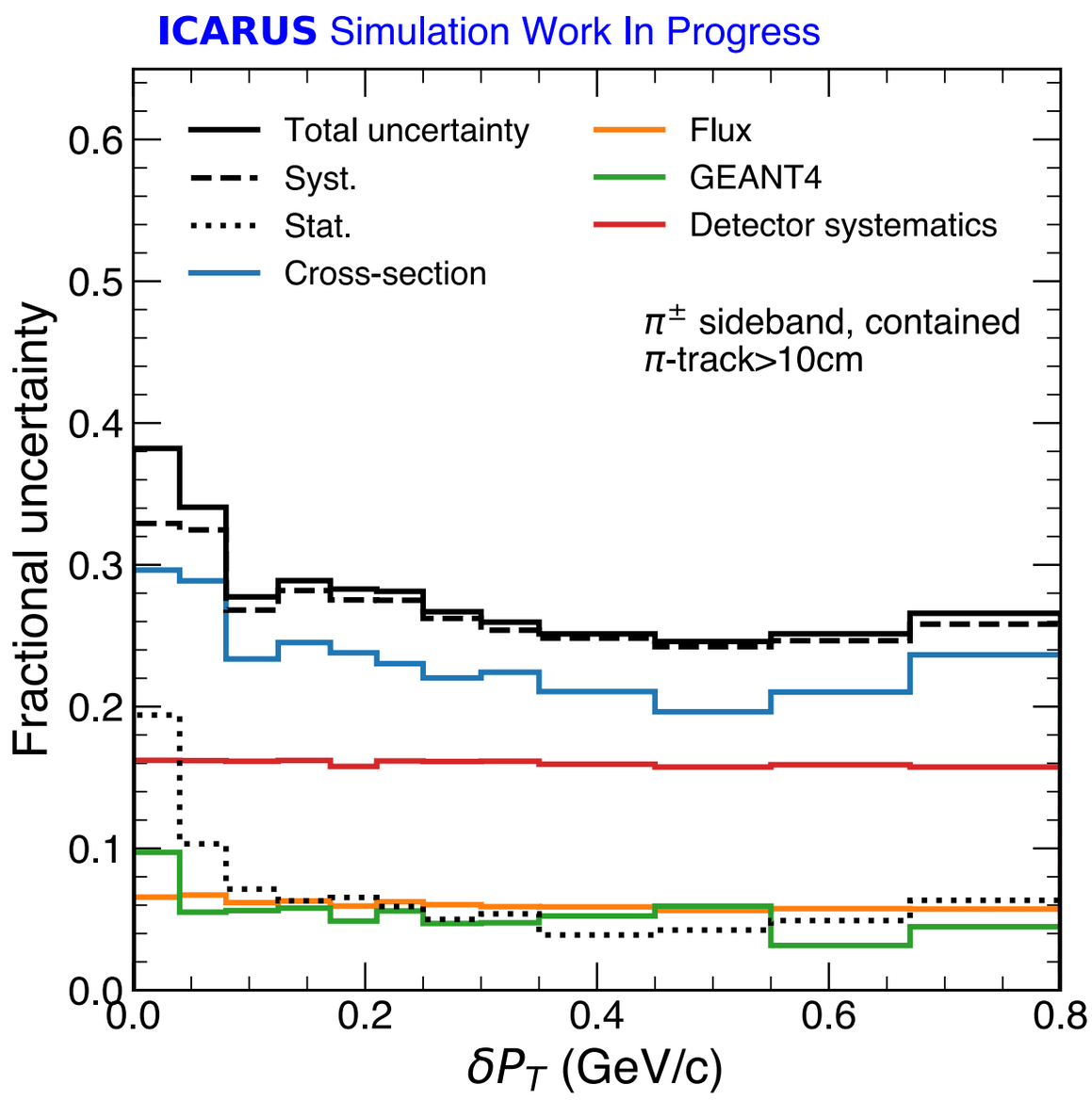
# Back Slides

# Detector Systematics

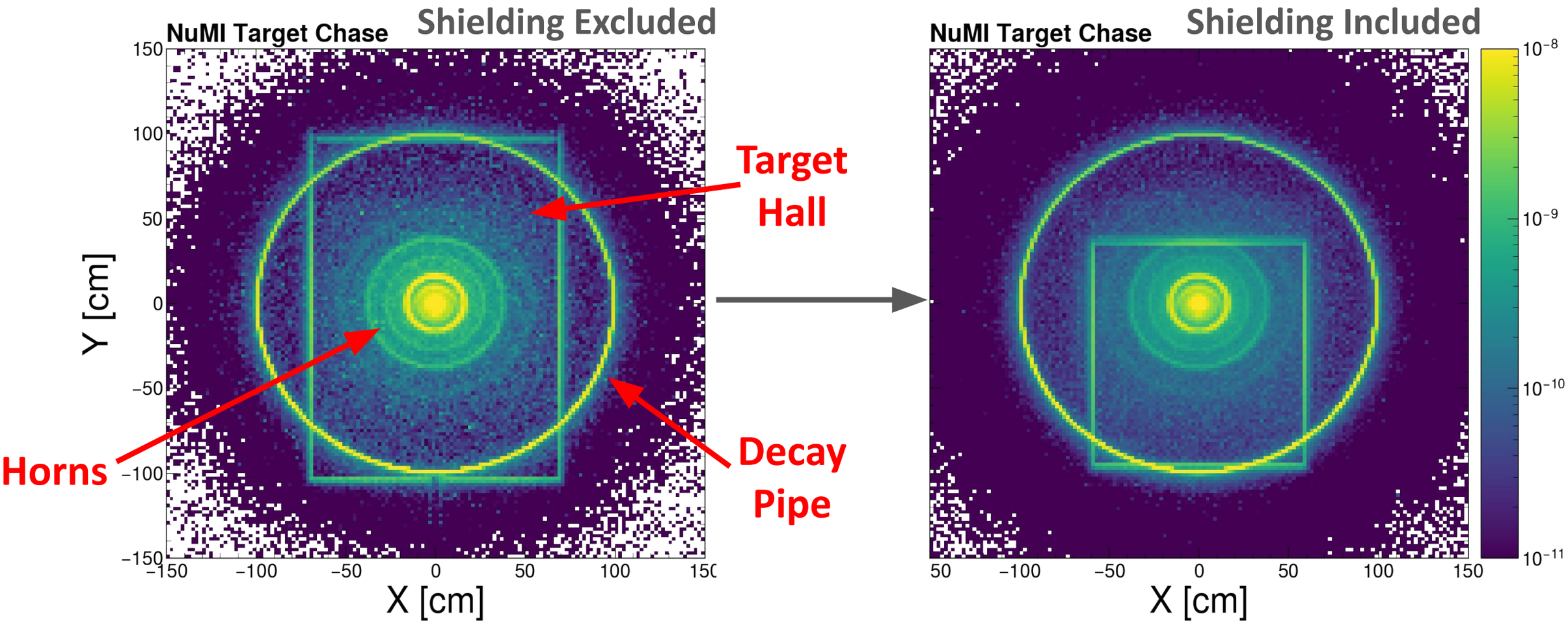
- Main detector systematics
  - Gain
  - Noise (signal to noise ratio)
  - Signal shape
  - Induction 2 transparency
- Other detector systematics:
  - Space-charge effect
  - Diffusion parameter variation
- Calibration systematics
  - Uncertainties on dE/dX is calculated by varying parameters in the recombination fit

# Fractional Uncertainty in the Sideband



# Missing NuMI Geometry Components (X/Y cross section of case )




Concrete-encased steel shielding blocks omitted from NuMI simulation for O(10 yrs)

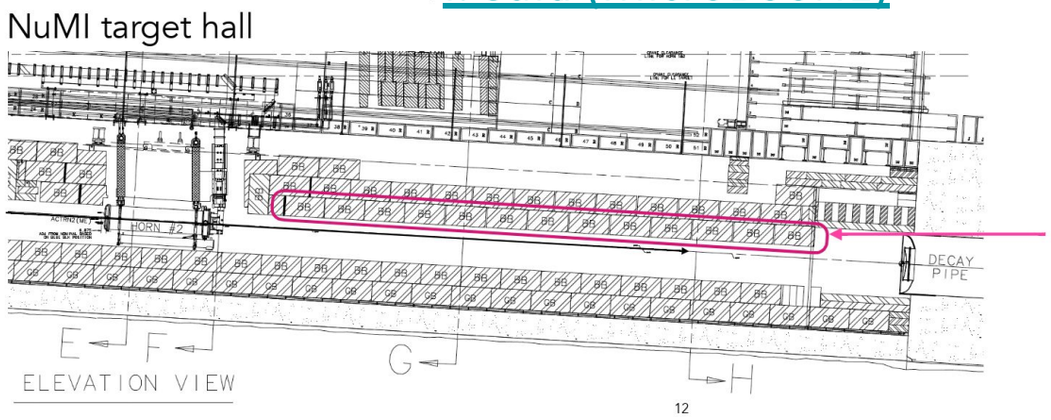
Reduces chase ceiling height by ~60 cm

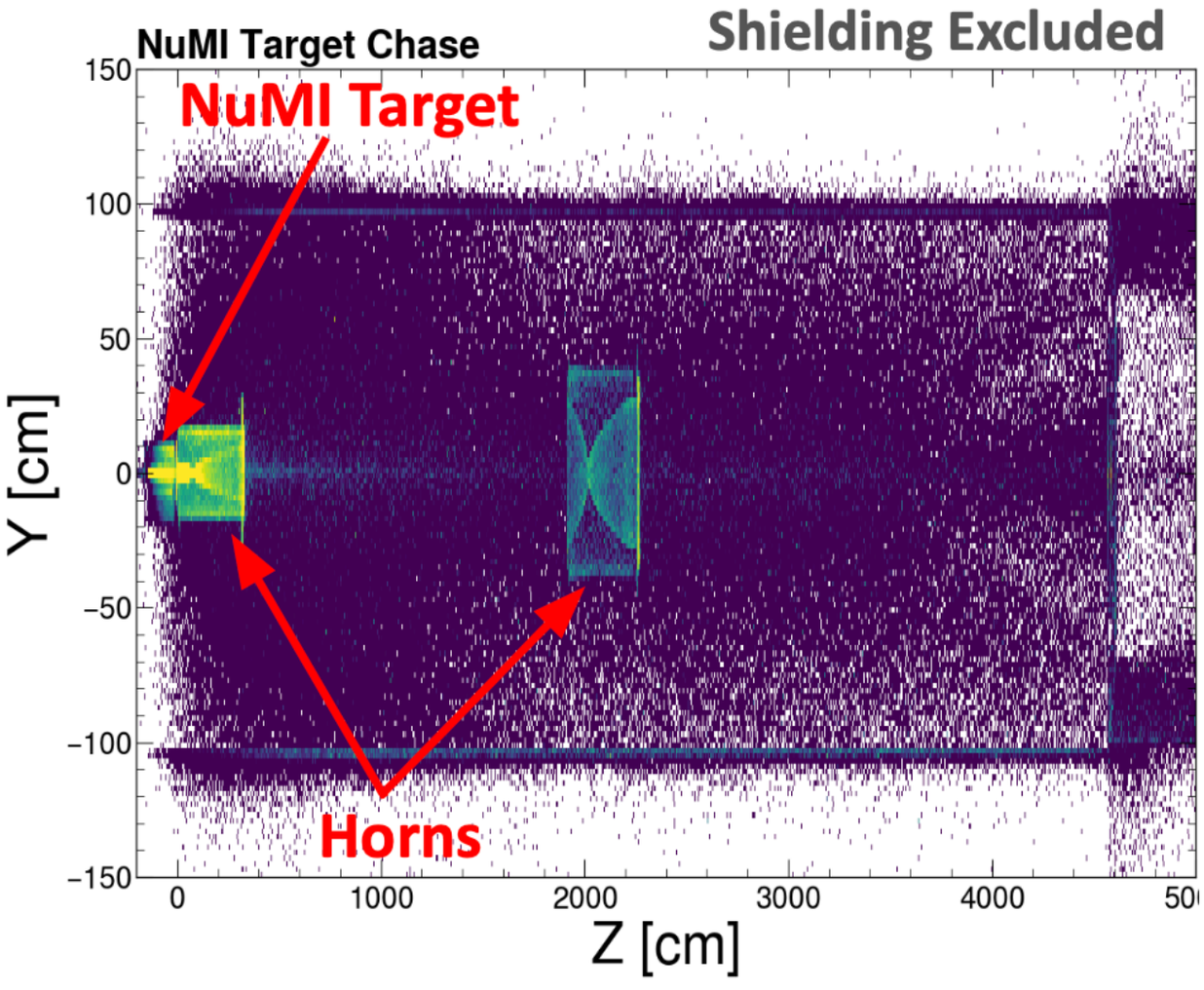


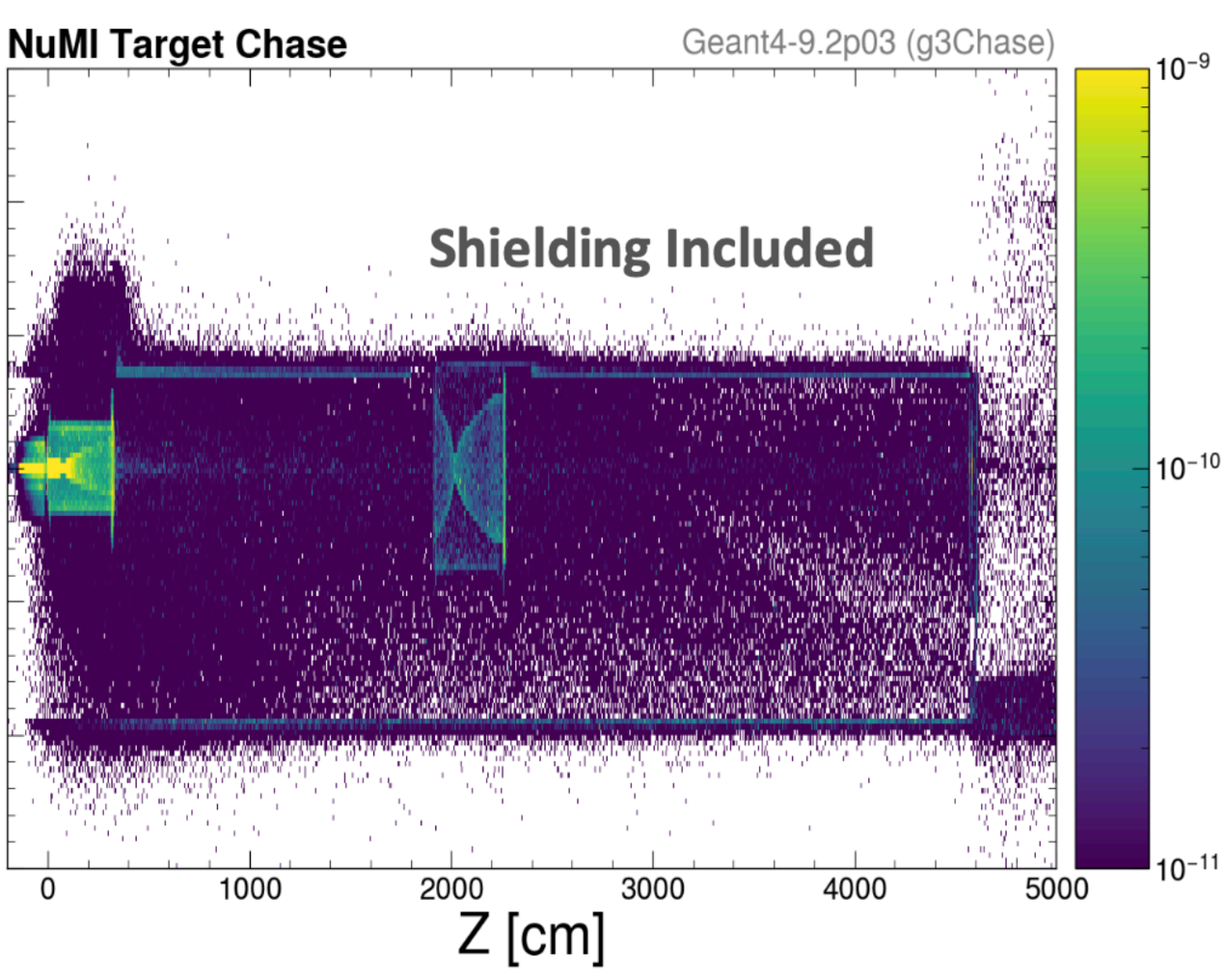
Fermilab

# Missing Geometry Components

I. Safa (MicroBooNE)



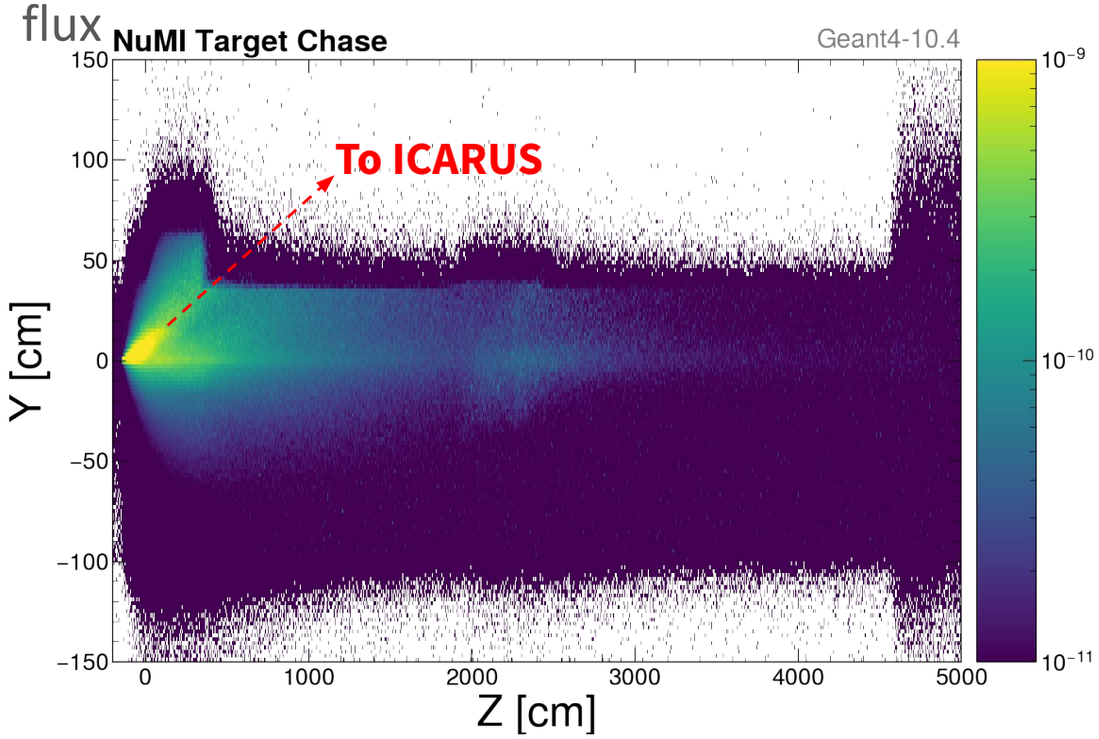

$\nu$ parent decay positions (Y vs. Z)

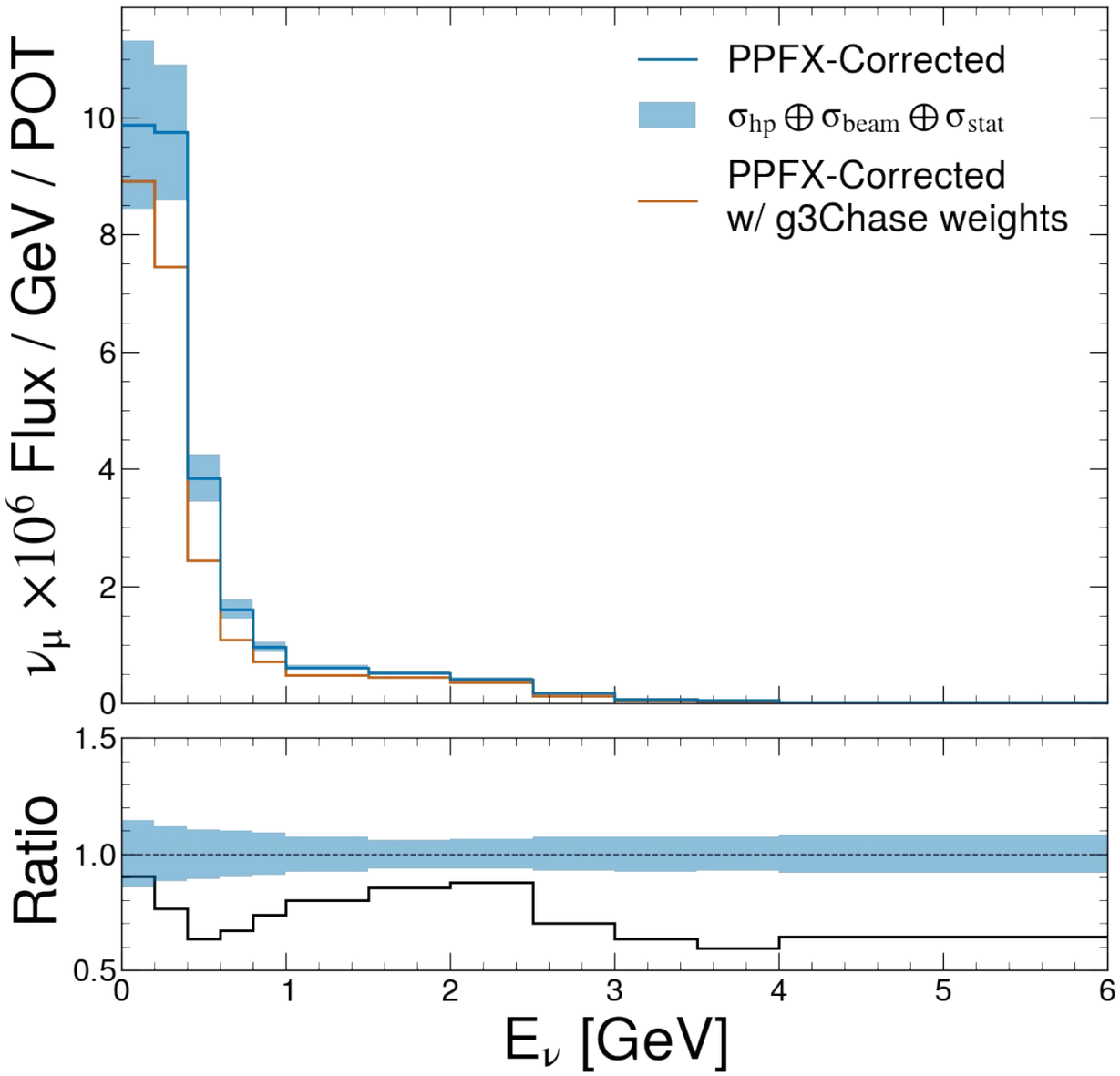


Fermilab

# Flux Attenuation from External Material

- Additional material added resulted in ~20-30% (avg) attenuation of the flux
  - Less space for π/K to decay in flight
- Calculated weights based on the new geometry and applied to the PPFX-corrected flux



# Muon Neutrino 0$\pi$ with 2 protons in Progress