



Current Status and First Physics Highlights from ICARUS

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ND All-Hands Meeting

August 6, 2024

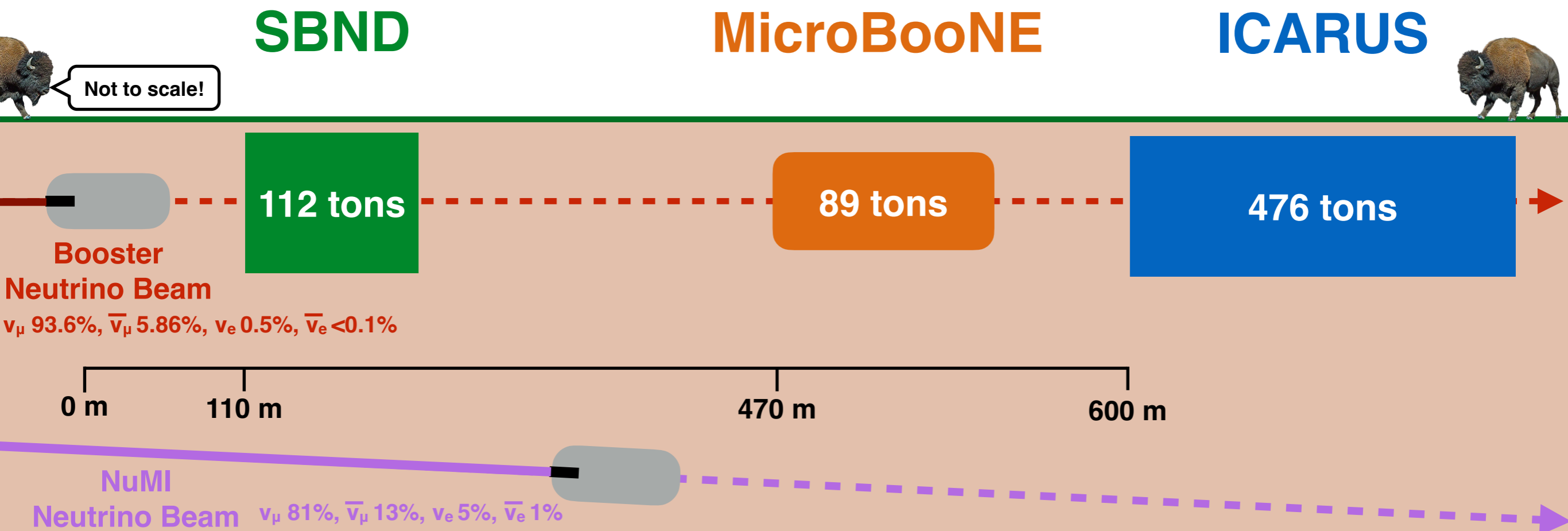
Overview

- What is ICARUS?
- 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

What is ICARUS?

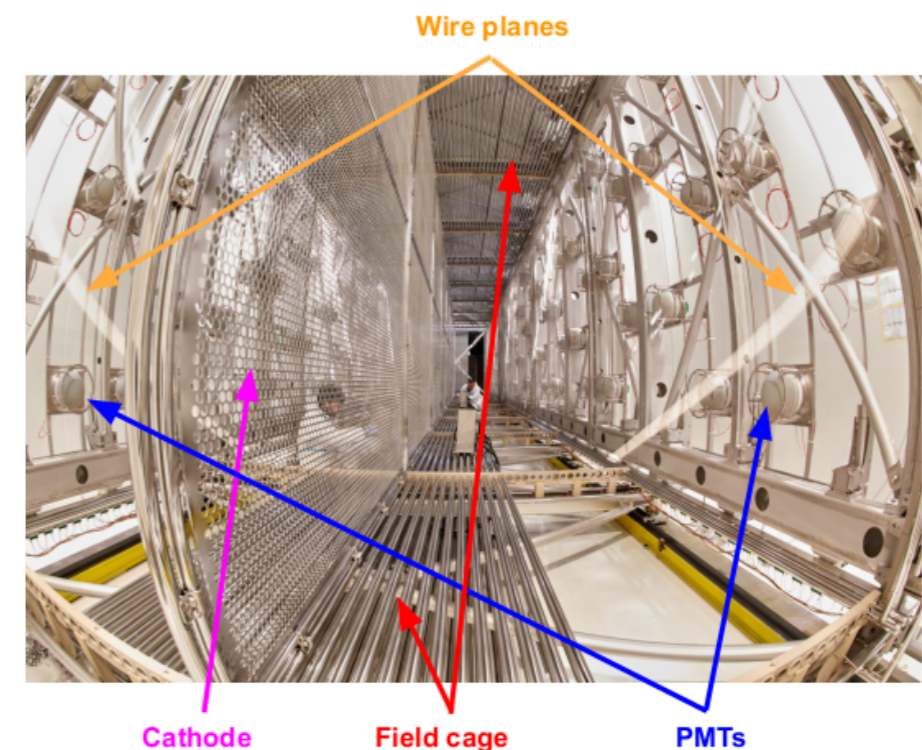
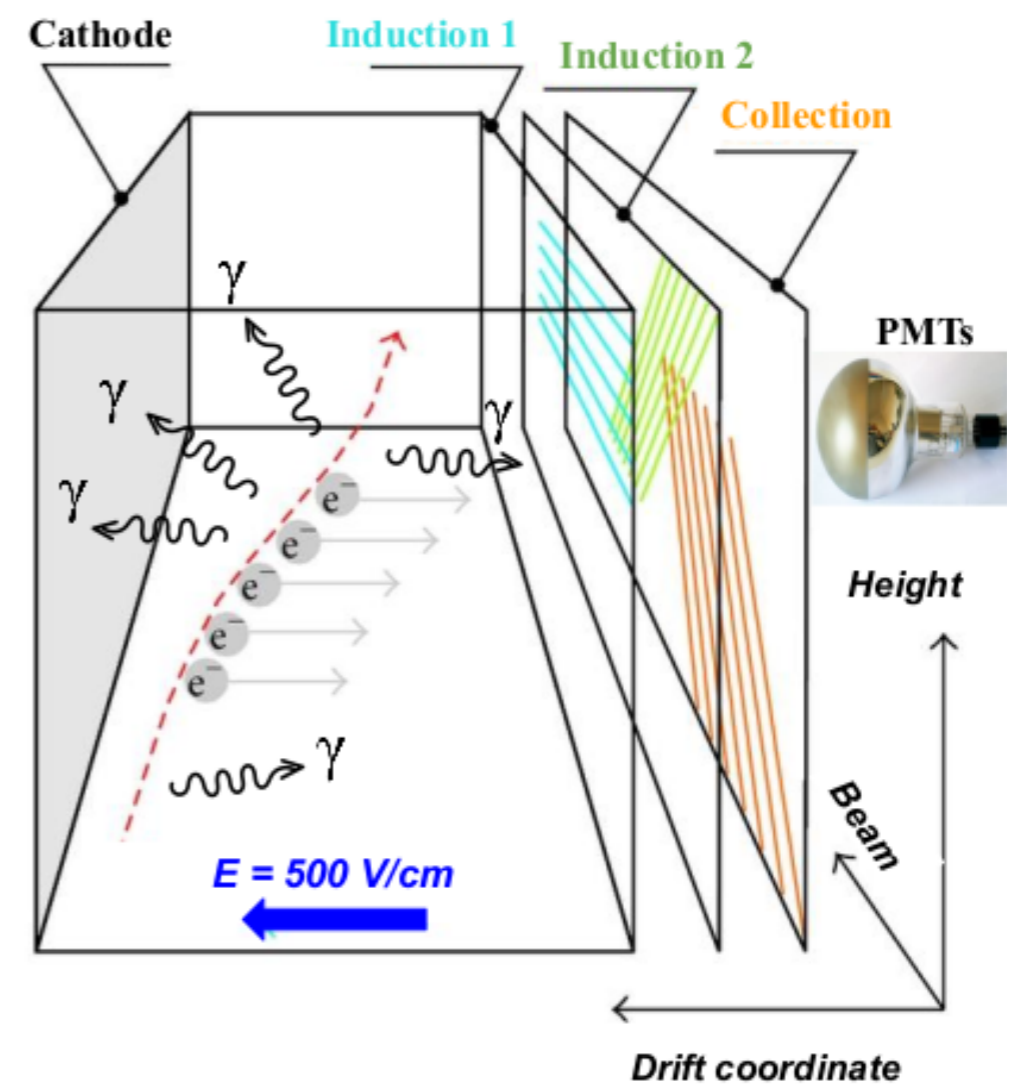
The Fermilab Short Baseline Neutrino (SBN) Program

- Program based at Fermilab designed to definitively probe the sterile neutrino hypothesis of the MiniBooNE anomaly
- The detectors all 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!



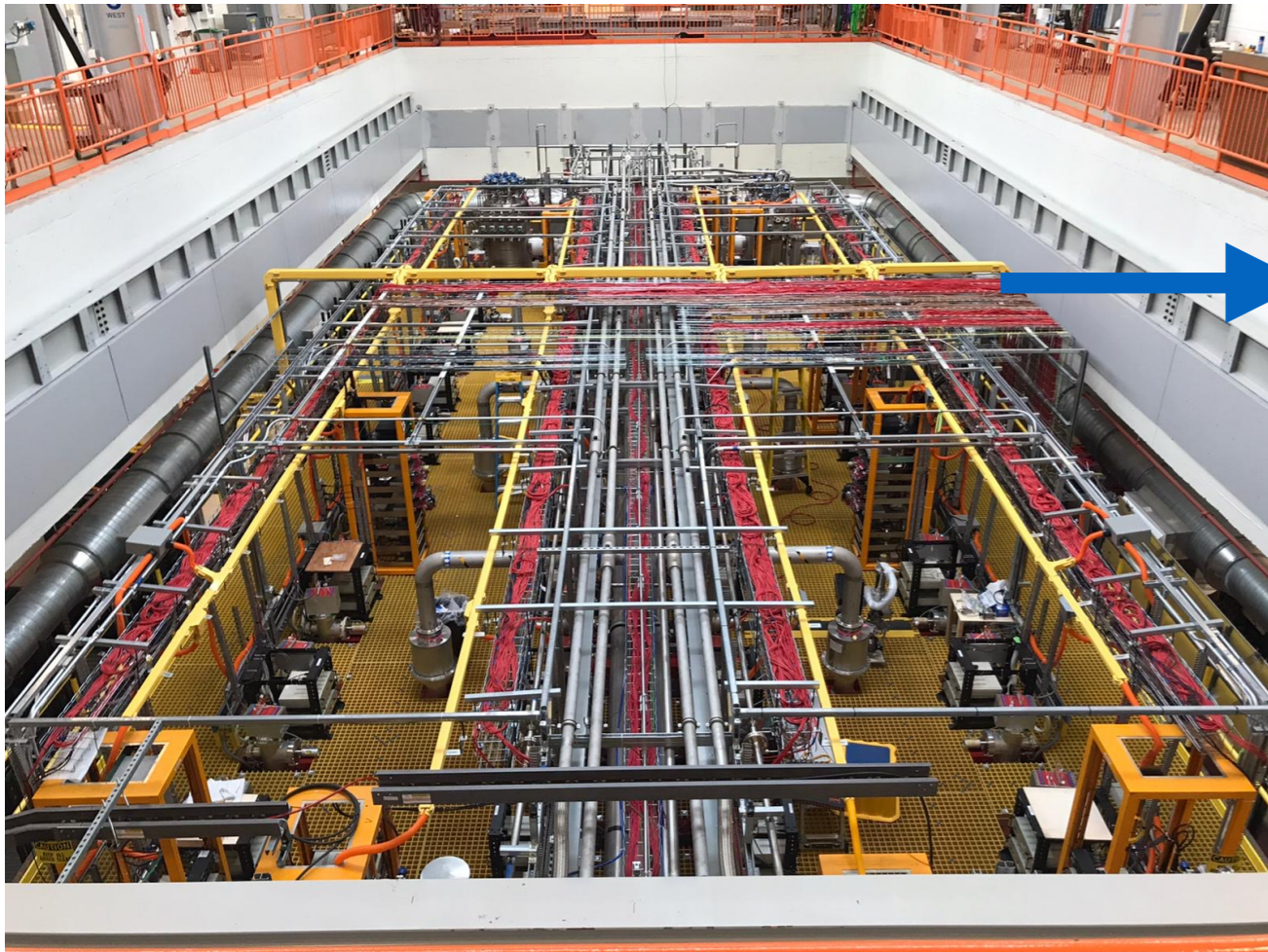
The ICARUS Detector

- 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

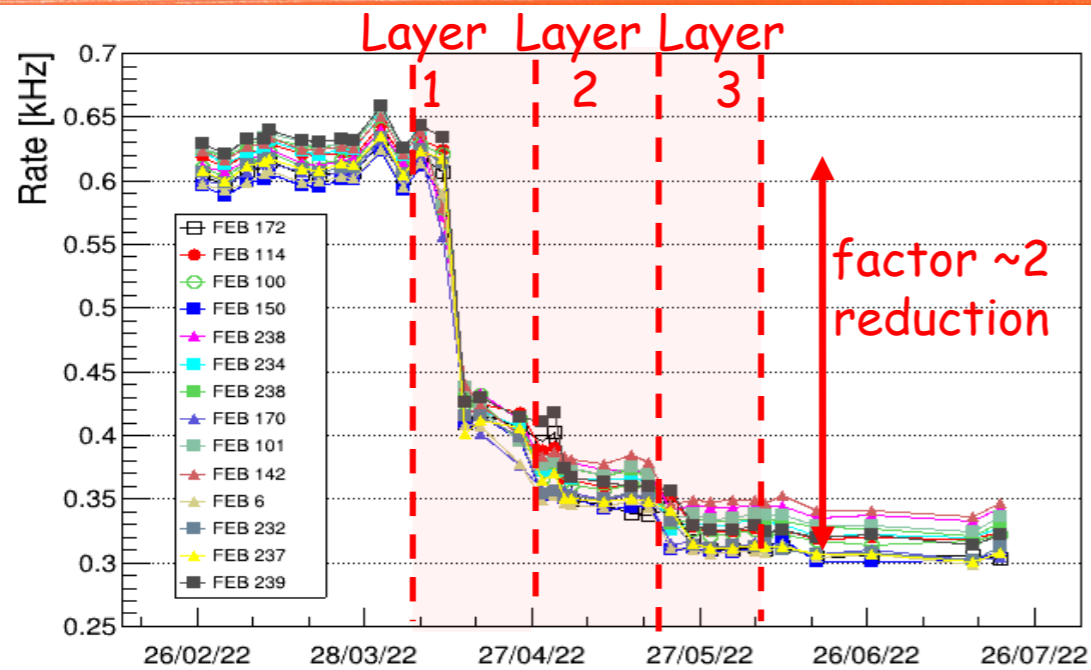
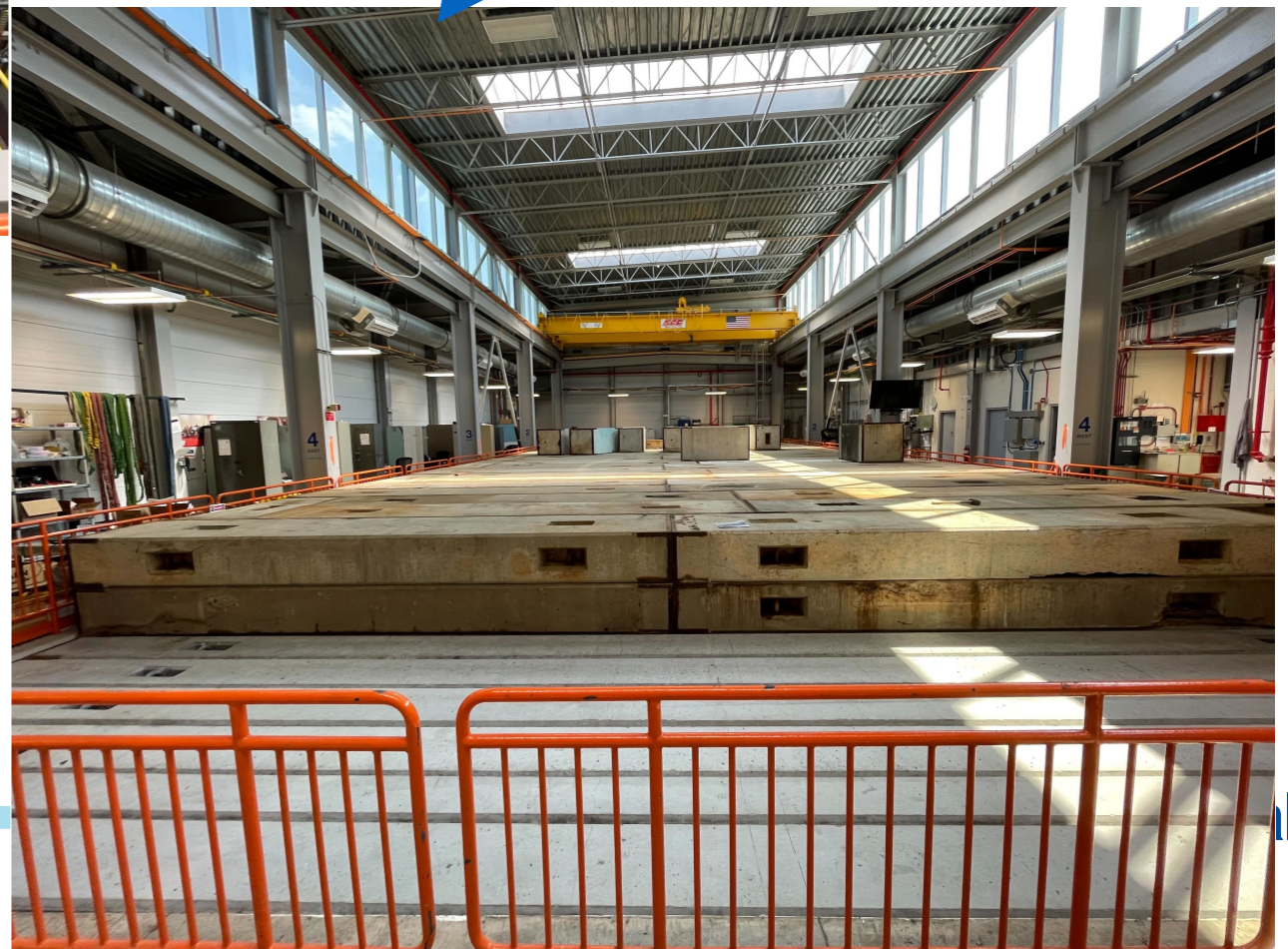
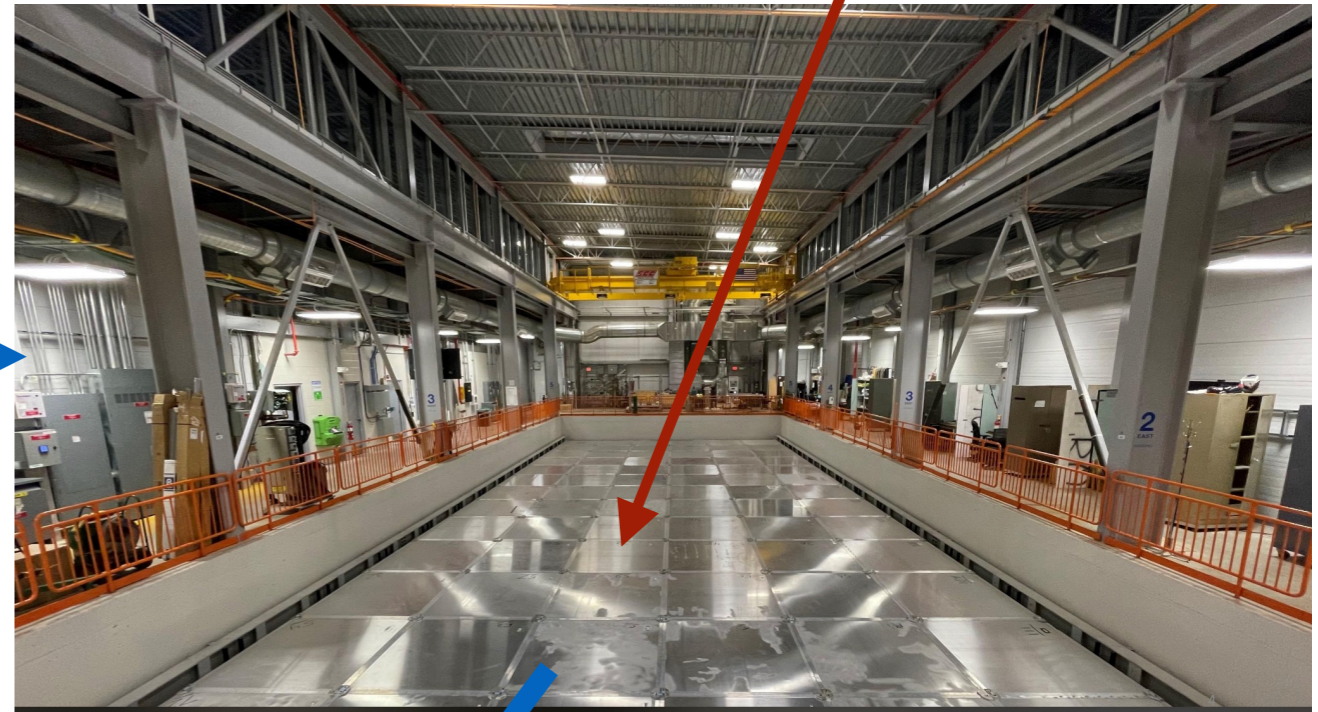


Installing and Operating ICARUS at Fermilab

ICARUS Installation



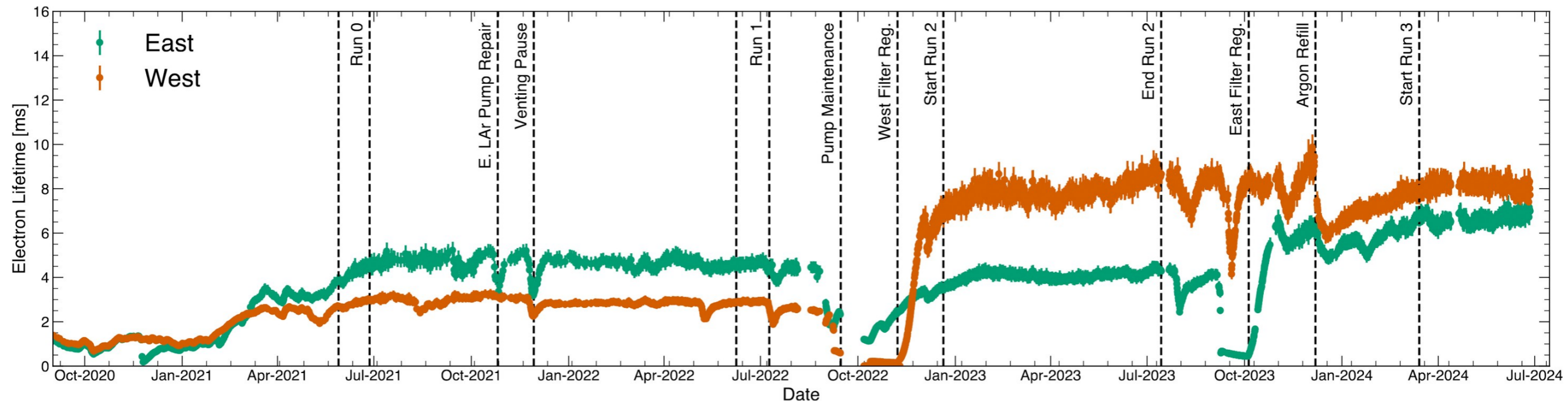
Top CRT panels



Operating the ICARUS detector at Fermilab

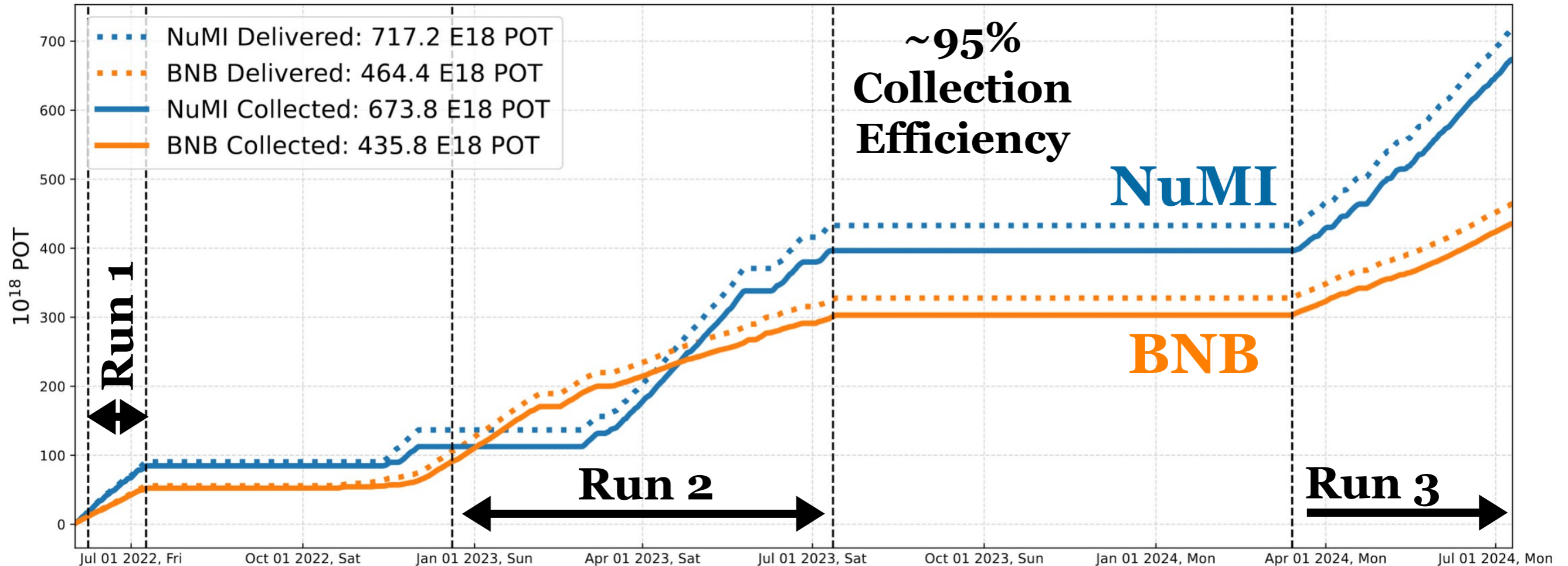
- ICARUS filled with LAr in April 2020 and was fully operational in August 2020
- Commissioning completed in 2022 and began physics data taking
- Electron lifetime reached the > 3 ms target for quality physics data during each beam operation period, now at 6-9 ms in the latest data taking period
- During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

ICARUS Electron Lifetime



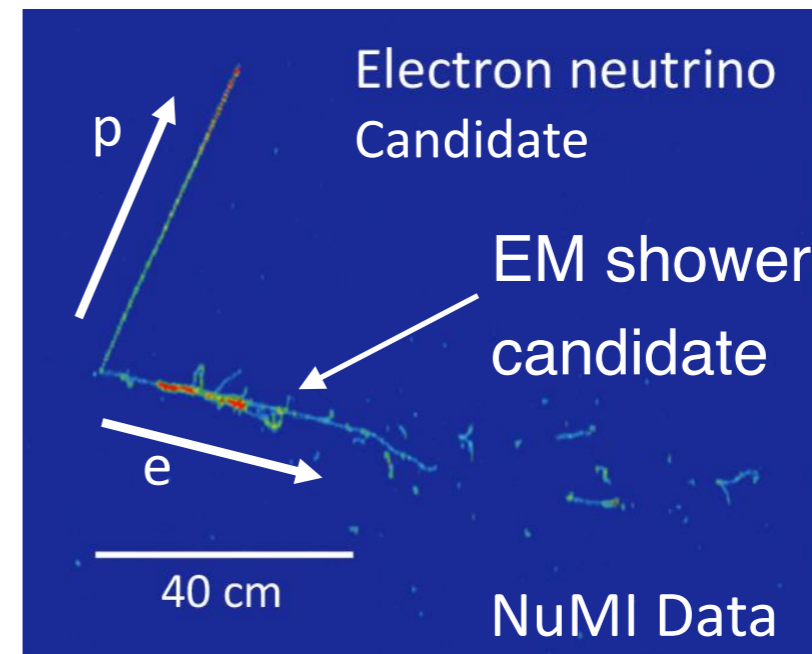
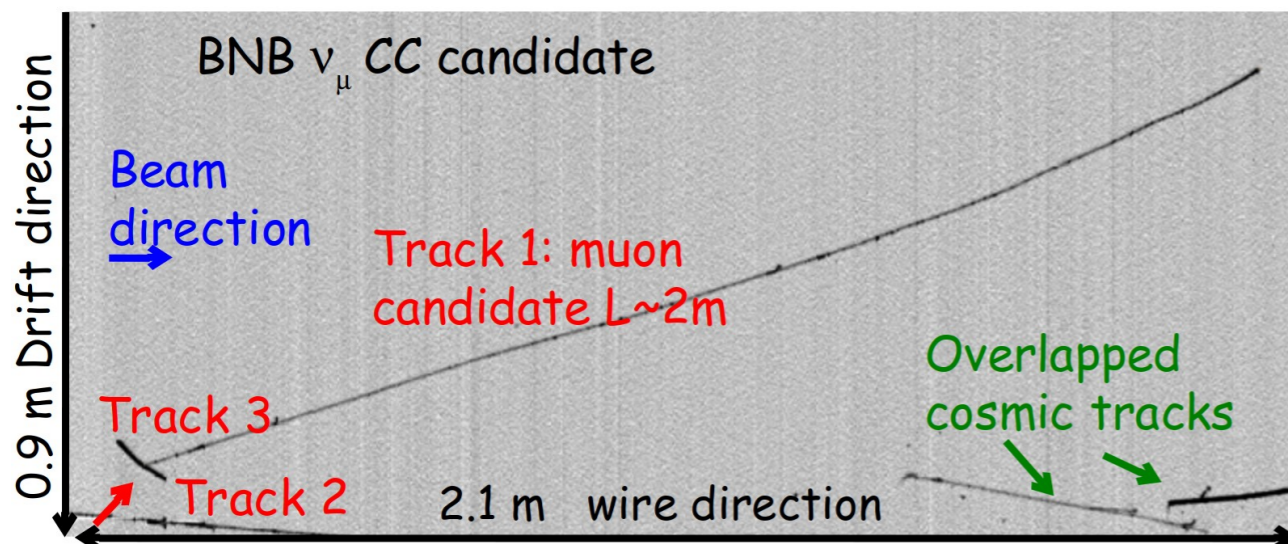
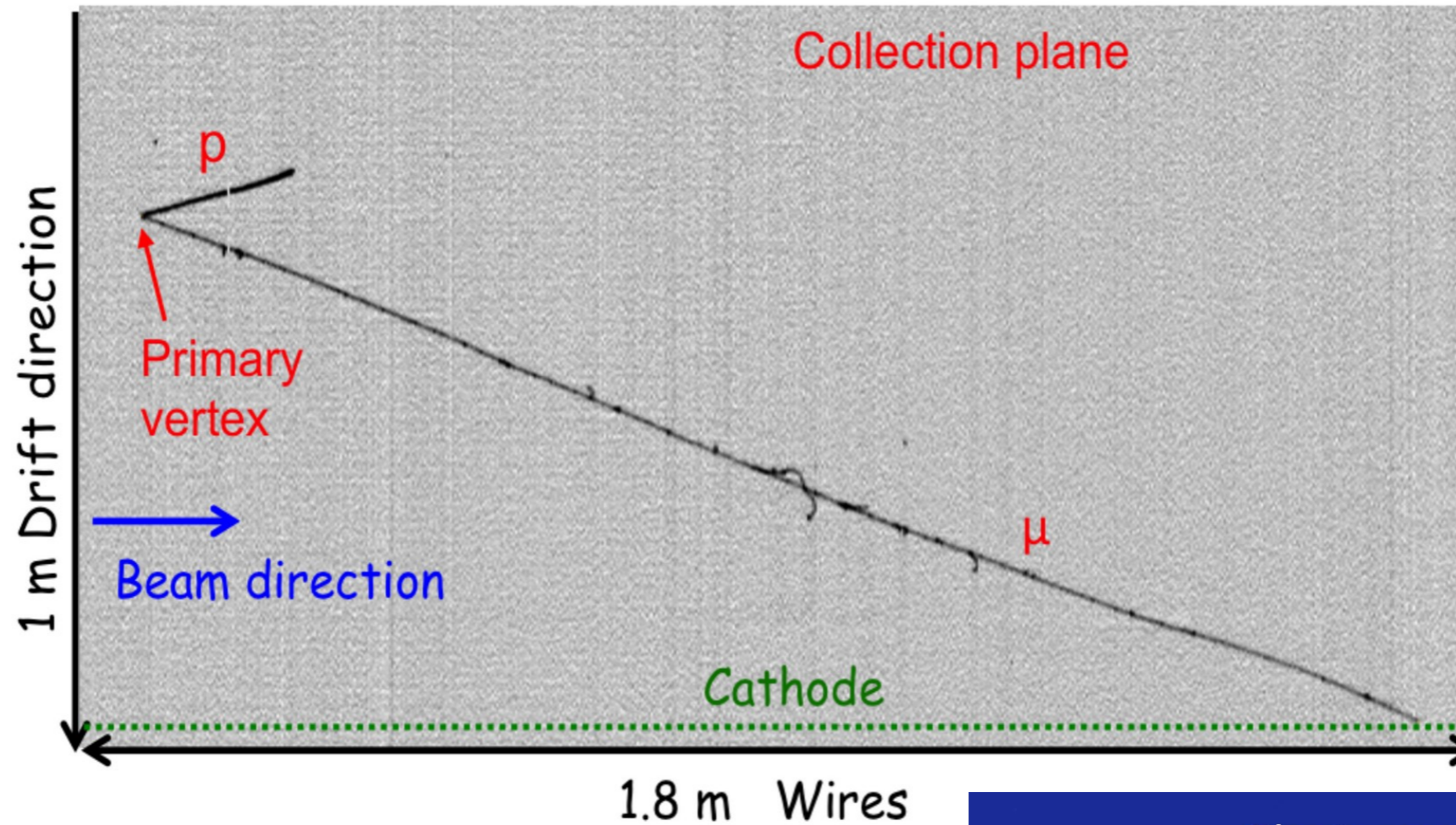
Commissioning of ICARUS at FNAL: Eur. Phys. J. C 83, 467 (2023)

The collected data with ICARUS at Fermilab



- ICARUS has steadily operated during periods of accelerator operations reaching a POT collection efficiency of ~95%
- 3 data taking periods up to July 2024
- BNB Run1/Run2/Run3: 0.4/2.1/1.4 x 10²⁰ POT
- NuMI Run1/Run2/Run3: 0.7/2.7/2.8 x 10²⁰ POT in FHC/FHC/RHC configuration

So what do neutrinos in the data actually look like?



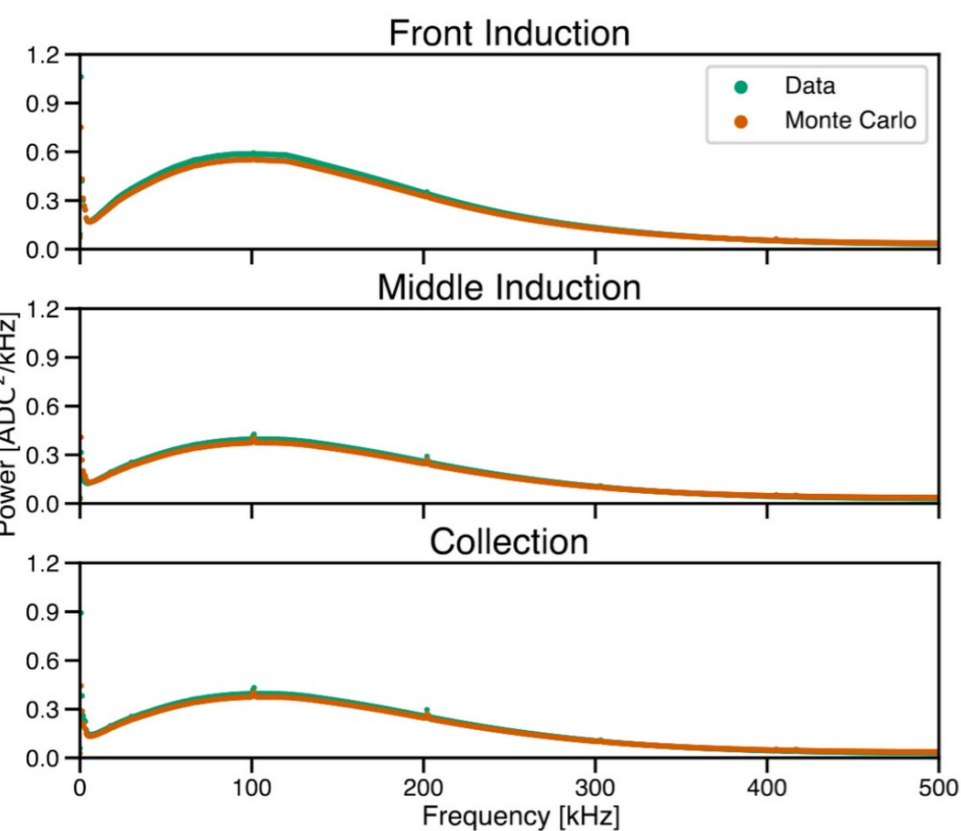
What ICARUS can do with its data

- 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 ν_μ disappearance channel in the BNB beam, which demonstrates the ability to perform these analyses in view of a joint SBN analysis
 - 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
 - This is the first physics result from ICARUS at Fermilab!
- Joint sterile neutrino oscillation search combined with SBND towards the goals of the combined SBN program

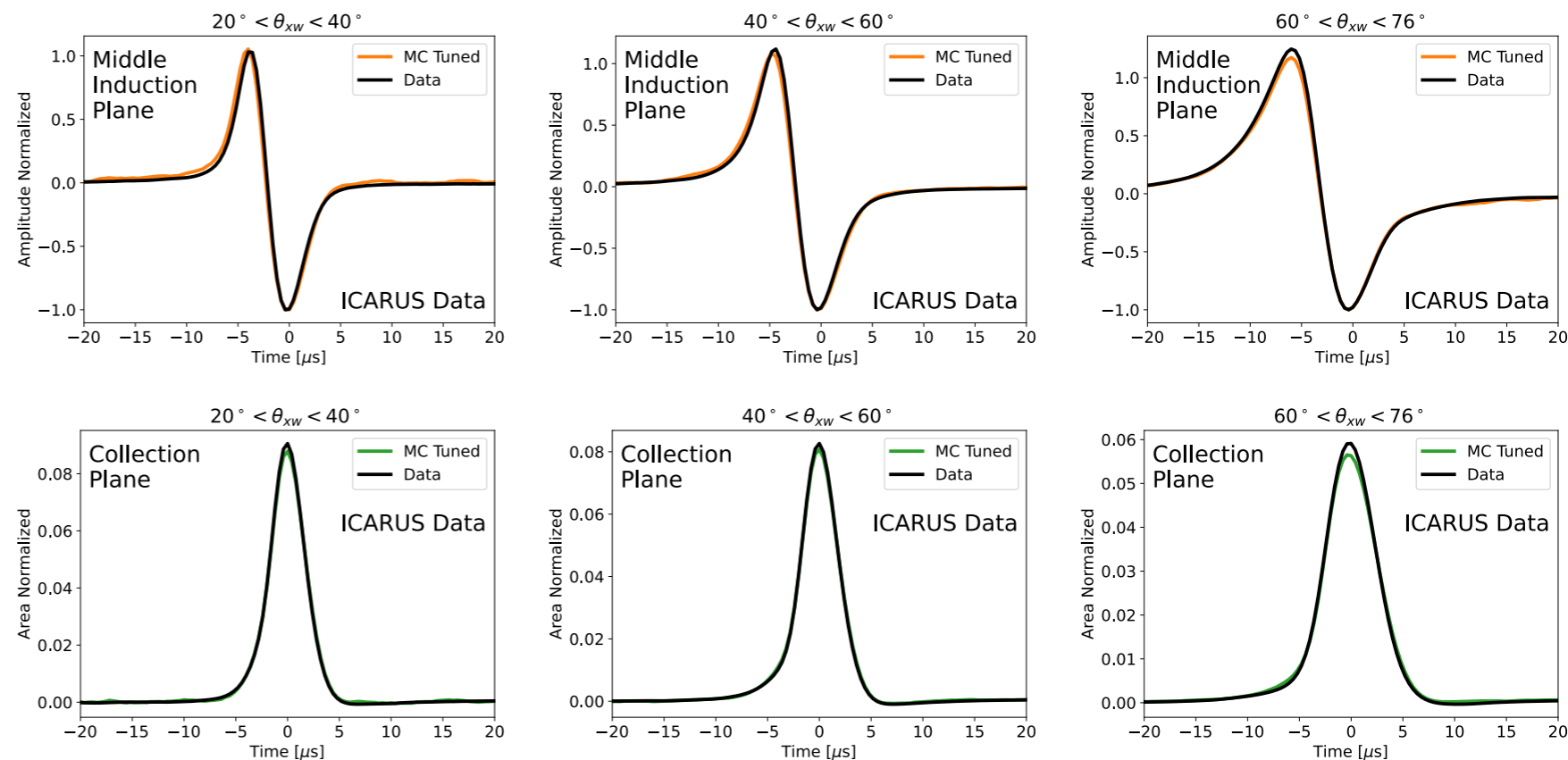
Understanding the ICARUS Detector

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



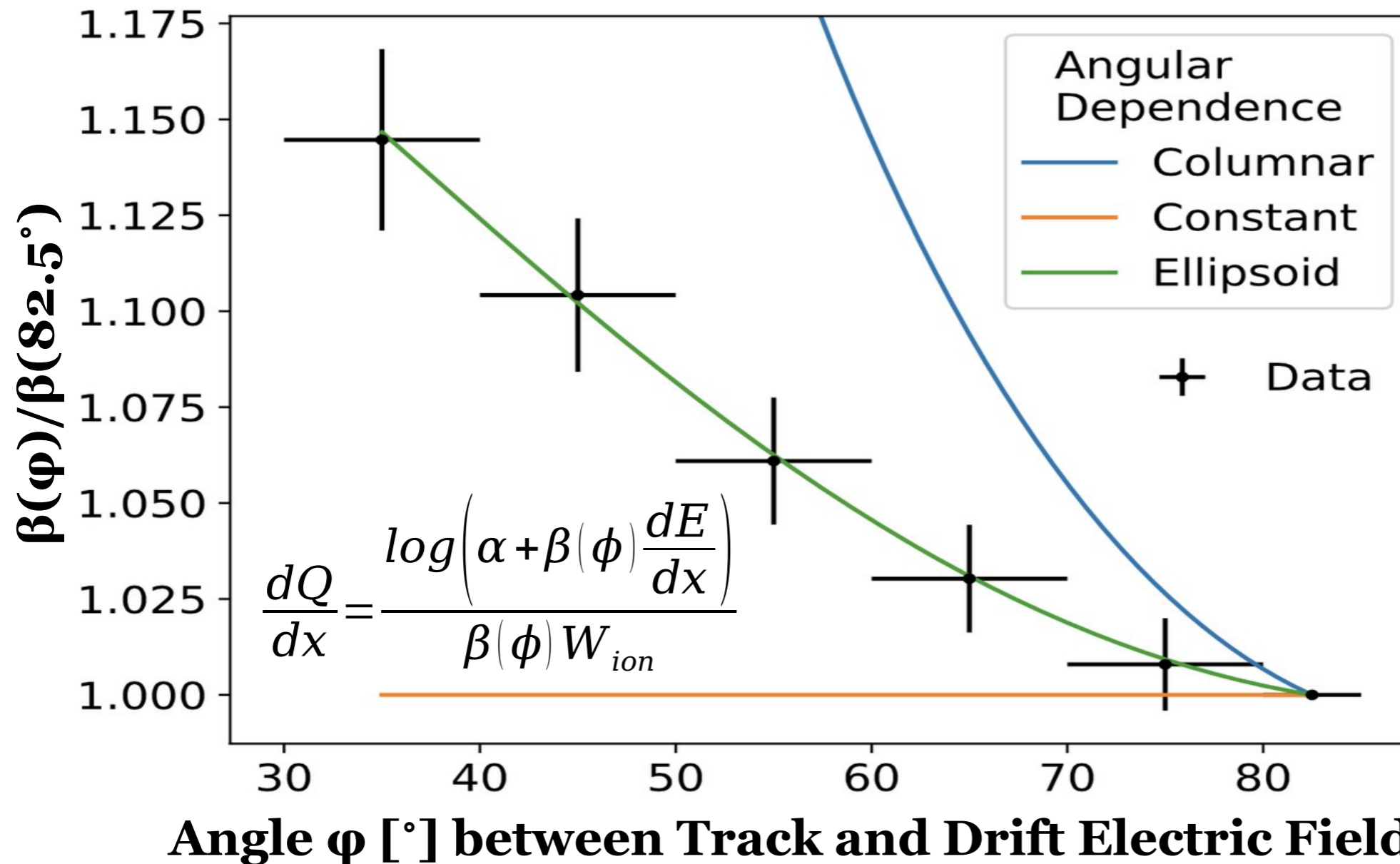
TPC Signal shape comparison after tuning procedure

arXiv:2407.11925, submitted to JINST

Recombination measurement at ICARUS

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

Dependence of Recombination on Track Angle

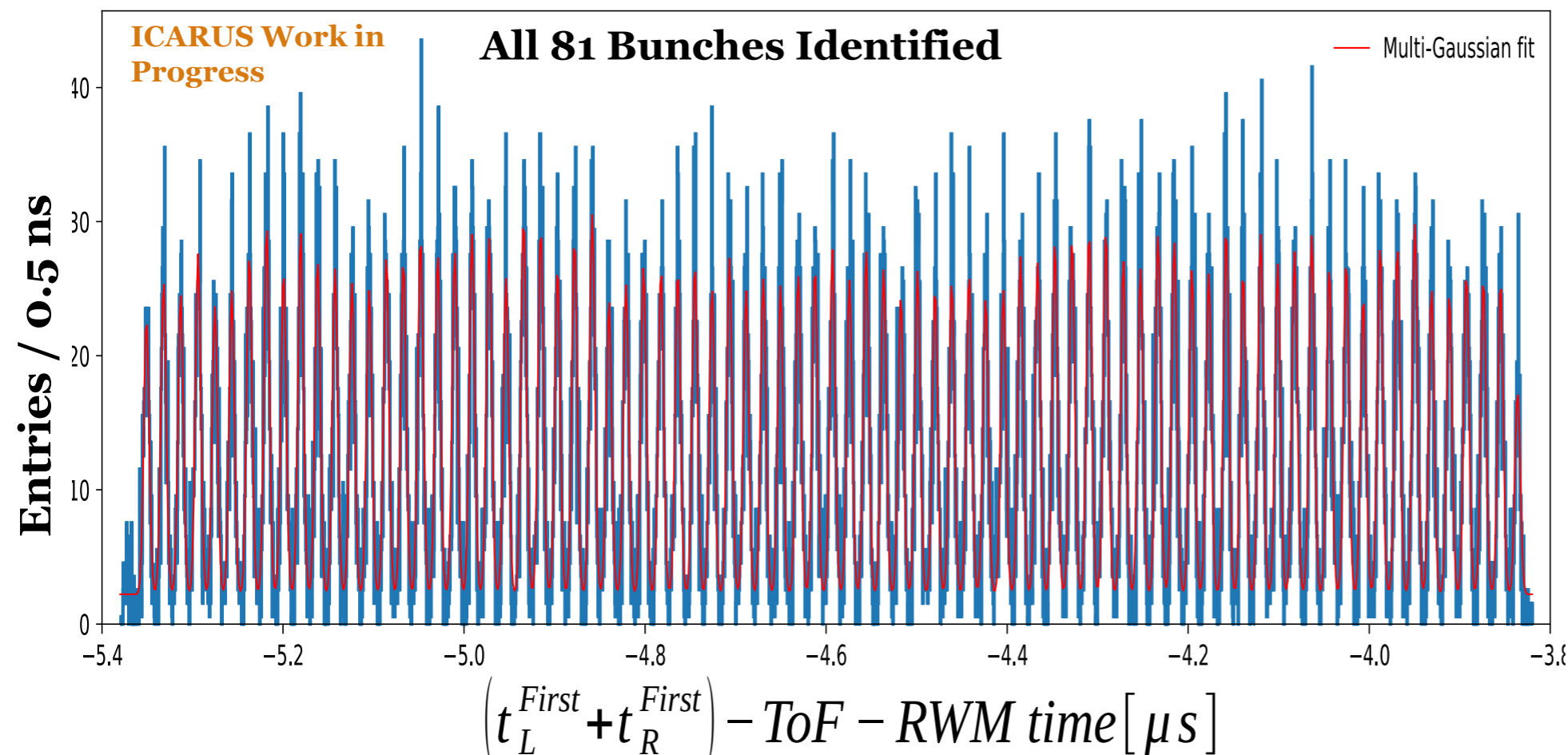


Select proton-like tracks in the data

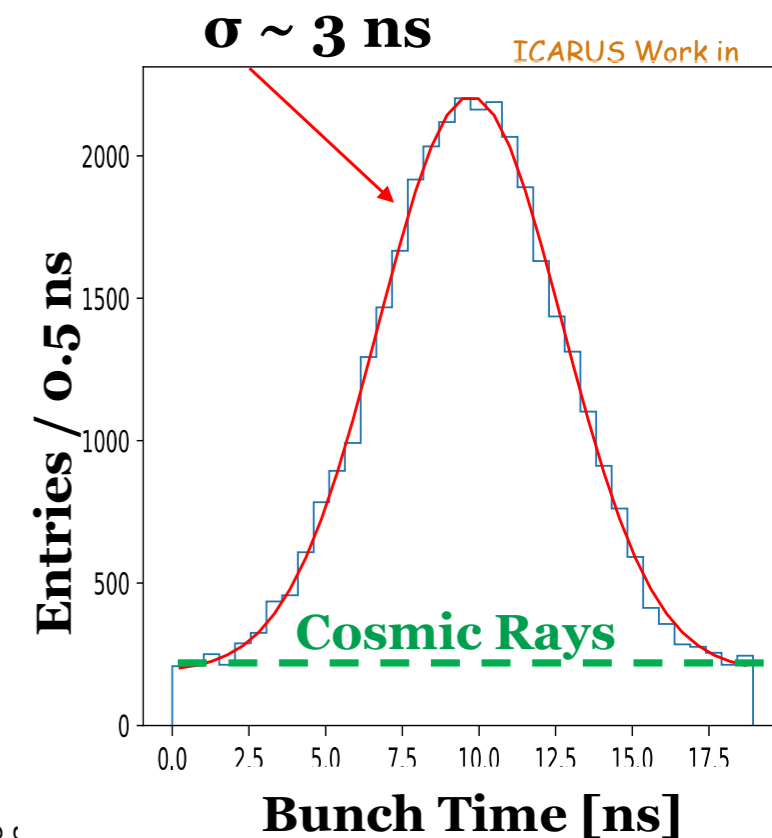
arXiv:2407.12969, submitted to JINST

Seeing the beam bunch structure in the data!

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



Bunch structure from the BNB beam!



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

Moving towards neutrino physics results

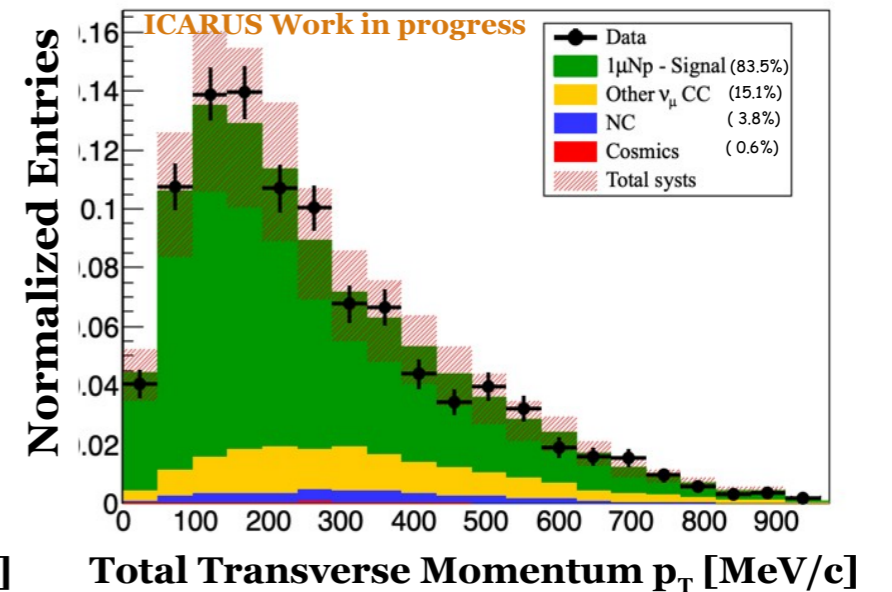
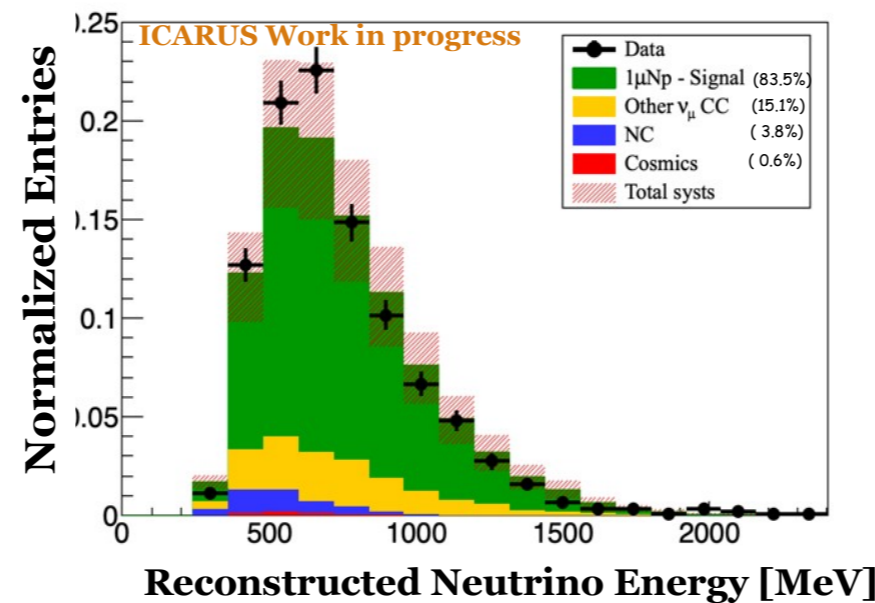
Performing a Neutrino Oscillation Measurement with ICARUS

- 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 ν_μ and ν_e disappearance with two detectors
 - Use BNB ν_μ/ν_e data for both SBND and ICARUS and additionally NuMI ν_μ/ν_e for ICARUS
- With SBND in the commissioning phase of the experiment, ICARUS is currently pursuing a single-detector neutrino oscillation search initially focusing on the BNB ν_μ disappearance channel and muon neutrino events
 - Useful to develop all the tools in preparation and a demonstration for the full two-detector measurements for the full SBN program
- Focus is on $1\mu 1p 0\pi / 1\mu N p 0\pi$ final states from events in coincidence with the BNB with two reconstruction pathways
 - Pandora - pattern recognition based software used in previous LArTPC experiments
 - SPINE - machine-learning based reconstruction chain

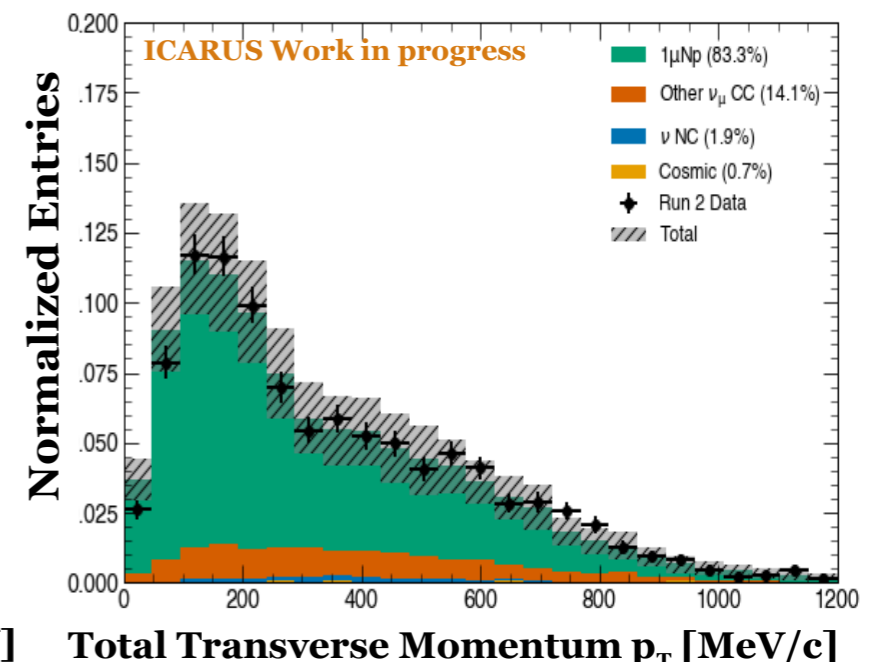
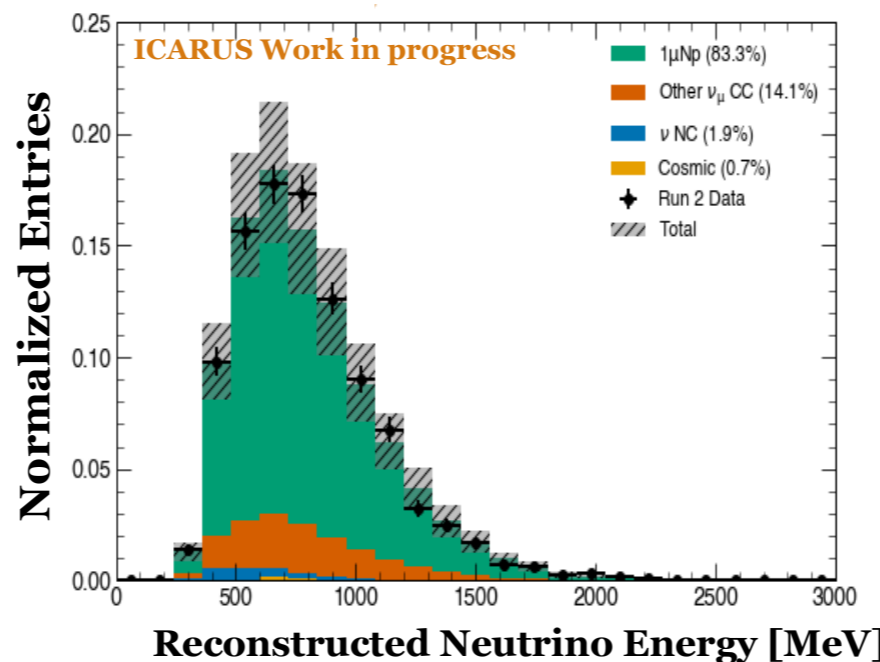
Event Selections for Neutrino Oscillation Physics

- 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

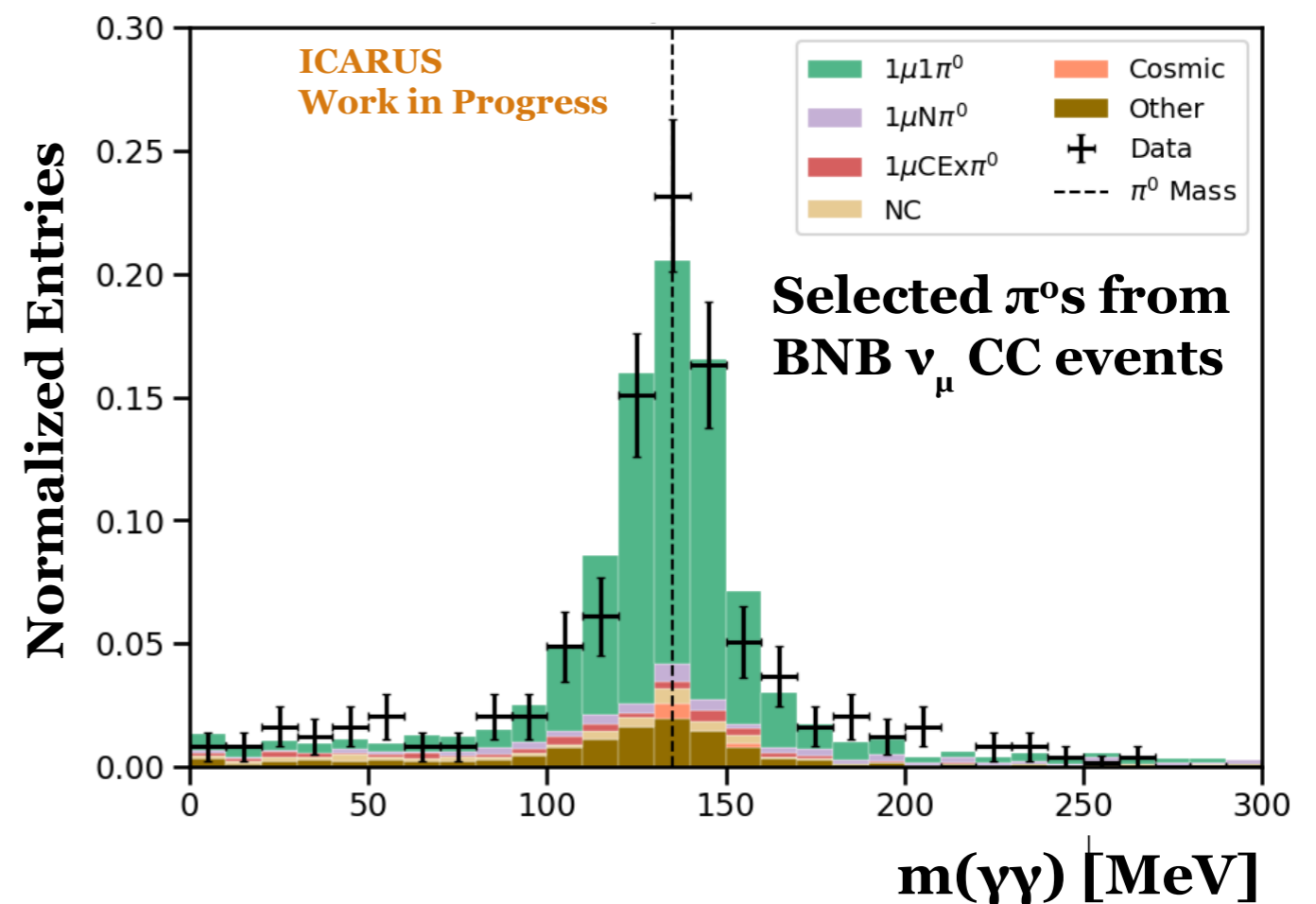


SPINE Selection



What about the shower-based signatures?

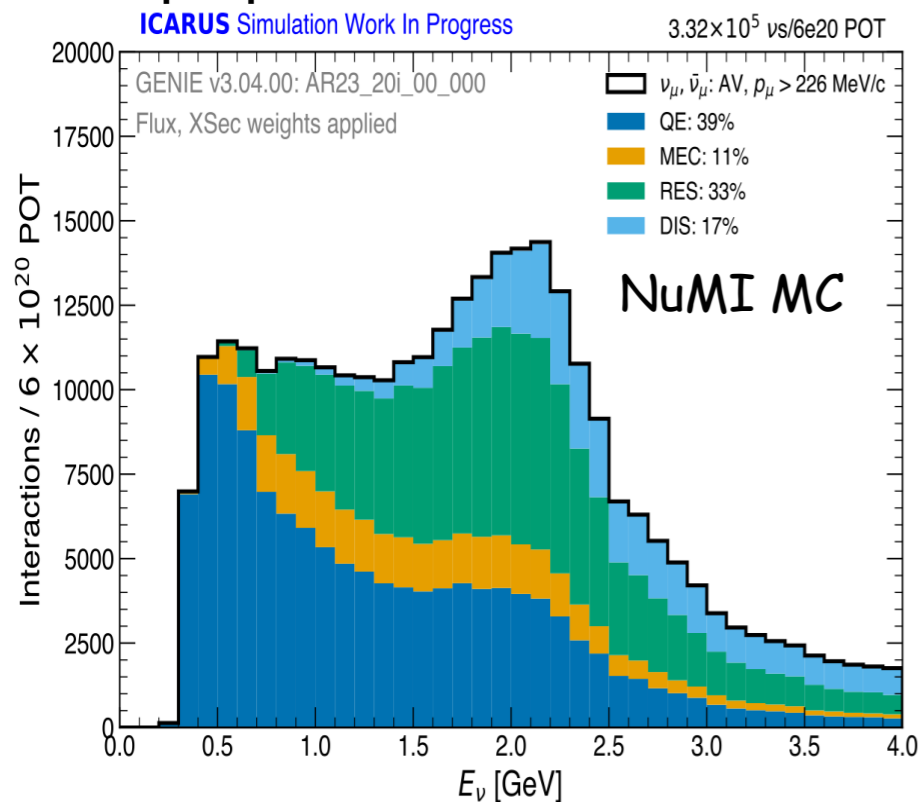
- Electromagnetic shower-based events selections (for electron neutrino events) making progress for both reconstruction paradigms but not as advanced as those for track-like events
- Studies using the SPINE reconstruction show promising ability to reconstruct π^0 events which are used to calibrate the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



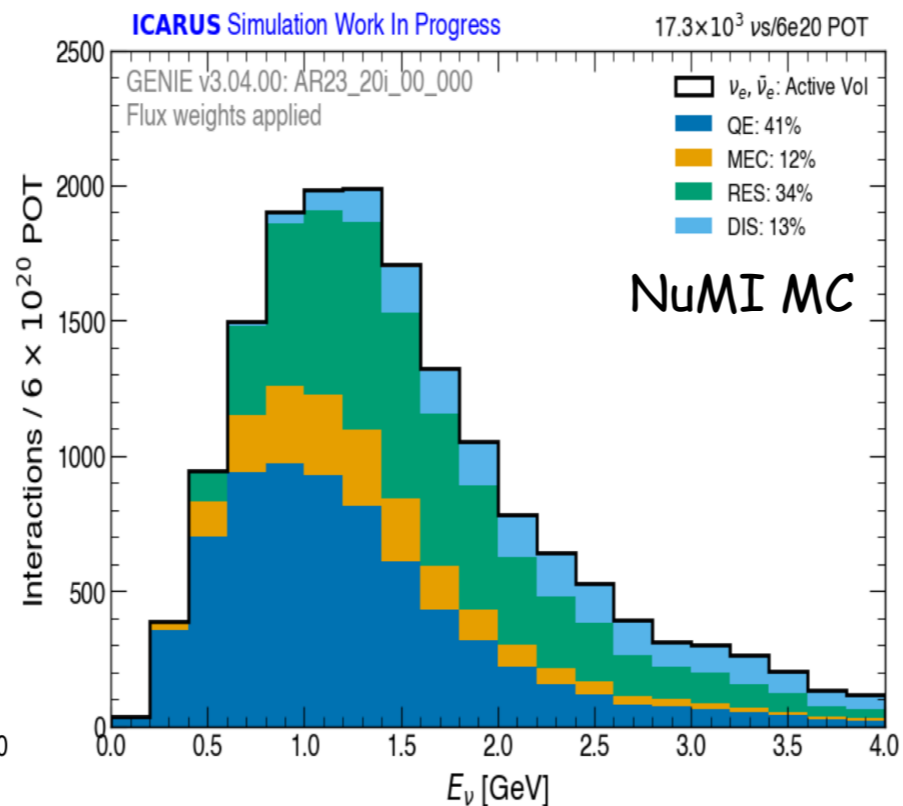
Neutrino-argon cross section measurements

- 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 6×10^{20} POT
- Relevant for the first oscillation maximum for DUNE

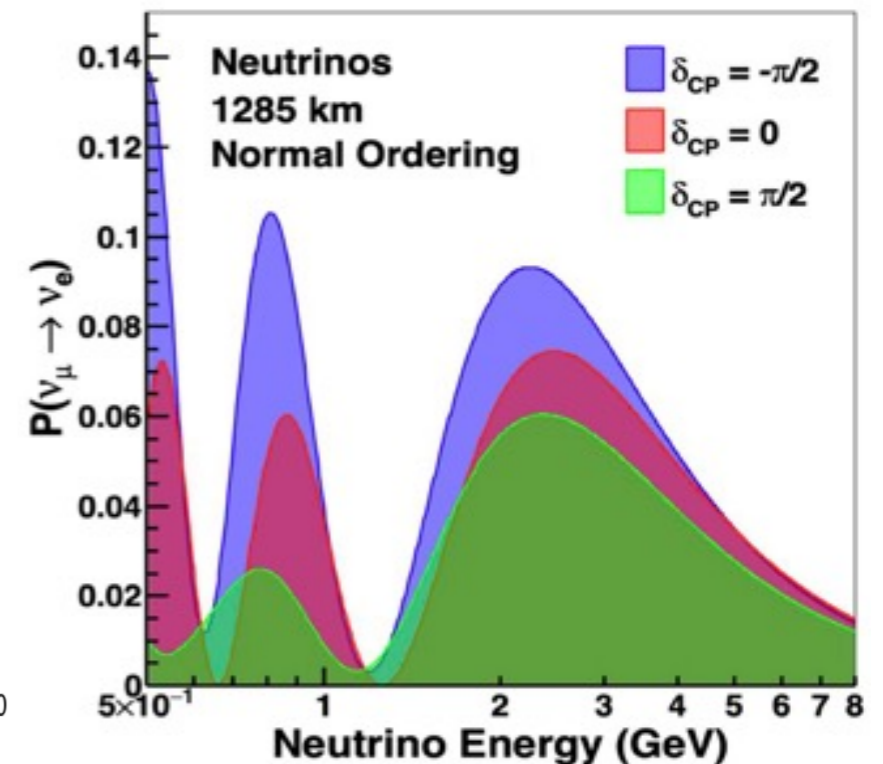
$\nu_\mu, \bar{\nu}_\mu$ from NuMI at ICARUS



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

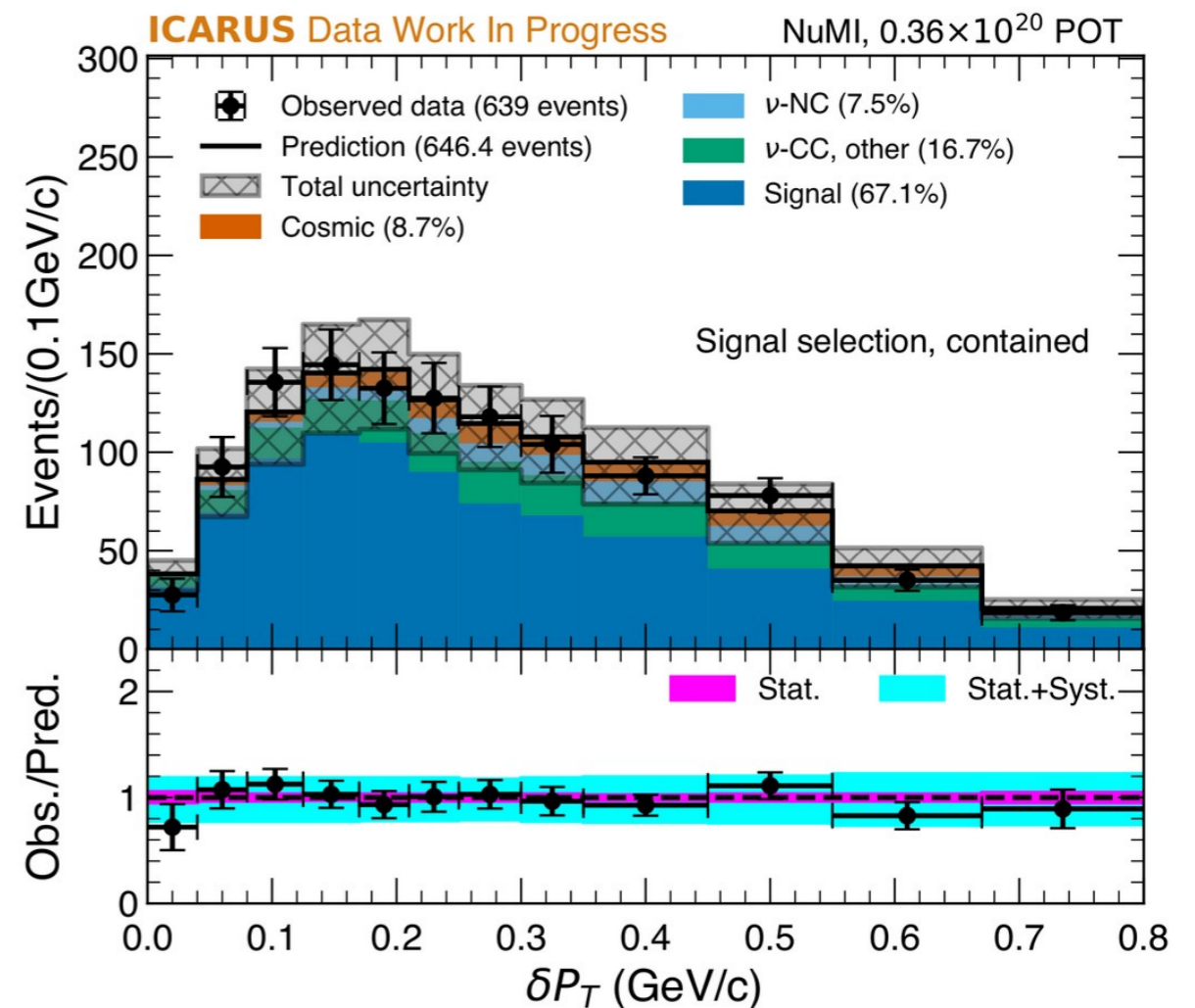
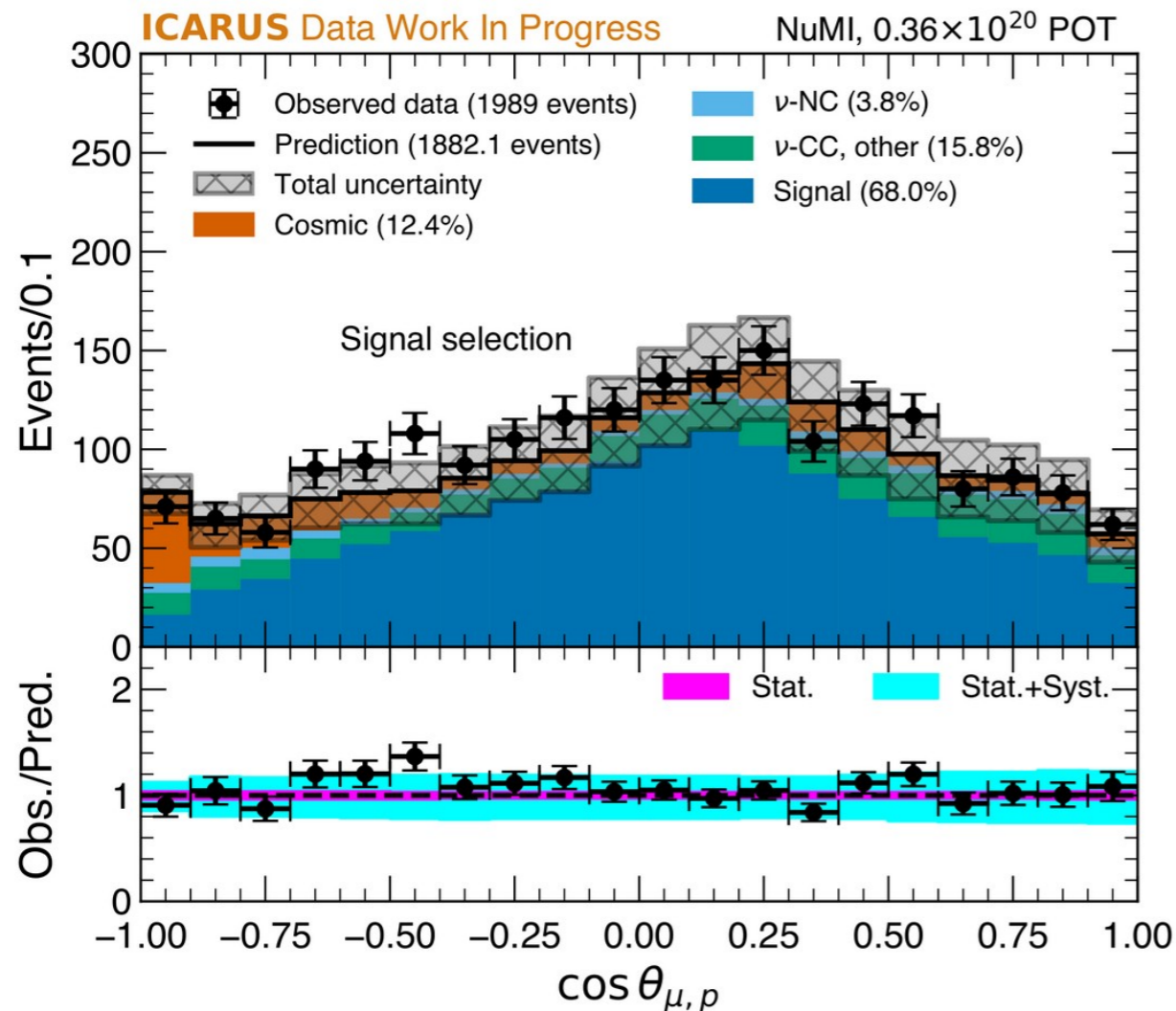


Oscillation probability at DUNE



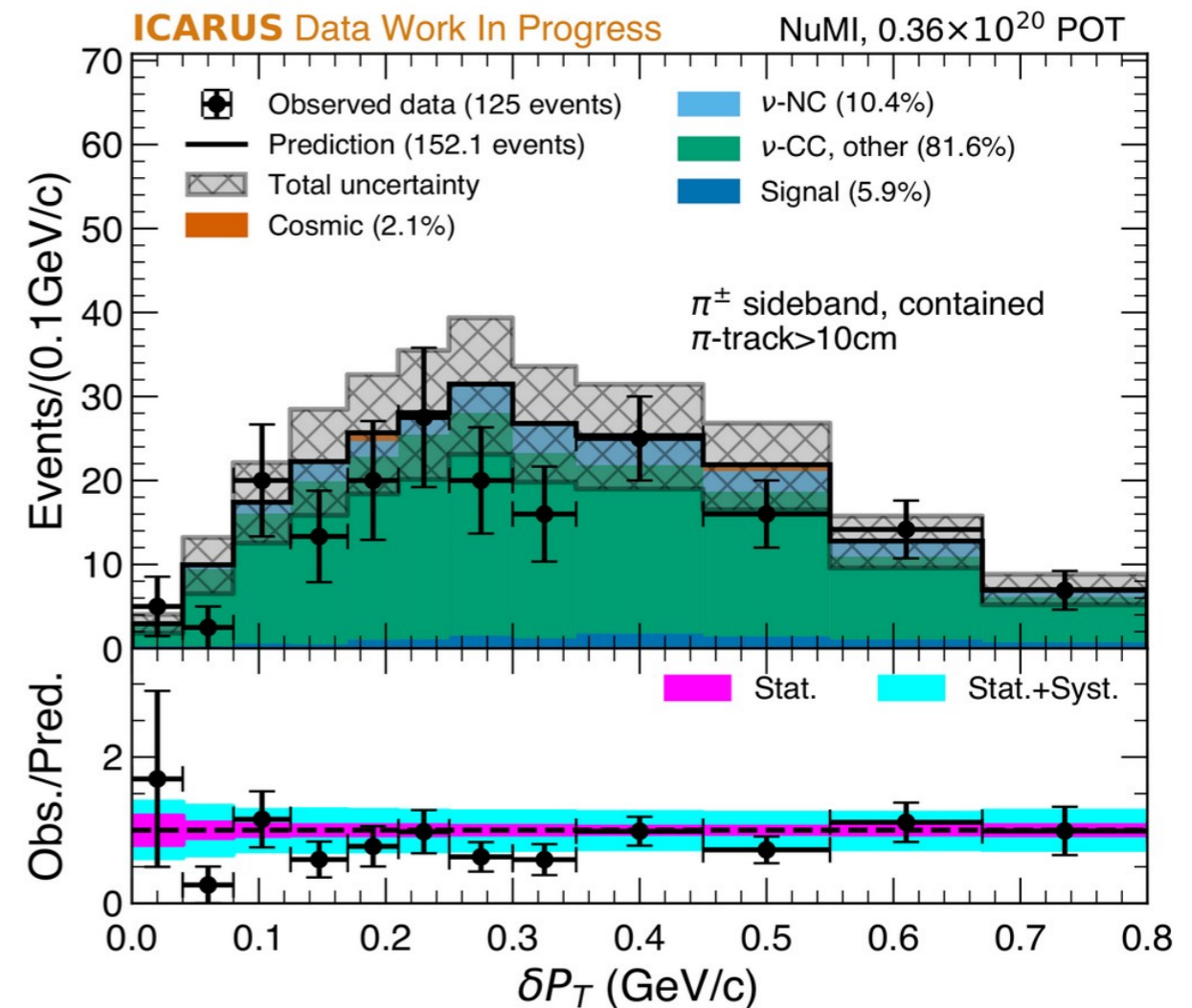
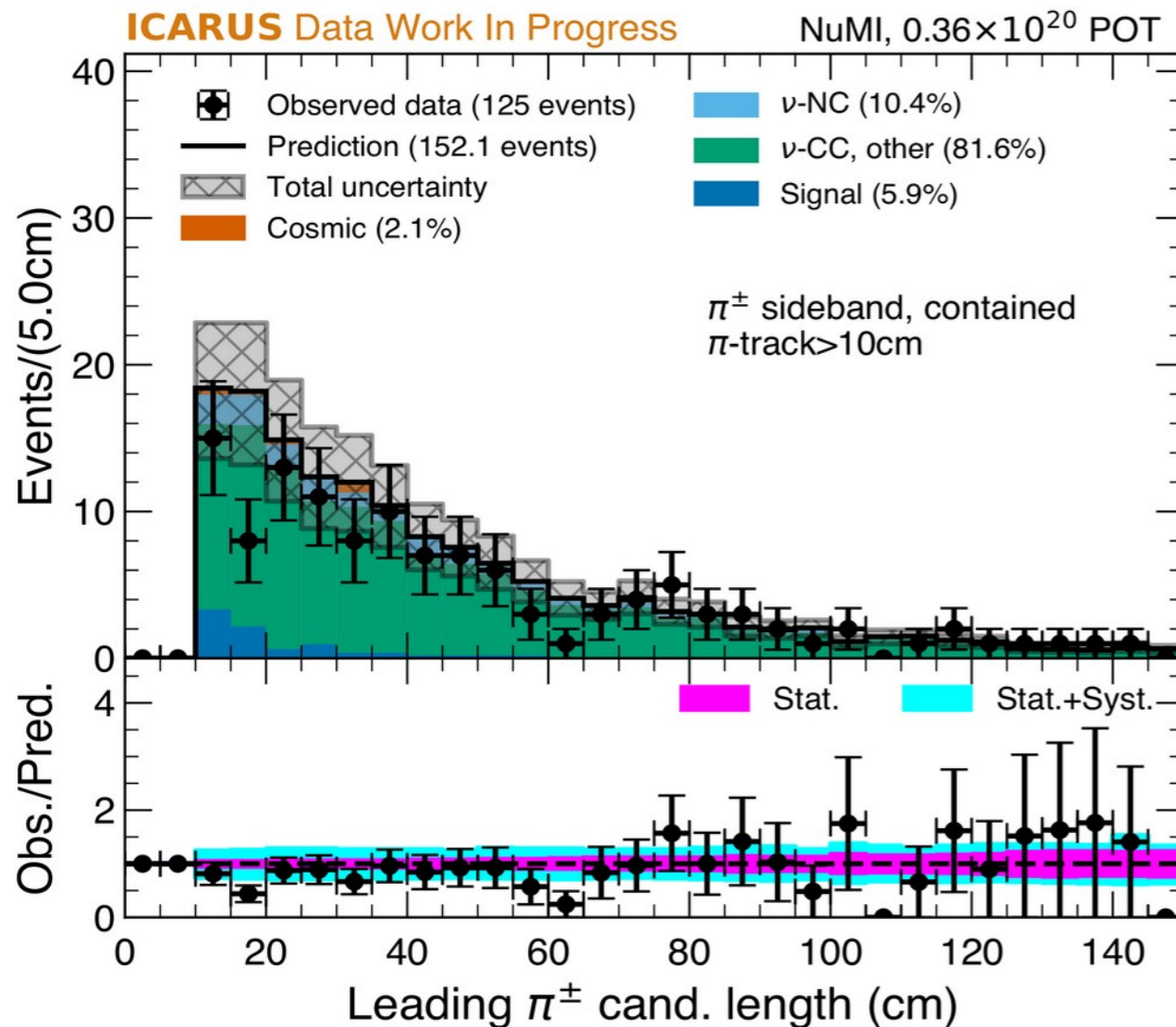
Progress towards first NuMI cross section measurements

- First cross section measurement focuses also on $1\mu N p 0\pi$ 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



Progress towards first NuMI cross section measurements

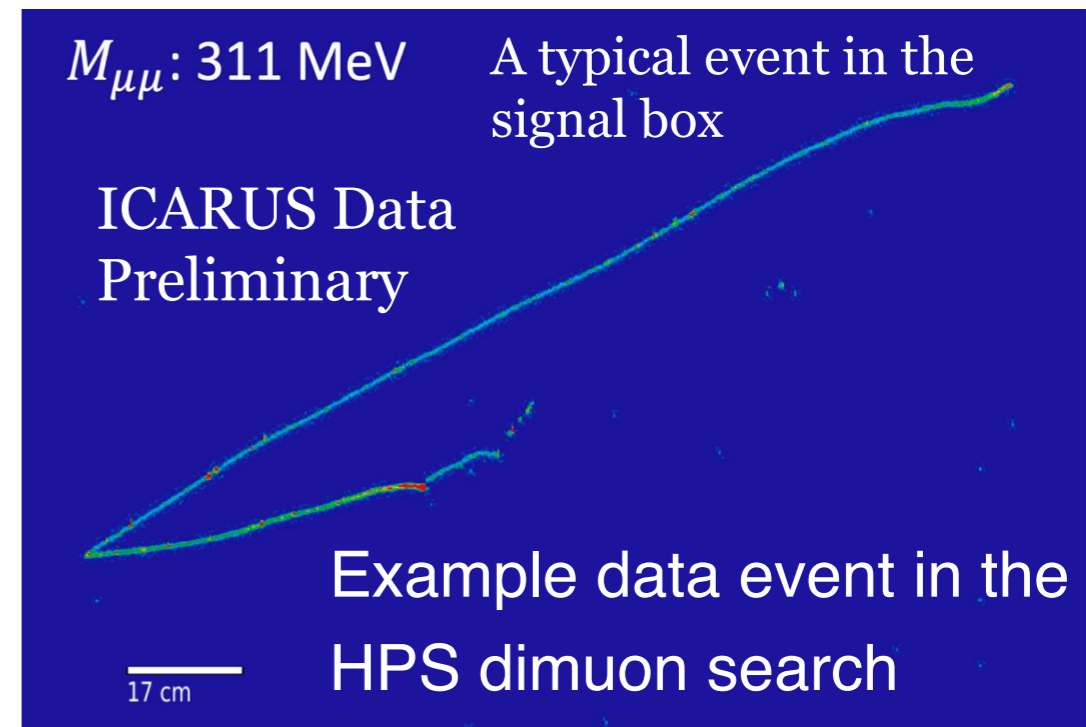
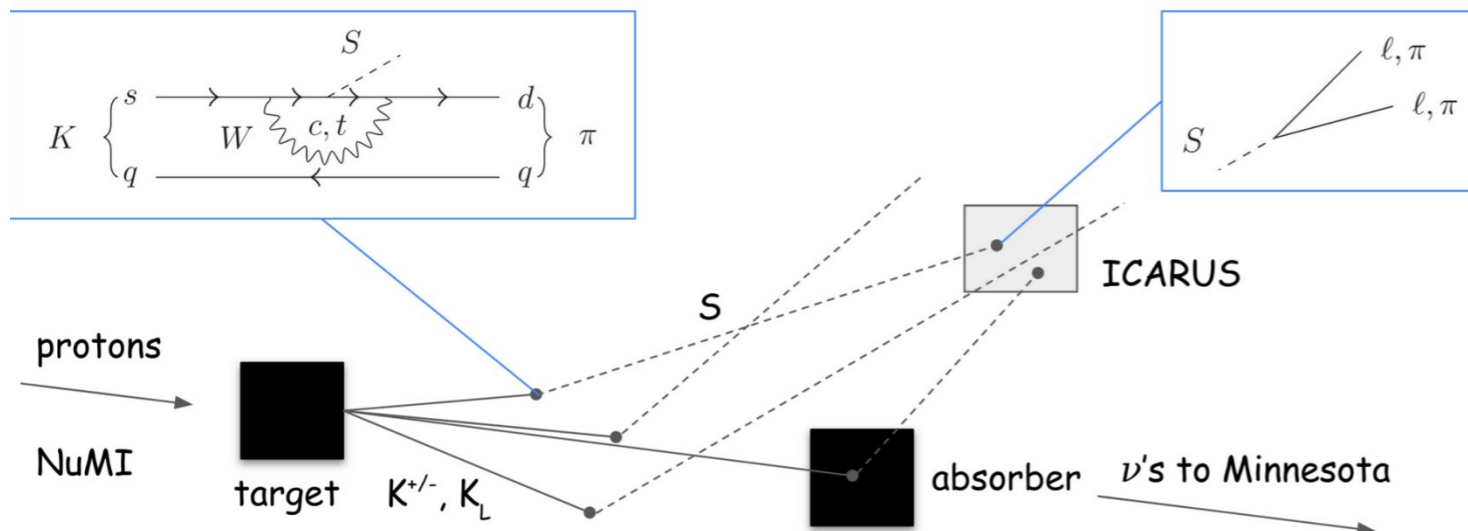
- Analysis is in very advanced state, close to unblinding full data set
- Initial sideband studies focusing on charged pion sample to understand pion-proton mis-identification
 - Select on two muon/pion-like tracks



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

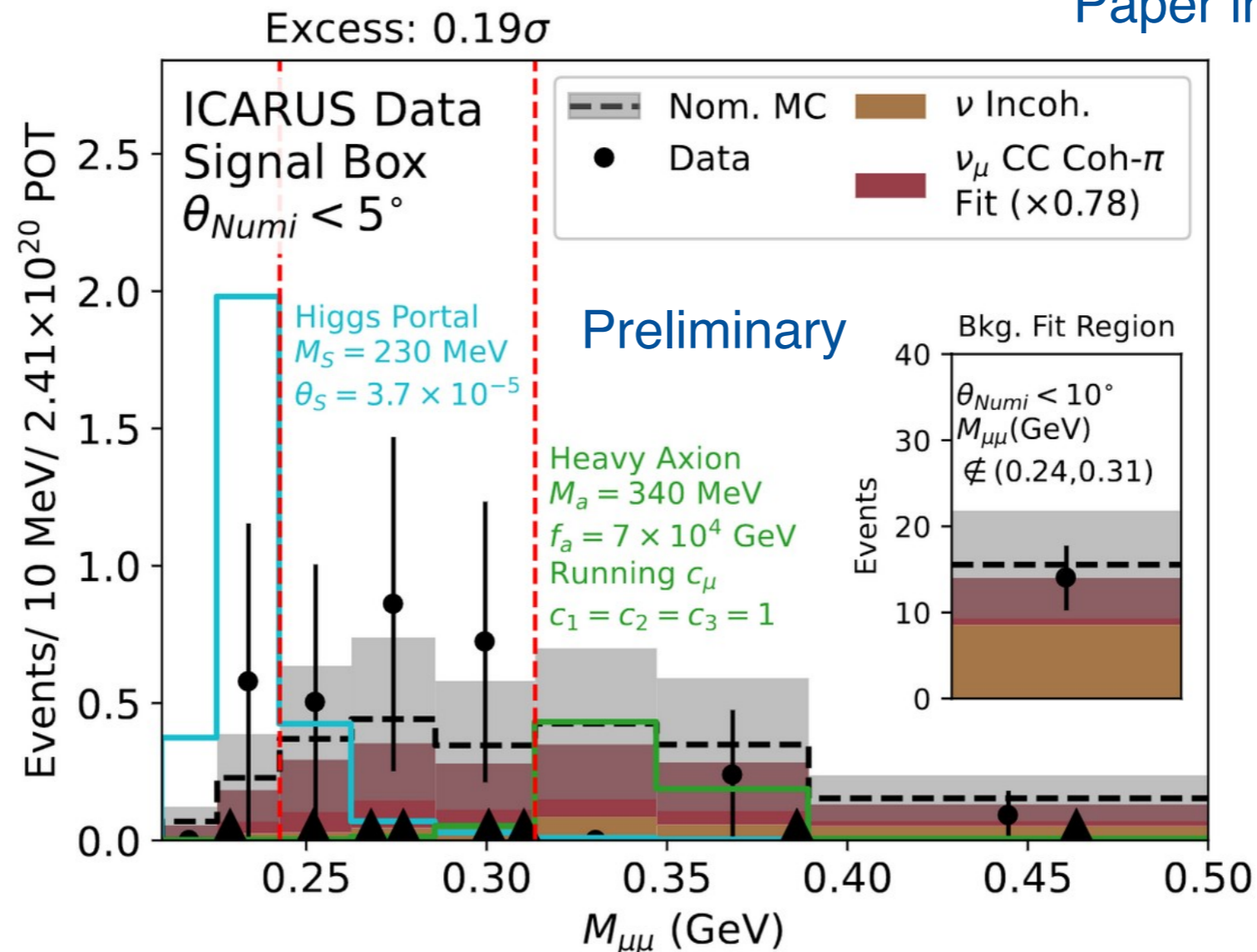
Below: Production and decay of a Scalar particle (the Higgs Portal Scalar) in ICARUS with the NuMI beam.



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

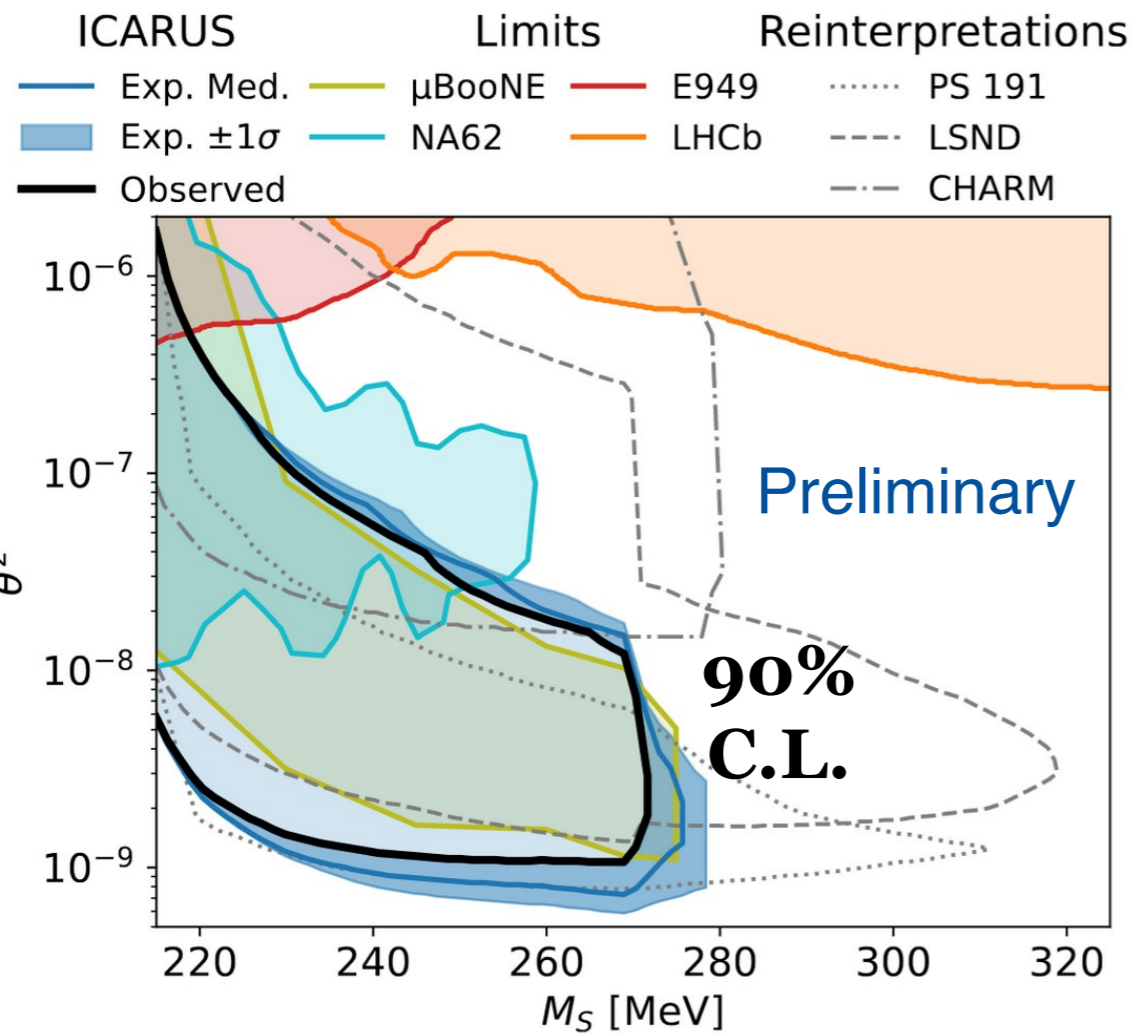
Paper in preparation



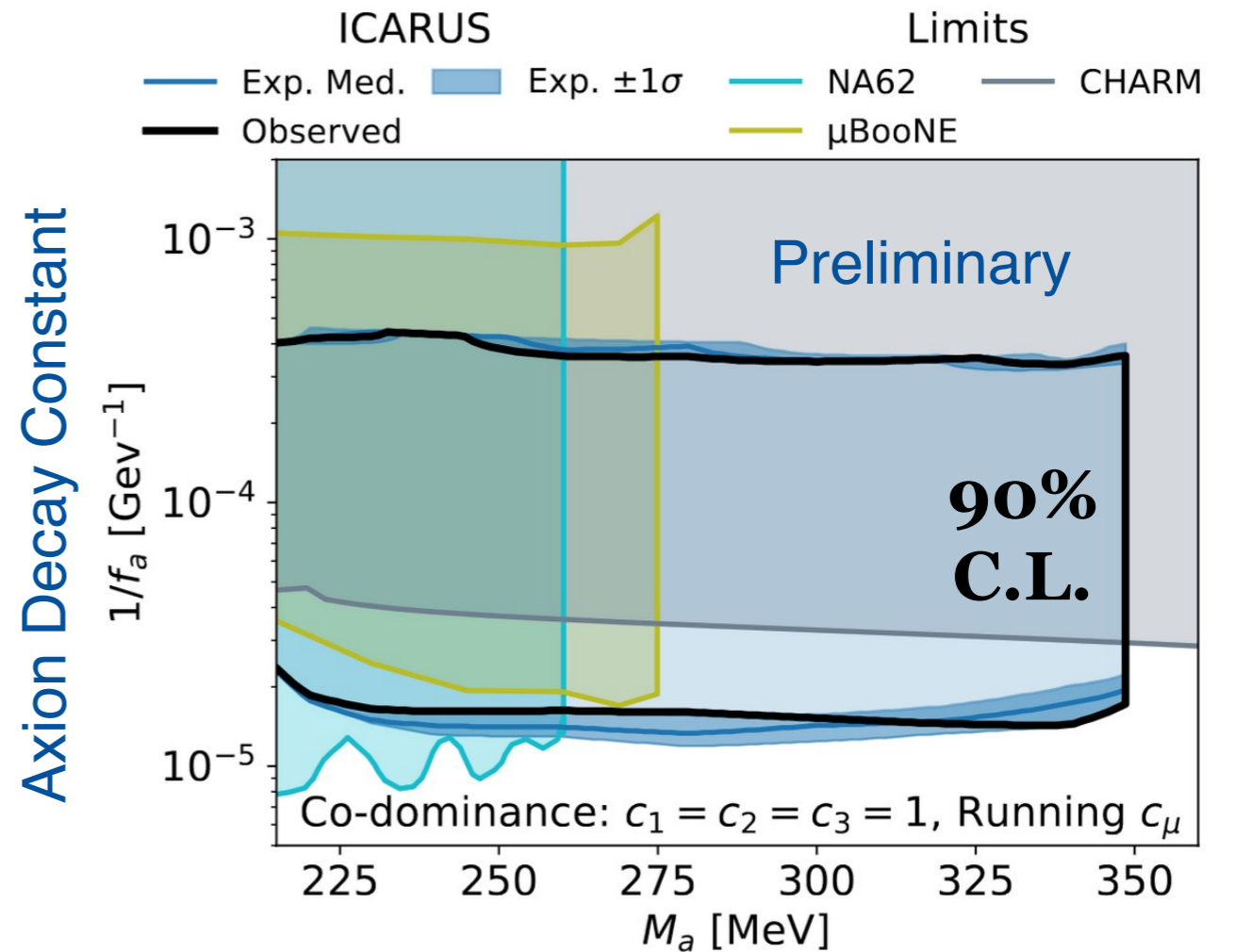
The first physics result with ICARUS at Fermilab!

- The search can place limits on the HPS/ALP parameter space

Higgs Portal Scalar Exclusion



Heavy Axion Exclusion



Paper in preparation

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?