Current Status and Future Prospects of the ICARUS Experiment

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On behalf of the ICARUS Collaboration

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U.S. DEPARTMENT OF ENERGY

Office of Science

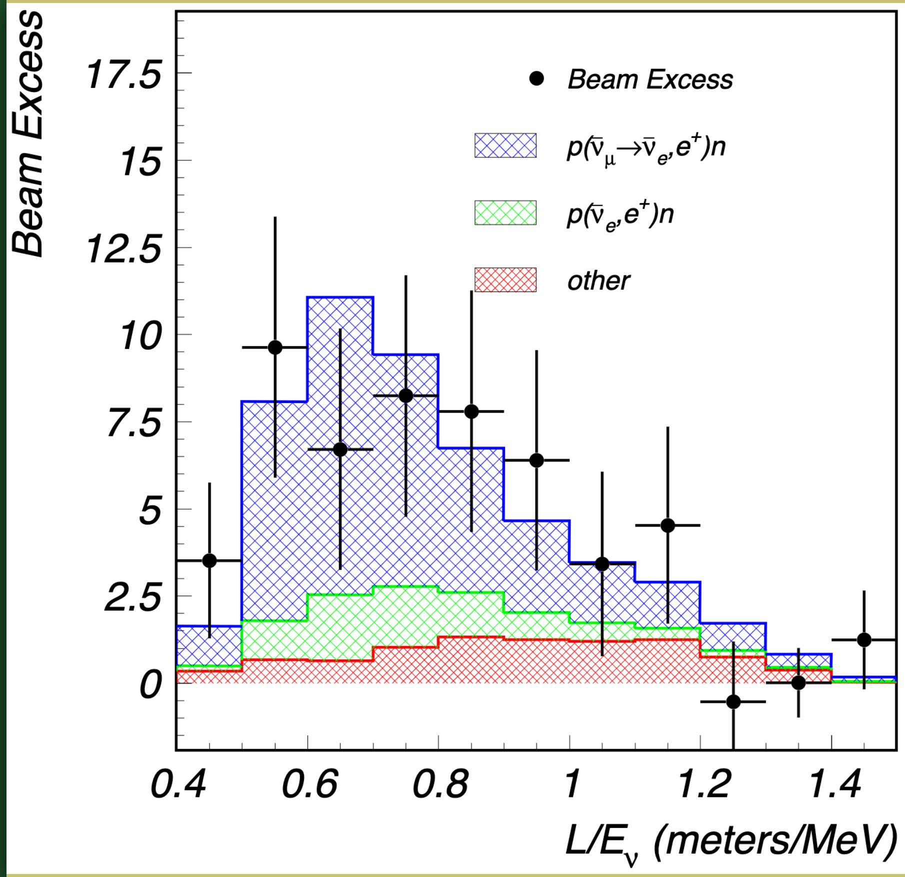
Colorado State University

Additional Neutrinos?

LSND and MiniBooNE found anomalous excess of low-energy ν_e candidates at short baselines

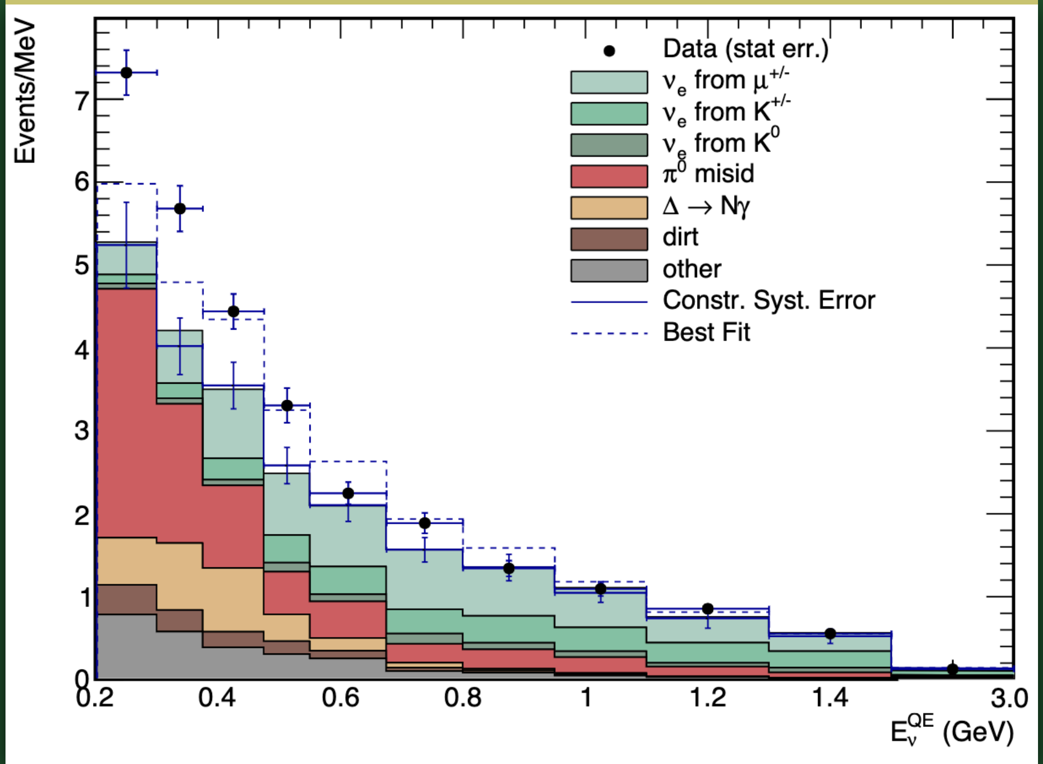
- 3-flavor ν-oscillation cannot explain these observations
  - Sterile neutrino(s)?
  - Photonic background?
    e/γ separation is hard!
  - BSM explanations?

LSND



Phys. Rev. D 64, 112007 (2001)

MiniBooNE



Phys. Rev. D 103, 052002 (2021)

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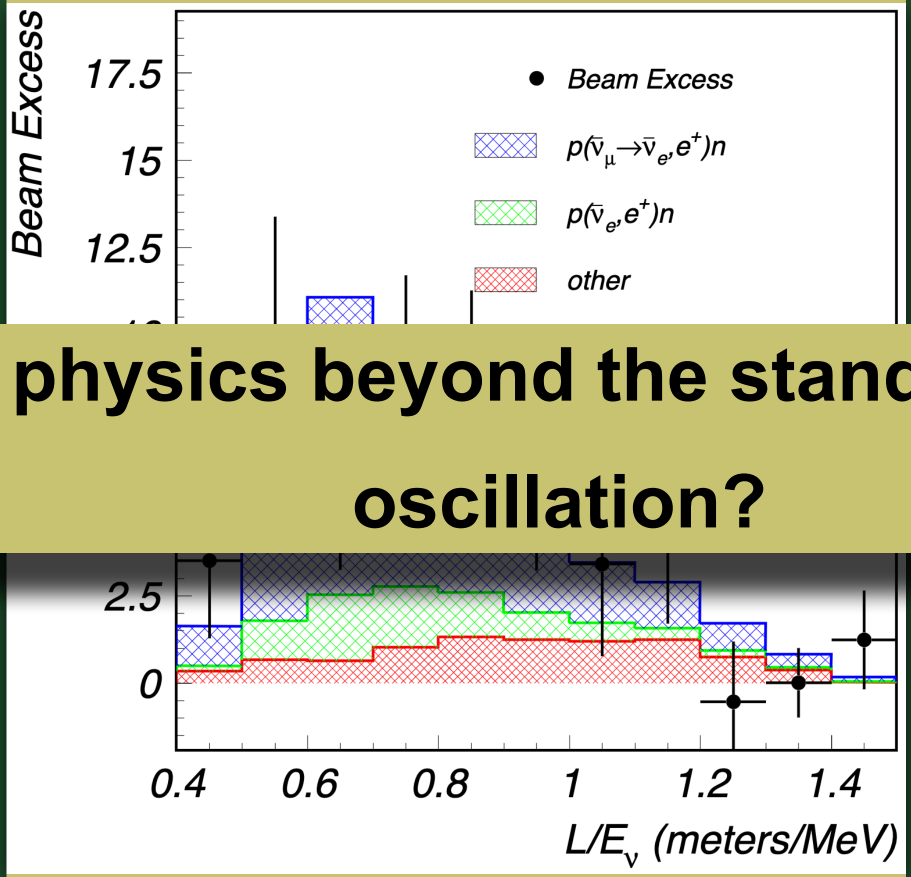

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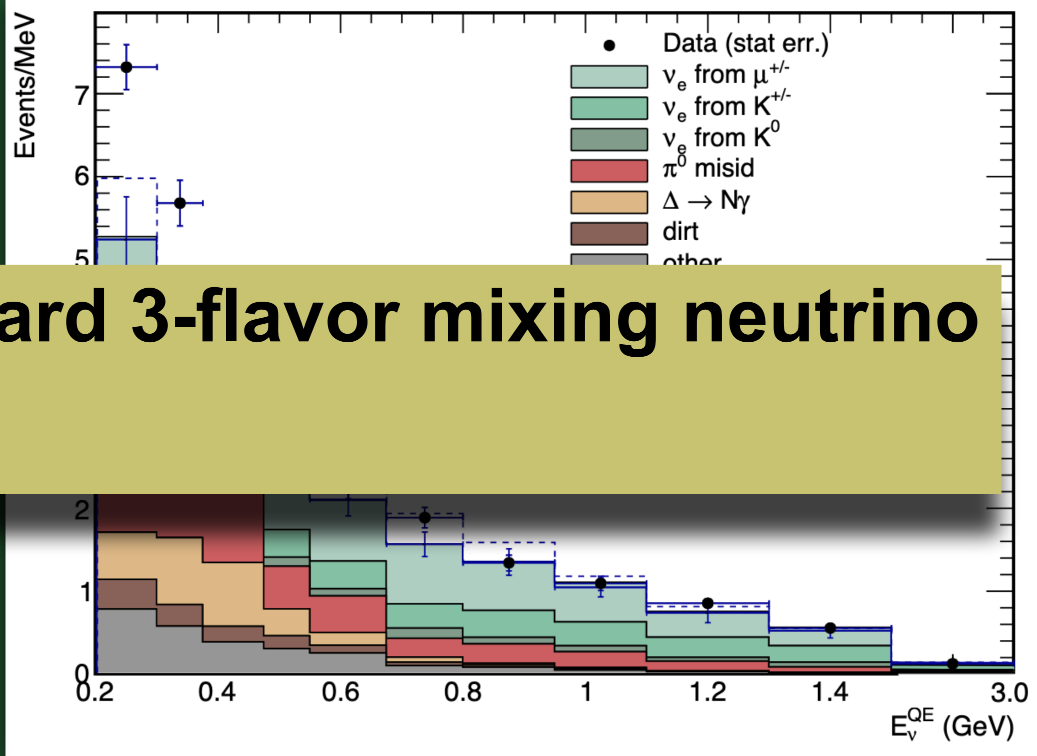
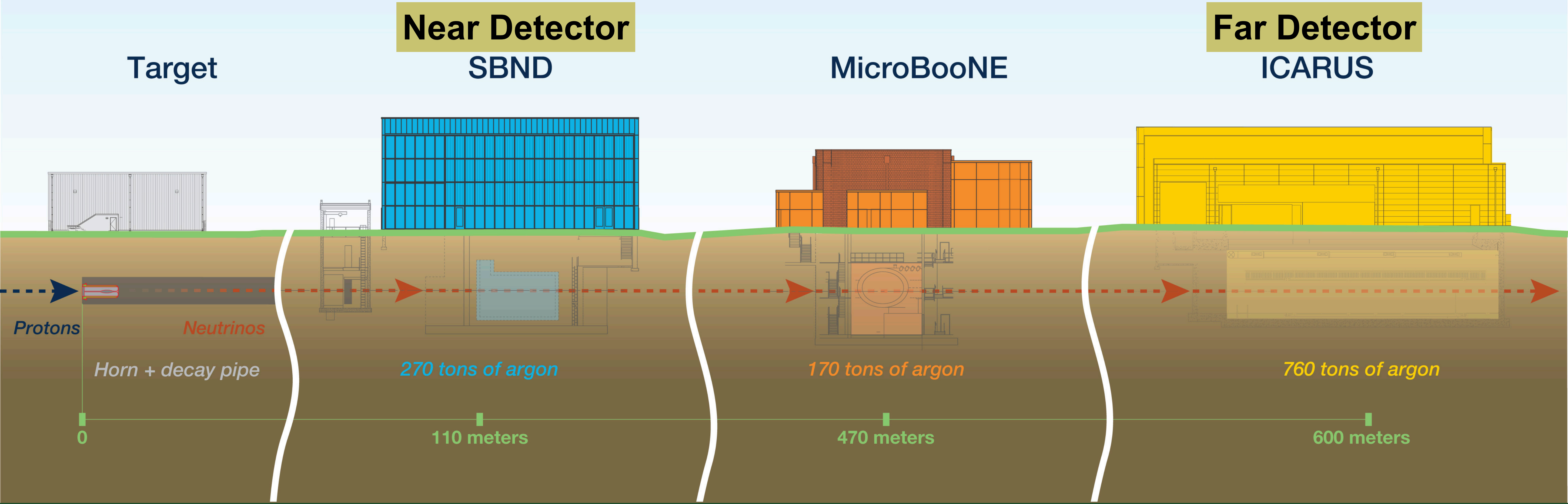


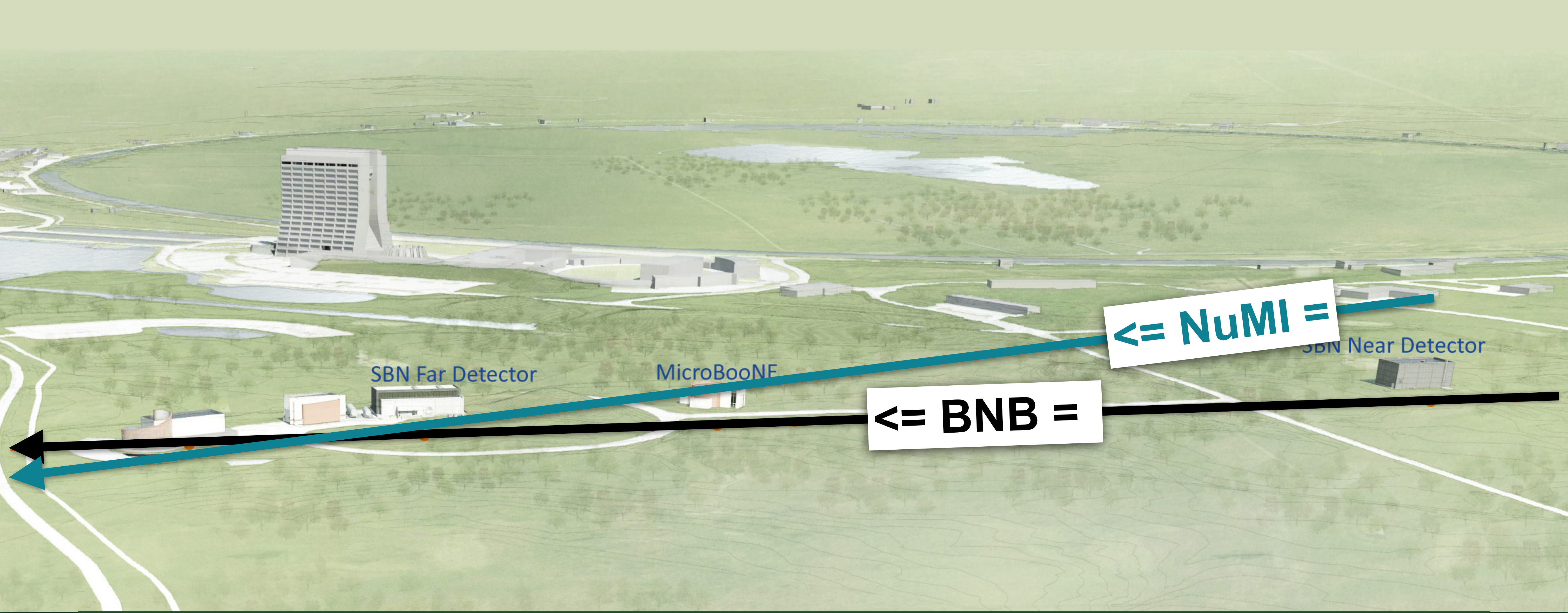
Phys. Rev. D 103, 052002 (2021)

Is there any additional physics beyond the standard 3-flavor mixing neutrino oscillation?

Short-Baseline Neutrino Program at Fermilab



- SBN consists of three detectors utilizing the liquid argon time-projection chamber (LArTPC) technology to sample neutrinos from the Booster Neutrino Beam (BNB) at different baselines
- Capable of ***both*** muon neutrino disappearance and electron neutrino appearance searches
- Our main goal is the discovery or exclusion of sterile neutrino oscillations near $\Delta m^2 = 1 eV^2$



- In addition to receiving the Booster Neutrino Beam, ICARUS is also located 6 degrees off-axis of the Neutrinos at the Main Injector (NuMI) beam
- NuMI opens up a rich physics program of BSM searches and ν-Ar interaction measurements at ICARUS

LArTPCs

The Liquid Argon Time Projection Chamber (LArTPC) is a common detector technology in neutrino physics characterized by:

High spatial resolution

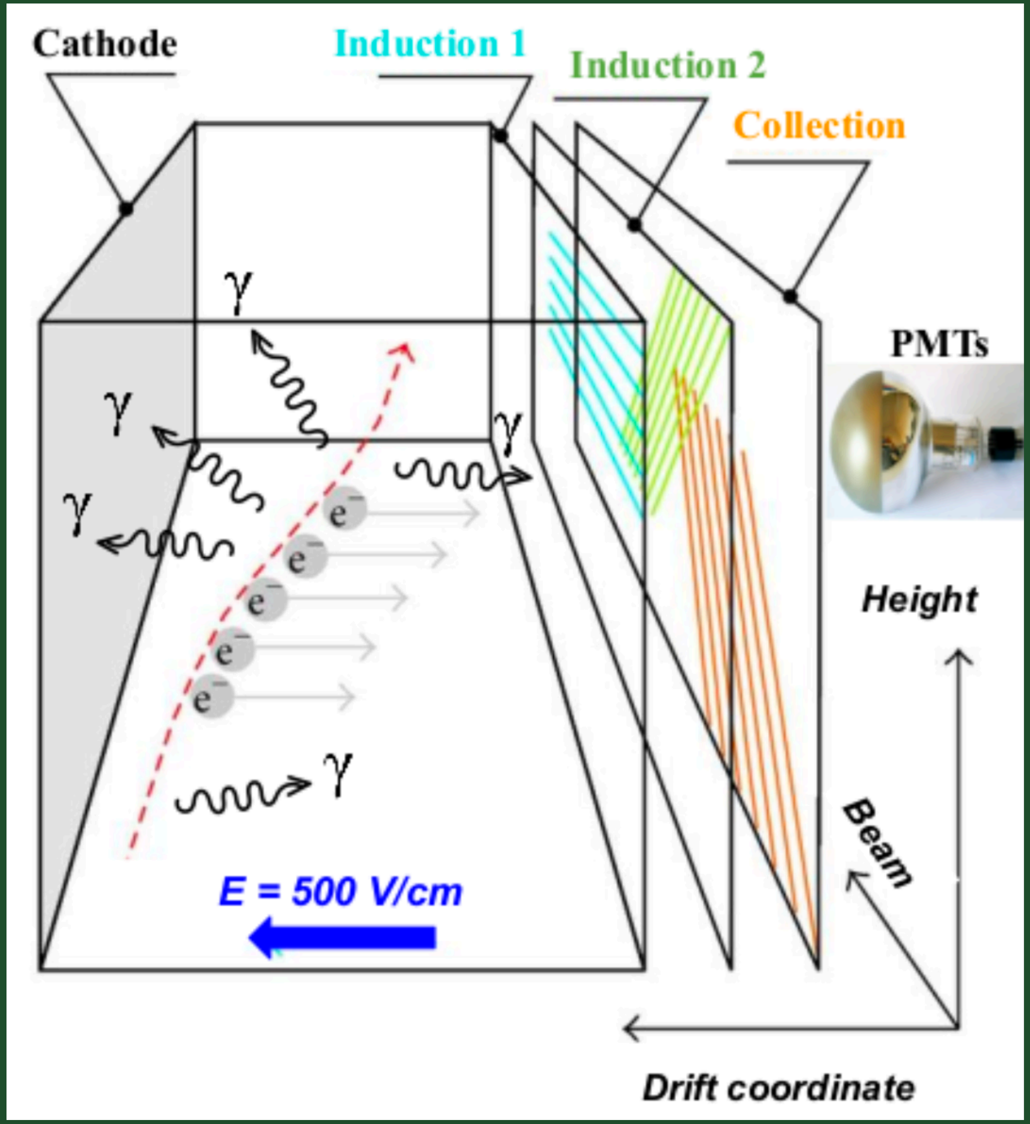
- Millimeter scale spatial resolution
- Visible gap for e/γ shower separation

Excellent calorimetry

- Precise reconstruction of particle kinematics
- Particle ID from dE/dx measurements
- e/γ separation using dE/dx

Scalability

- Modular drift volumes
- Channel count does not scale with volume

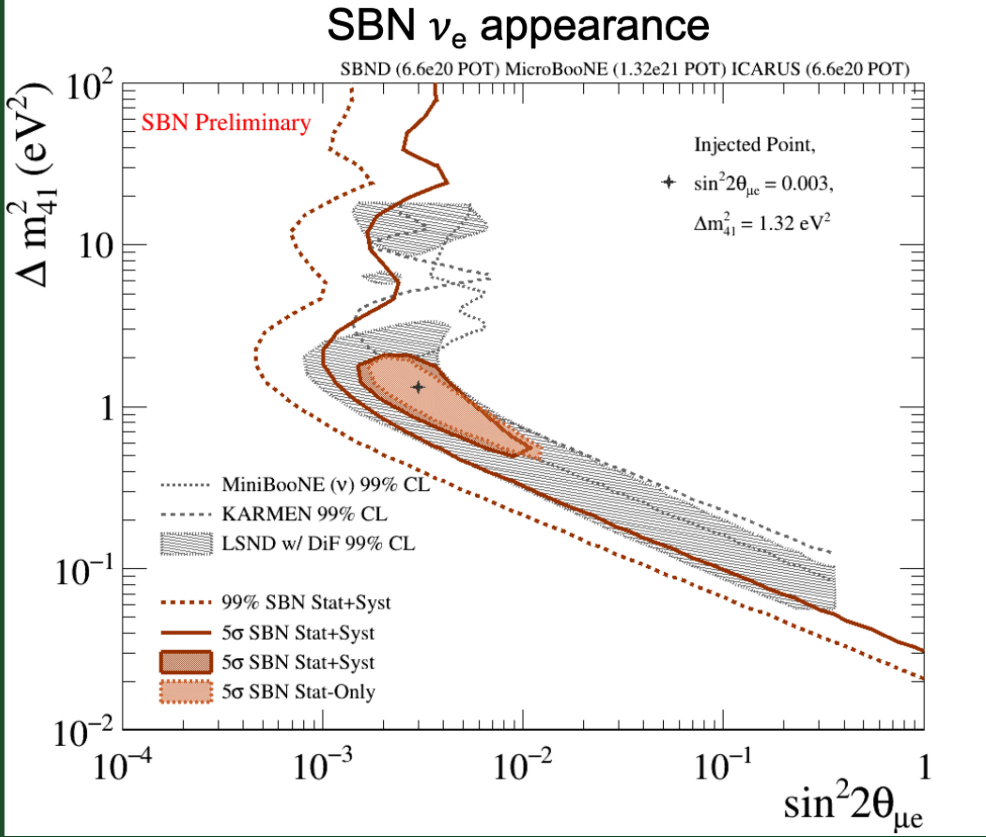


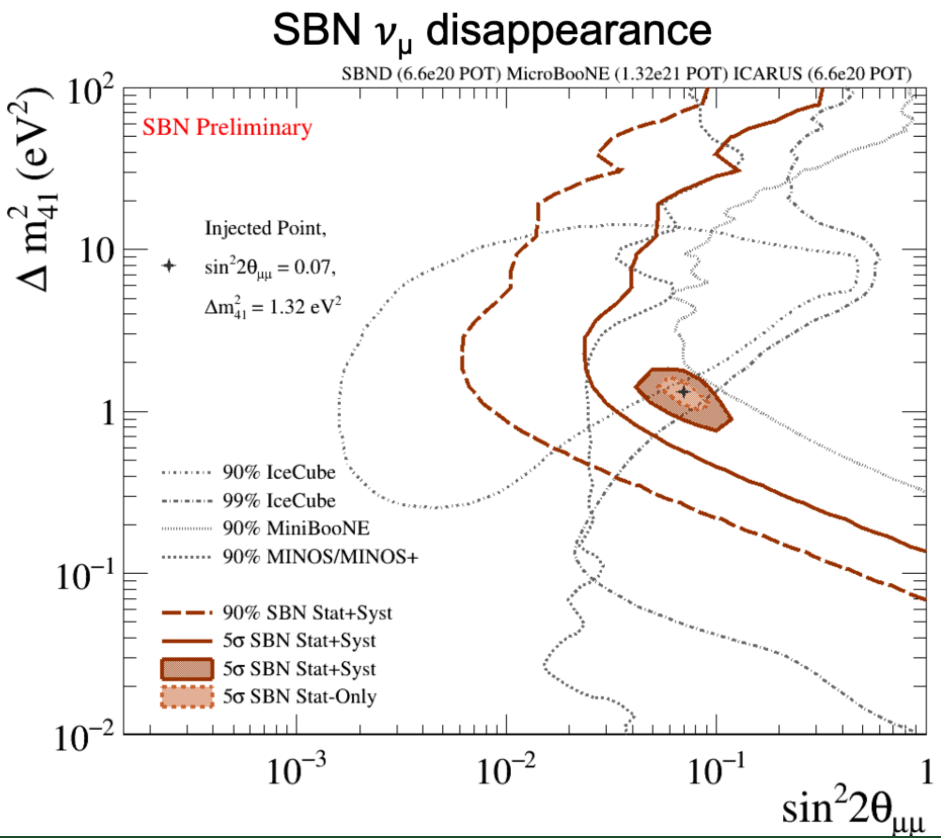
SBN Program

The SBN program will probe the light sterile neutrino hypothesis and provide a 5σ coverage of the LSND/ MiniBooNE anomaly parameter space

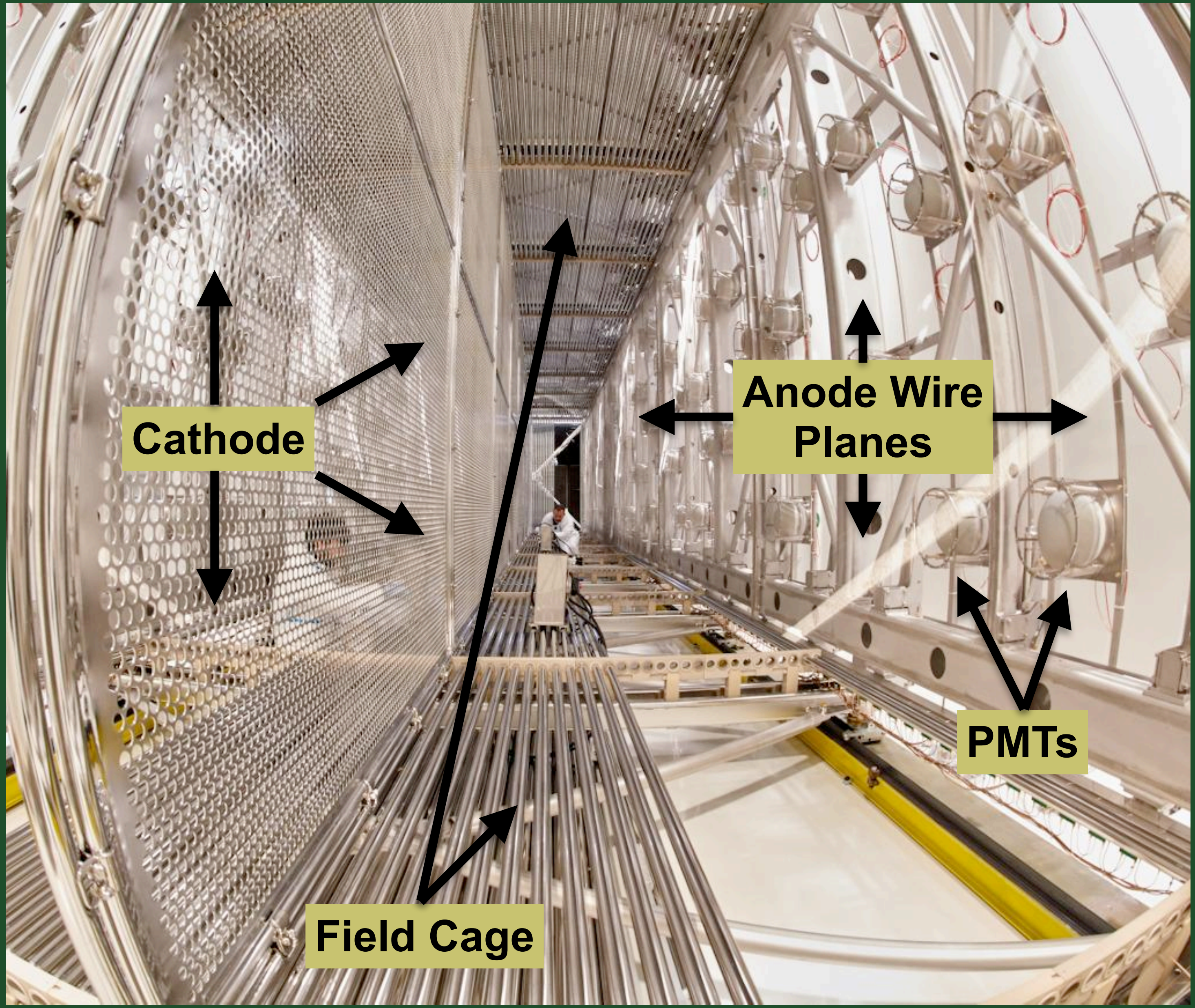
- SBN will leverage simultaneously both the ν_e appearance and the ν_μ disappearance channels
- Using a near detector and far detectors with the same detector technology (LArTPCs) reduces the effect of systematics

SBN sensitivities for 6.6e20 BNB protons on target (POT) — Actual dataset anticipated to be larger for both SBND and ICARUS





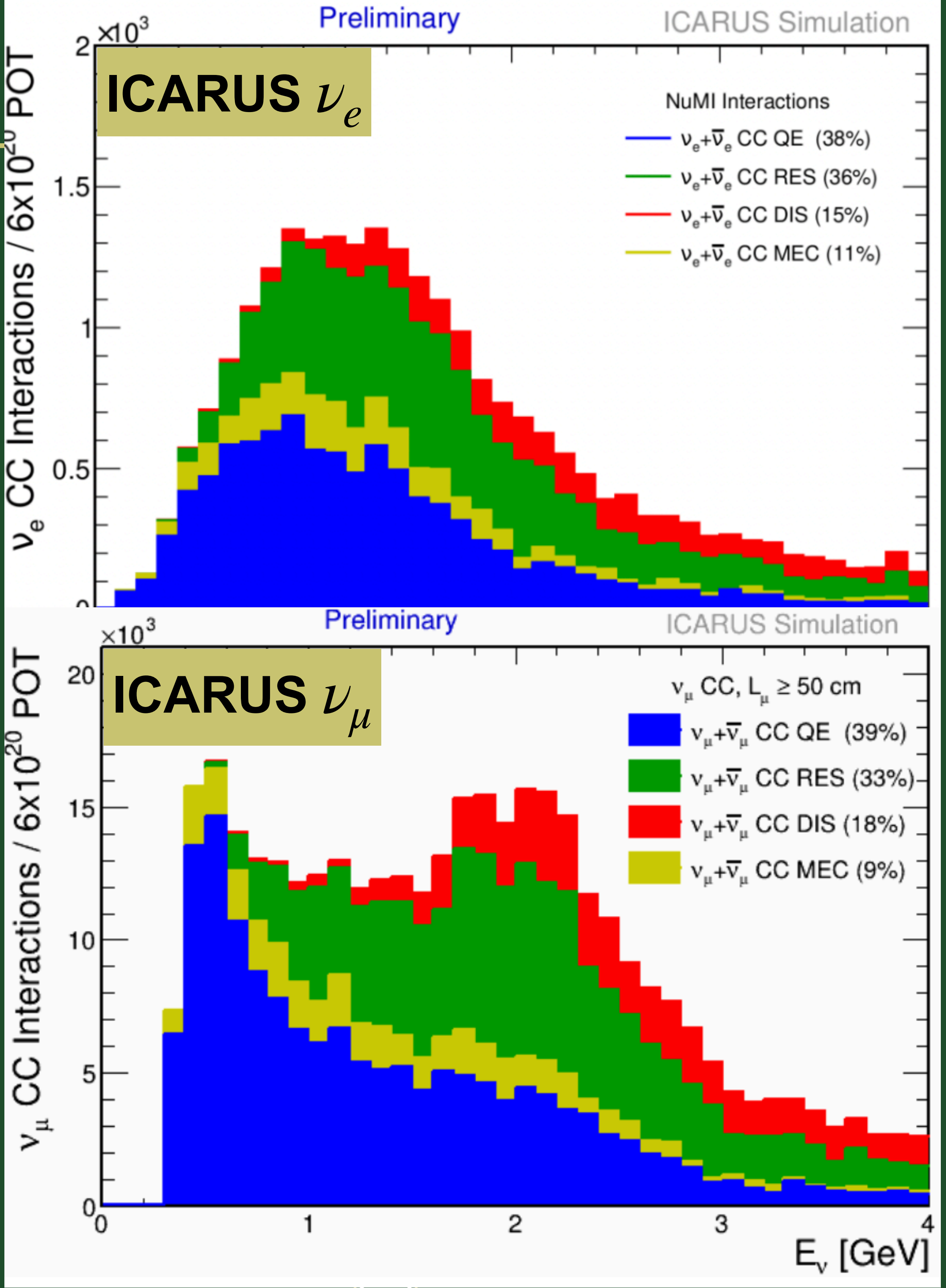
ICARUS at a Glance



- ICARUS is comprised of **four** LArTPCs in **two** identical volumes
  - Each volume has a central cathode shared by two TPCs
- 54,000 channels spread out amongst **three** wire planes (0, $\pm 60^{\circ}$ from horizontal)
- Three distinct subsystems:
  - TPC: precise imaging of particle ionization
  - Photomultiplier Tubes (PMTs): provides timing and triggering
  - Cosmic Ray Tagger (CRT): tags particles as they cross into/out of detector volume

NuMI @ ICARUS

- NuMI provides excellent statistics for both ν_e and ν_μ — Understanding ν-Ar interactions (e.g. cross sections, nuclear effects, final states) is important to oscillation analyses and constraining systematics!
- The ν_e spectrum from NuMI is also relevant for DUNE — ICARUS covers the second oscillation maximum with a tail extending through the majority of the DUNE phase space
- The ν_μ spectrum similarly covers the majority of the DUNE phase space



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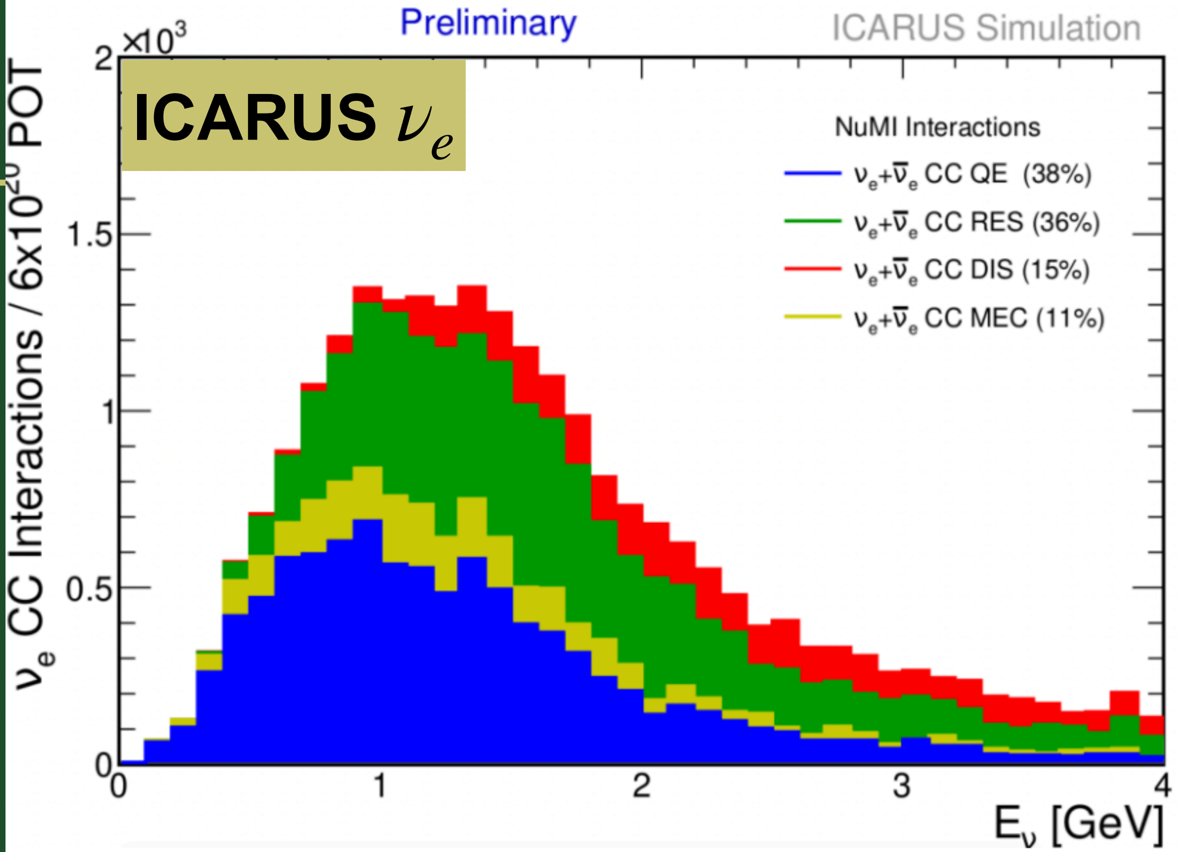

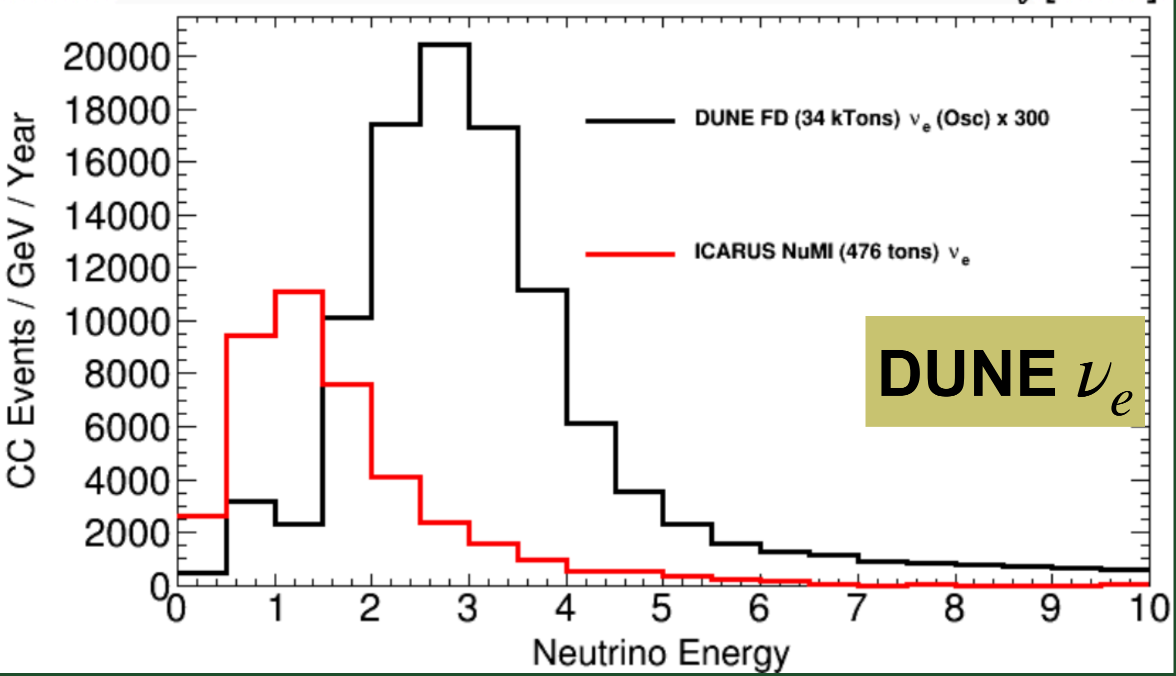

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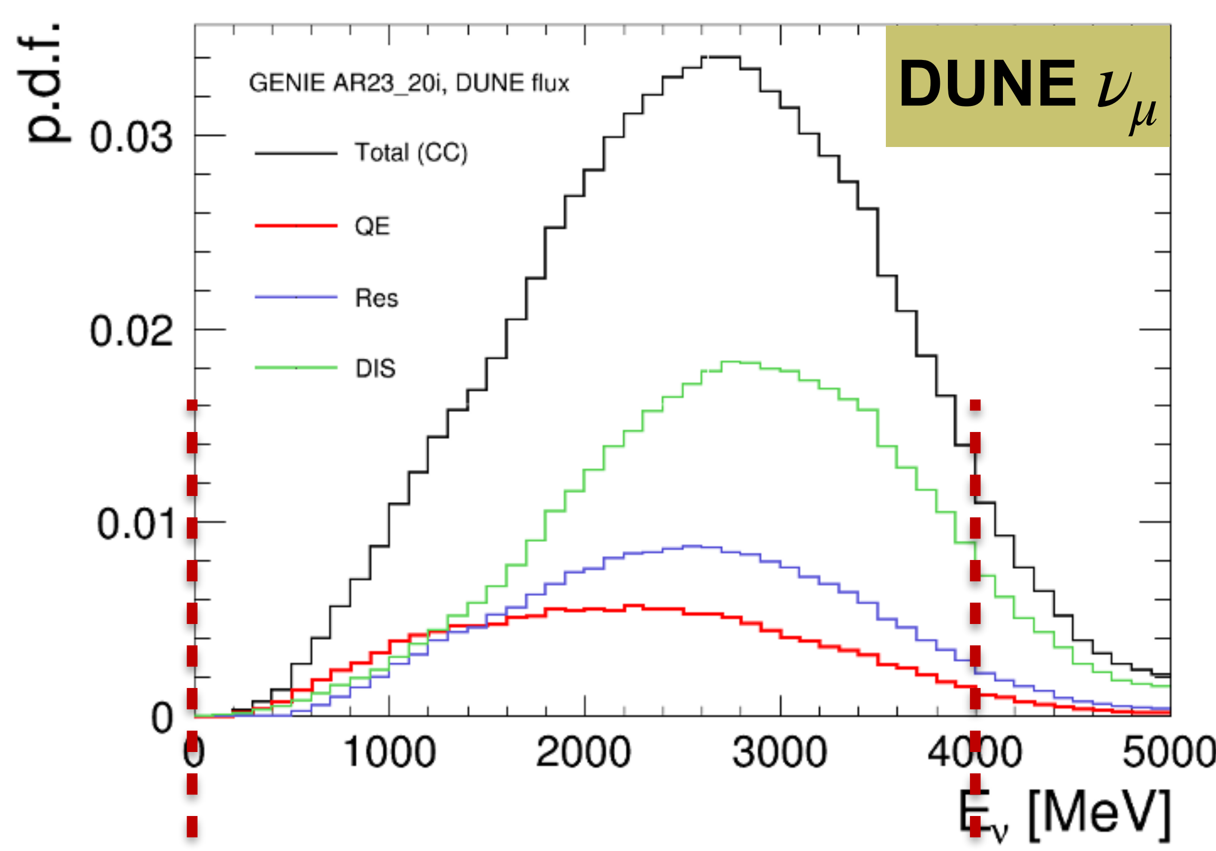
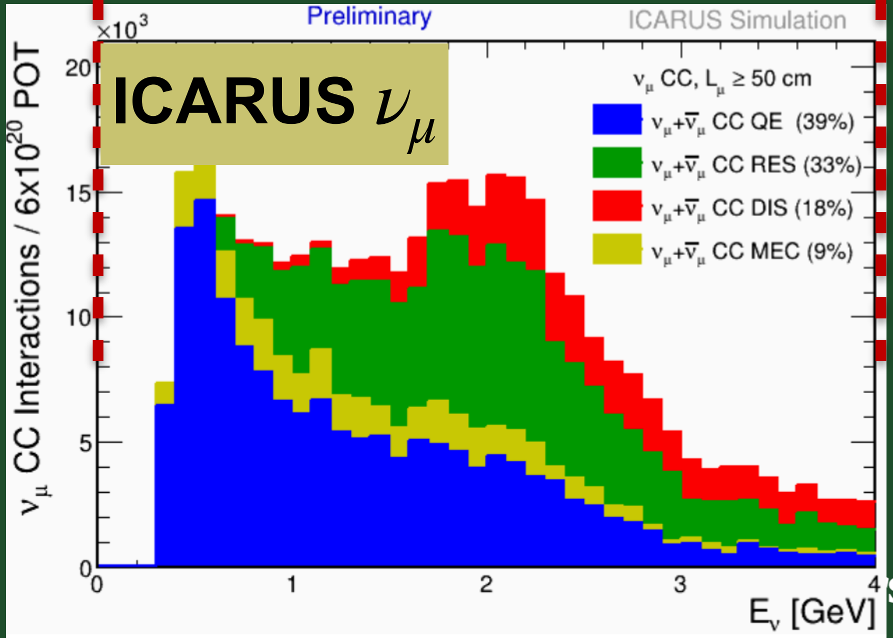


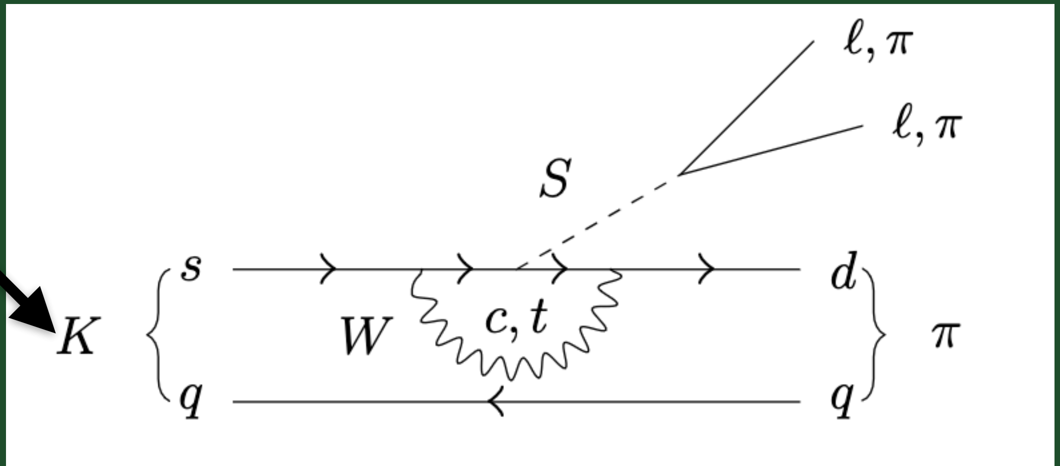


Higgs Portal Scalar @ ICARUS

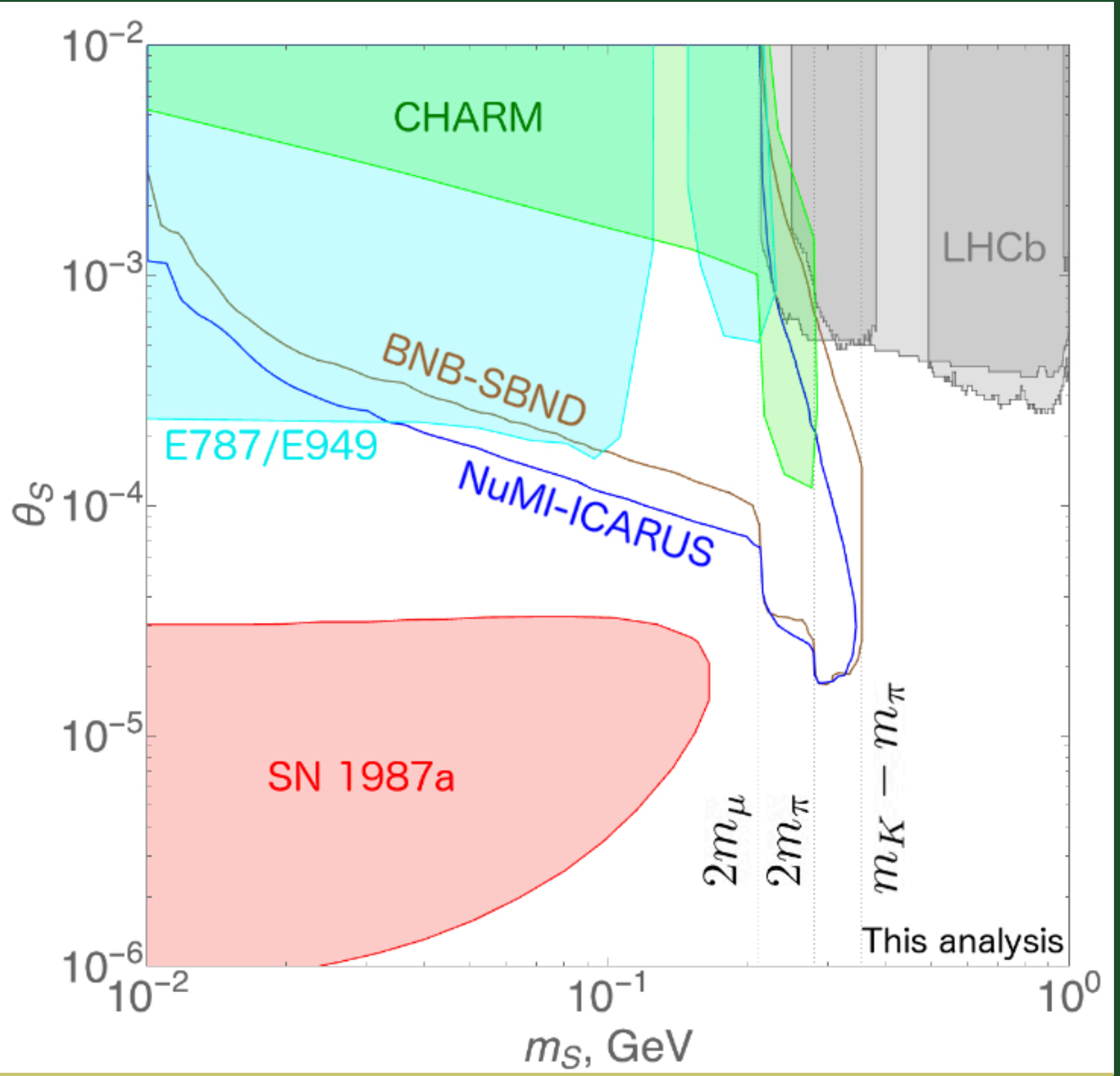
- The extension of the Standard Model to include a dark scalar S, which interacts via the Higgs portal, is testable using NuMI @ ICARUS

Dominant production and interaction modes

Kaon production in NuMI



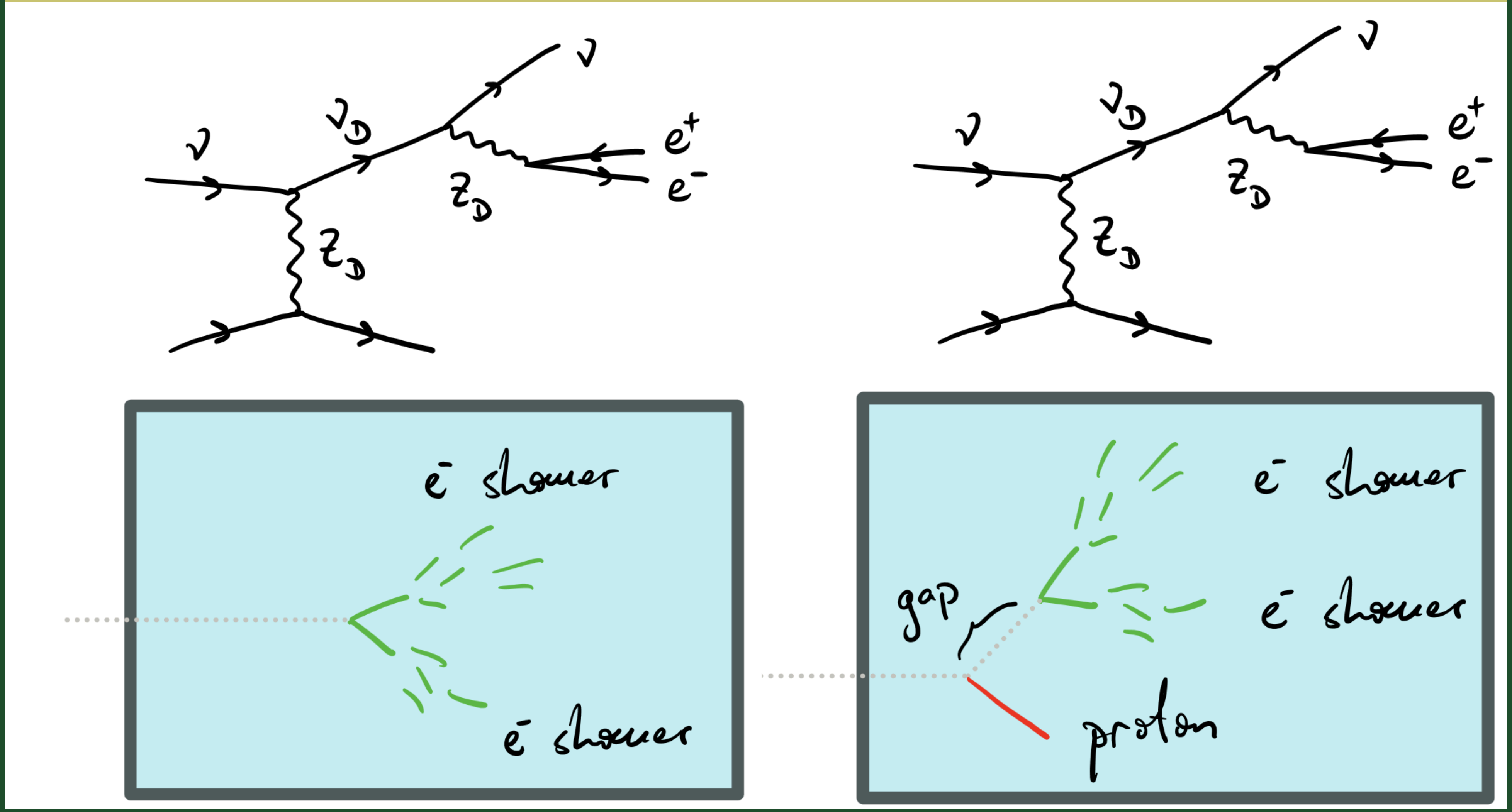
- Experimental signatures in ICARUS are pairs of collinear e^+/e^- showers, μ^+/μ^-, and π^+/π^- with a common vertex — A cut on the angle with respect to the beam may also help with background rejection (decay at rest)



B. Batell, J. Berger, A. Ismail
Phys. Rev. D 100, 115039 (2019)

Other BSM Explanations for ν-Anomaly

Dark neutrinos with light Z_D	Dark neutrinos with heavy Z_D

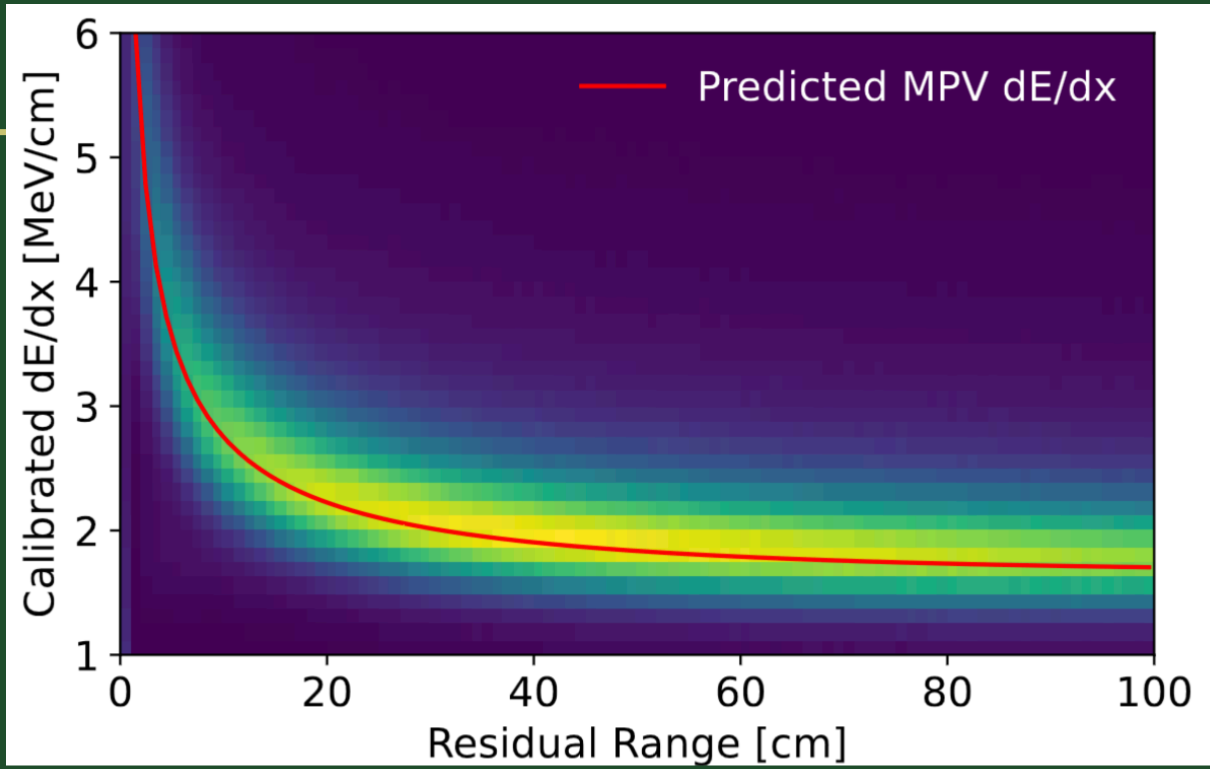


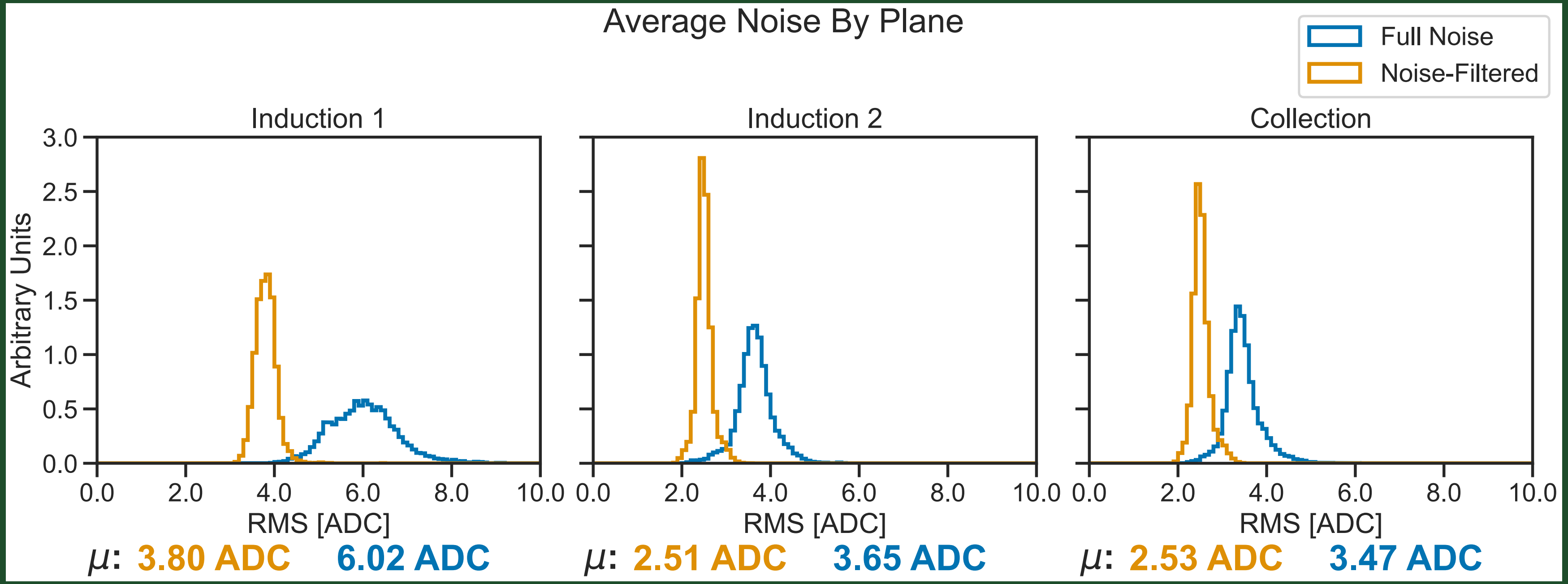
There are many additional theorized models that one could test in LArTPCs

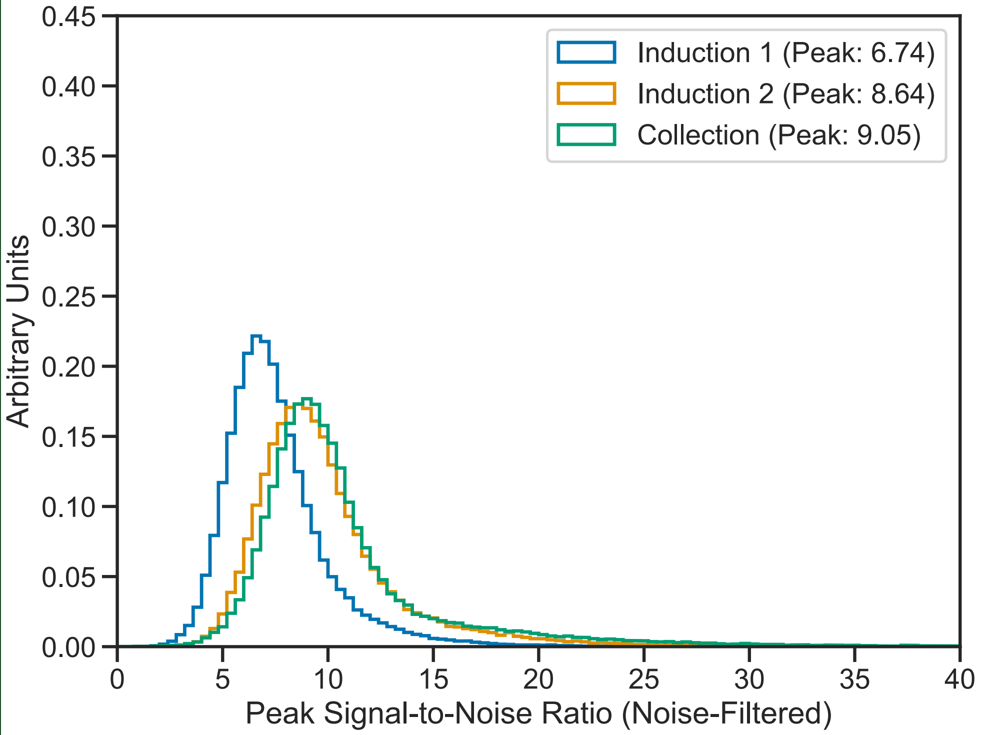
Shown here are two examples taken from **P. Machado's slides** that could result in the excess of electron events in MiniBooNE

Detector Performance

- Commissioning at ICARUS has concluded with physics data taking beginning in June 2022
- Performance of the detector studied rigorously
  — High enough to meet physics goals







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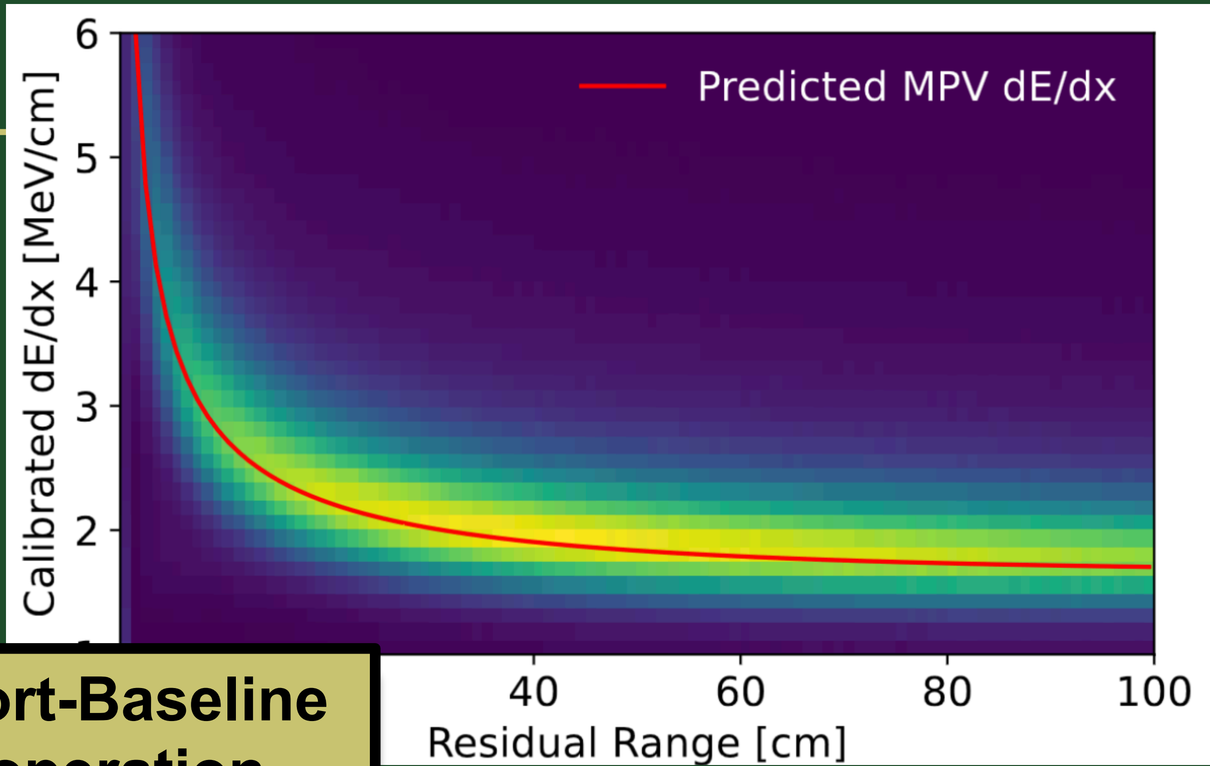
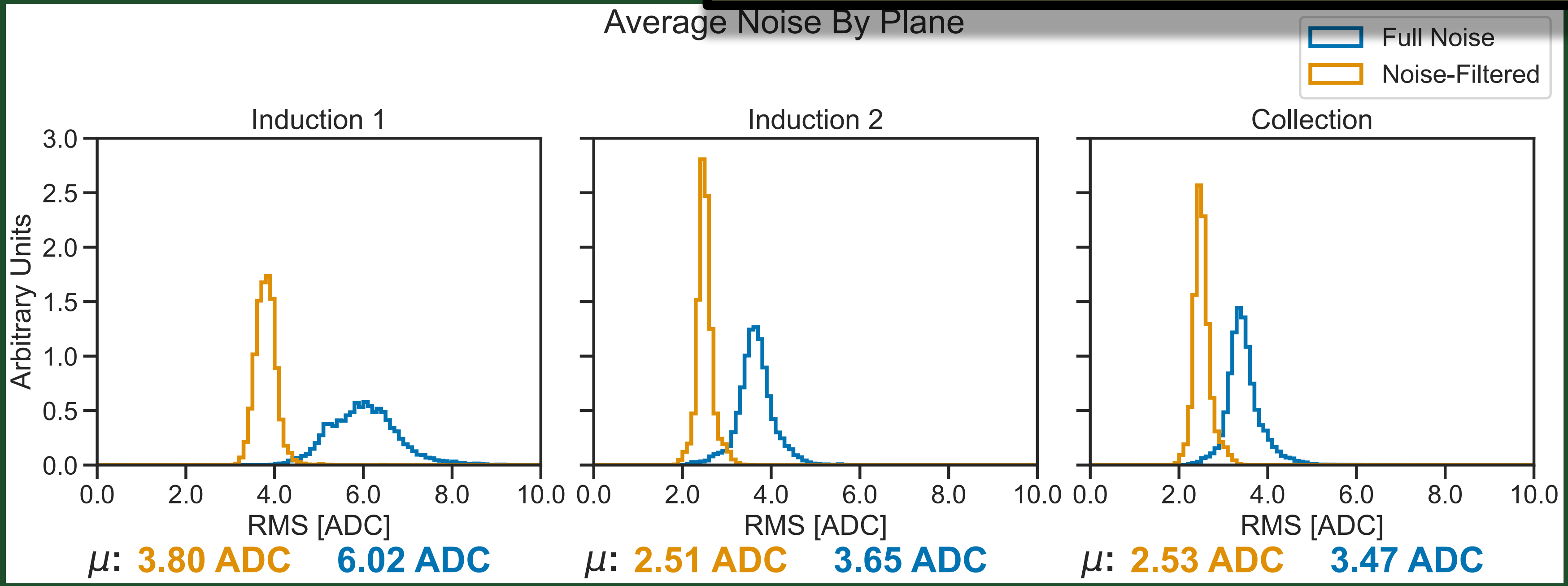
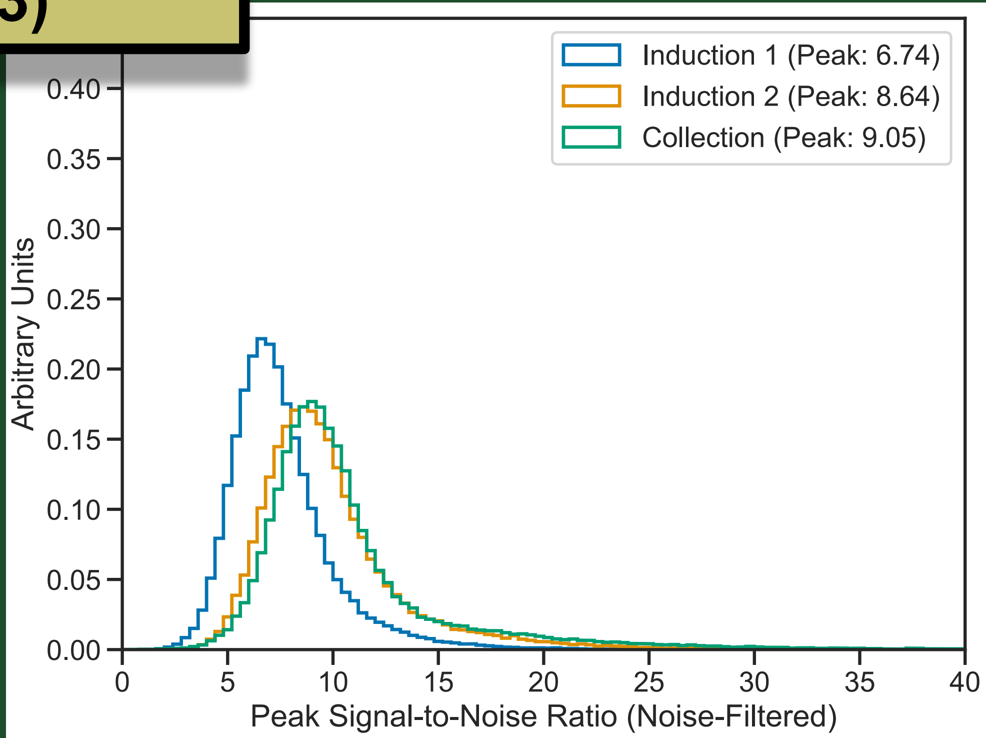


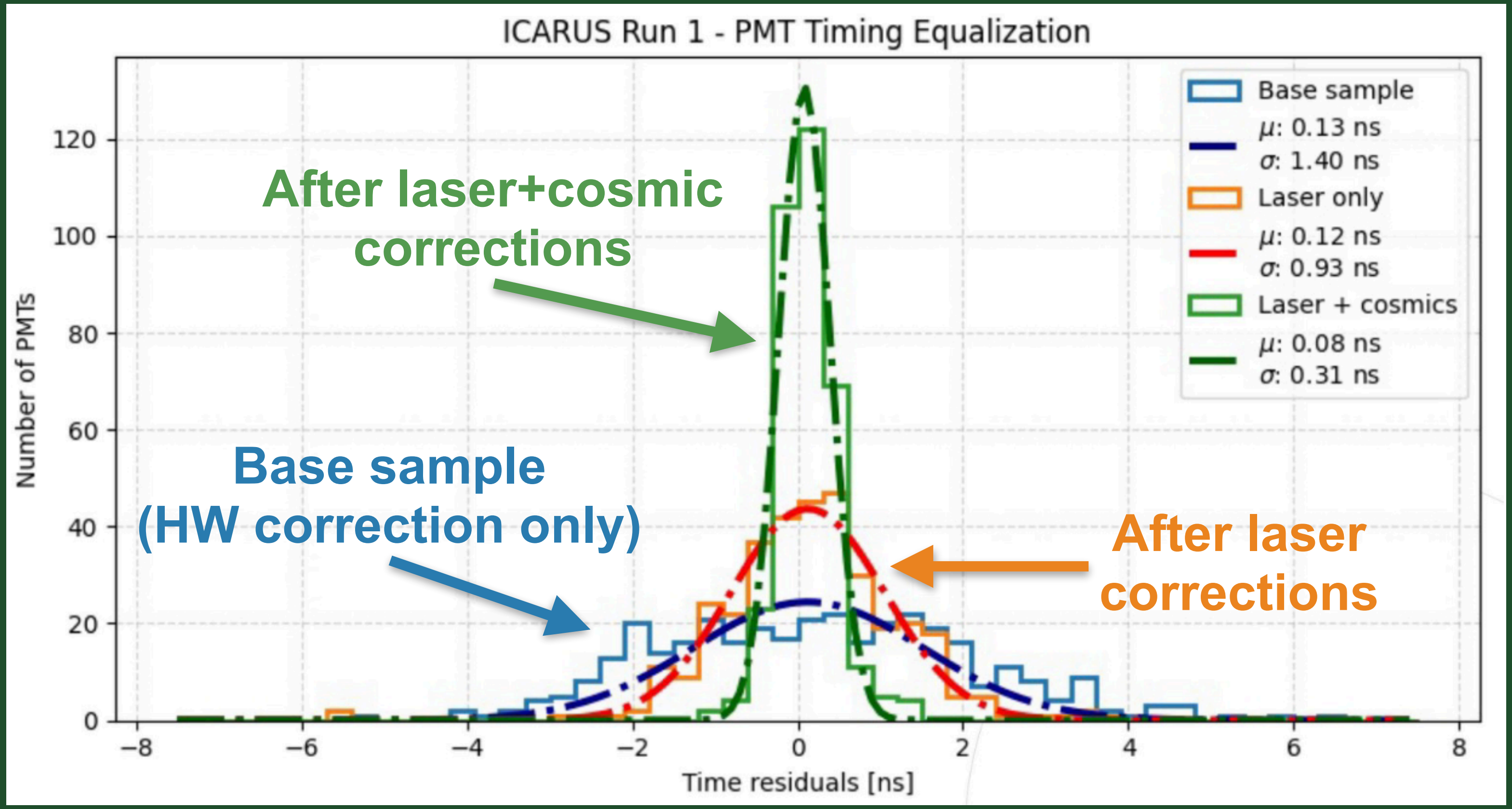
ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation
Eur. Phys. J. C 83, 467 (2023)

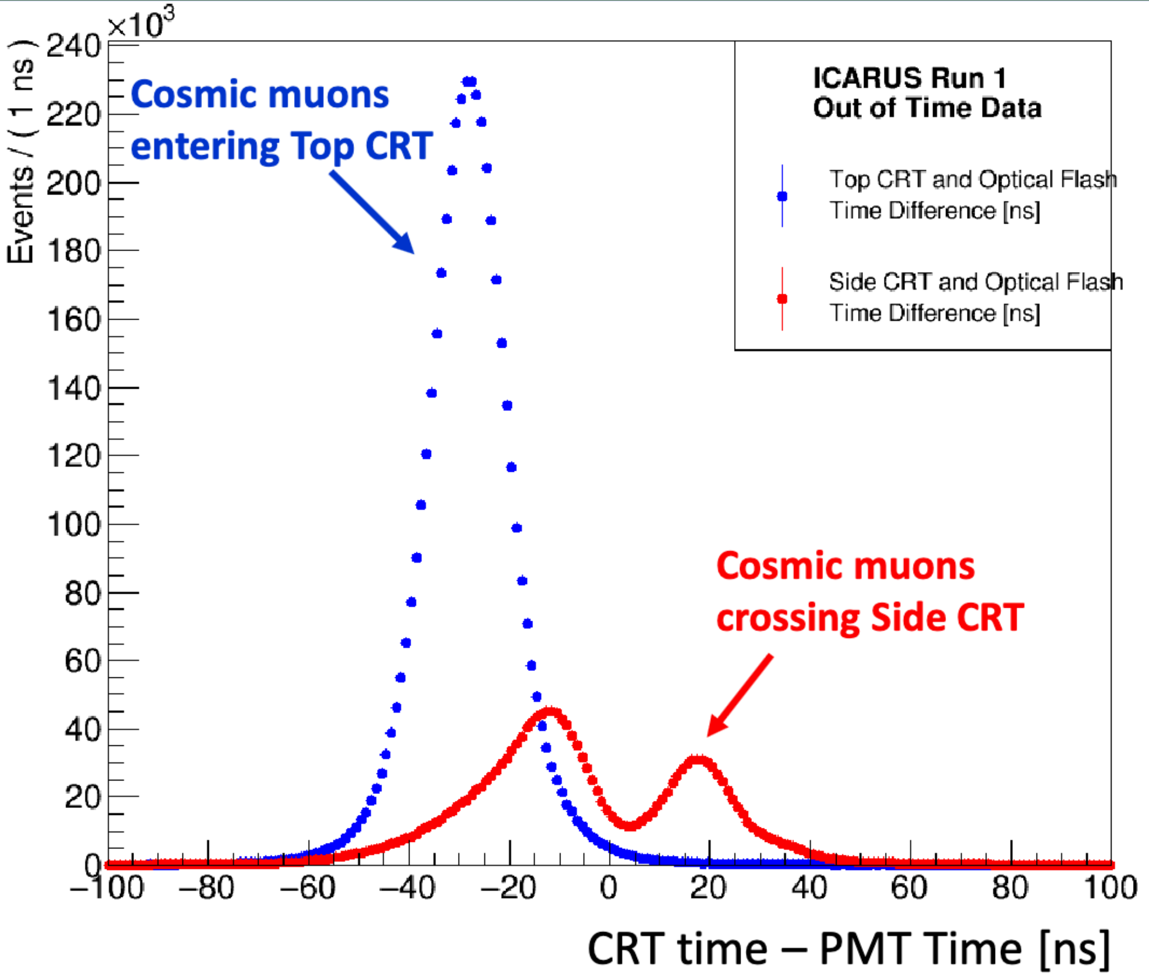




PMT and CRT Timing

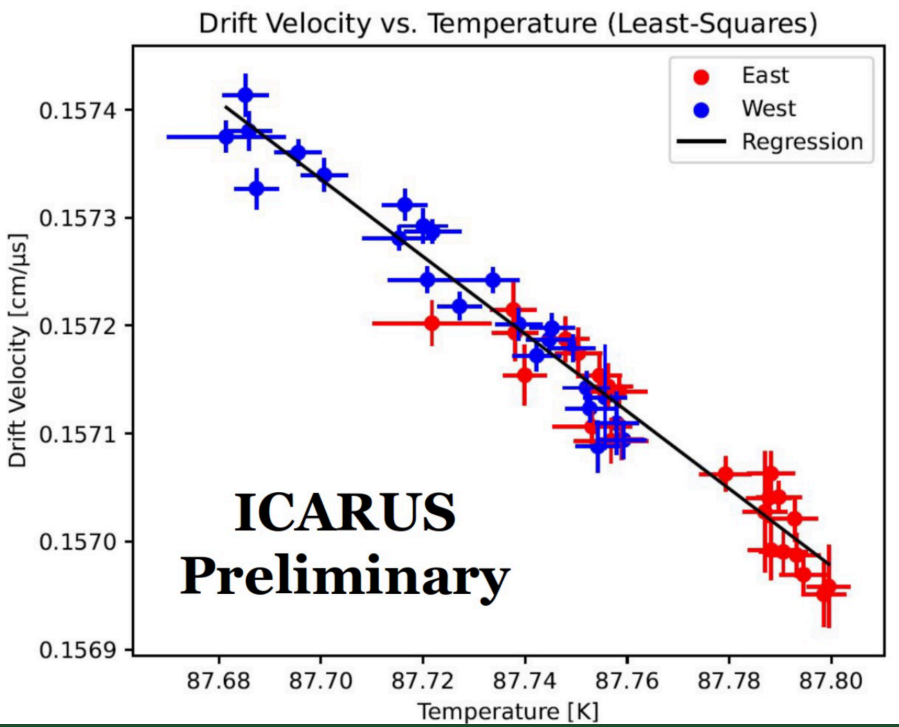
The PMT relative timing has been calibrated with both a laser system and a cosmic sample — achieves a timing resolution of ~300 ps



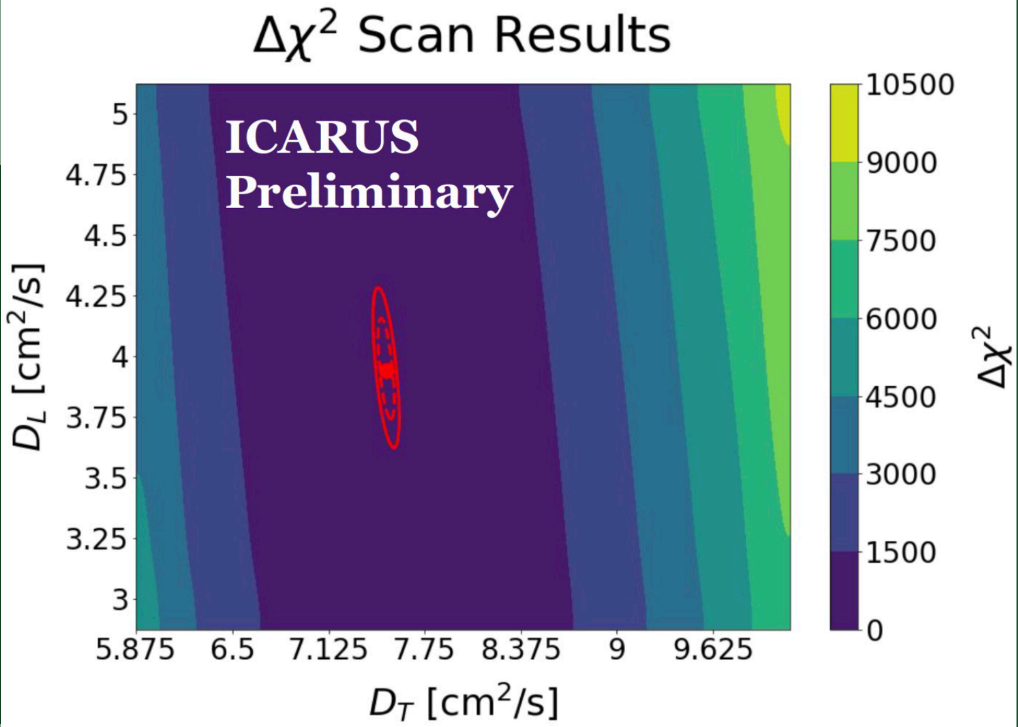


Cosmic muons entering/exiting the detector can be tagged by the relative offset of the CRT and PMT signals — resolution on this quantity of ~ 5ns

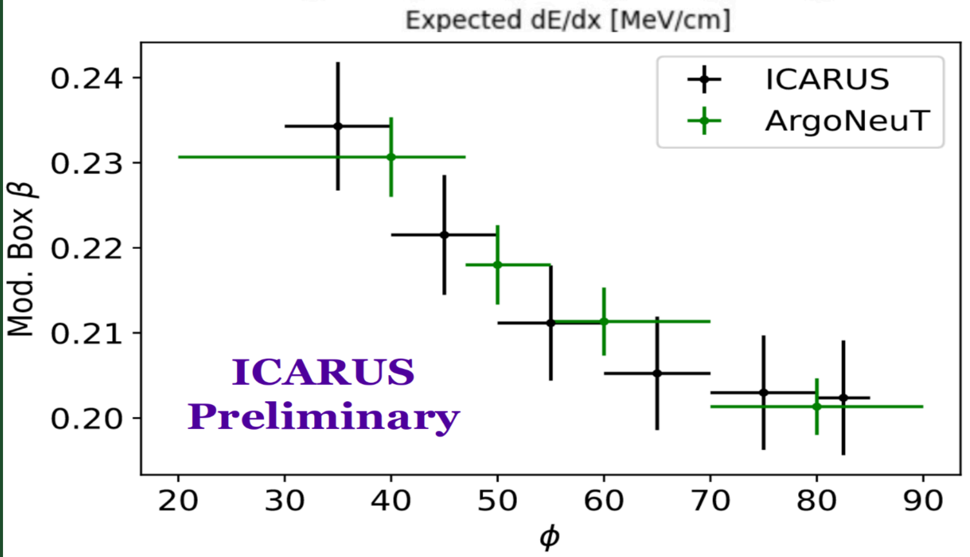
Detector Physics Measurements



Observed dependence of electron recombination on track angle ϕ w.r.t the drift direction for high-dE/dx (protons) — consistent with previous ArgoNeuT measurement



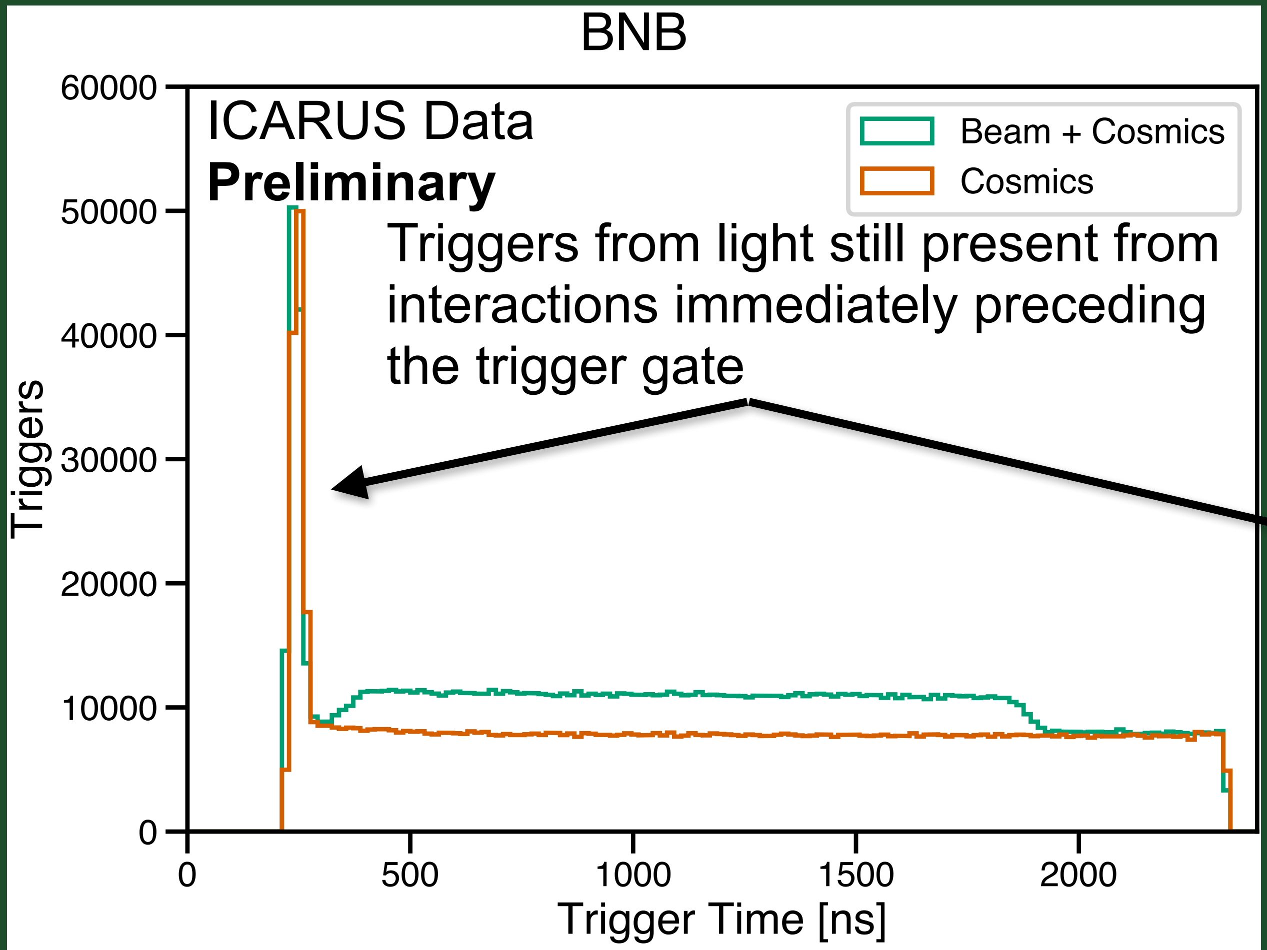
Electron drift velocity (@ 500 V/cm) measured as a function of cryogenic temperature in liquid argon

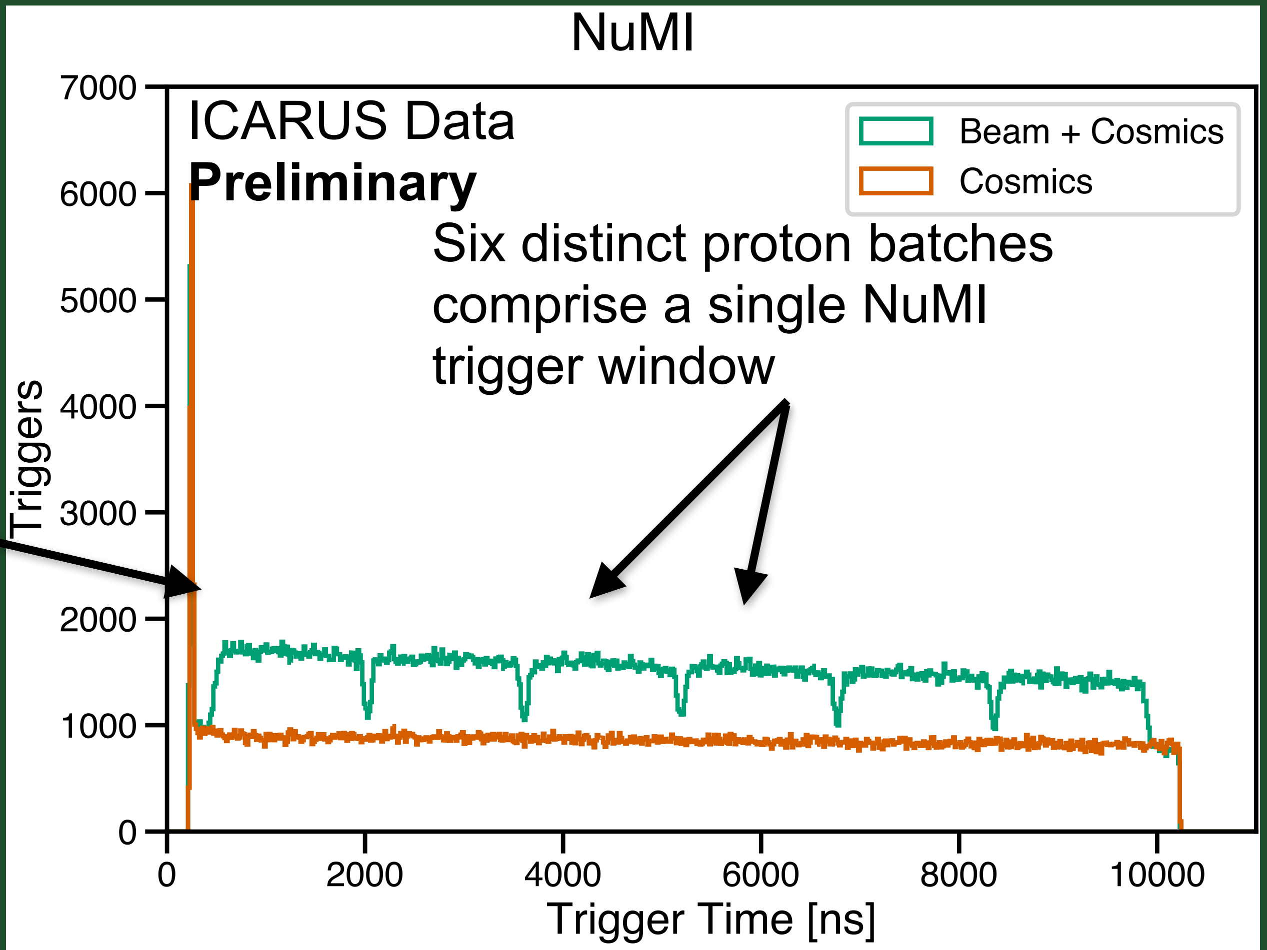


TPC signal widths from cosmic tracks have been used to measure ionization diffusion coefficients transverse (D_T) and longitudinal (D_L) to the drift field — first transverse measurement < 1kV/cm

Seeing Neutrinos with the Trigger

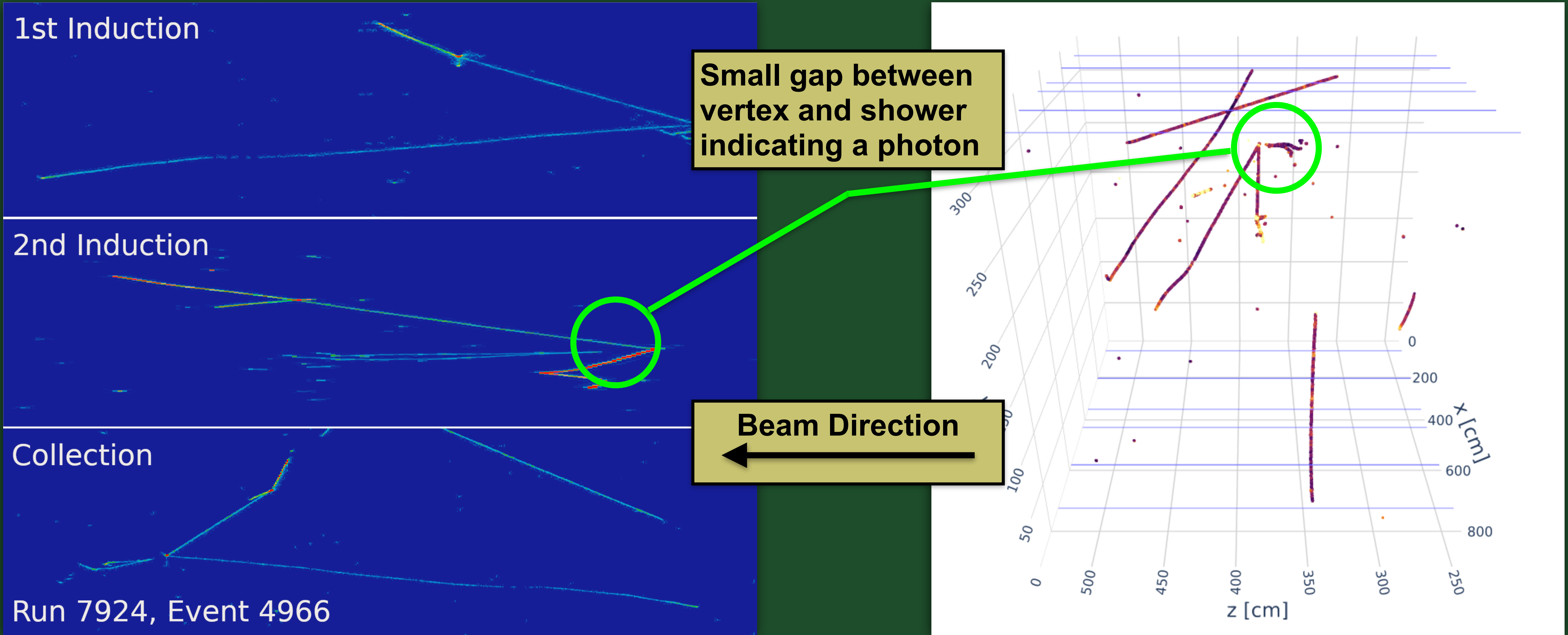
- A trigger is issued when sufficient light activity is observed in the detector in coincidence with a beam gate (**beam + cosmics**) or an artificial gate with the same length, but out-of-time with the beam (**cosmics only**)
- By comparing these two for each beam, we can clearly see the presence of neutrinos as an excess over the cosmic background





Neutrino Interactions @ ICARUS

ICARUS has been collecting beam data since 2020, which has allowed a visual event scanning campaign to create a sample of neutrino candidates for testing our reconstruction



Data Collection @ ICARUS

- ICARUS was first fully operational in June 2021 before the summer beam shutdown, and was immediately able to continue taking commissioning data when the beam resumed in November 2021
- Two successful physics runs with a combined 2.45e20 POT (BNB) and 3.42e20 POT (NuMI)

Run	Type	BNB POT	NuMI POT	BNB Eff.	NuMI Eff.
	Commissioning	2.96e20	5.03e20	88.6%	87.7%
Run 1	Physics	0.41e20	0.68e20	93.2%	92.9%
Run 2	Physics	2.04e20	2.74e20	95.0%	95.6%

Neutrino Reconstruction

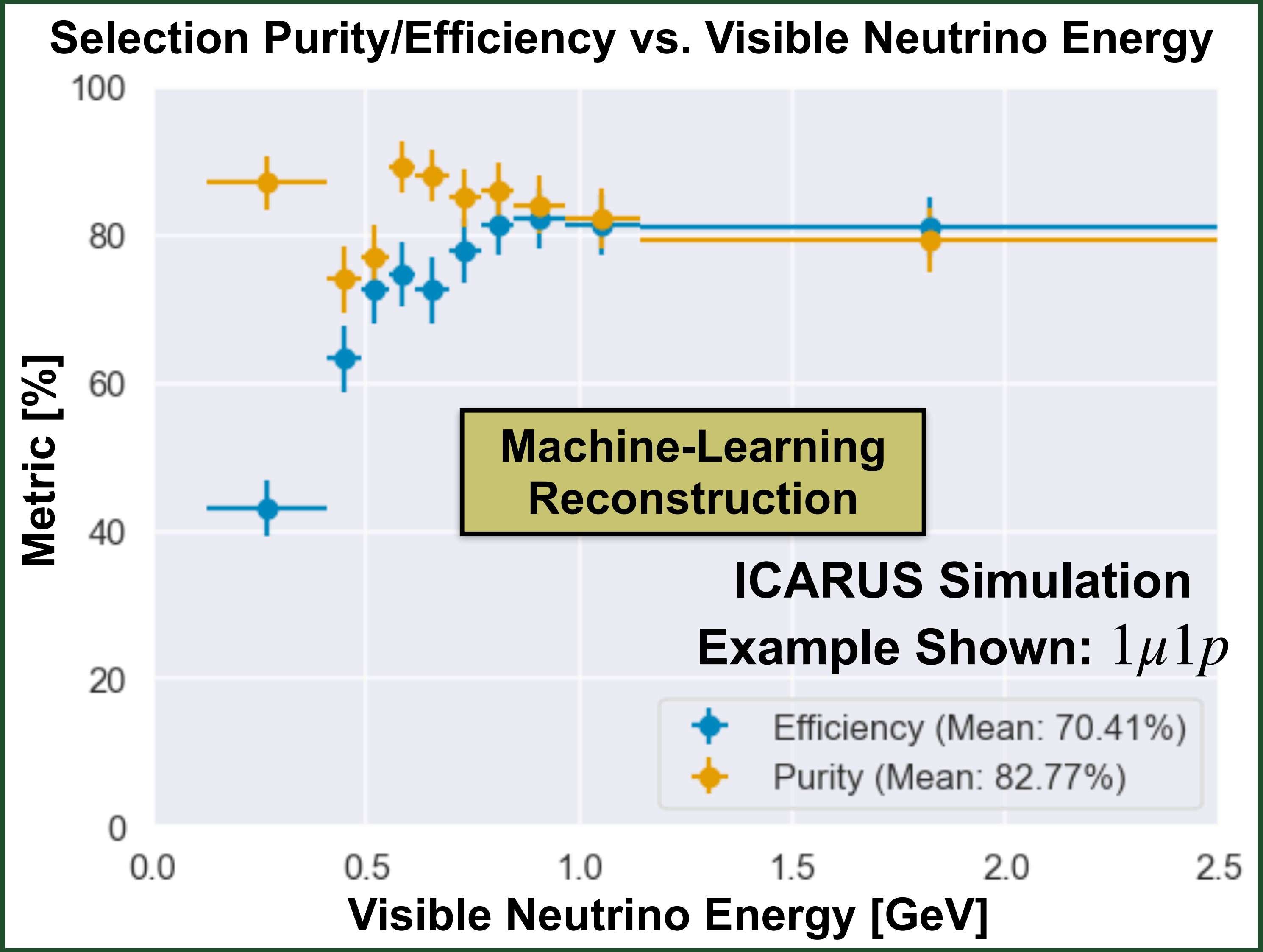
- The $1\mu1p$ channel is a CC QE-like signature that will be a major component of first analyses

- Selections for this signal channel are being developed with two independent reconstruction frameworks — one based on the Pandora pattern recognition tool and one using an end-to-end machine-learning reconstruction chain

- Both reconstructions show promising performance on data

Purity: Percent of selected interactions which are true 1μ1p

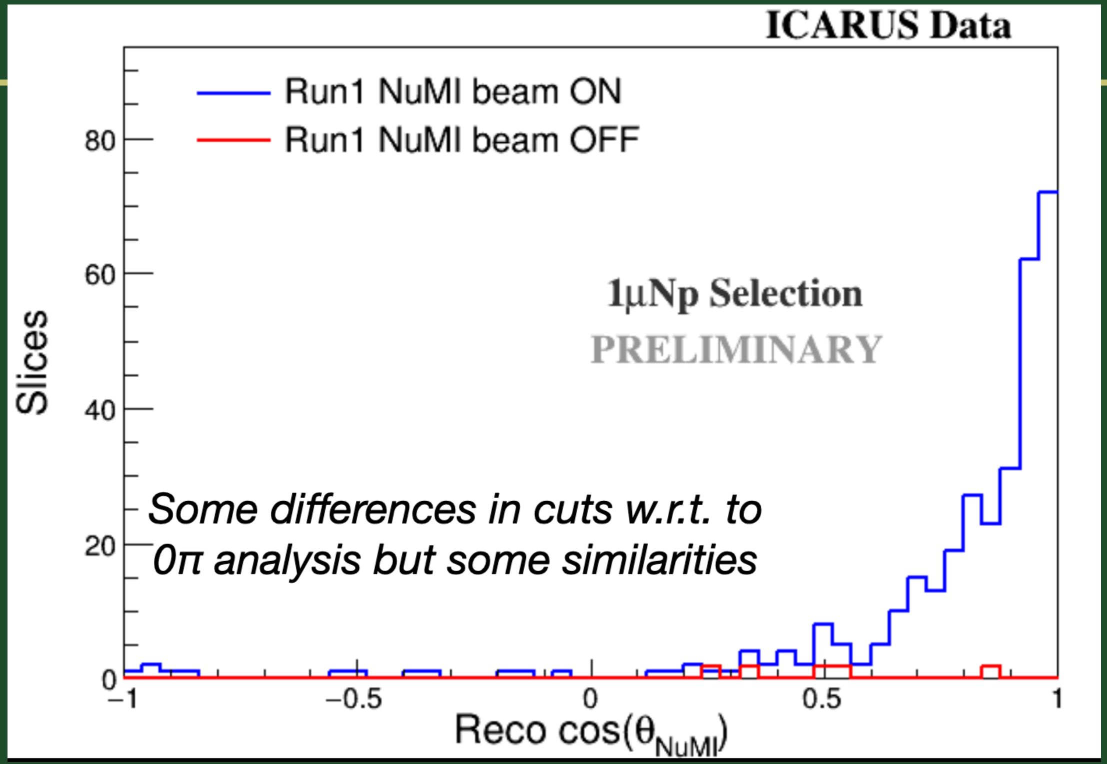
Efficiency: Percent of true 1μ1p selected

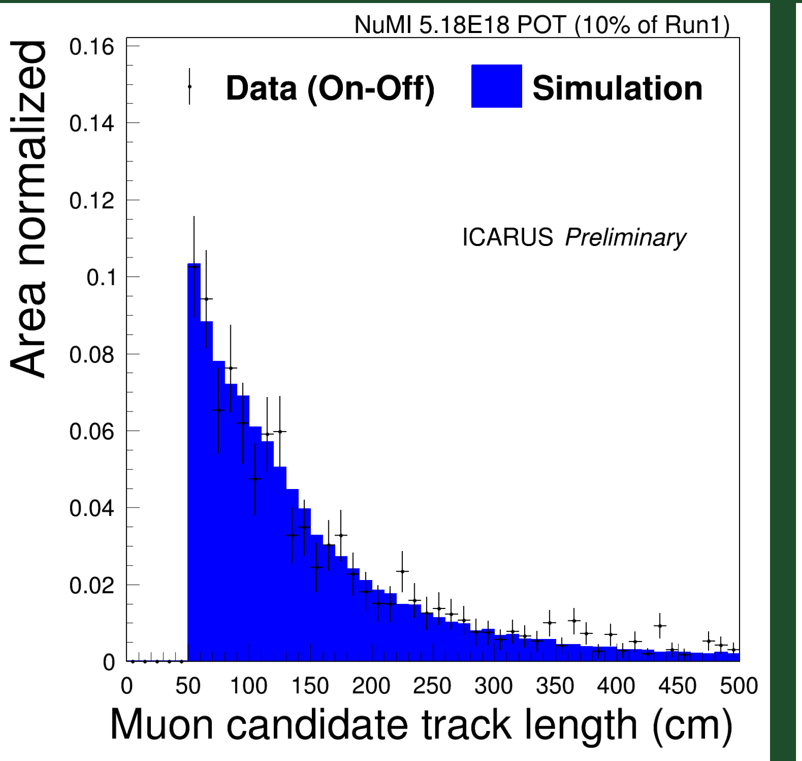


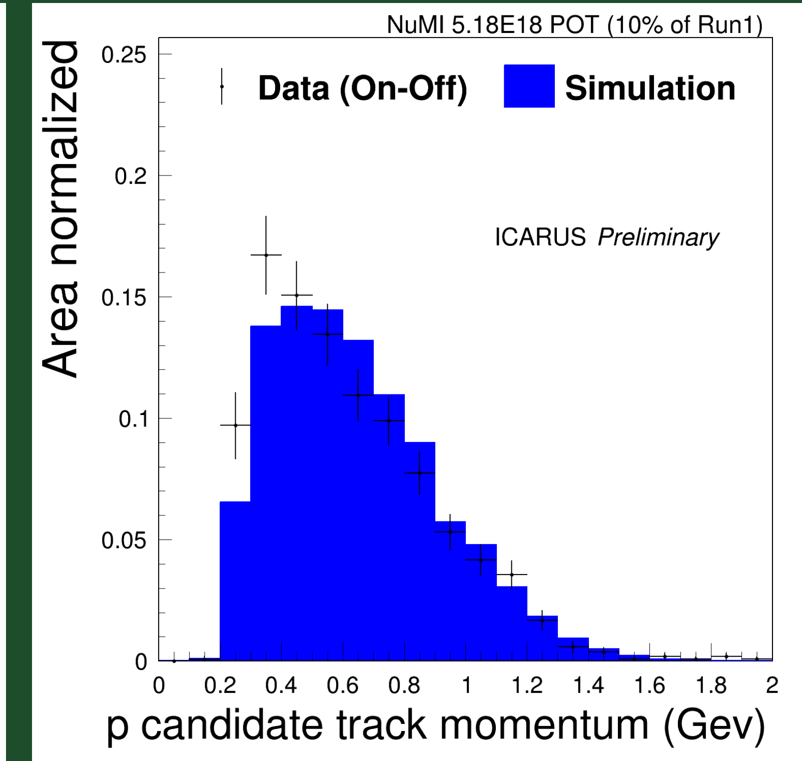
NuMI Cross Sections

- ICARUS is also targeting a $1\mu Np$ signal with NuMI in the context of cross section measurements

- Preliminary area normalized data/MC comparisons of muon and proton kinematics look promising







Conclusion

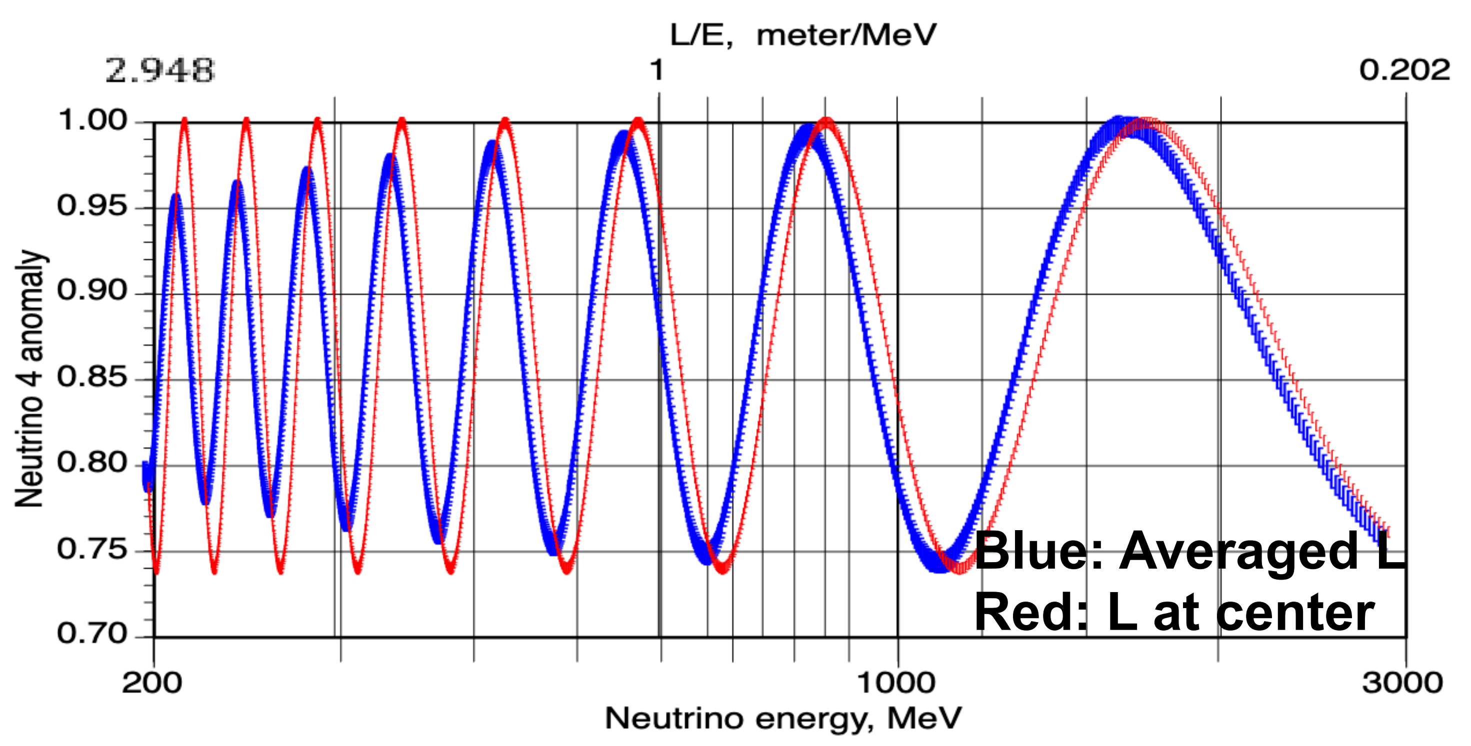
- ICARUS is the far detector of the SBN program with a primary physics goal of testing the eV scale 3+1 neutrino hypothesis
- The location of ICARUS off-axis from the NuMI beam opens up a rich program of neutrino interaction measurements and BSM searches
- Commissioning of the ICARUS detector was completed in June of 2022 and significant datasets for both BNB and NuMI have accumulated
- ICARUS is actively pursuing a wide-variety of physics results — stay tuned!

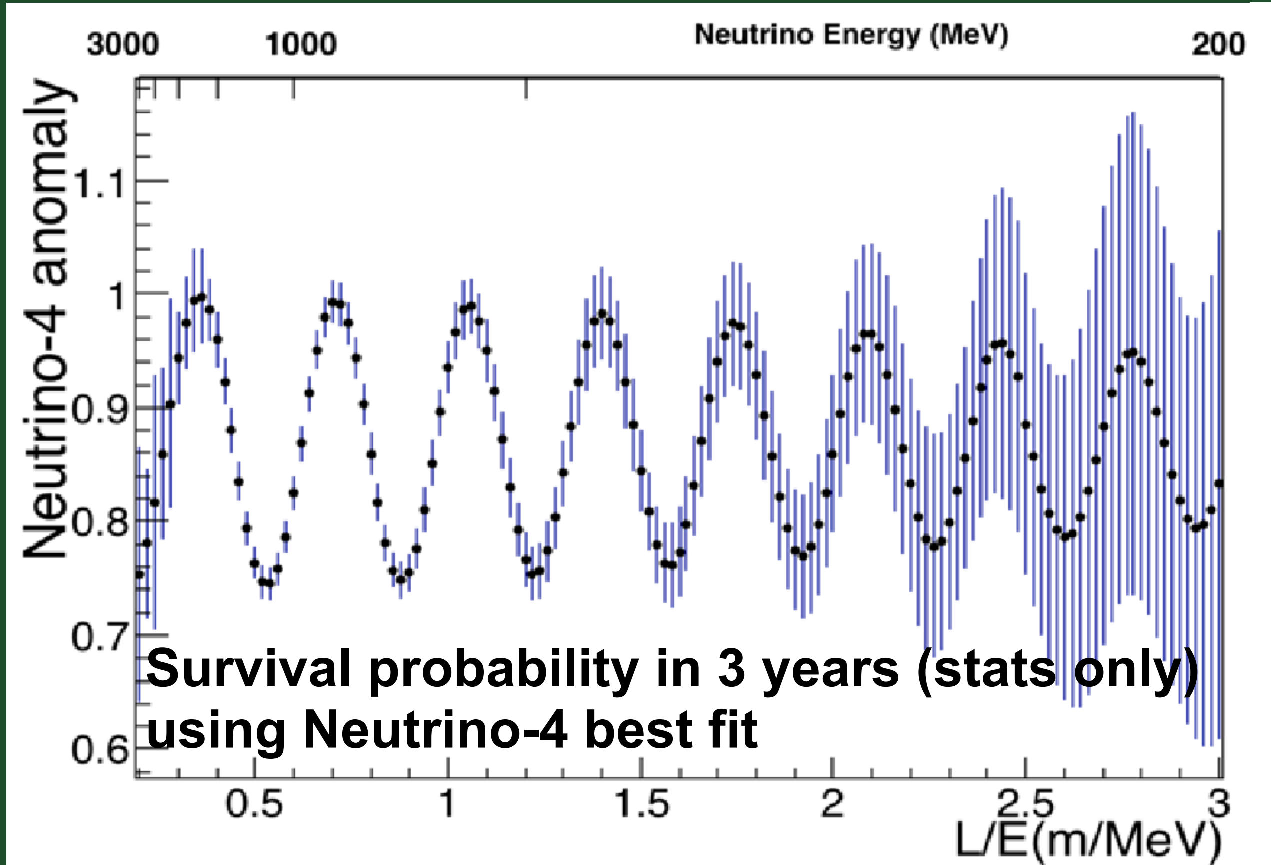
This work is supported by the US Department of Energy

Backup

Neutrino-4 Oscillation Signal

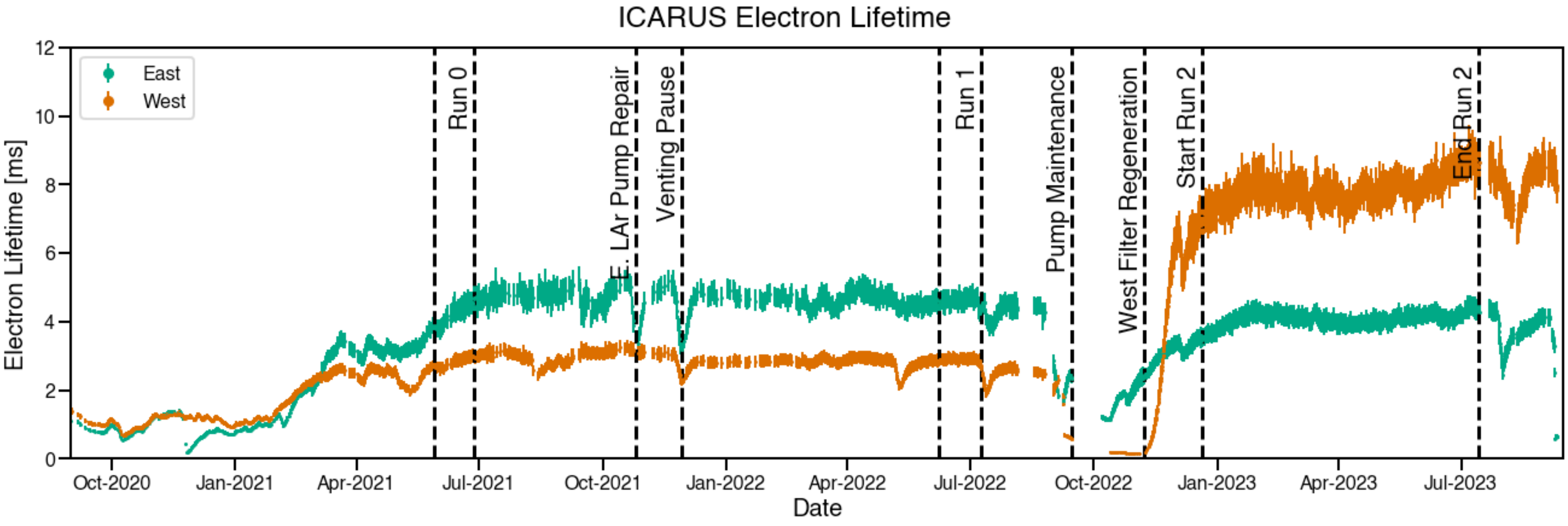
- The Neutrino-4 Collaboration claimed a reactor neutrino disappearance signal with a modulation of L/E ~ 1-3 m/MeV
- ICARUS is sensitive to a similar L/E, but with two distinct samples:
  - ν_μ disappearance with the BNB beam-line using a CC QE-like signature with contained muons $\geq$ 50 cm
  - ν_e disappearance with the NuMI beam-line using a CC QE-like contained electron shower sample





Electron Lifetime at ICARUS

"Electron lifetime" describes the 1/e time associated with charge loss from electronegative impurities



Reconstruction Overview

1. Build 3D points using the three wire plane projections

2. Classify points and identify points of interest

3. Build clusters of related points

4. Particle aggregation and shower primary identification

5. Interaction aggregation, particle ID, primary identification