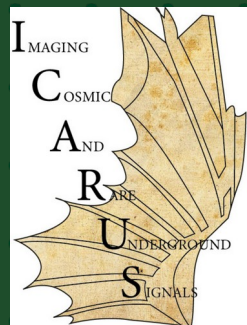


# Science at the SBN Program Far Detector: **ICARUS**

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**Mike Mooney (Colorado State University)**  
on behalf of the ICARUS Collaboration

*XXXII International Conference on Neutrino  
Physics and Astrophysics (Neutrino 2026)*  
22 June 2026



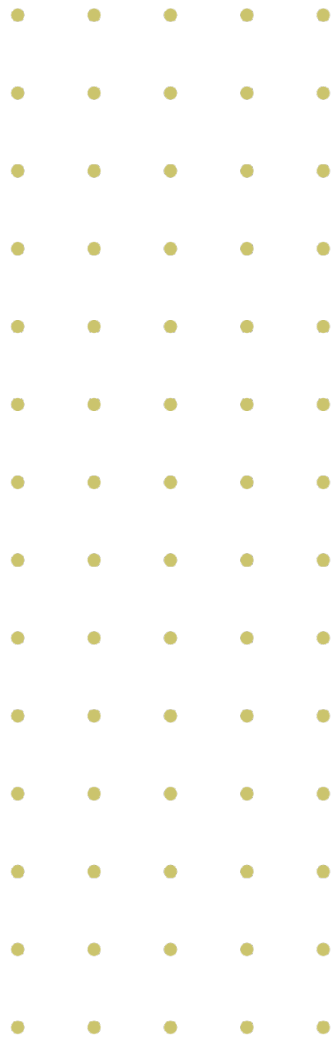
U.S. DEPARTMENT  
of ENERGY



**Fermilab**



Colorado State University

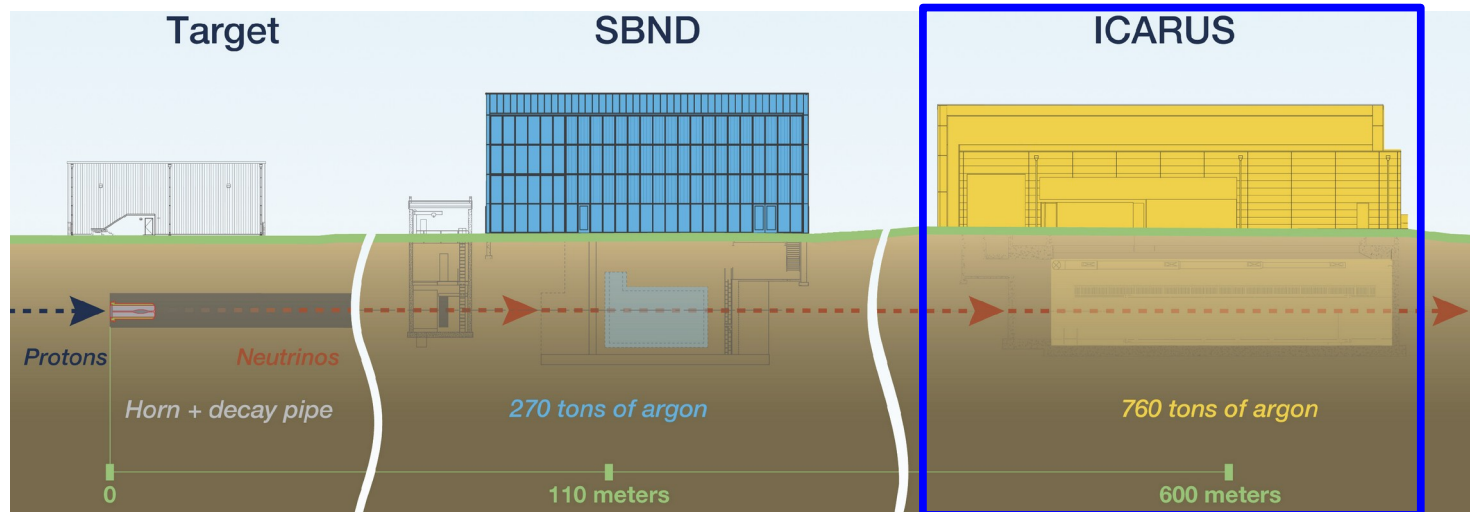


# Overview

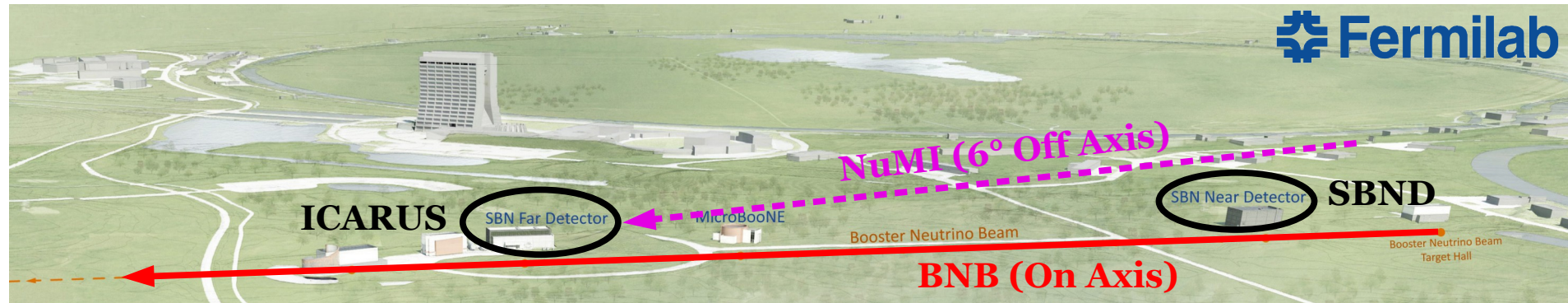
# ICARUS and the SBN Program

- ◆ **ICARUS:** far detector of Short-Baseline Neutrino (SBN) Program at Fermilab
- ◆ Originally operated at LNGS (Gran Sasso, Italy); shipped to US in 2018
- ◆ Primary physics goal: **study anomalous neutrino oscillations** (e.g. sterile neutrinos) at short baselines ( $L \sim 600$  m) and  $L/E \sim 1$  m/MeV using the **BNB**

**Booster  
Neutrino  
Beamline  
(BNB)  
@  
Fermilab**



# Neutrino Beams

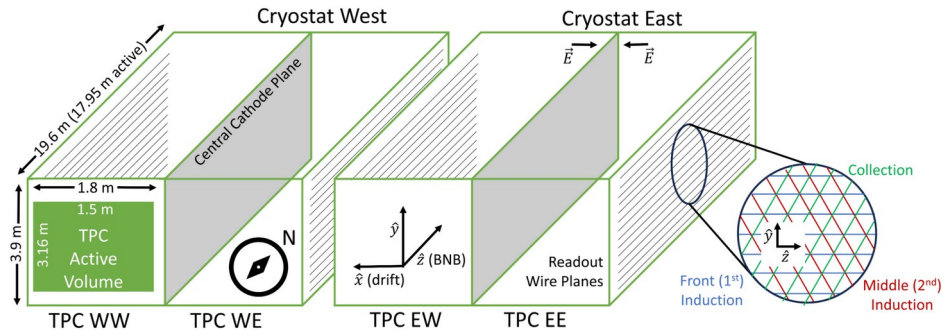
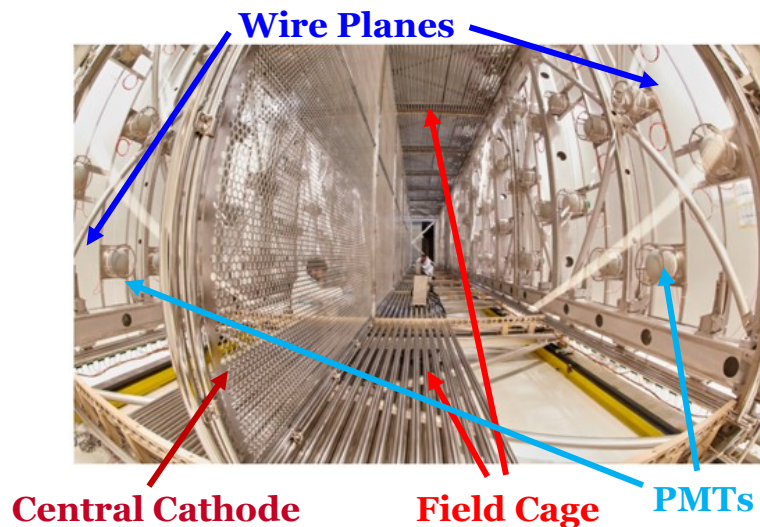


- ◆ Measure  $\nu_\mu$  disappearance +  $\nu_e$  appearance at same experiment w/ **BNB**
  - SBND: **LArTPC** near detector; provides flux and  $\nu$ -Ar cross section constraint
  - ICARUS: **LArTPC** far detector; measures oscillated neutrino spectrum
- ◆ ICARUS also sees **NuMI** neutrinos → extra handle on  $\nu$ -Ar cross sections
  - NuMI target, absorber: sources for BSM physics searches
  - Potentially extend reach of SBN oscillation physics program via  $\nu_e$  disappearance

# ICARUS Detector

- ◆ **TPC:** wire-based LArTPCs with ~54,000 channels across two cryostats (four drift volumes) for imaging neutrino interactions
- ◆ **PDS:** 360 PMTs behind anode wire planes (90 per anode) for event triggering/timing using scintillation light
- ◆ **CRT:** top/side cosmic ray tagger panels (scintillator + SiPM readout) for tagging cosmics

## Inner View of an ICARUS TPC



# Installation



Top CRT



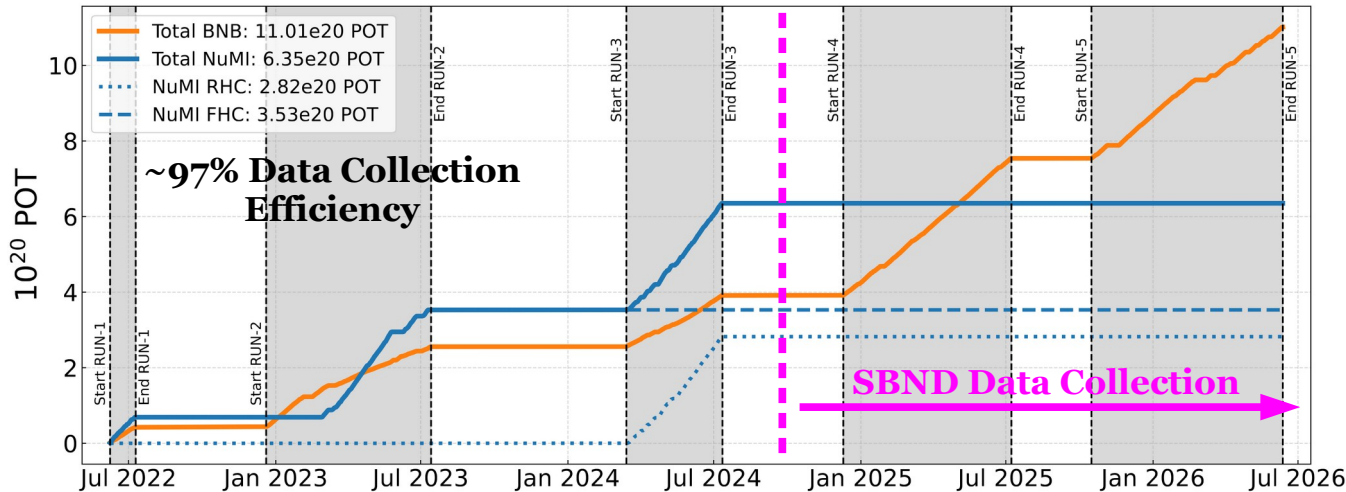
Side CRT



- ◆ **Detector installation: 2018–2020**
- ◆ **CRT installed in 2021–2022**
  - ~95% tagging efficiency
- ◆ **Concrete overburden (~7 m.w.e)** above top CRT for cosmic  $\gamma/n$  suppression
  - ~50% rate reduction seen in CRT



# ICARUS Data Collection



**ICARUS Total Projected POT (Depending on Accelerator Operations)**

**BNB:**  
 $13-16 \times 10^{20}$

**NuMI:**  
 $8-10 \times 10^{20}$

- ◆ Cold commissioning initiated in September 2020
- ◆ Started taking physics data in June 2022; still collecting data from BNB
  - Roughly  $7 \times 10^{20}$  POT of overlapping BNB data-taking w/ SBND (Runs 4 and 5)
  - NuMI beamline under maintenance since 2024

# Imaged Neutrinos at ICARUS

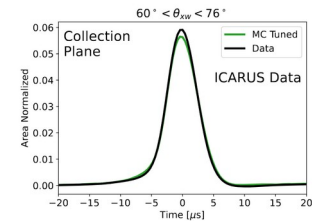
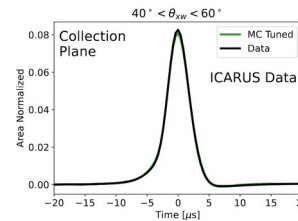
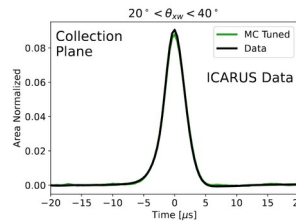
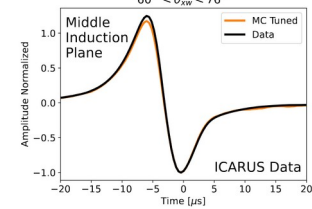
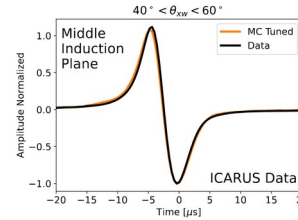
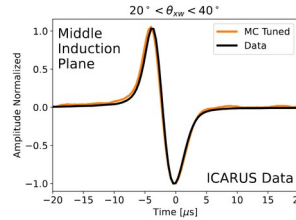
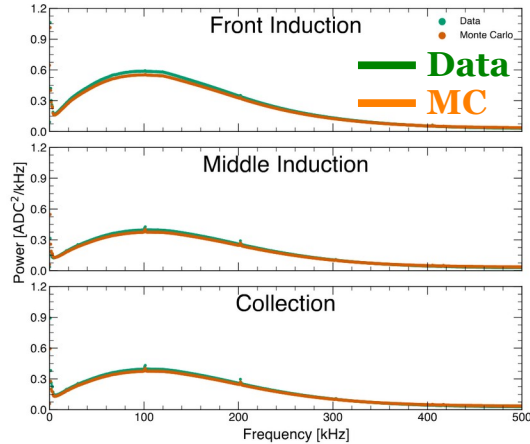
Time ↑  
Wire →



# Detector Calibration

JINST 20 P01032

TPC  
Noise  
Tuning



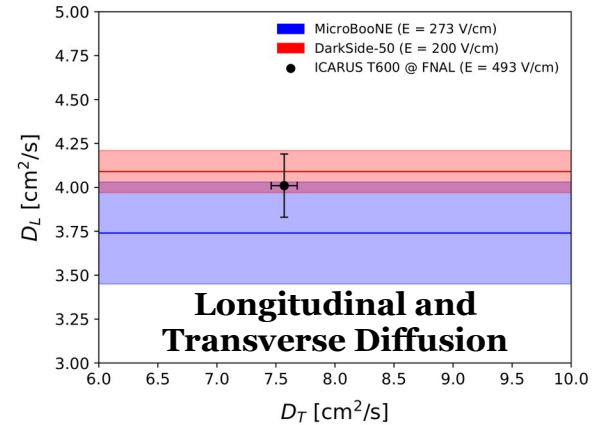
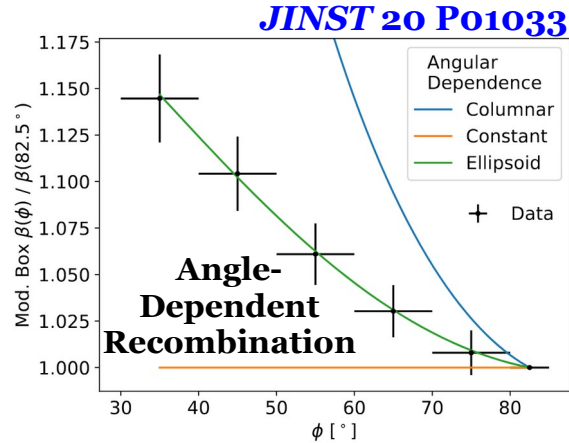
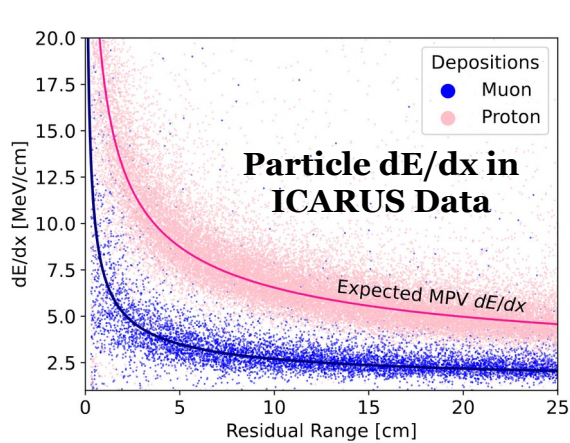
MC  
Data

TPC  
Signal  
Tuning

MC  
Data

- ◆ **TPC response tuning:** tuned noise model and wire signal response in Monte Carlo simulation using minimum bias data and cosmic muon data, respectively
- ◆ **Particle energy calibrations:** extracted electronics gain factors, electron lifetime correction, and electron-ion recombination correction w/ cosmic data
- ◆ **LAr property measurements w/ ICARUS data:** recombination, diffusion

# Detector Calibration



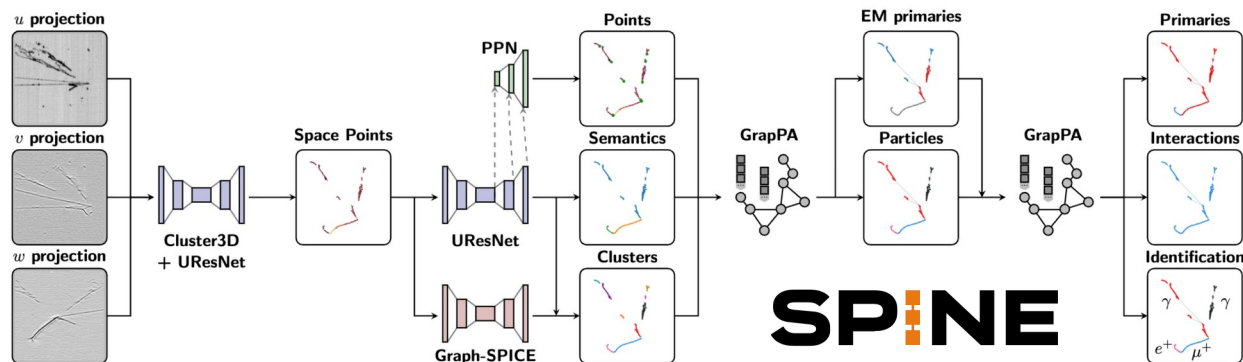
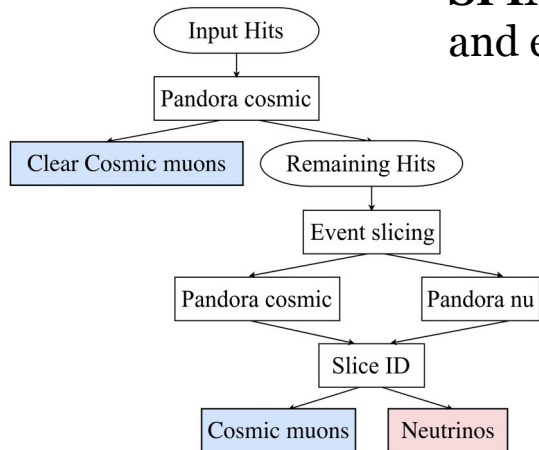
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- ◆ **LAr property measurements w/ ICARUS data:** recombination, diffusion

# Event Reconstruction Paradigms

## ◆ Two main event reconstruction paradigms at ICARUS:

- **Pandora (ICARUS version):** 2D hits (single wire signals) → particle hierarchies w/ BDTs for event classification, vertex reconstruction
  - In development: **NuGraph2 (ML)**, GNN for event reconstruction
- **SPINE (ML):** 3D space points → CNNs/GNNs for particle clustering/ID and event classification

## Pandora @ ICARUS

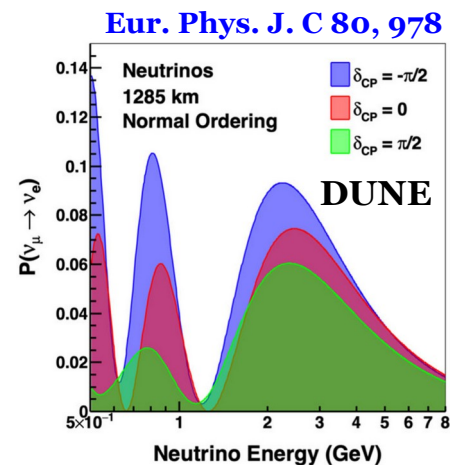
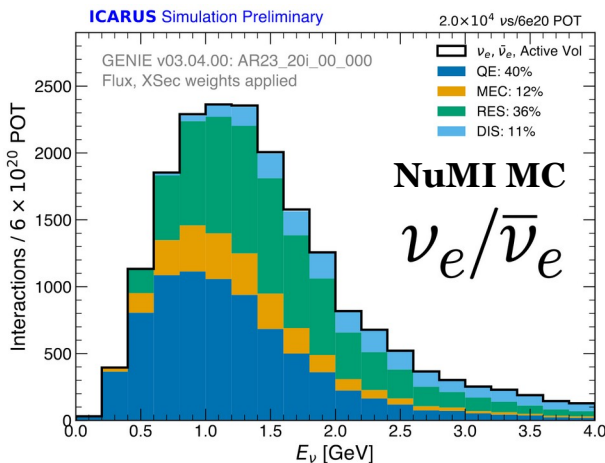
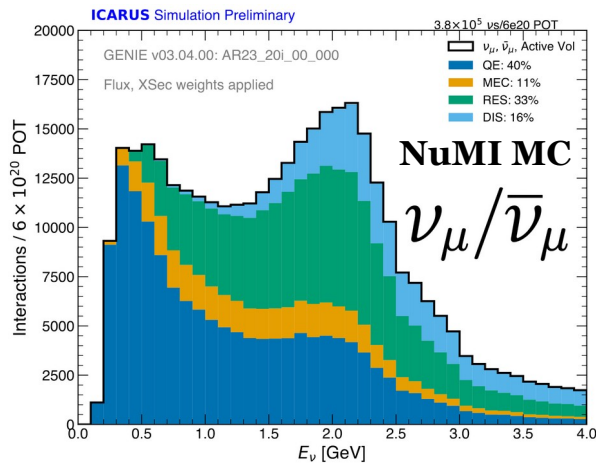




# ICARUS Science

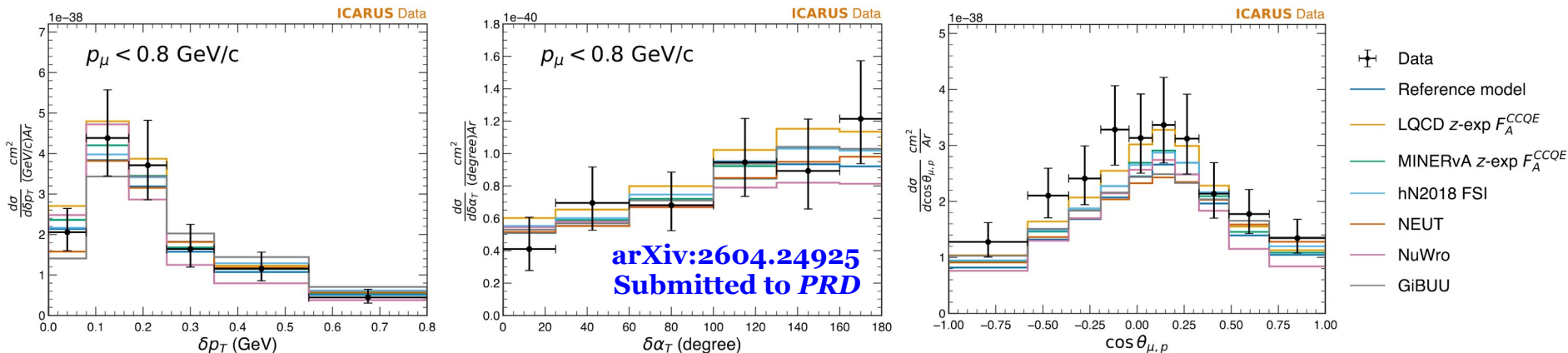
# Cross Section Physics Overview

- ◆ Large dataset from NuMI beam for cross section measurements:
  - Muon neutrinos/antineutrinos:  $\sim 380\text{k}$  CC events for  $6 \times 10^{20}$  POT
  - Electron neutrinos/antineutrinos:  $\sim 20\text{k}$  CC events for  $6 \times 10^{20}$  POT  $\leftarrow \sim 5\%$  of NuMI
- ◆ Relevant for first oscillation maximum of DUNE (high neutrino energy, low L/E)

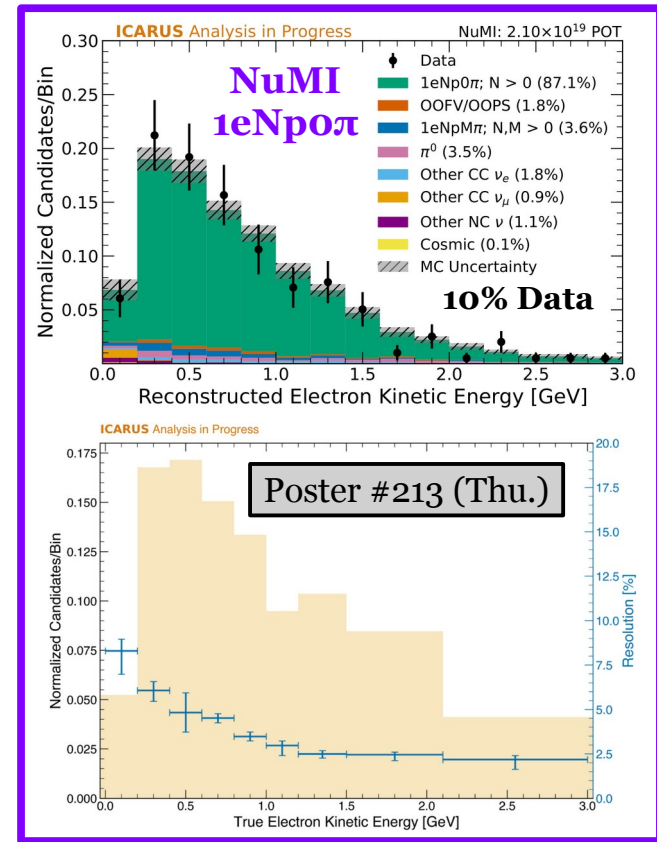
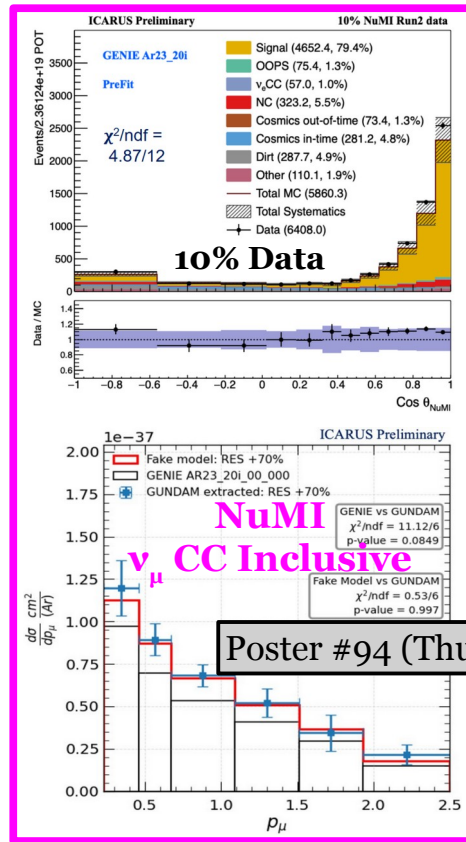
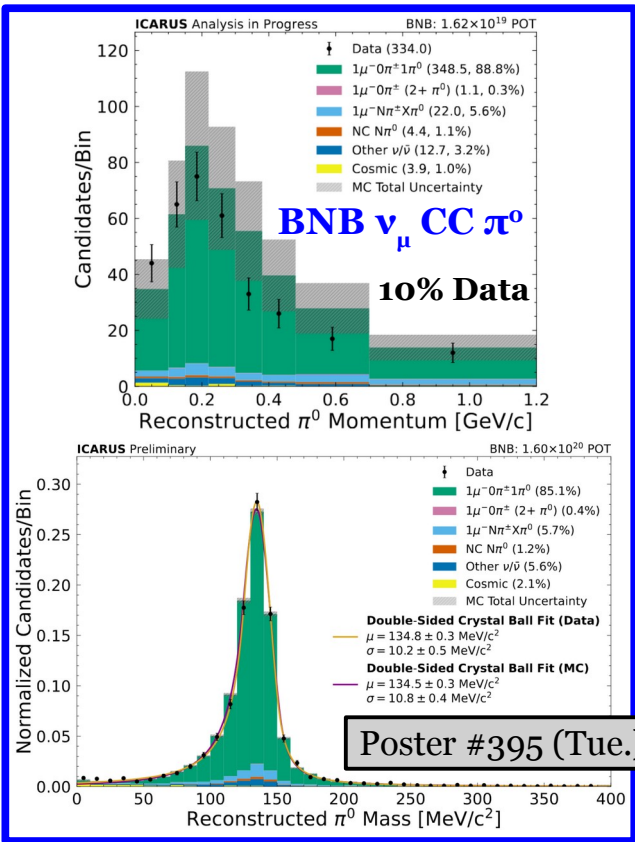


# New Cross Section Result: $1\mu N p \pi$

- ◆ First NuMI cross section measurement:  $1\mu N p \pi$  final state (probes QE, 2p2h)
  - Require one muon ( $p_\mu > 226$  MeV/c), *at least* one proton ( $0.4 < p_p < 1.0$  GeV/c)
- ◆ Probed observables include transverse kinematic variables,  $\mu$ -p opening angle
- ◆ Reported cross sections are consistent with various modeling predictions
  - Follow-up analysis underway with improved detector systematics and more data

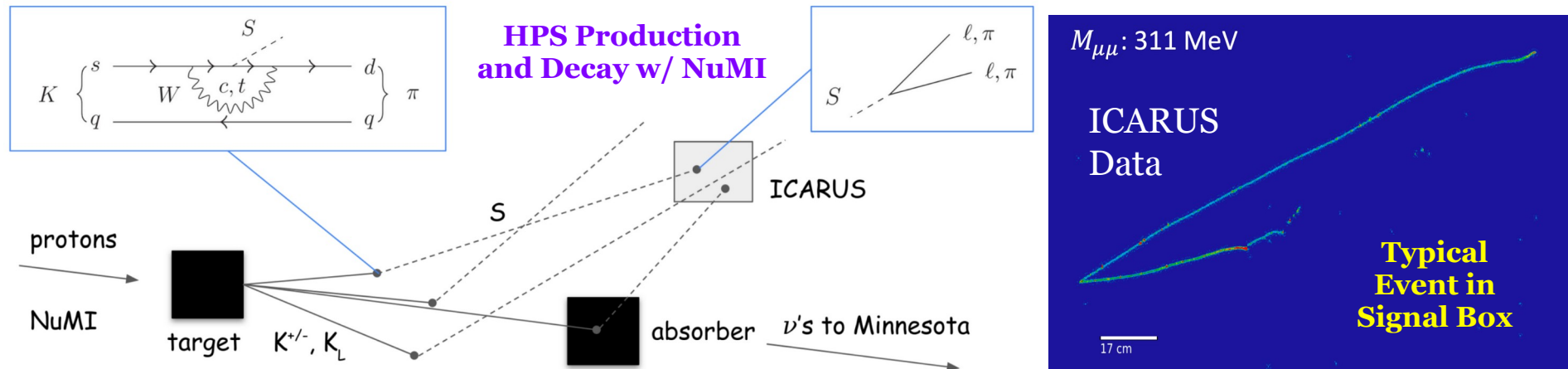


# Upcoming Cross Section Results

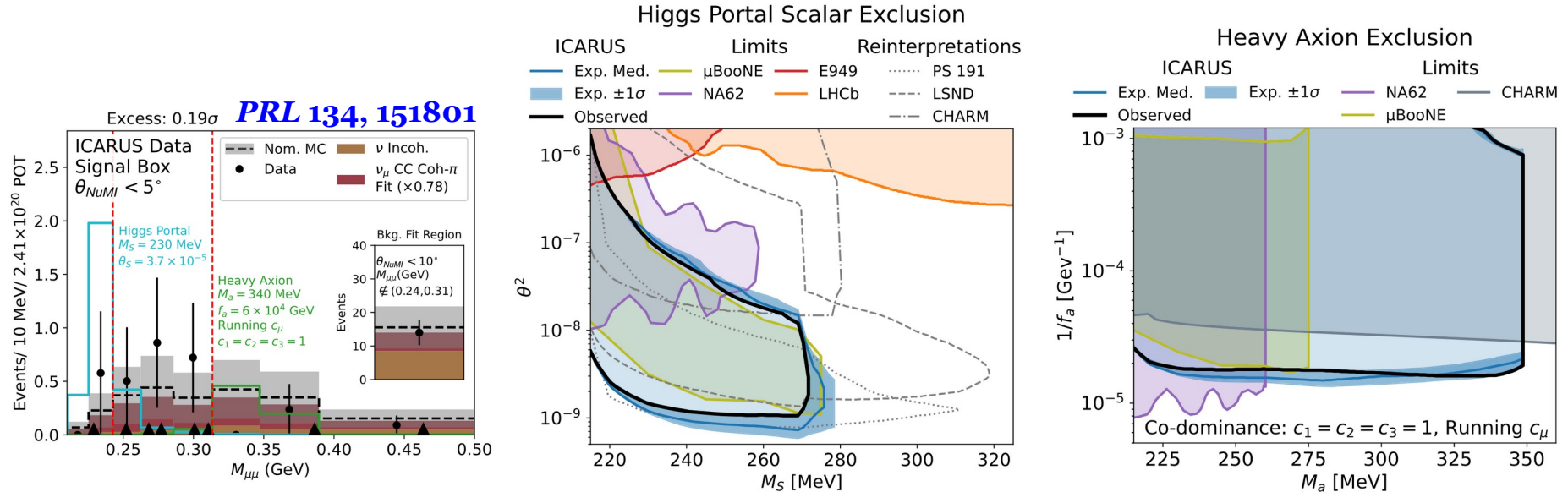


# BSM Physics Overview

- ◆ Rich BSM physics program at ICARUS w/ **off-axis NuMI beam**
- ◆ BSM models considered for first analysis, both involving *kaon decay*, contained *dimuon final states*: **Higgs Portal Scalars (HPS)** and **Axion-Like Particles (ALP)** – mixing with Higgs boson and pseudoscalar mesons, respectively
- ◆ New SBN dark sector event generator: **MeVPrtl** (see [arXiv:2605.11321](https://arxiv.org/abs/2605.11321))



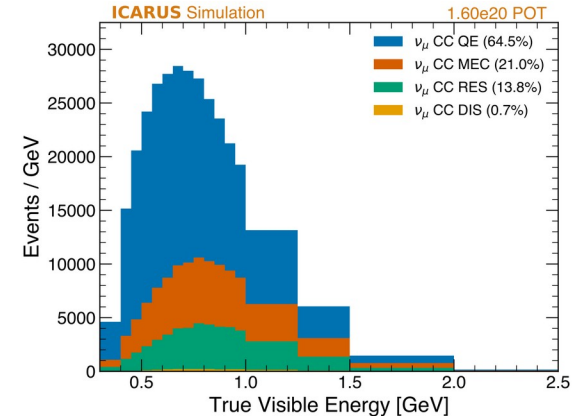
# HPS/ALP Search Results



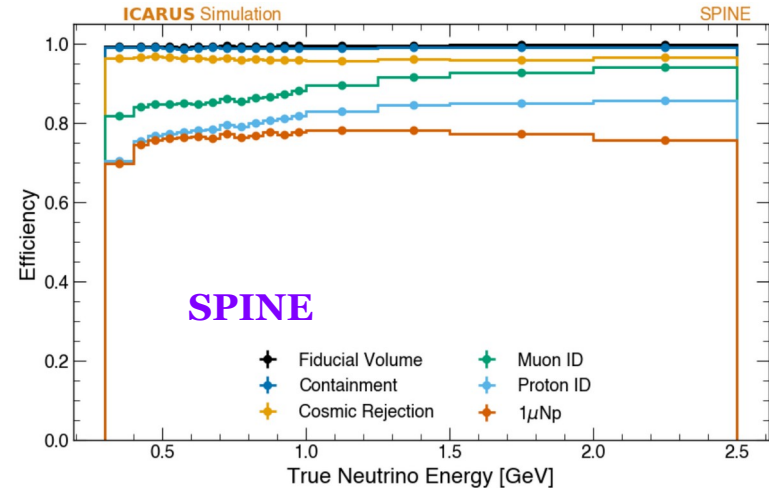
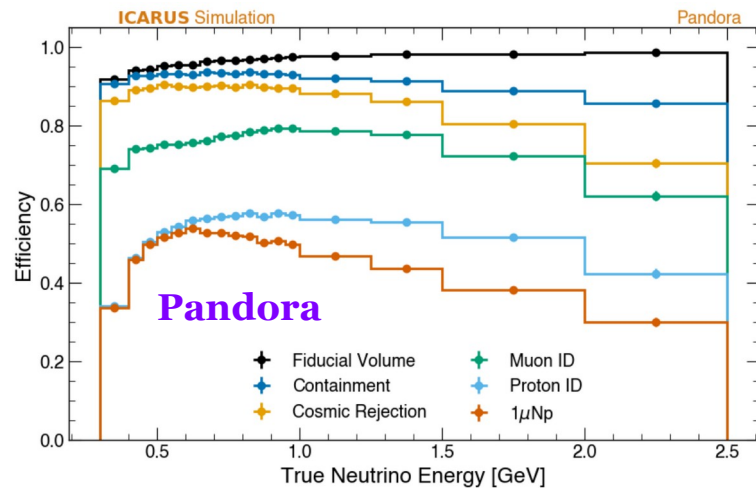
- ◆ Look for resonance at specific value of  $M(\mu\mu) \rightarrow$  **no BSM signal observed**
- ◆ **Additional analyses in pipeline:** non-contained  $\mu+\mu$ ,  $\mu+\pi$ , final states that involve showers ( $e/\gamma$ ); use of SPINE ML to improve reconstruction efficiency

# Oscillation Physics Overview

- ◆ Ultimate oscillation physics goal for ICARUS is to provide oscillated neutrino spectrum as far detector of SBN Program
  - Measure  $\nu_\mu$  disappearance +  $\nu_e$  appearance (and disappearance) w/ two detectors
- ◆ During SBND commissioning, ICARUS has pursued **single-detector** neutrino oscillation physics probing **muon neutrino disappearance**
  - Pathway for tool developments (e.g. fitter, systematics) in preparation for eventual two-detector measurements of full SBN Program
- ◆ Use  $1\mu\text{N}\rho\pi$  BNB final states and two reconstruction approaches: **Pandora-based** and **SPINE ML**
  - Enables important cross-check between results



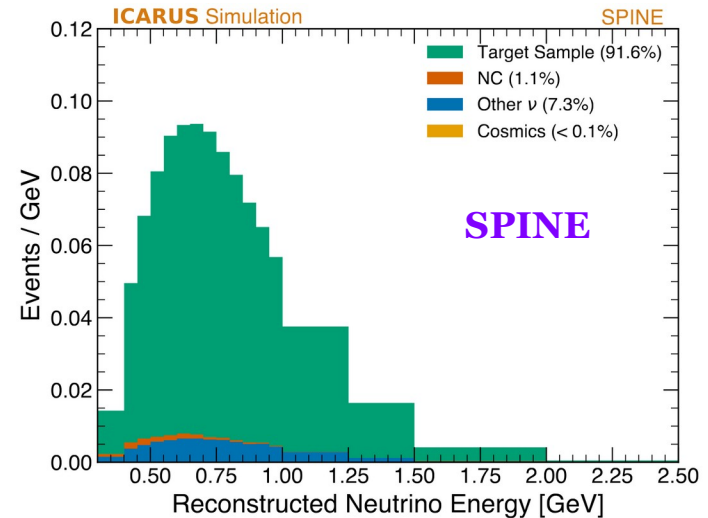
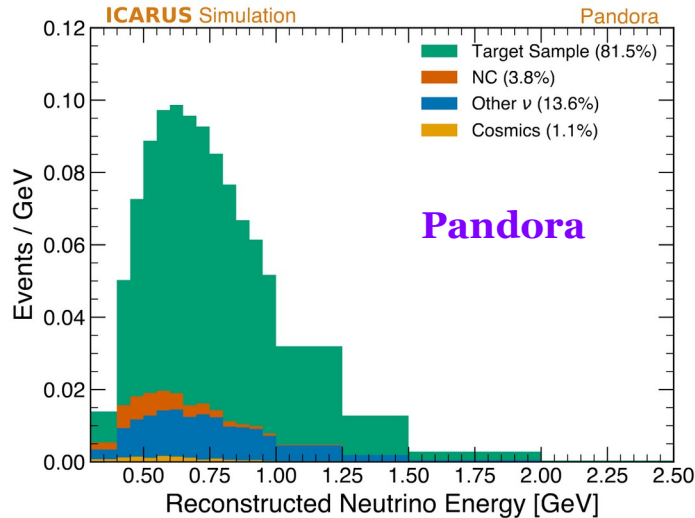
# Osc. Selection Performance



## ◆ Performant $1\mu\text{Np}\rho\pi$ selections:

- **Pandora:** ~48% selection efficiency, ~82% selection purity
- **SPINE:** ~77% selection efficiency, ~92% selection purity

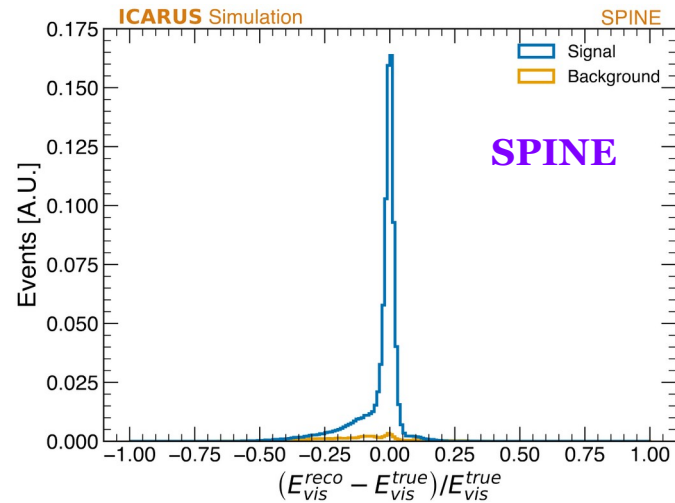
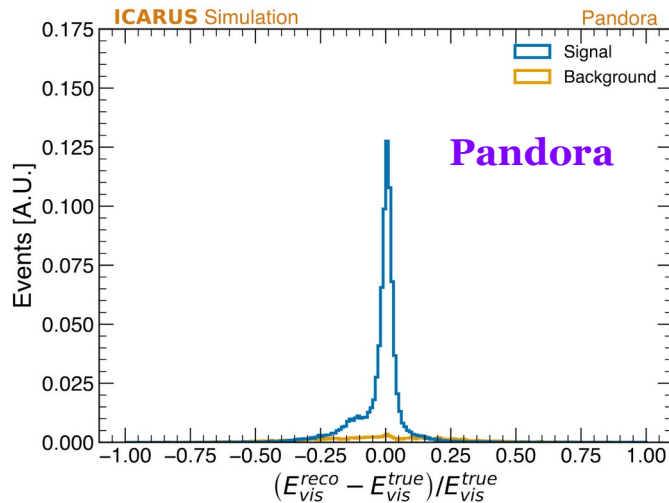
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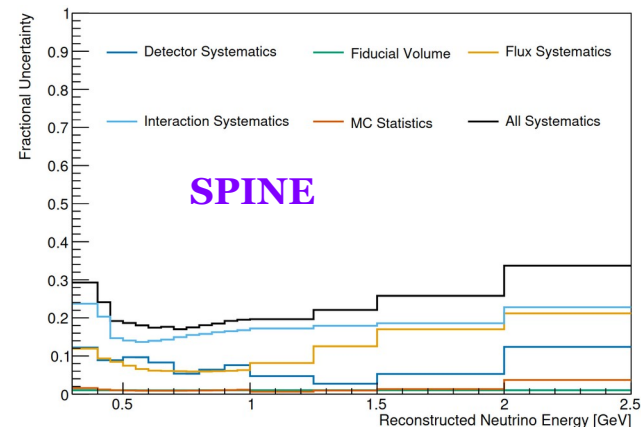
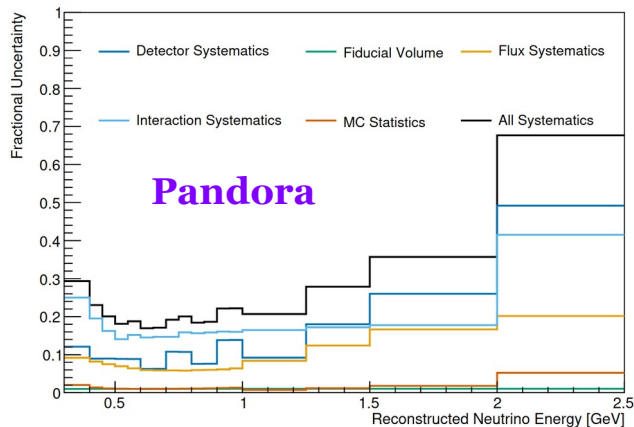
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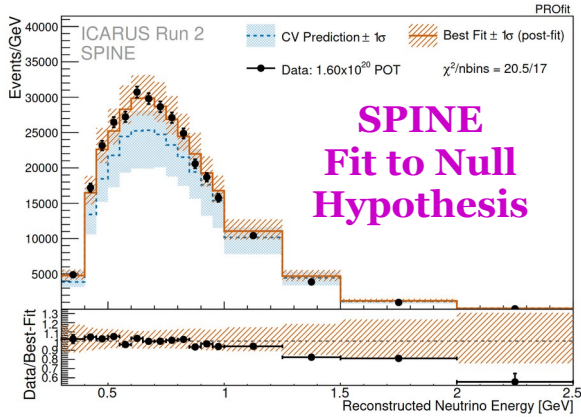
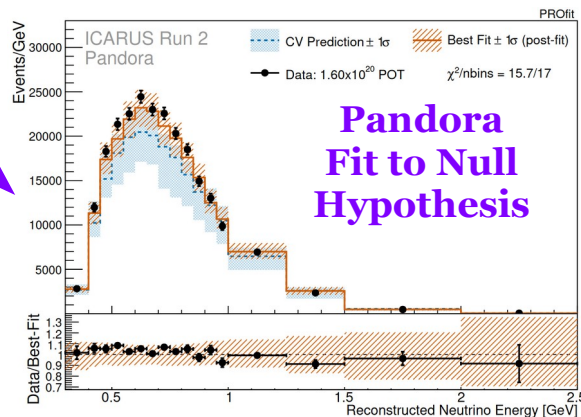
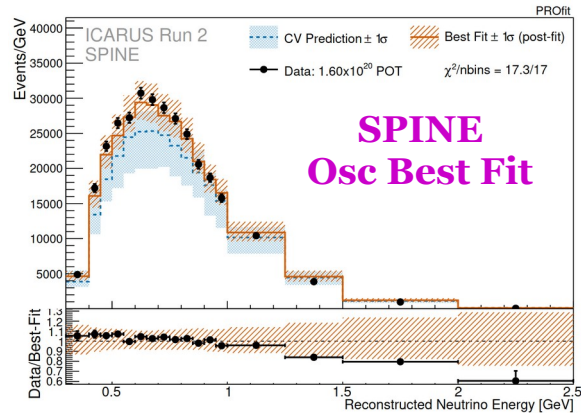
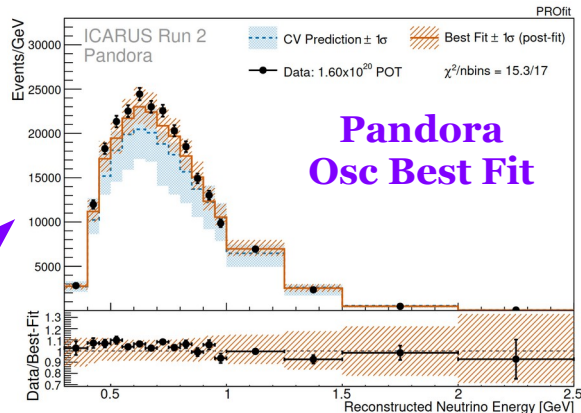
# Osc. Systematic Uncertainties



- ◆ Flux model and uncertainties same as used by MicroBooNE/MiniBooNE
- ◆ Interaction modeling uses GENIE AR23 (shared model choice for SBN, DUNE)
  - Uncertainties (event weights) taken from GENIE + few extra via nuSystematics (DUNE)
- ◆ Detector systematics use auxiliary MC samples with varied detector parameters
  - Vary noise, TPC gain and signal shape, detector response non-uniformity, light yield, etc.



# Osc. Fit Results

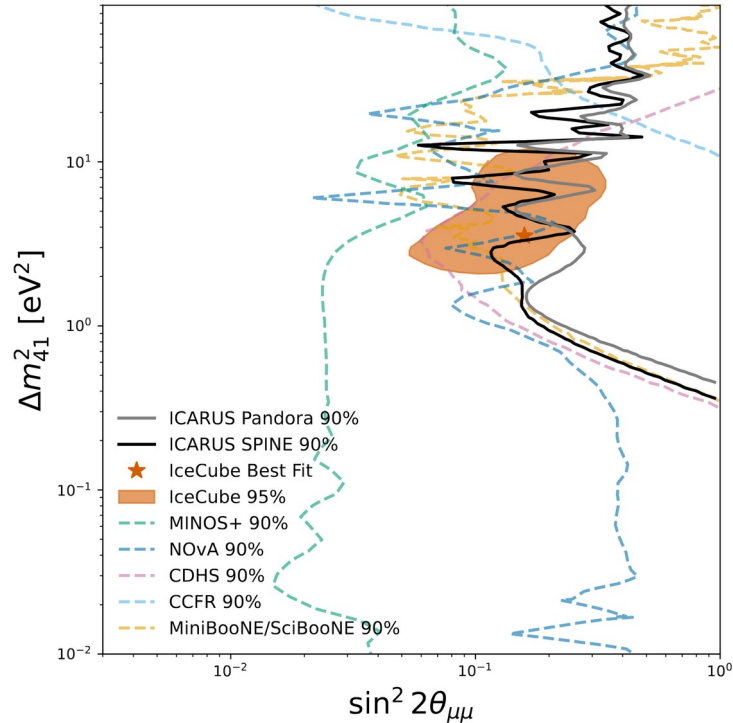


$\Delta\chi^2 \sim 0.4$

$\Delta\chi^2 \sim 3.2$

# Osc. Exclusion Contours

arXiv:2603.22557  
Submitted to PRD



- ◆ No signs of significant neutrino oscillations from either analysis → set exclusion contours
  - Exclusion contours include Feldman-Cousins corrections
- ◆ First ICARUS  $\nu_{\mu}$  disappearance results are *systematics limited* (both Pandora and SPINE analyses)
  - Forthcoming SBN Program oscillation physics measurements will reduce all major source of systematic uncertainties, by design

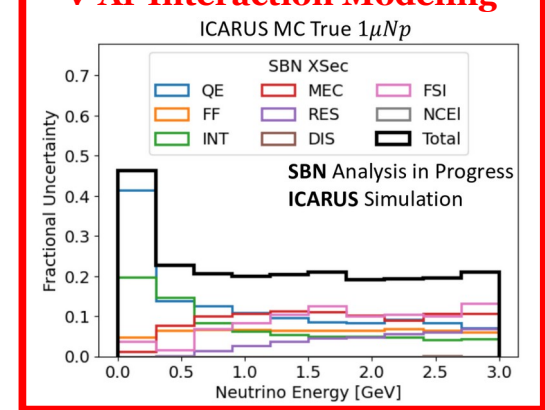
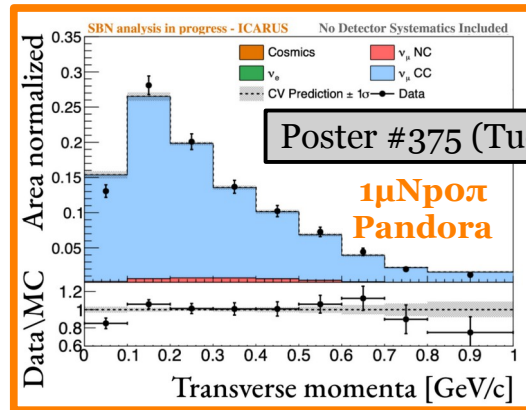
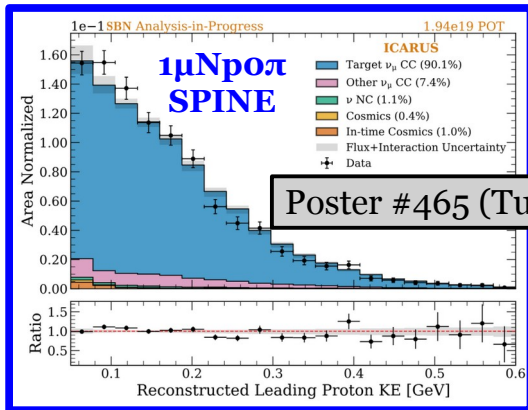
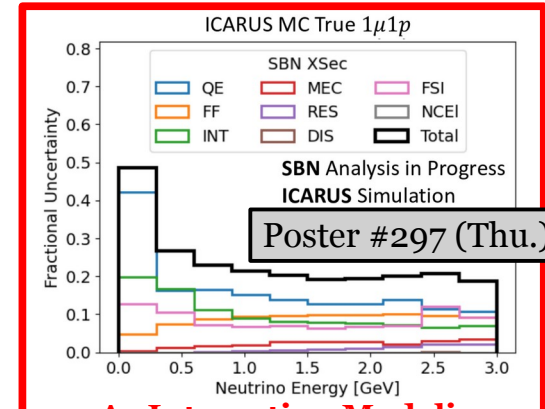
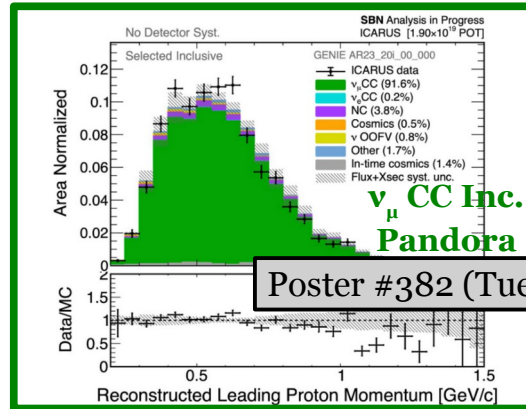
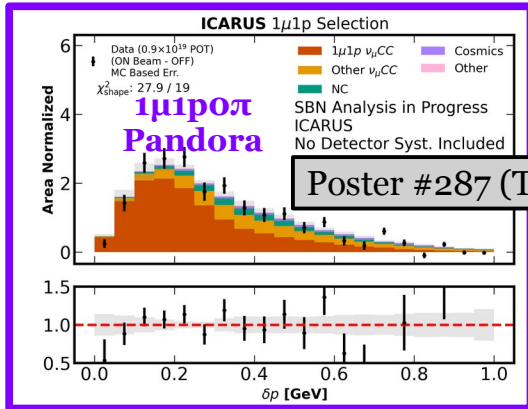


# **Future Science at the SBN Program**

# SBN Oscillation Physics Program

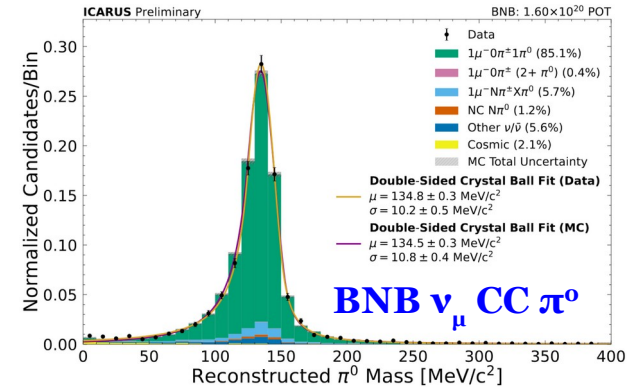
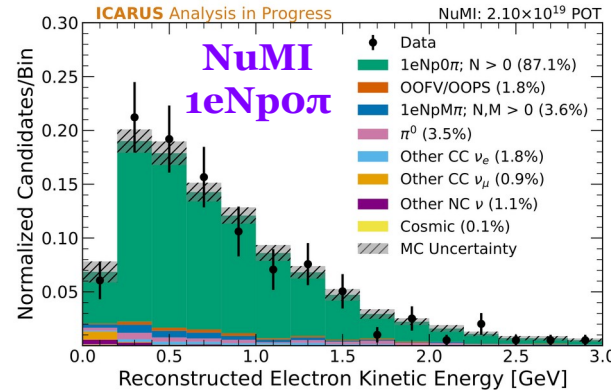
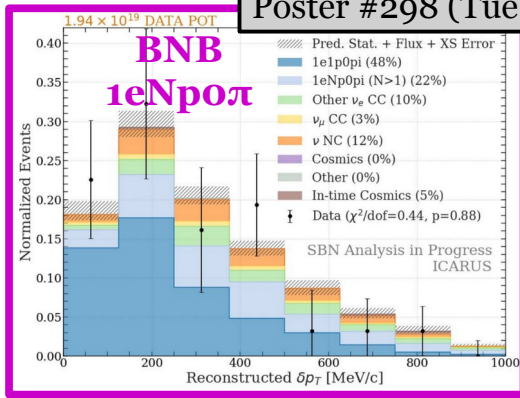
- ◆ SBN oscillation physics follows a natural progression:
  - **Past** – ICARUS  $\nu_\mu$  disappearance analysis (focusing on  $1\mu\text{N}\rho\pi$ )
  - **Present** – SBN  $\nu_\mu$  disappearance analysis (adding SBND data)
  - **Future** – SBN  $\nu_\mu$  disappearance and  $\nu_e$  appearance/disappearance (adding  $\nu_e$  data)
- ◆ Ongoing SBN  $\nu_\mu$  disappearance effort features multiple final states, approaches
  - **$1\mu\text{I}\rho\pi$**  using Pandora reconstruction, PROfit for fitter
  - **$1\mu\text{N}\rho\pi$**  using Pandora and SPINE ML reconstruction, PROfit for fitter
  - **$\nu_\mu$  CC inclusive** using Pandora reconstruction, VALOR for fitter
- ◆ Many posters at this conference discussing progress – check them out!

# SBN $\nu_\mu$ Disappearance Analysis



# Future SBN Oscillation Physics

Poster #298 (Tue.)



- ◆ Already making great progress with  $\nu_e$  reconstruction toward oscillation physics
  - Excellent energy resolution for showers (e/ $\gamma$ ) through use of SPINE ML
  - Can include NuMI  $\nu_e$  events to reduce phase space degeneracy (a la MicroBooNE)
- ◆ Pioneering ML/AI work at ICARUS (SPINE, NuGraph2) key in untangling short-baseline anomalies  $\rightarrow$  more complicated final states really benefit from ML/AI

# Summary

- ◆ First results out from ICARUS:
  - **Oscillation Physics** – ICARUS  $\nu_\mu$  disappearance analysis w/ BNB ( $1\mu\text{Np}\pi$ )
  - **Cross Section Physics** – NuMI  $1\mu\text{Np}\pi$  cross section analysis
  - **BSM Physics** – HPS/ALP search involving kaon decay and a dimuon final state
  - **Detector Physics** – electron-ion recombination, transverse/longitudinal diffusion
- ◆ More cross section results and BSM physics searches in the pipeline
- ◆ *Exciting science* to come from ICARUS as the far detector of the SBN Program
  - Two-detector paradigm will dramatically reduce systematic uncertainties
  - First SBN  $\nu_\mu$  disappearance analysis results anticipated early next year – stay tuned!

# Thank You!

