



# First Results of the ICARUS Experiment at Fermilab

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NuFact 2024

Argonne National Laboratory, Lemont, IL

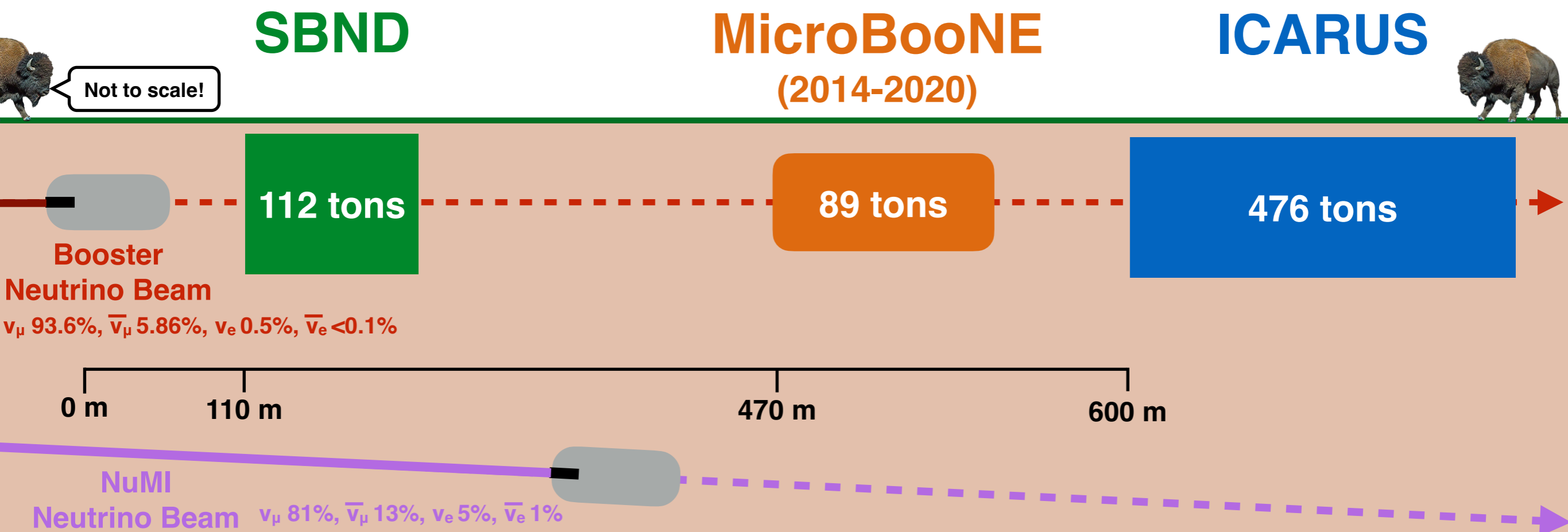
September 19, 2024

# Overview

- ICARUS and the Short Baseline Neutrino Program
- Installing and operating the ICARUS detector at Fermilab
- The (current) physics program at ICARUS
  - Detector physics and calibration
  - Oscillation physics
  - Cross-section physics
  - Beyond the Standard Model searches
- Summary

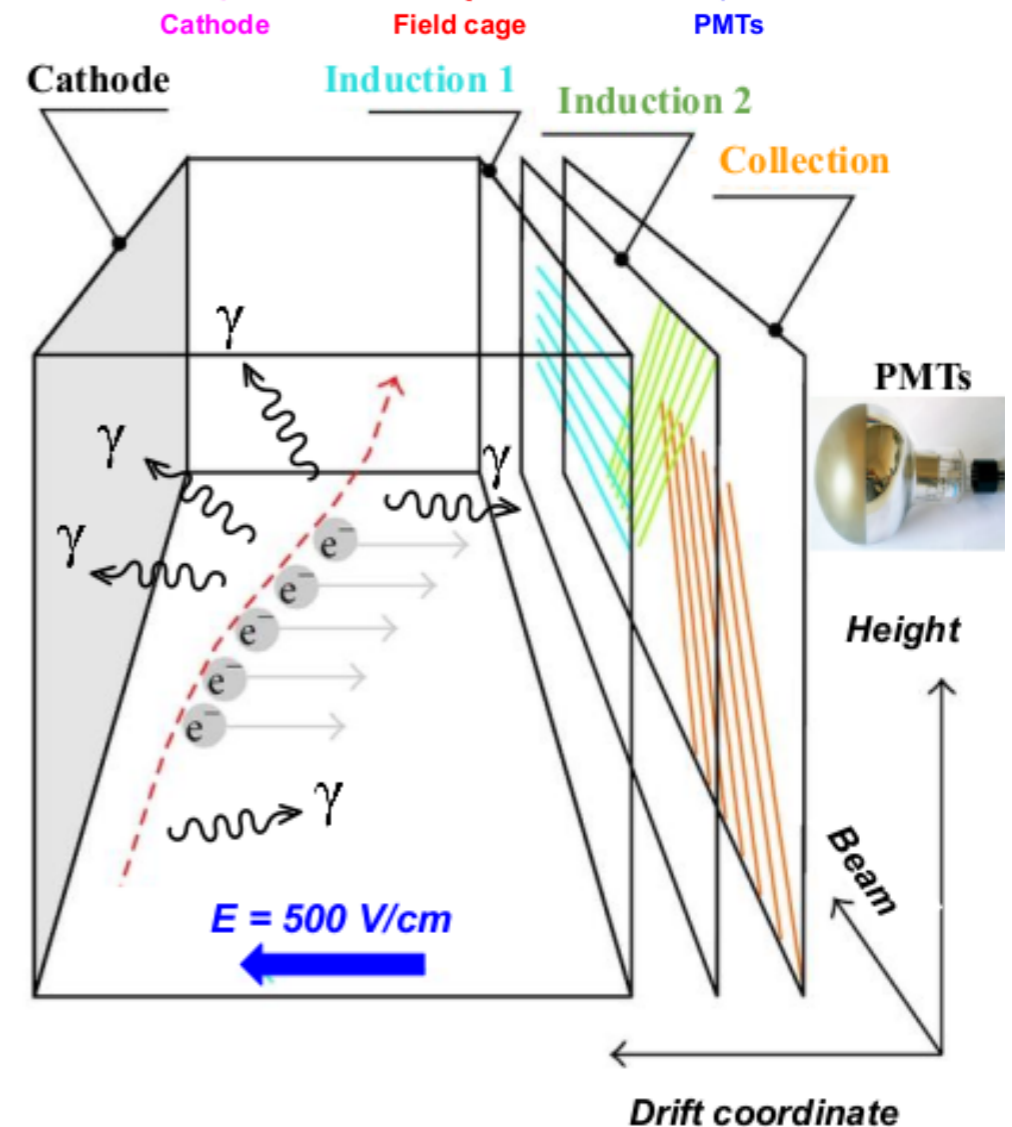
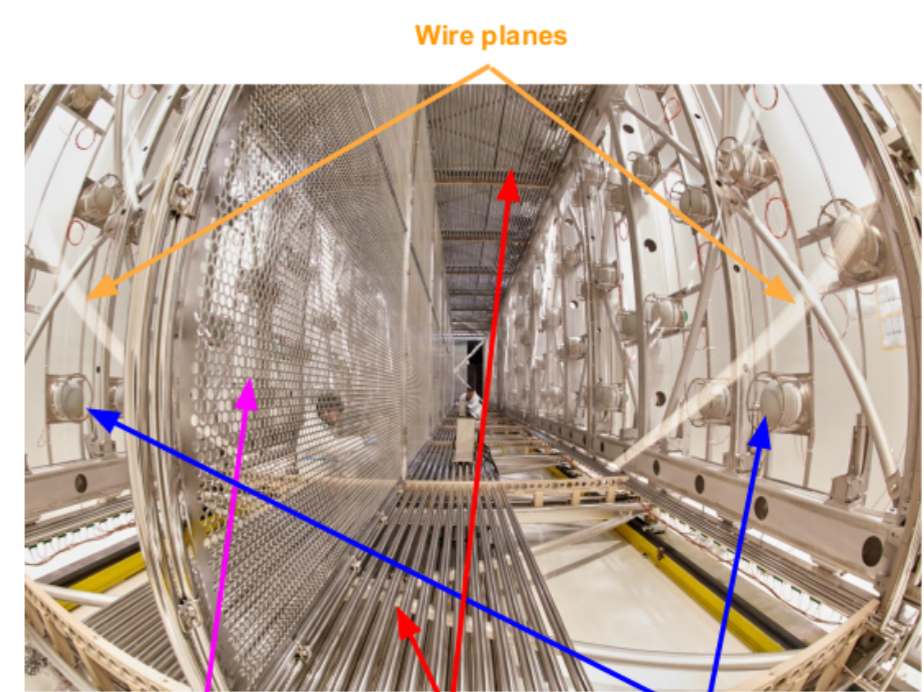
# The Fermilab Short Baseline Neutrino (SBN) Program

- Program based at Fermilab designed to definitively probe the sterile neutrino hypothesis of the MiniBooNE anomaly
- The detectors use the common liquid argon TPC (LArTPC) technology as well as the Booster Neutrino Beam (BNB) as a common beamline
- Ability to also measure neutrino-argon interaction cross sections and also Beyond the Standard Model (BSM) signatures
  - ICARUS is also exposed to the Neutrinos from Main Injector (NuMI) beam at 6 degrees off axis!



# The ICARUS Detector

- ICARUS underwent refurbishment at CERN from 2014-2016 after running at LNGS
  - Arrived at Fermilab in 2018
- LArTPC detector with 760 tons total mass and 476 tons active mass
- Two identical cryostats each divided into 2 TPCs with a central cathode
  - 1.5 m drift distance, 3 wire planes
  - Drift field at 500 V/cm
- Instrumented with 360 PMTs coated with the wavelength shifter TPB
- High coverage cosmic ray tagger (CRT) system to tag and remove cosmic backgrounds

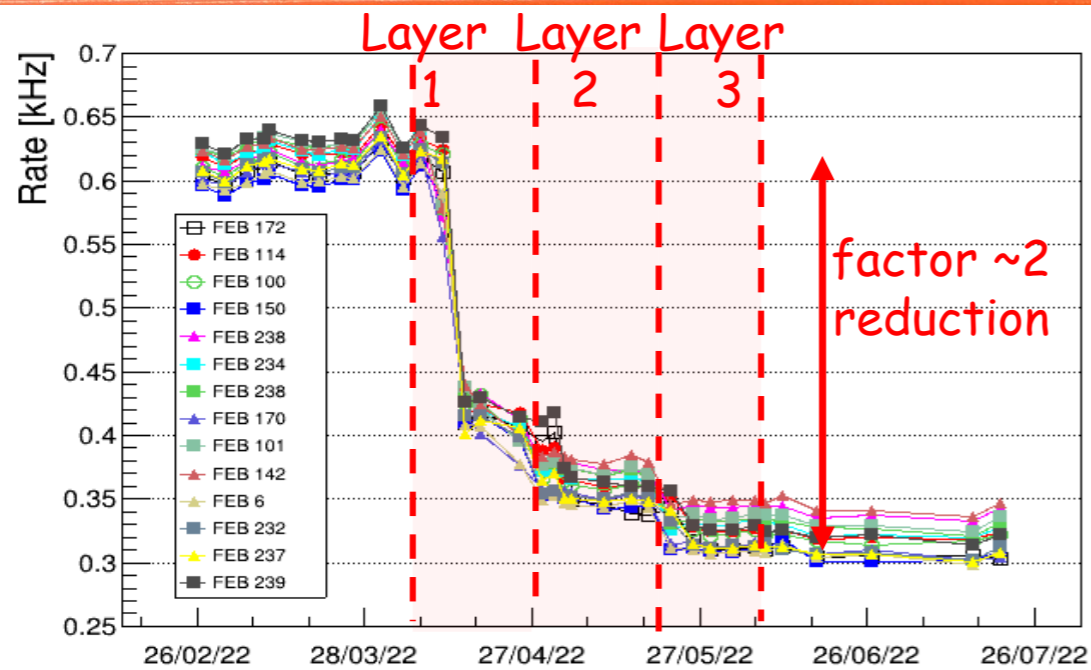
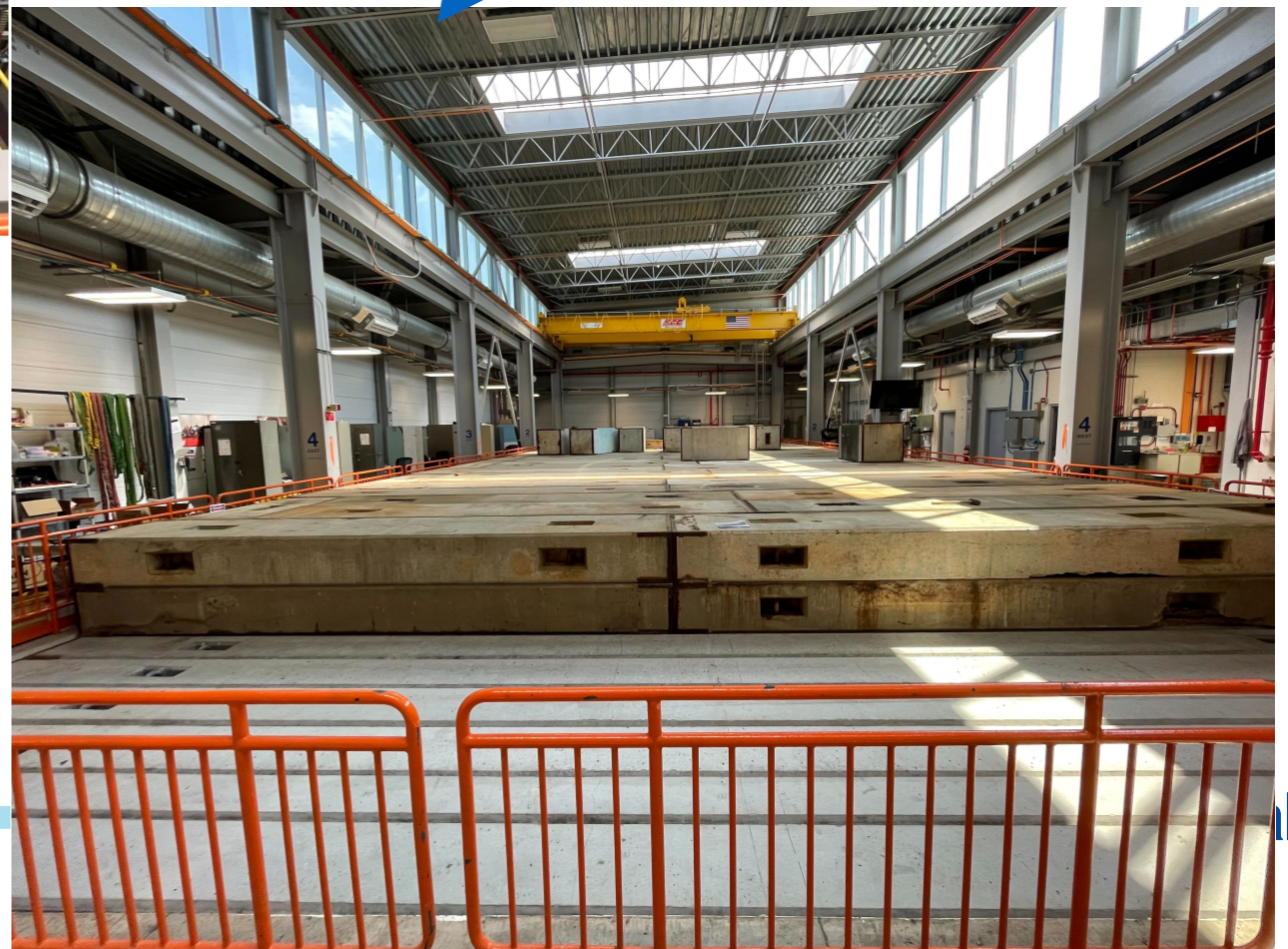
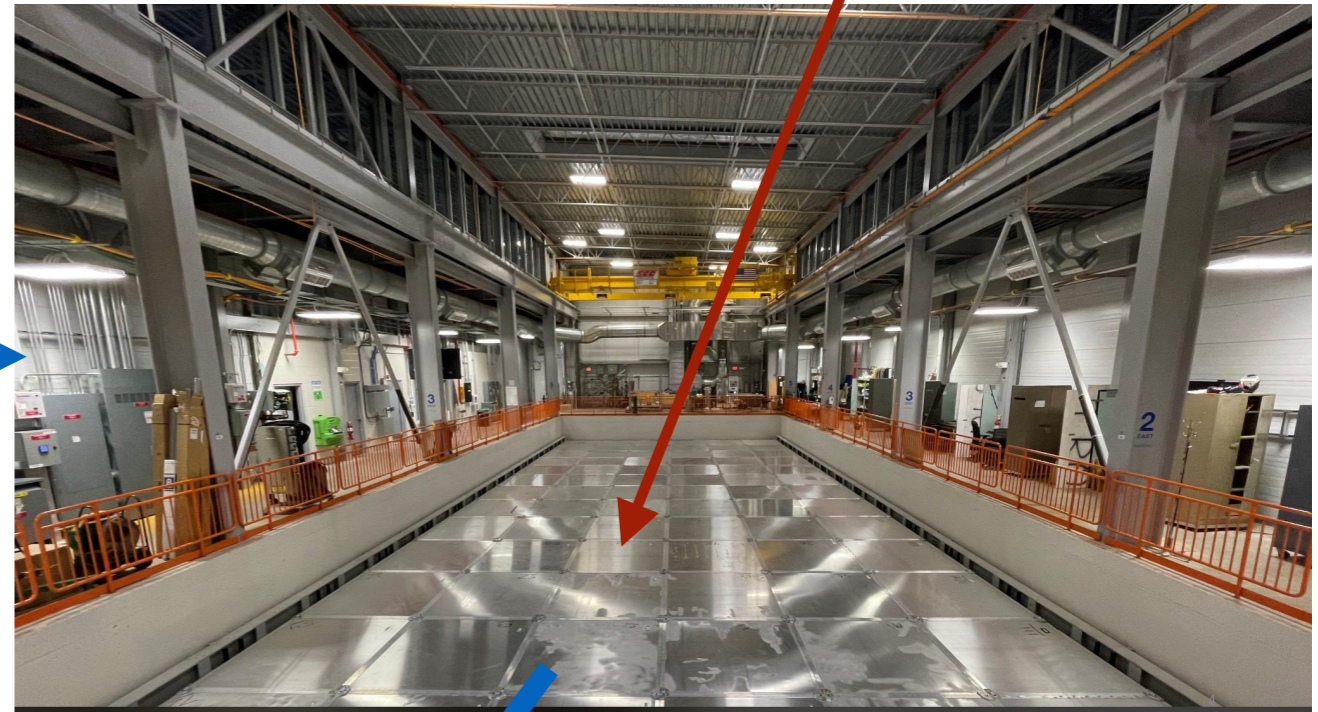


# Installing and Operating ICARUS at Fermilab

# ICARUS Installation



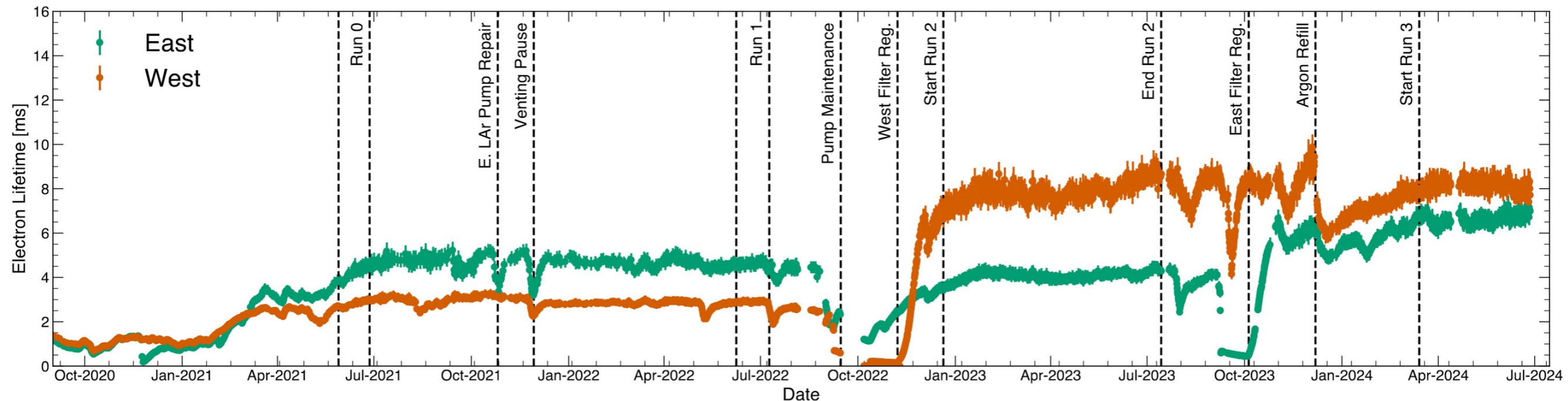
Top CRT panels



# Operating the ICARUS detector at Fermilab

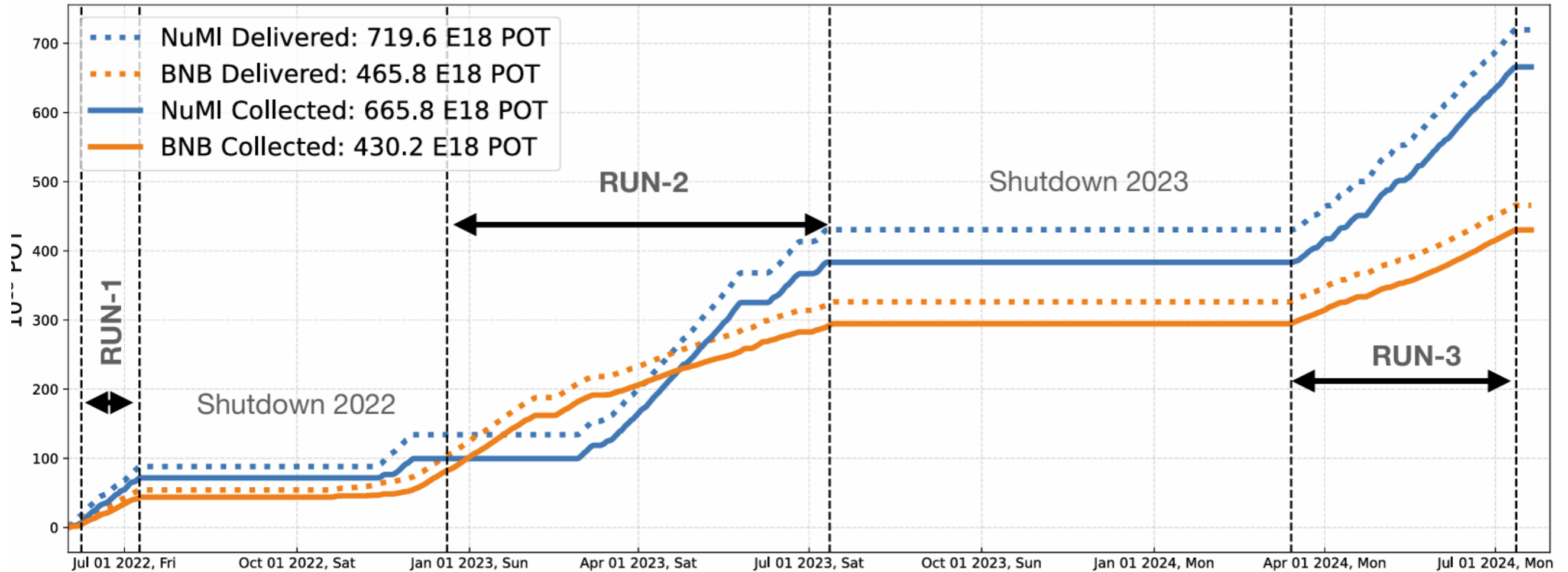
- ICARUS filled with LAr in April 2020 and was fully operational in August 2020
- Commissioning completed in 2022 and began physics data taking
- Electron lifetime reached the  $> 3$  ms target for quality physics data during each beam operation period, now at 6-9 ms in the latest data taking period
- During beam periods, operate with a light-based trigger system in coincidence with the beam spills, for BNB events we measure  $> 90\%$  triggering efficiency for energies  $> 200$  MeV

ICARUS Electron Lifetime



Commissioning of ICARUS at FNAL: *Eur. Phys. J. C* 83, 467 (2023)

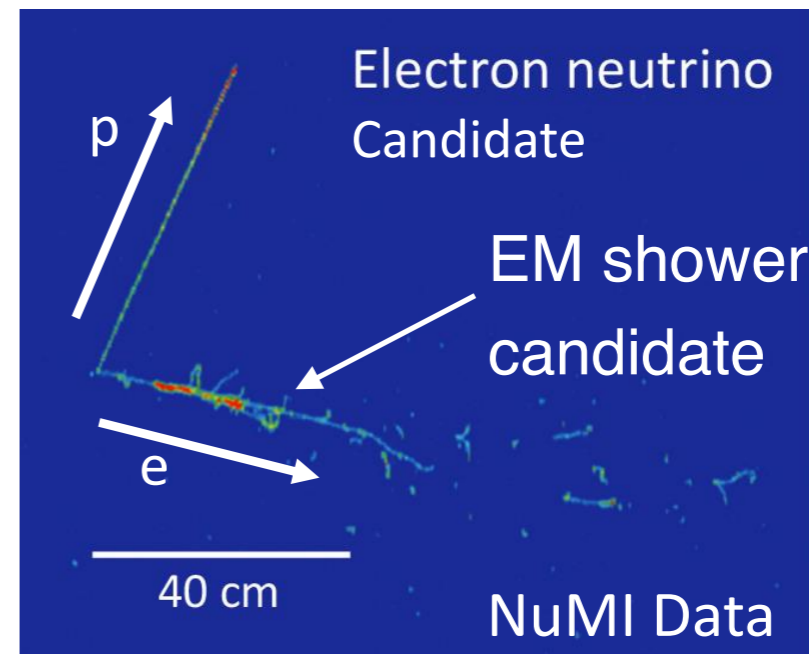
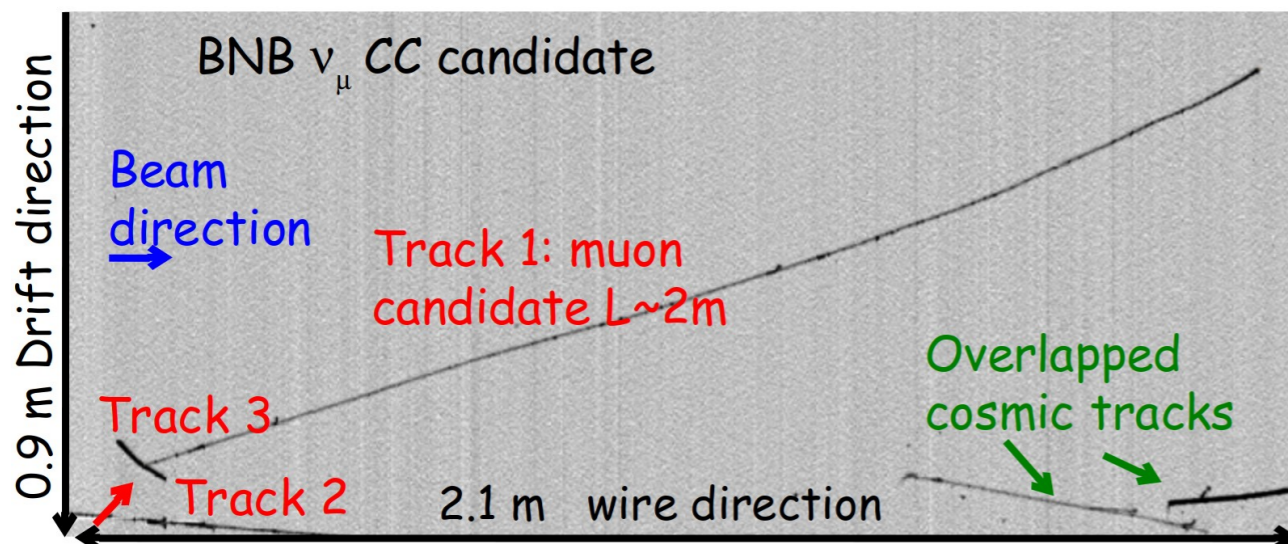
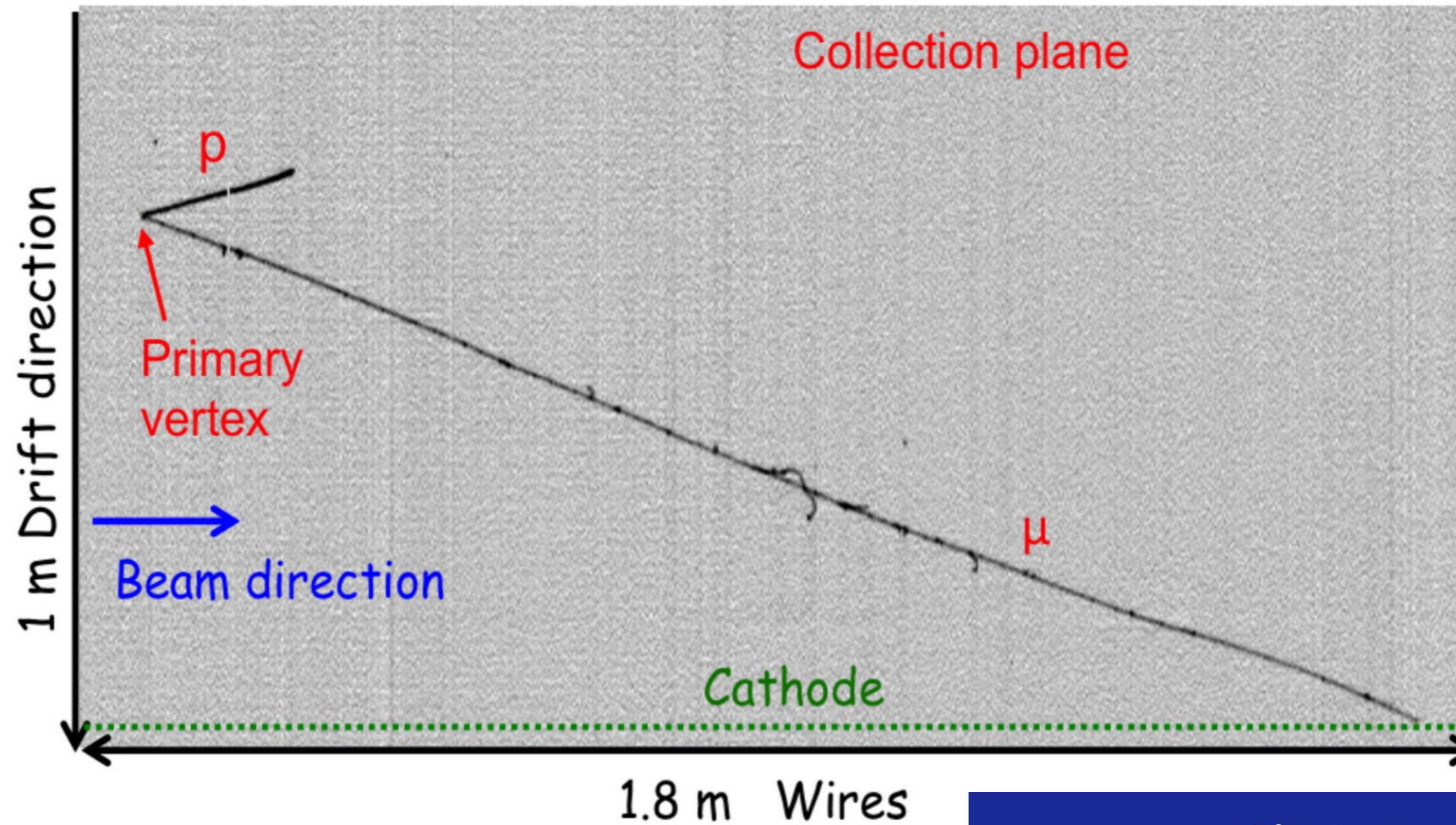
# The collected data with ICARUS at Fermilab



- ICARUS has steadily operated during periods of accelerator operations reaching a POT collection efficiency of  $\sim 95\%$
- 3 data taking periods up to July 2024
- BNB Run1/Run2/Run3:  $0.4/2.1/1.4 \times 10^{20}$  POT (total  $3.9 \times 10^{20}$  POT)
- NuMI Run1/Run2/Run3:  $0.7/2.7/2.8 \times 10^{20}$  POT in FHC/FHC/RHC configuration (total  $3.4/2.8 \times 10^{20}$  POT in FHC/RHC configuration)



# So what do neutrinos in the data actually look like?



## What ICARUS can do with its data

- Rich program of detector physics and calibration after commissioning began to further the understanding of the LArTPC detector technology
- Before joint SBN operations, ICARUS is pursuing multiple physics thrusts with data from both BNB and NuMI
  - A single-detector oscillation search focusing on the  $\nu_\mu$  disappearance channel in the BNB beam
  - Neutrino-argon interaction cross section measurements using the NuMI beam off-axis
  - Beyond the Standard Model physics searches with the NuMI beam off-axis, first completed analysis was a search for contained dimuon decays
- Joint sterile neutrino oscillation search combined with SBND towards the goals of the combined SBN program

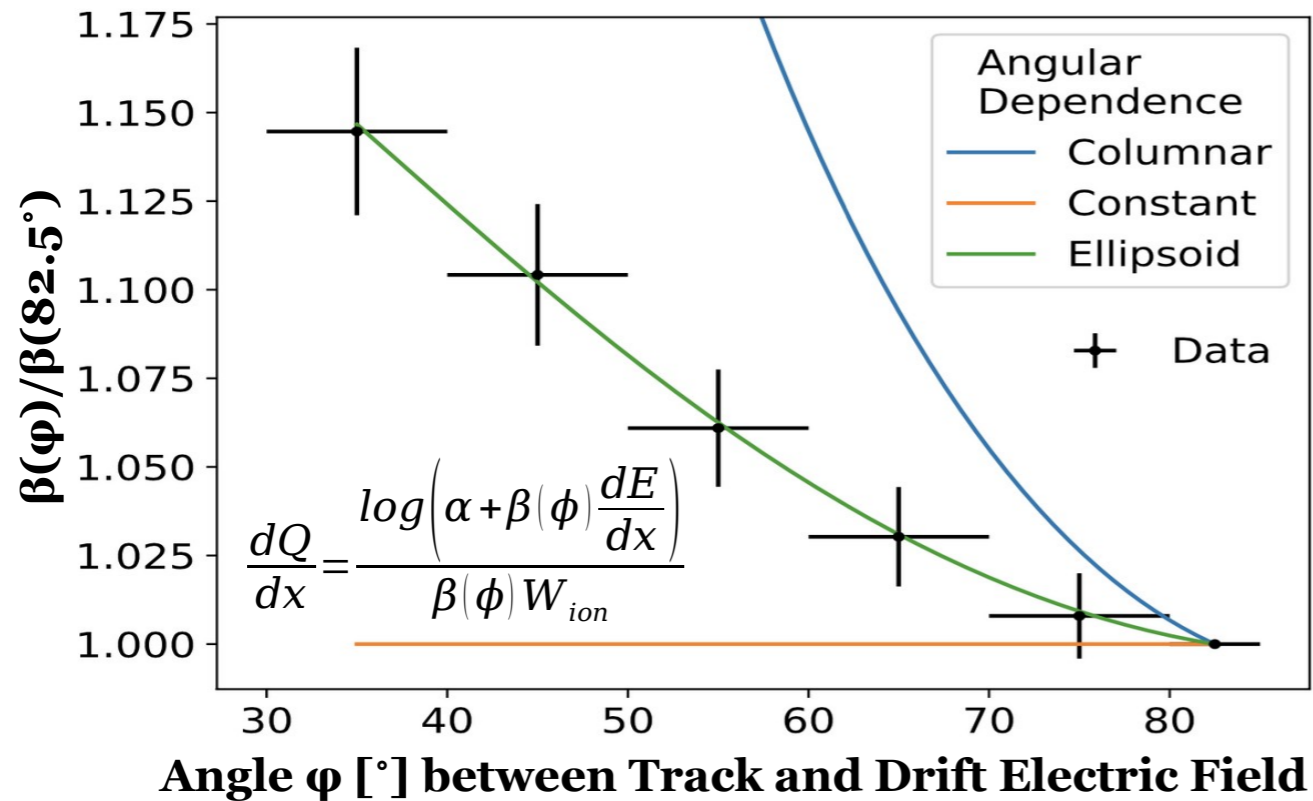
# Detector Physics

# Leveraging Calorimetric Information in LArTPCs

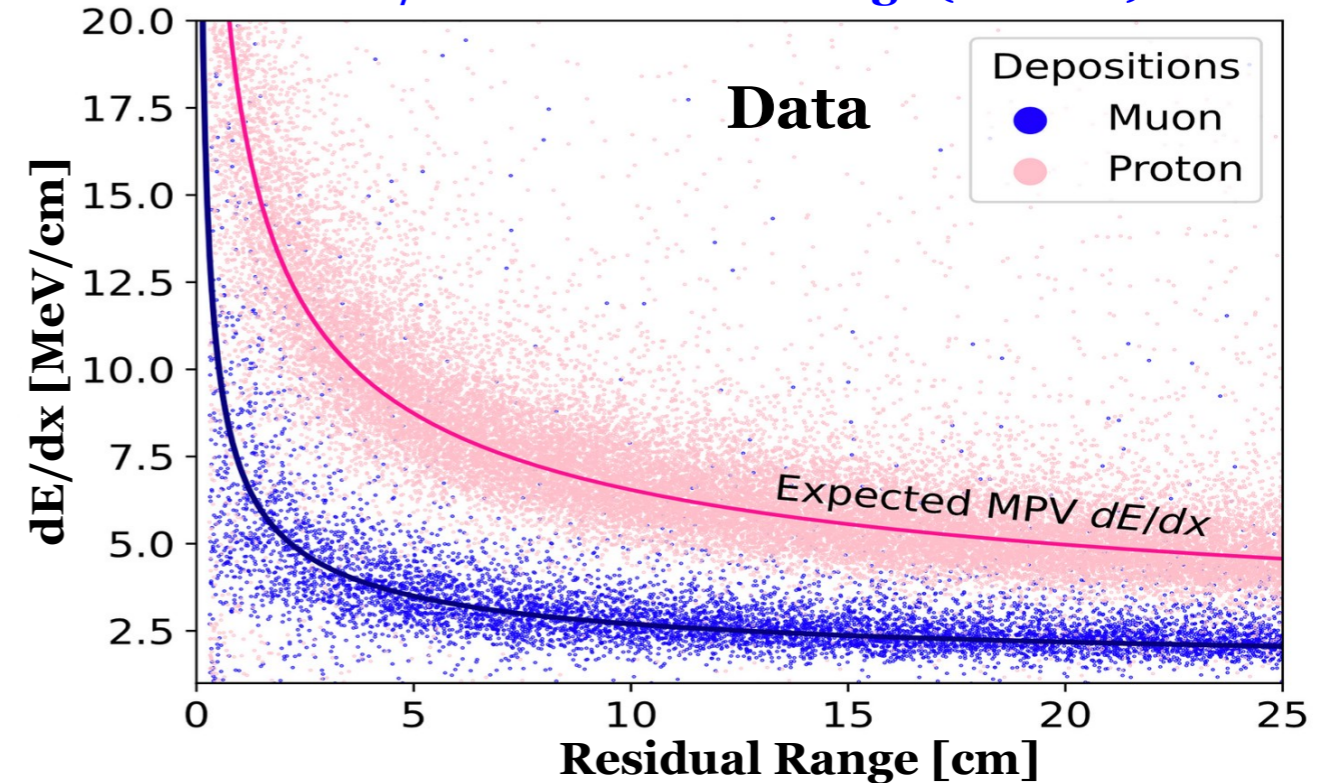
- Measurement with ICARUS data of the angular dependence of the liquid argon recombination model

- Particle identification through calorimetric measurements

**Dependence of Recombination on Track Angle**



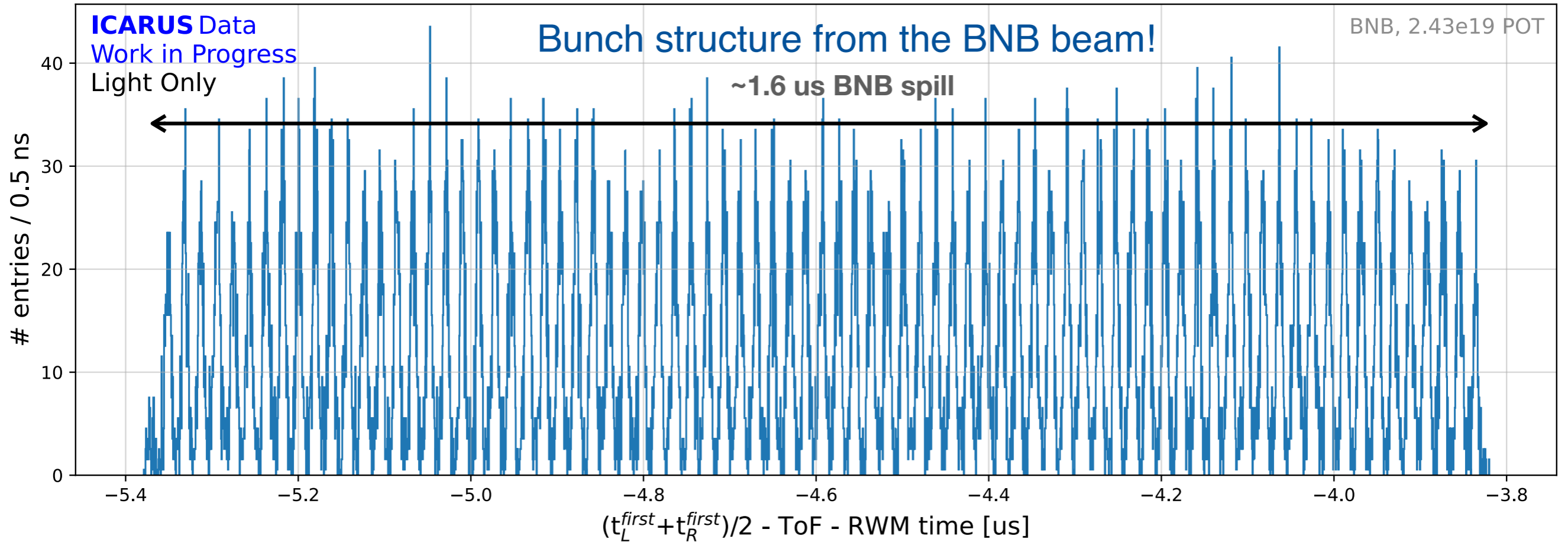
**dE/dx vs. Residual Range (for PID)**



Select proton-like tracks in the data

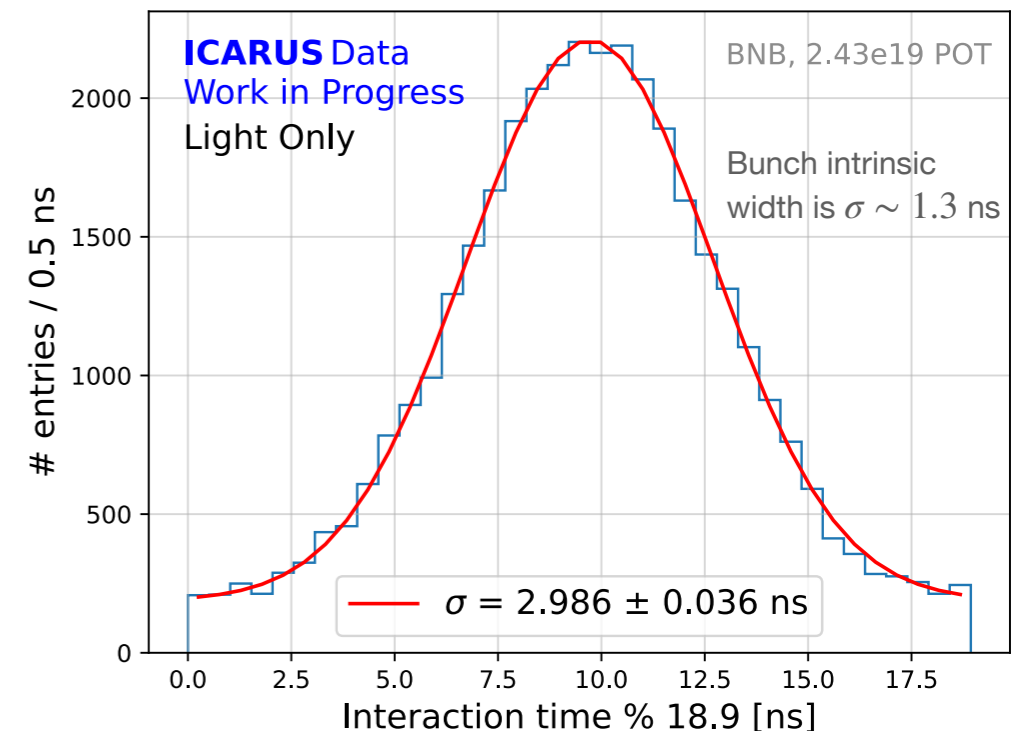
arXiv:2407.12969, submitted to JINST

# Seeing the beam bunch structure in the data!



- Recent work to use our PMT system to identify the BNB and NuMI beam bunch microstructure!

Individual bunch from the BNB (18.9 ns spacing between bunches)



# Moving towards neutrino physics results

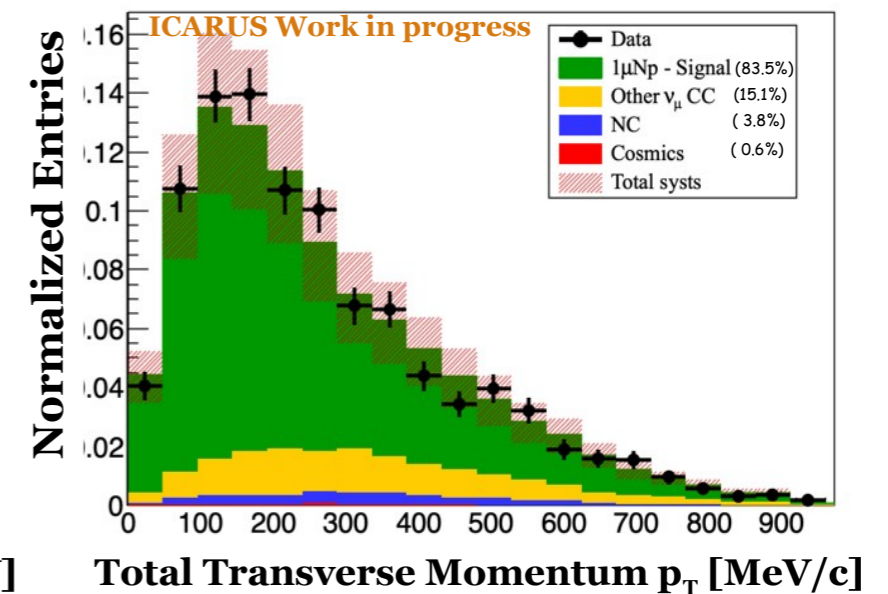
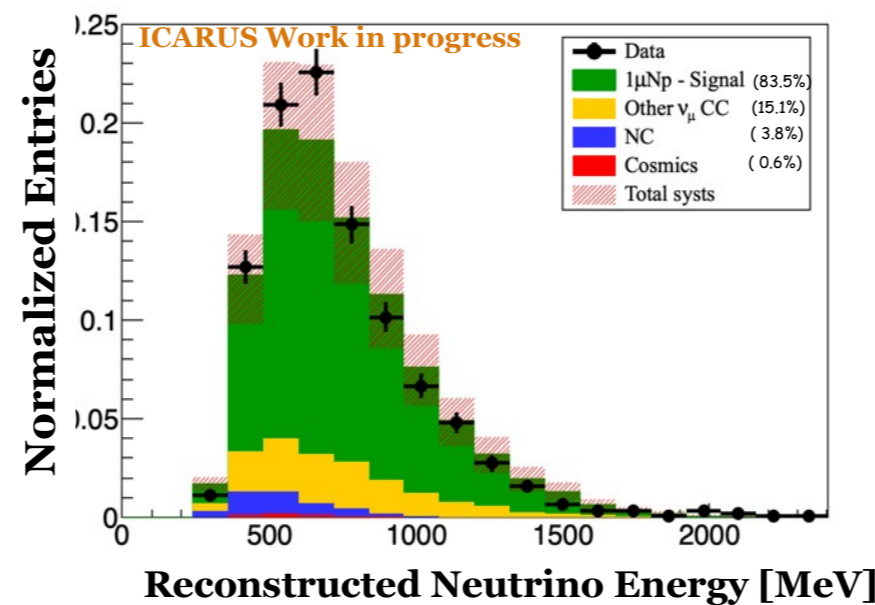
# Performing a Neutrino Oscillation Measurement with ICARUS

- ICARUS will provide the oscillated neutrino spectrum as the far detector for the SBN Program in concert with SBND as the near detector
  - Can measure both  $\nu_\mu$  disappearance and  $\nu_e$  appearance with two detectors
  - Use BNB  $\nu_\mu/\nu_e$  data for both SBND and ICARUS and additionally NuMI  $\nu_\mu/\nu_e$  for ICARUS
- Focus is on  $1\mu N p 0\pi$  final states from events in coincidence with the BNB for the ICARUS single-detector oscillation measurement with two reconstruction approaches
  - Pandora - pattern recognition based software used in previous LArTPC experiments
  - SPINE - machine learning based reconstruction chain

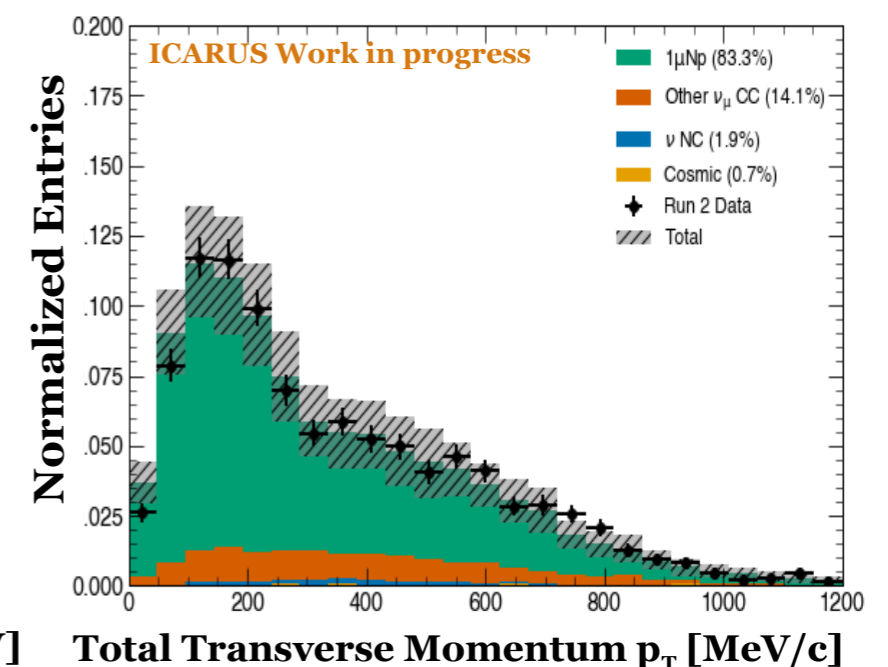
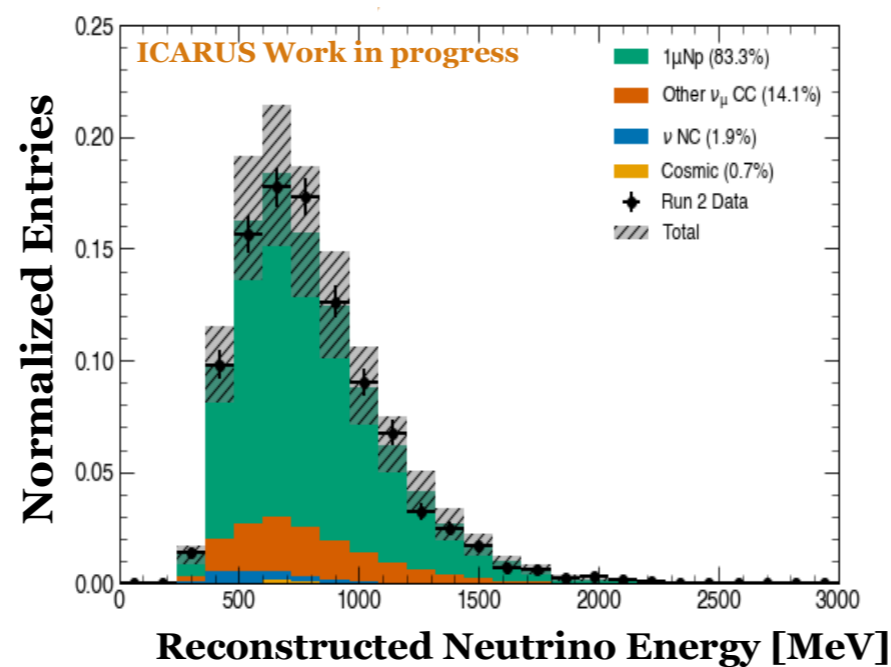
# Event Selections for Neutrino Oscillation Physics

- Advanced event selections are in place looking at  $1\mu\text{Np}0\pi$  final states
- Good data/MC agreement seen in 10% subset of the Run 2 (2023) data

## Pandora Selection



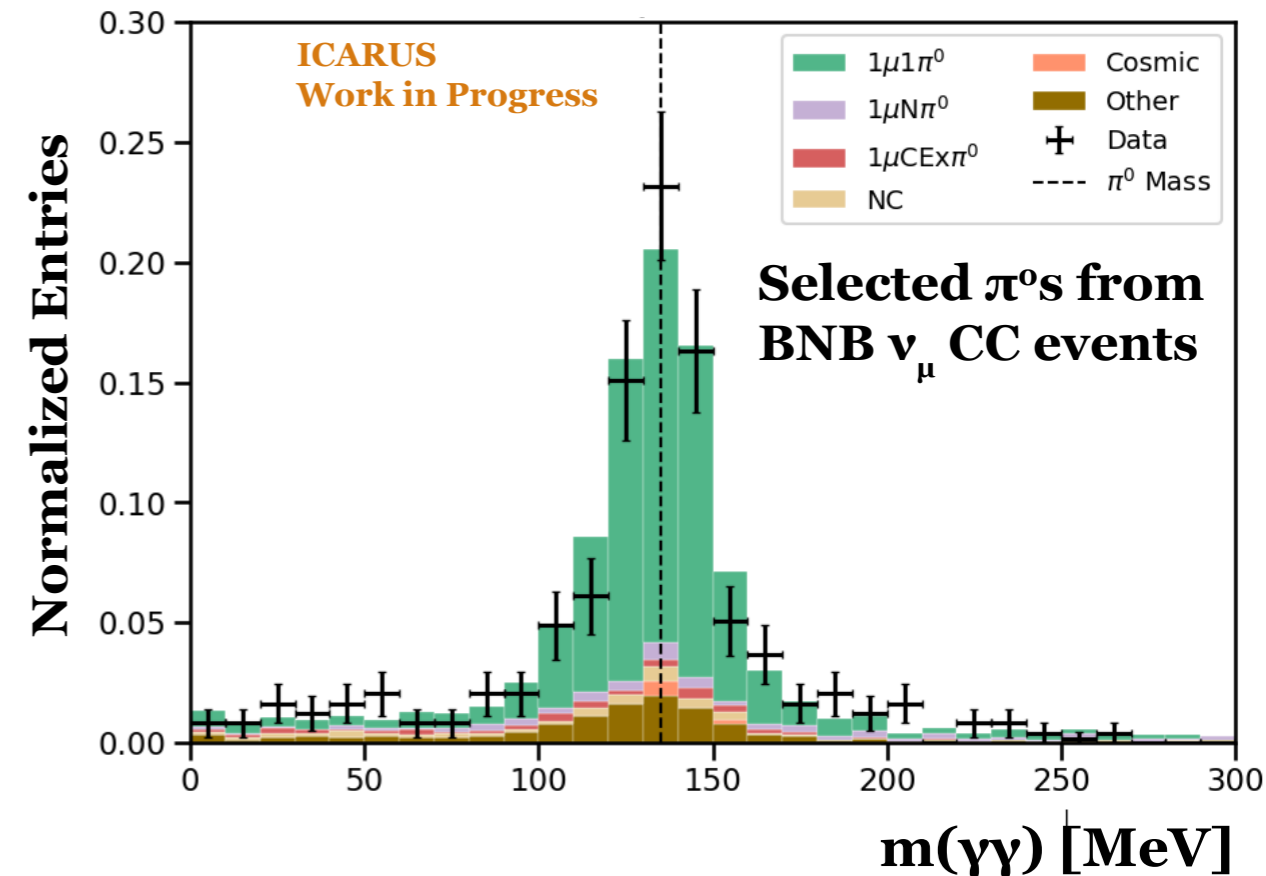
## SPINE Selection





# What about the shower-based signatures?

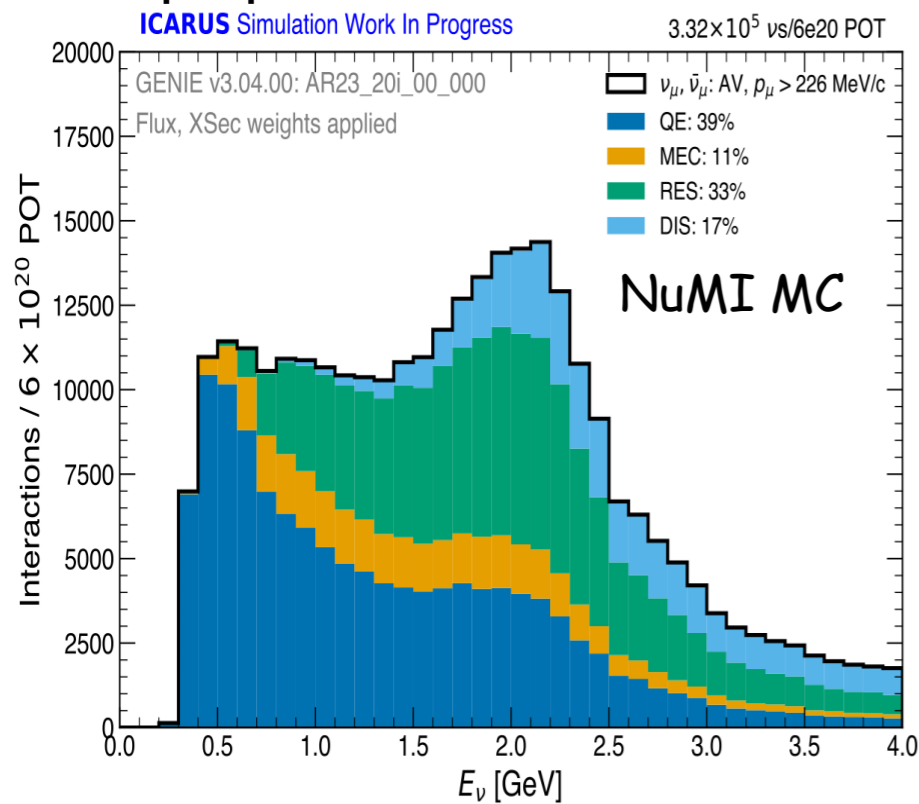
- Electromagnetic shower-based events selections (for electron neutrino events) making progress for both reconstruction paradigms but not as advanced as those for track-like events
- Studies using the SPINE reconstruction show promising ability to reconstruct  $\pi^0$  events which are used to calibrate the shower reconstruction
- Good data/MC agreement!



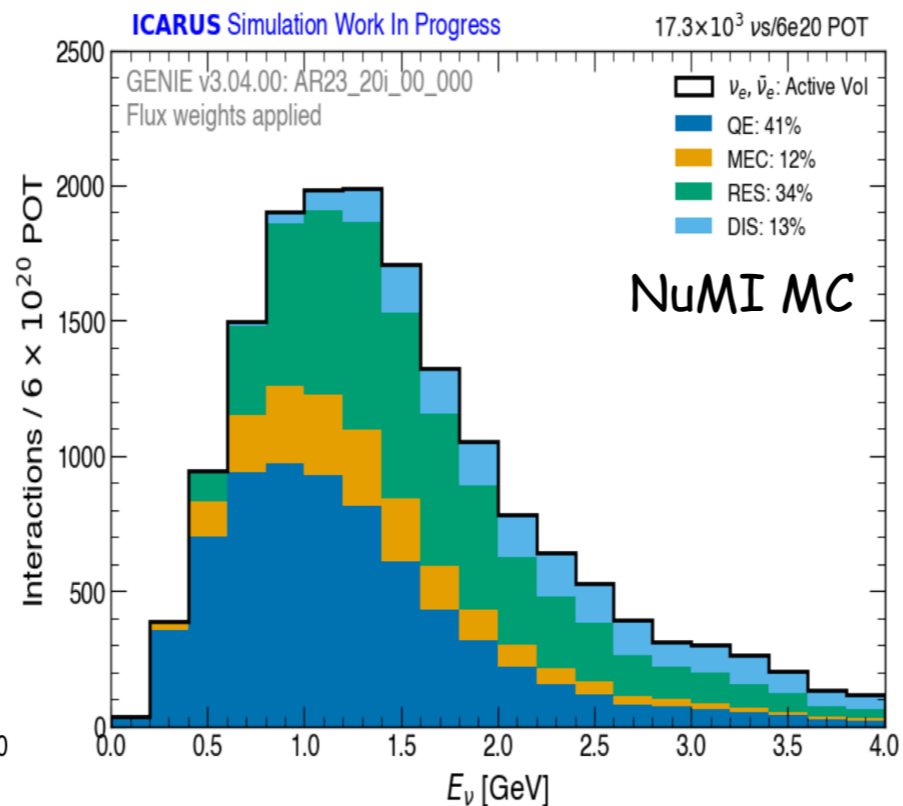
# Neutrino-argon cross section measurements

- ICARUS is exposed to the NuMI beam at 6 degrees off-axis
  - Provides high statistics for neutrino-argon cross section measurements: expect  $\sim 330\text{k}$  muon neutrinos and  $\sim 17\text{k}$  electron neutrinos in  $6 \times 10^{20}$  POT
- Relevant for the first oscillation maximum for DUNE

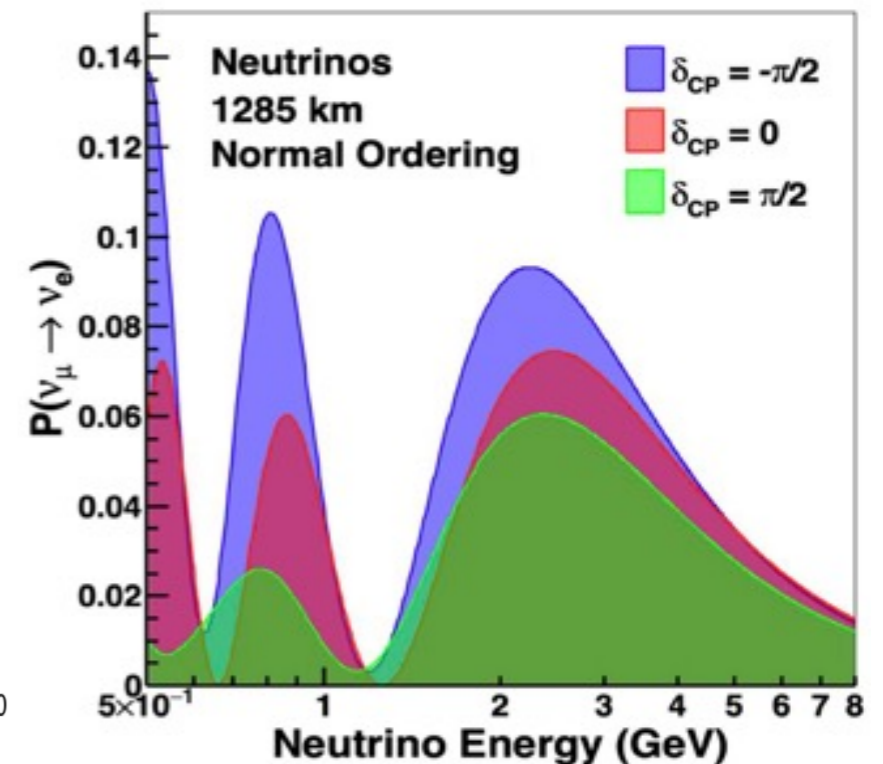
## $\nu_\mu, \bar{\nu}_\mu$ from NuMI at ICARUS



## $\nu_e, \bar{\nu}_e$ from NuMI at ICARUS

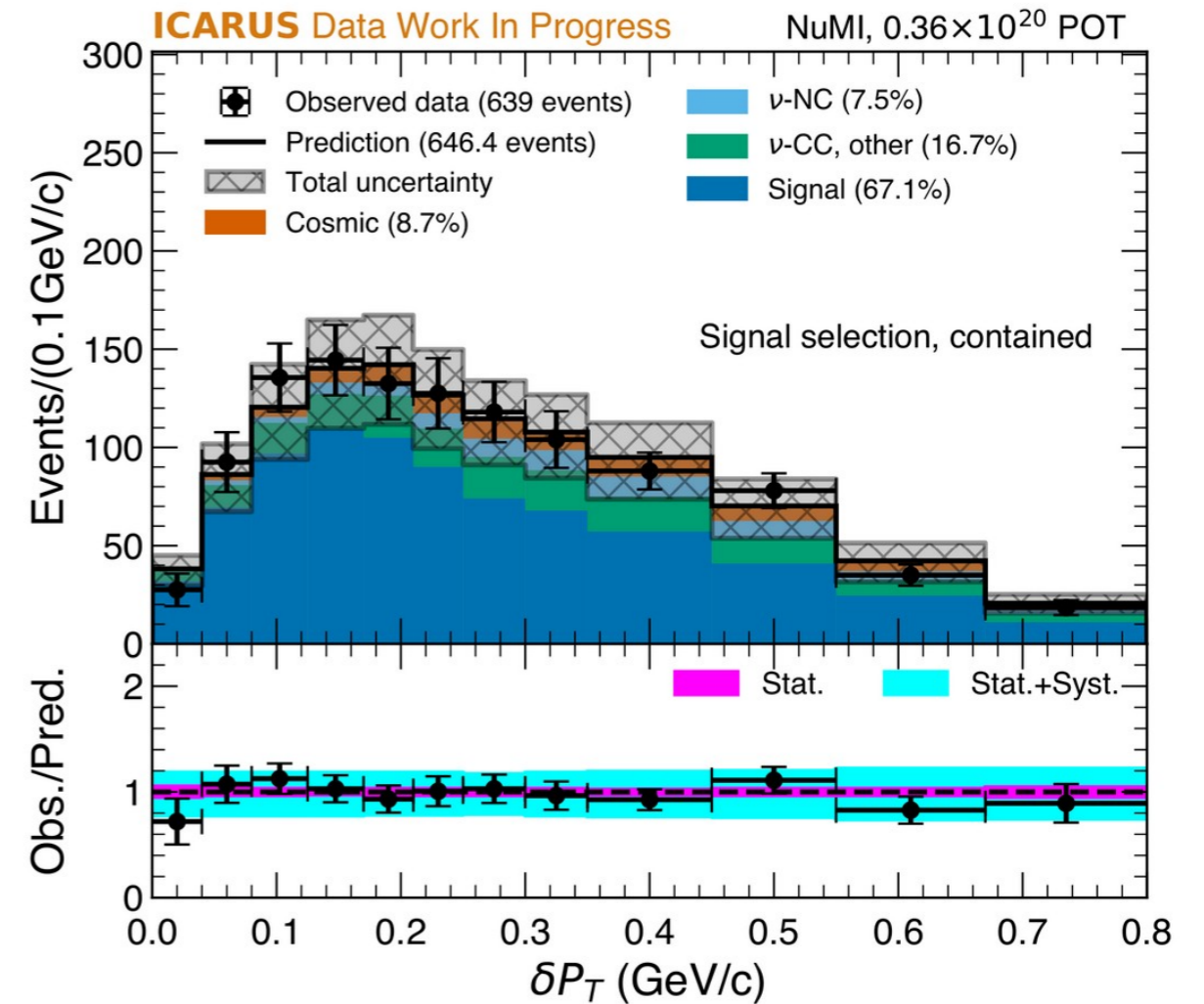
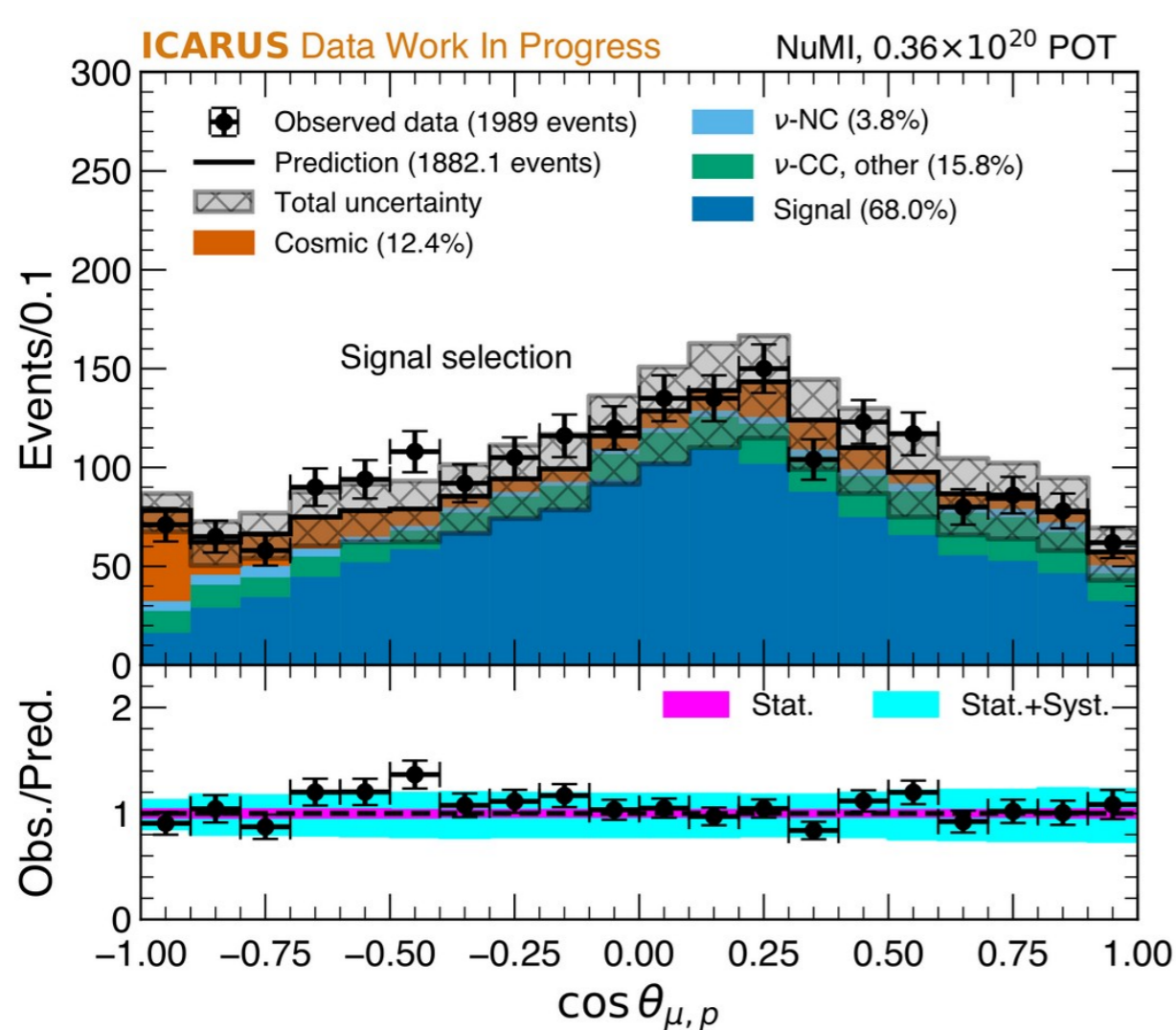


## Oscillation probability at DUNE



# Progress towards first NuMI cross section measurements

- First cross section measurement also focuses on  $1\mu Np0\pi$  final state
- Study both angles and transverse kinematic variables sensitive to final state interactions
- Also see good data/MC agreement with 15% subset of Run1+Run2 (2022+2023) data

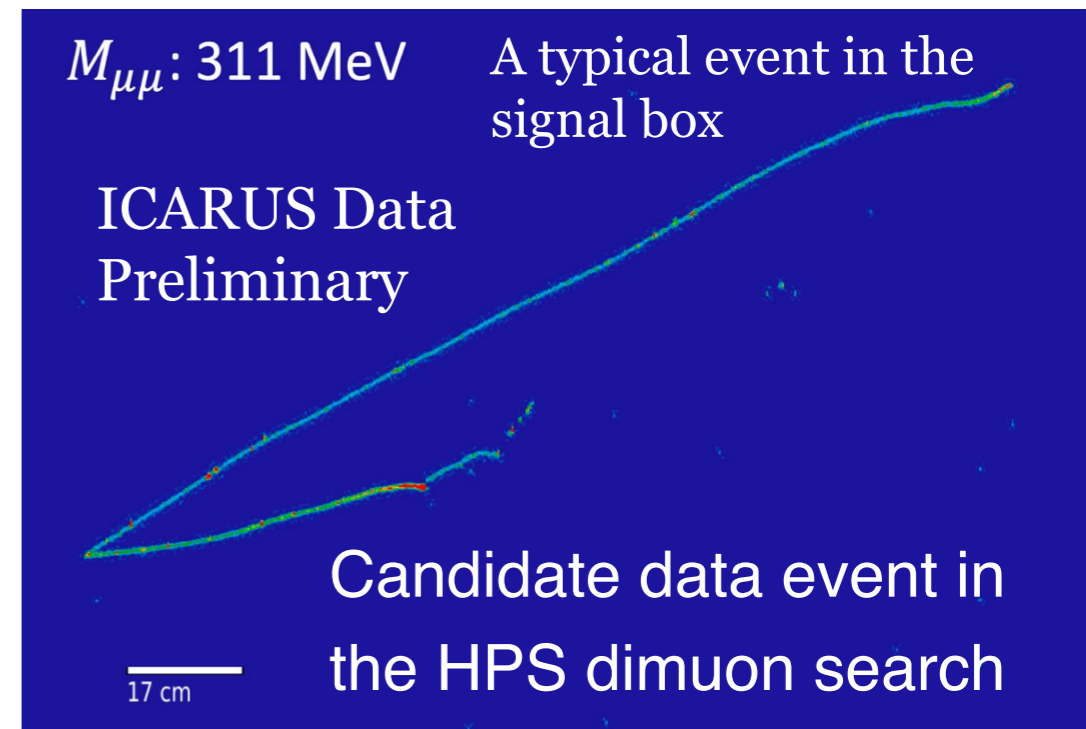
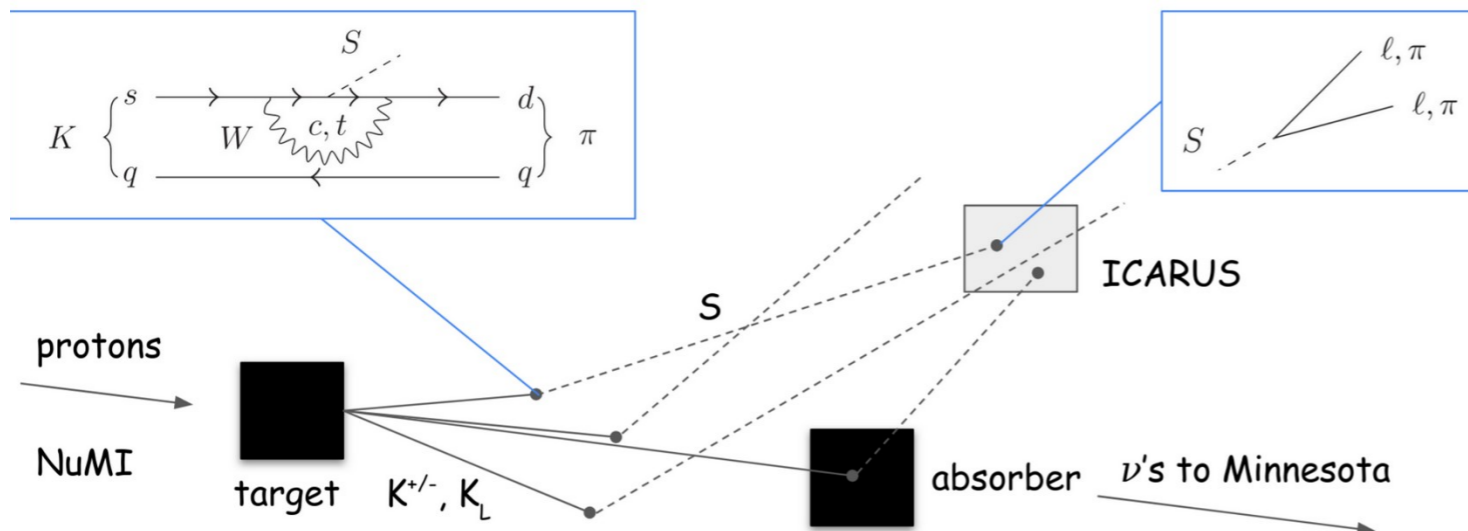


See talk by J. Smedley (next session, WG2) for more details!

# Beyond the Standard Model (BSM) Searches with ICARUS

- ICARUS can probe Beyond the Standard Model signatures with the greatest sensitivity coming from the off-axis NuMI beam
- Initial searches for the first BSM analyses involve kaon decay and contained dimuon final states
  - Higgs Portal Scalar (HPS): Scalar dark sector particles that undergo mixing with the Higgs Boson
  - Axion-Like Particles (ALP): Pseudoscalar particles that undergo mixing with pseudoscalar mesons
- Other search possibilities include i.e. thermal light dark matter and heavy neutral leptons

**Below: Production and decay of a Scalar particle (the Higgs Portal Scalar) in ICARUS with the NuMI beam.**

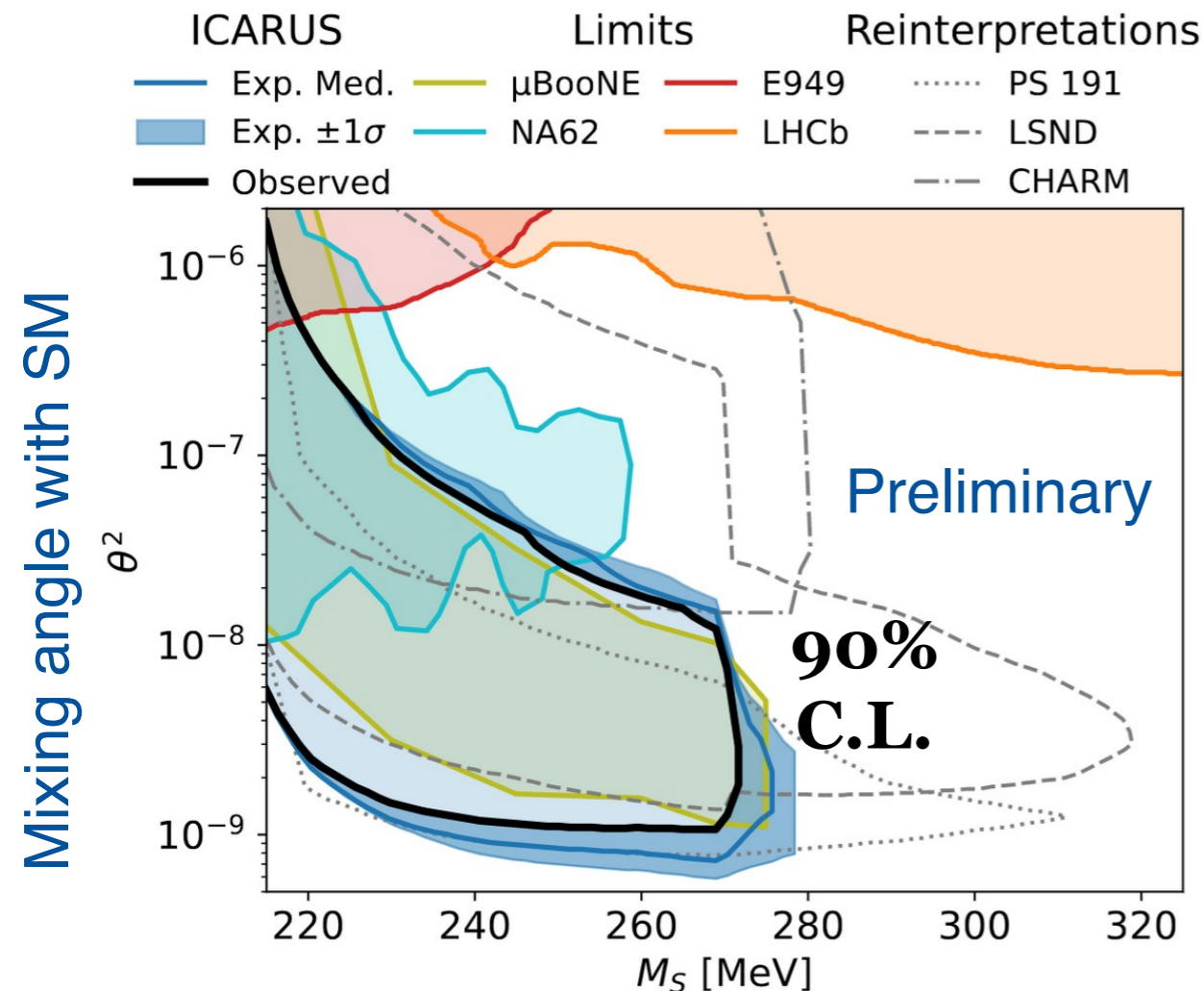


# The first physics result with ICARUS at Fermilab!

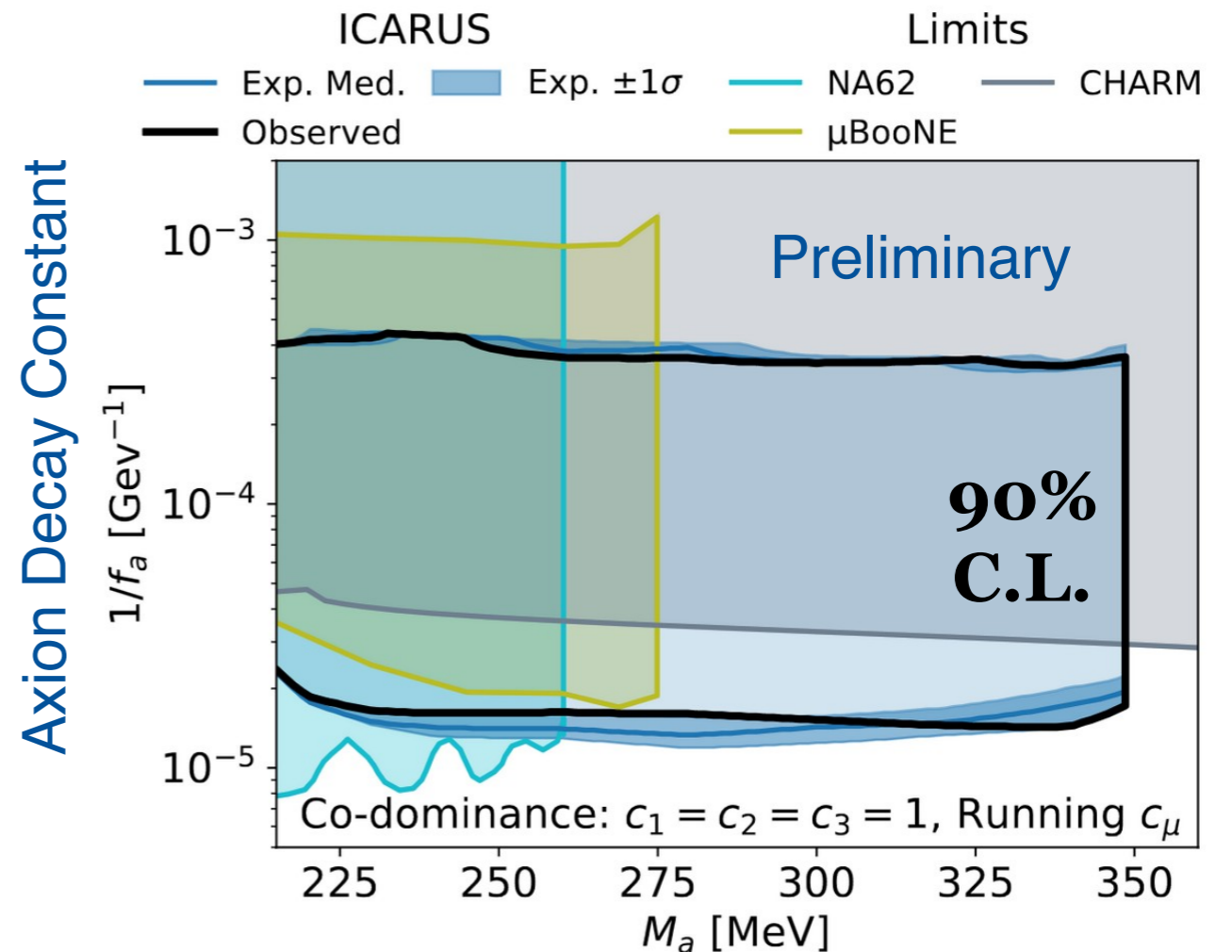
- For a HPS/ALP search the idea is to look for a resonance (“bump” above the background) at a specific value of the dimuon invariant mass
- Performing a search using the ICARUS Run1+Run2 (2022+2023) NuMI data there is no new physics signal observed and the observed events are consistent with the background expectation

Paper in preparation

### Higgs Portal Scalar Exclusion



### Heavy Axion Exclusion



See talk by N. Rowe (Monday afternoon) for more details!



# Summary

- The ICARUS experiment is currently operating at Fermilab as part of the SBN program and is currently taking physics data after completing its commissioning period in June 2022
- ICARUS can take advantage of both the BNB beam on-axis and the NuMI beam off-axis
- The ICARUS data can be used for neutrino oscillation searches, cross section measurements, and BSM physics
- Event selections for neutrino oscillations and neutrino-argon cross sections are in advance state with good data/MC agreement
- ICARUS has completed its first physics search looking for Higgs Portal Scalar and Axion-Like Particle BSM signatures
- Stay tuned for more exciting physics results from ICARUS!



Thank you!

Questions?

# Backup Slides

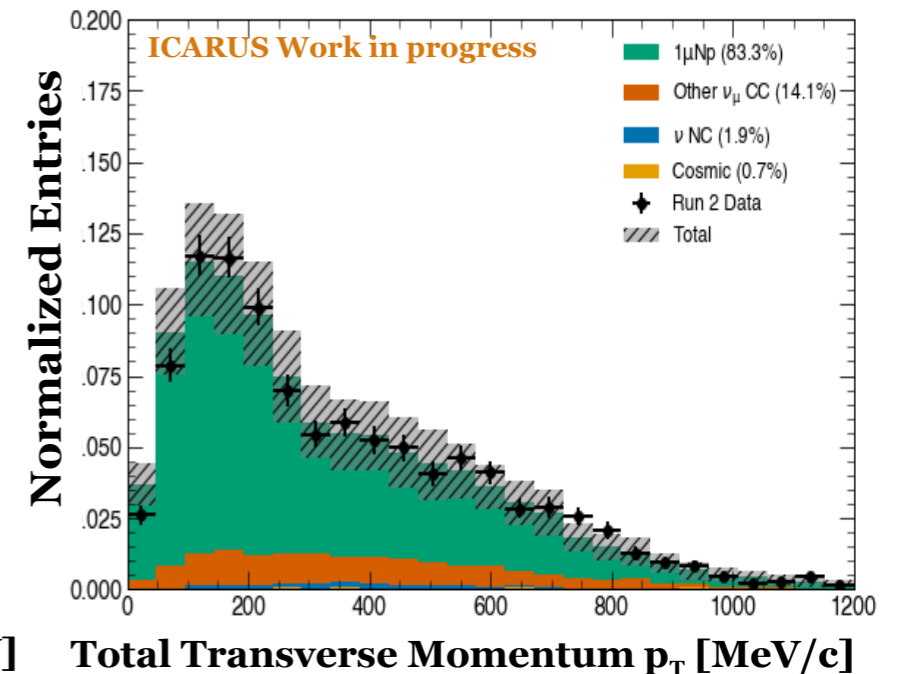
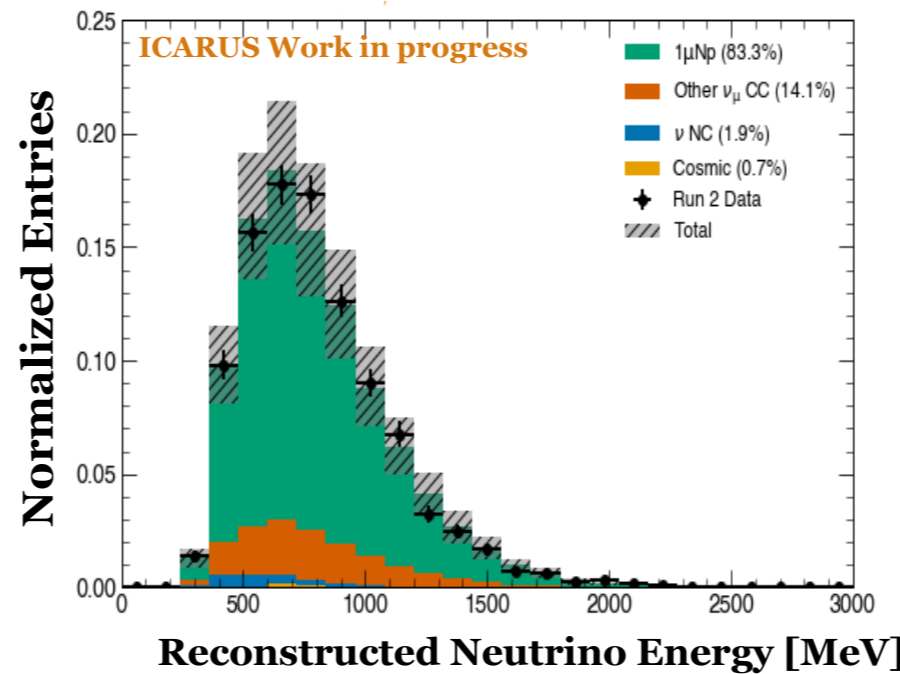
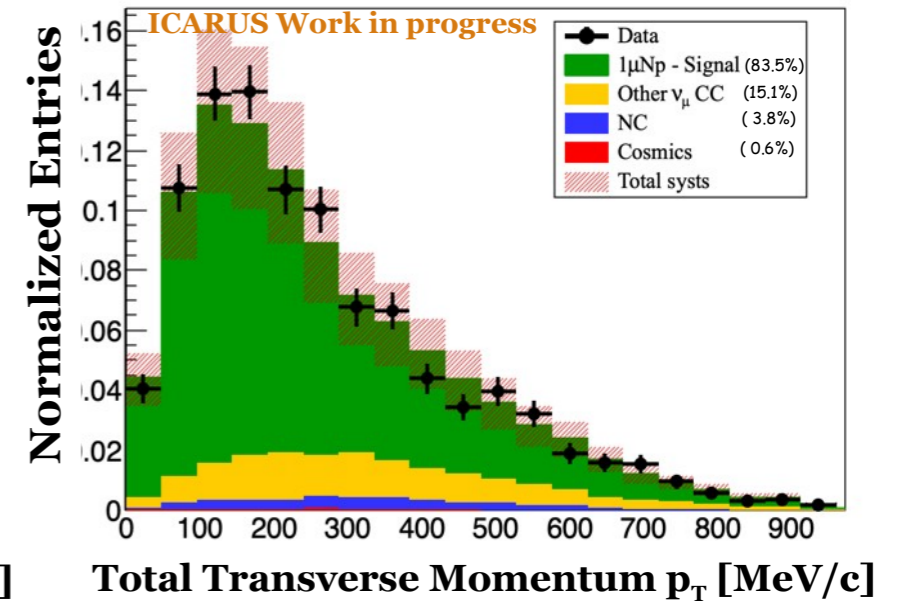
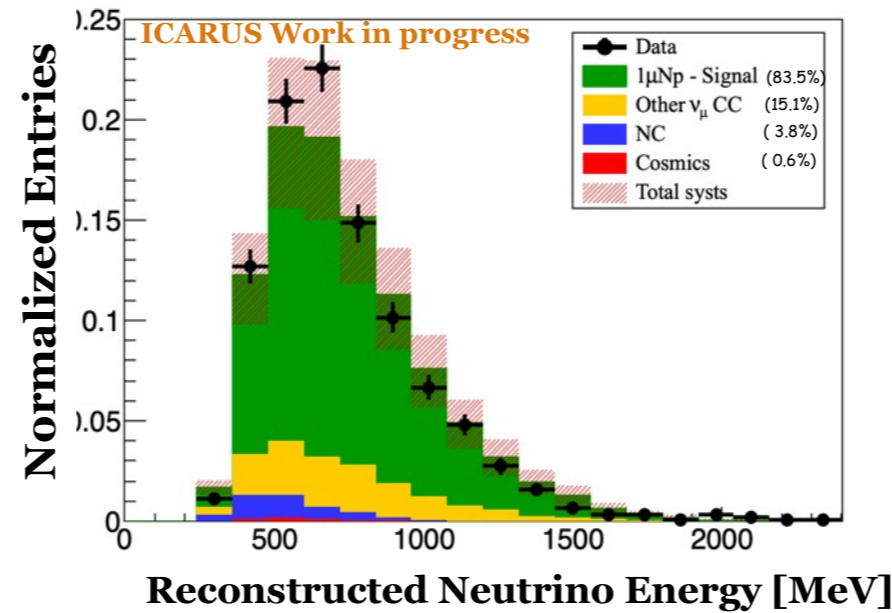


# Pandora $1\mu\text{Np}0\pi$ Selection

Efficiency  $\sim 50\%$   
Purity  $\sim 80\%$

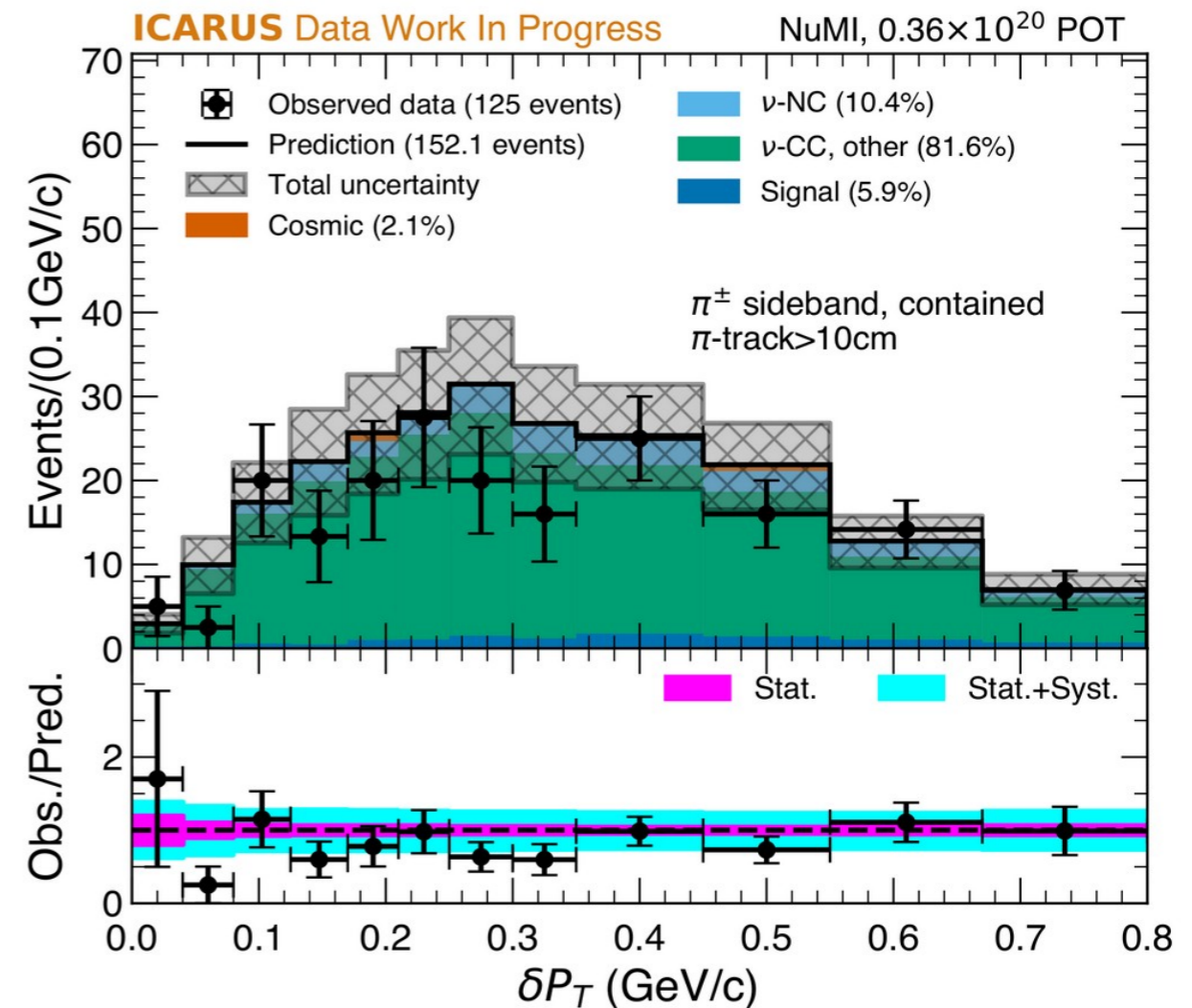
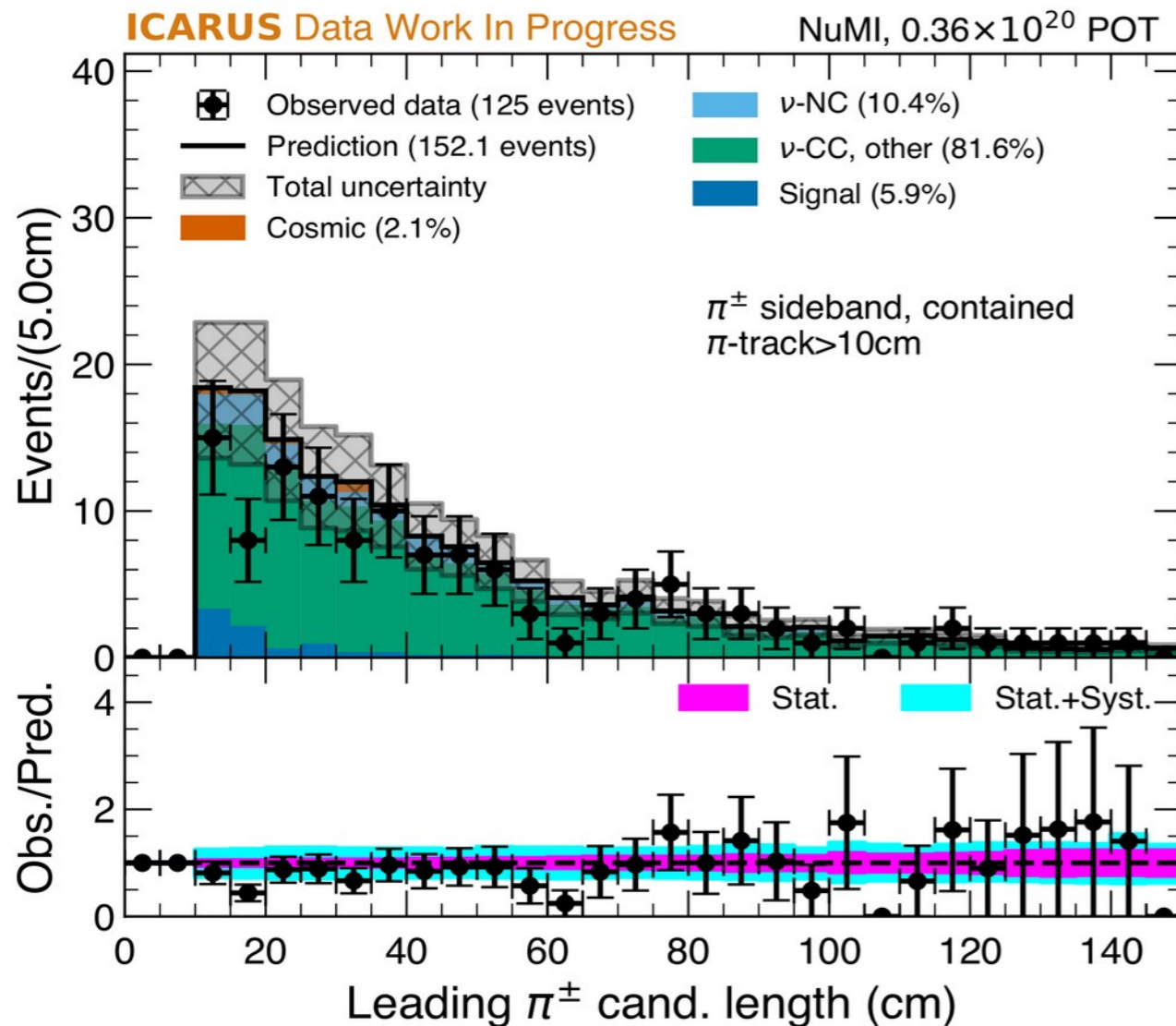
# ML (SPINE) $1\mu\text{Np}0\pi$ Selection

Efficiency  $\sim 75\%$   
Purity  $\sim 80\%$



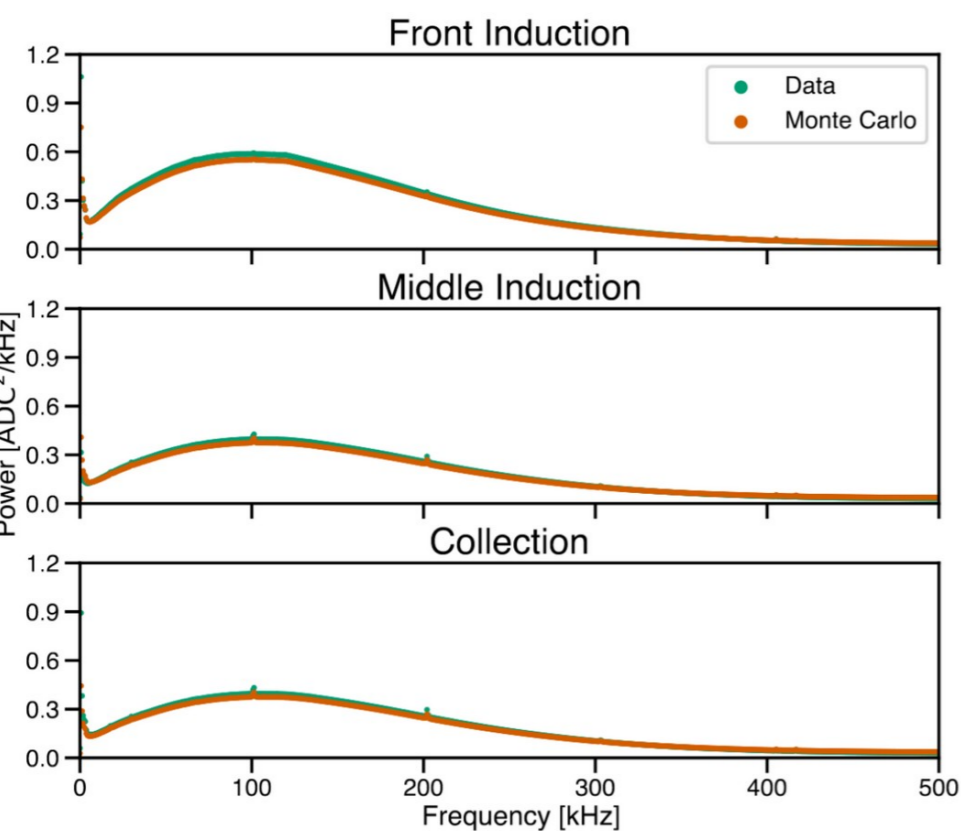
# Progress towards first NuMI cross section measurements

- Analysis is in very advanced state, close to unblinding full data set
- Initial sideband studies focusing on charged pion sample to understand pion-proton mis-identification
  - Select on two muon/pion-like tracks

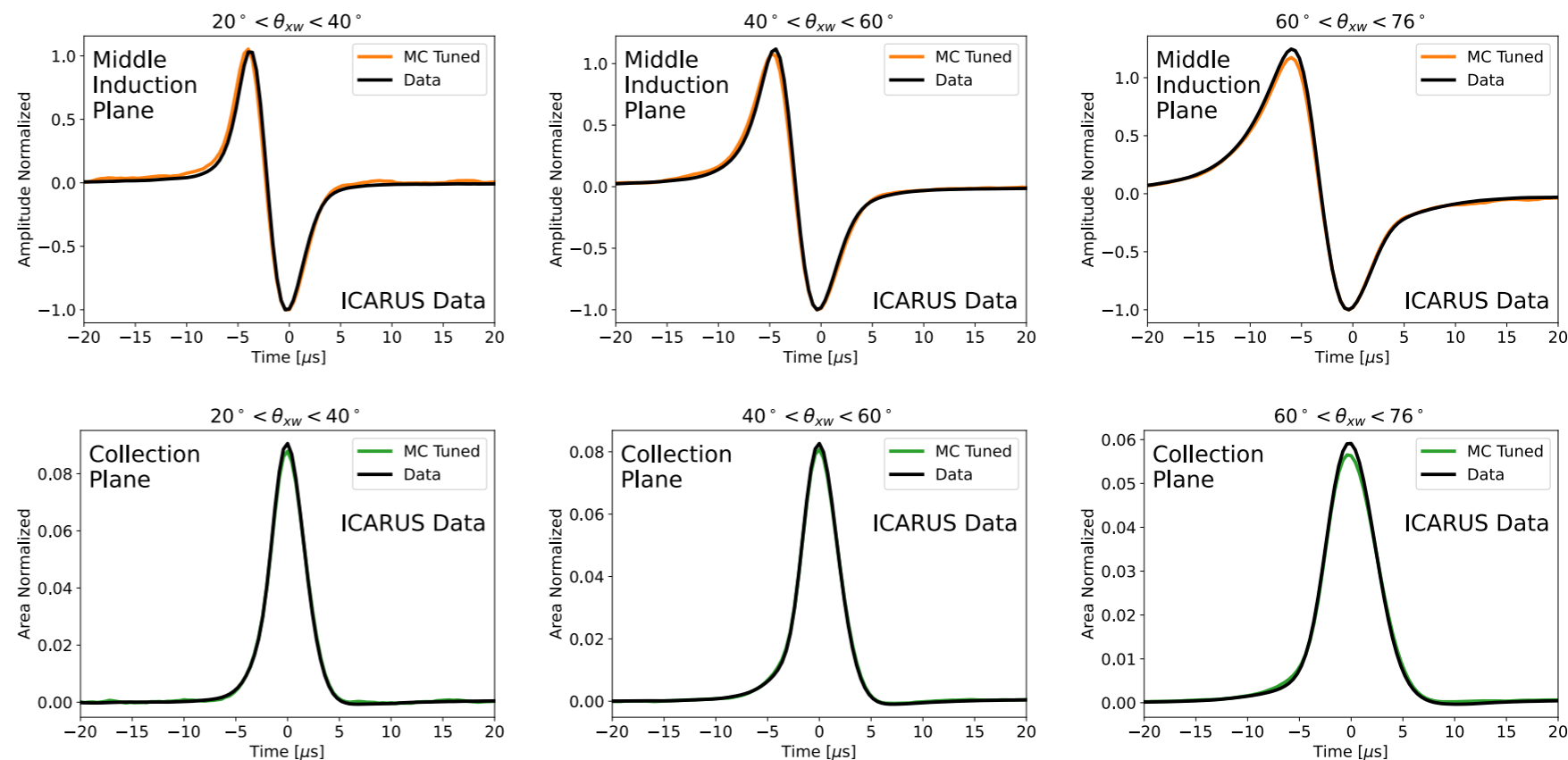


# Calibrating the ICARUS TPC

- Extensive effort to calibrate the ICARUS TPC to better understand our data
- Tuning of the simulated signals and noise on the wireplanes to match what we see in the data



TPC noise spectra



TPC Signal shape comparison after tuning procedure

arXiv:2407.11925, submitted to JINST