Prospects and the Current Status of the ICARUS Experiment

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On behalf of the ICARUS Collaboration

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U.S. DEPARTMENT OF ENERGY

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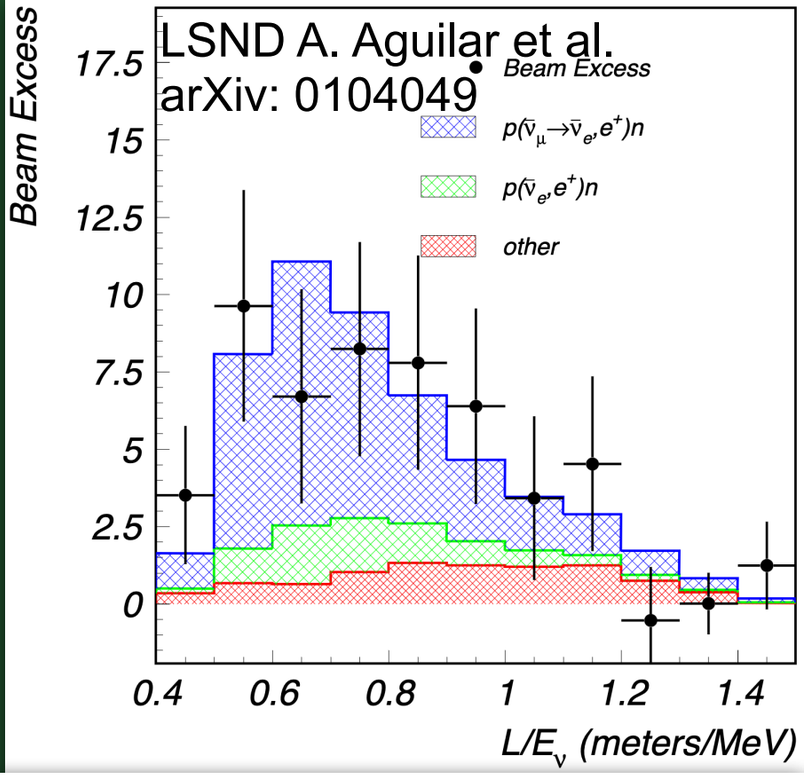
Colorado State University

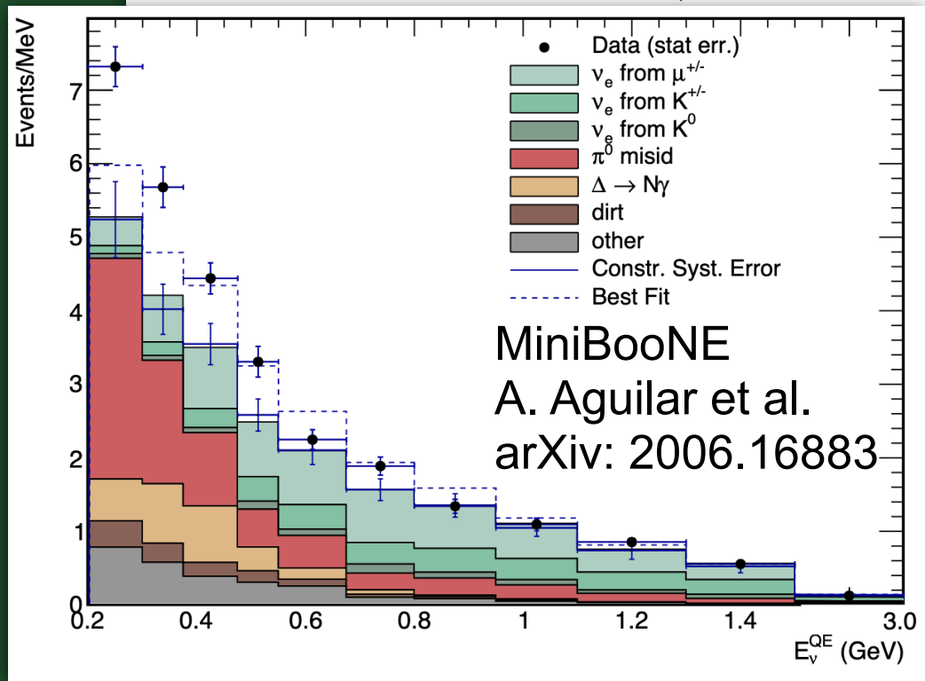
Additional Neutrinos?

- LSND and MiniBooNE found anomalous excess of low-energy ν_e candidates at short baselines
- Standard 3-flavor neutrino oscillation cannot explain these observations at this L/E
  - Possible interpretation: the presence of ≥ 1 sterile neutrino can allow for $\nu_\mu \rightarrow \nu_e$ oscillations at short baselines
  - Or: e/γ separation is tricky — maybe the excess is photons?
- More recently, the Neutrino-4 Collaboration has reported a possible hint of an oscillatory signature

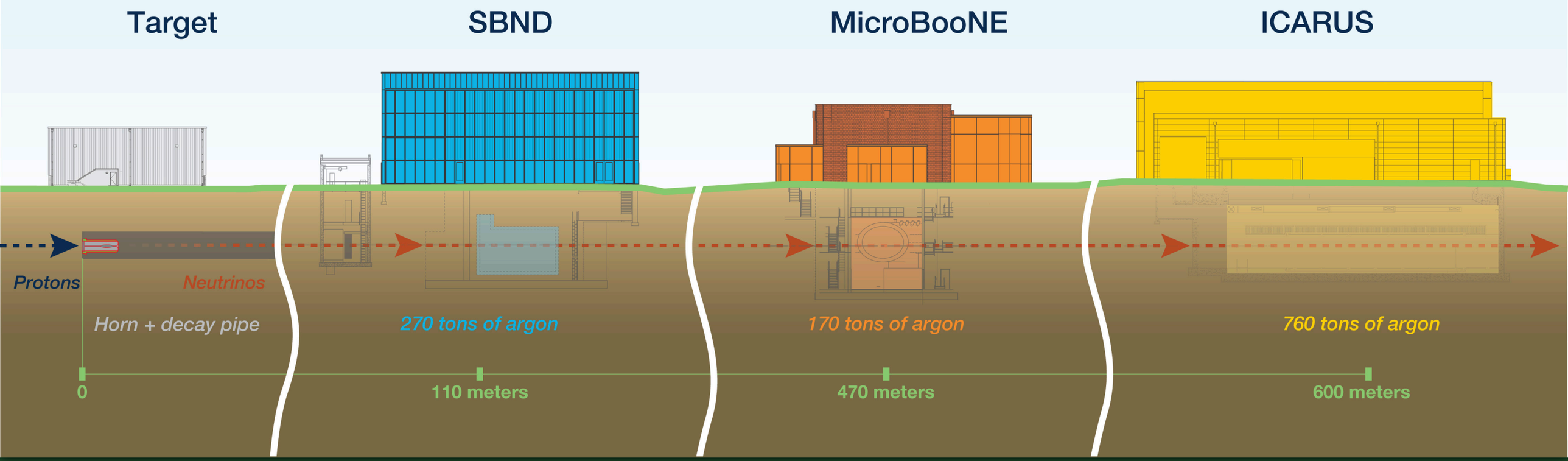
  See: (A. P. Serebrov et al. Phys. Rev. D 104, 032003 (2021))

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

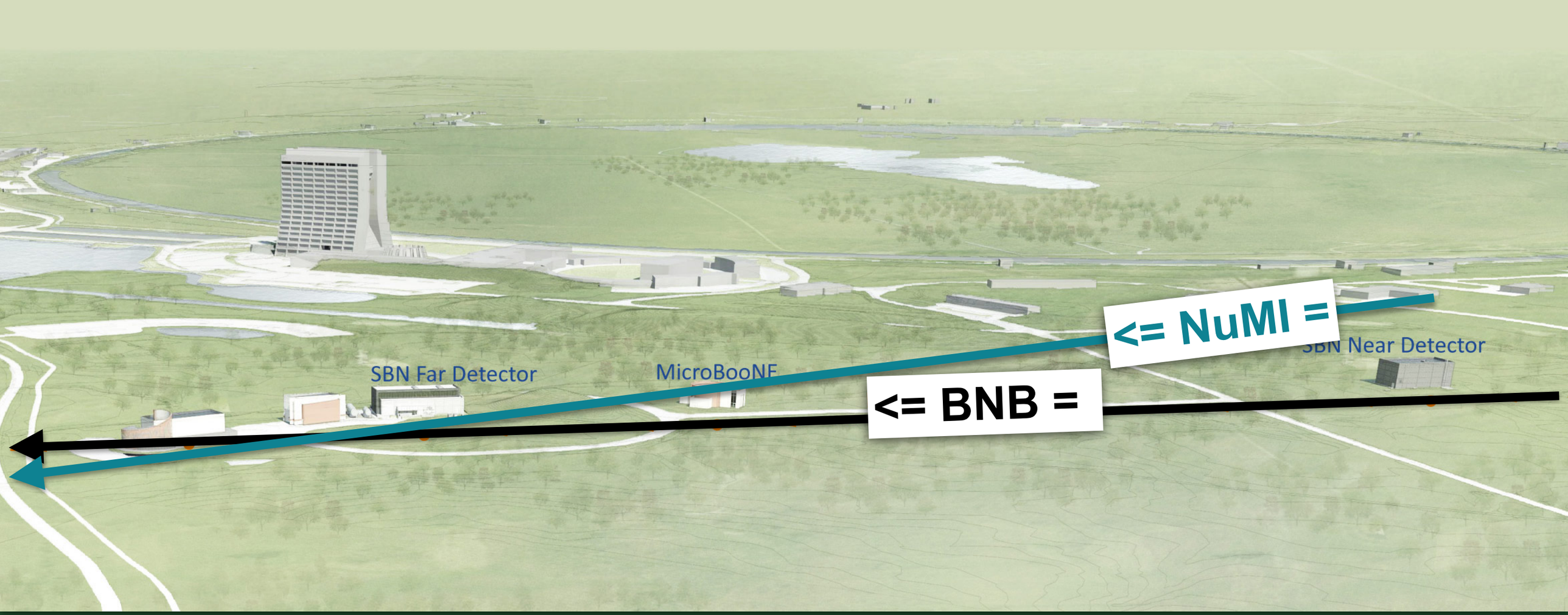




Short-Baseline Neutrino Program at Fermilab



- ICARUS is the Far Detector in the Short-Baseline Neutrino (SBN) 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
- 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

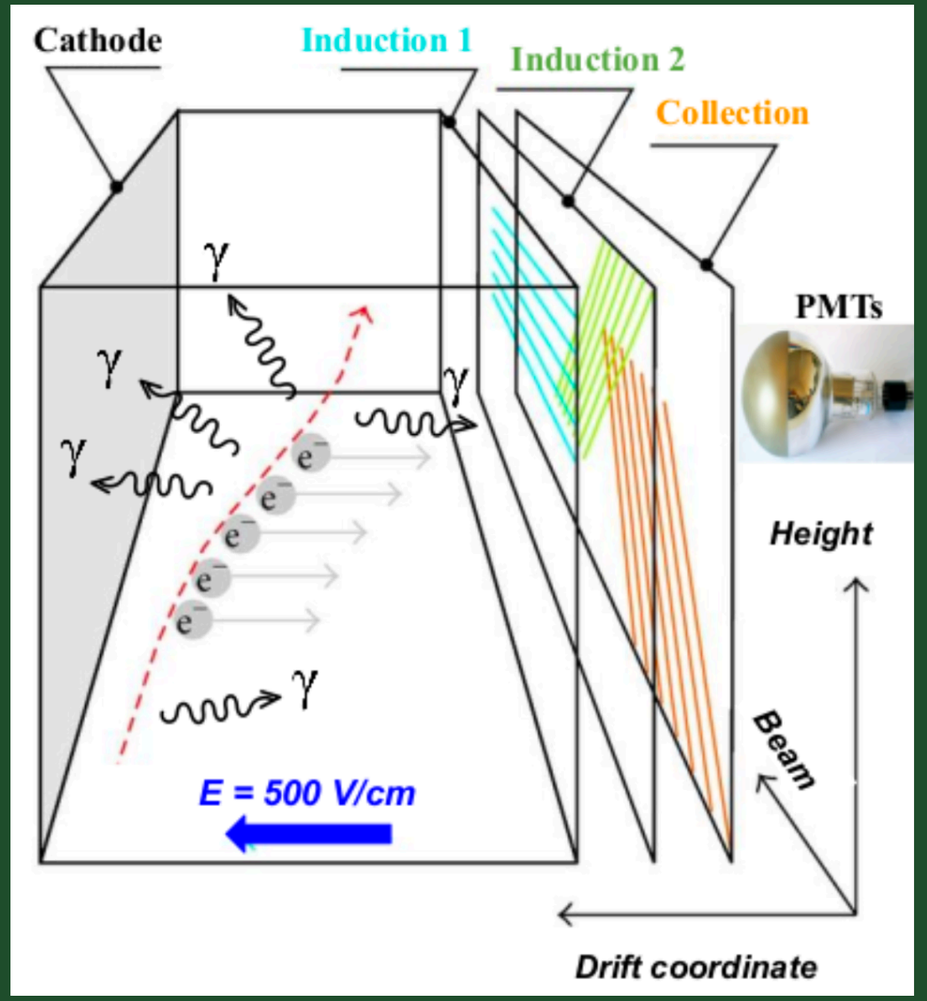
- Millimeter scale spatial resolution
- Visible gap for e/γ shower separation

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



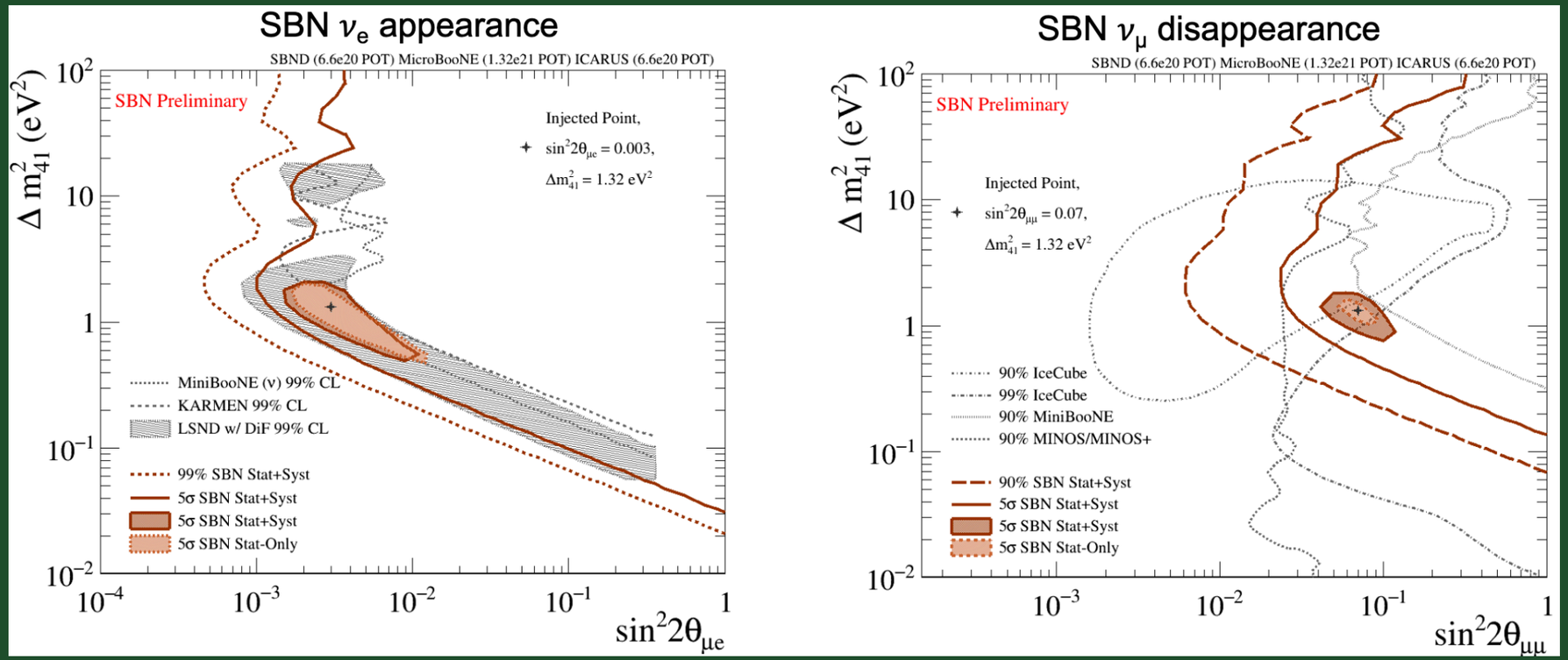
ICARUS at a Glance

- 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

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



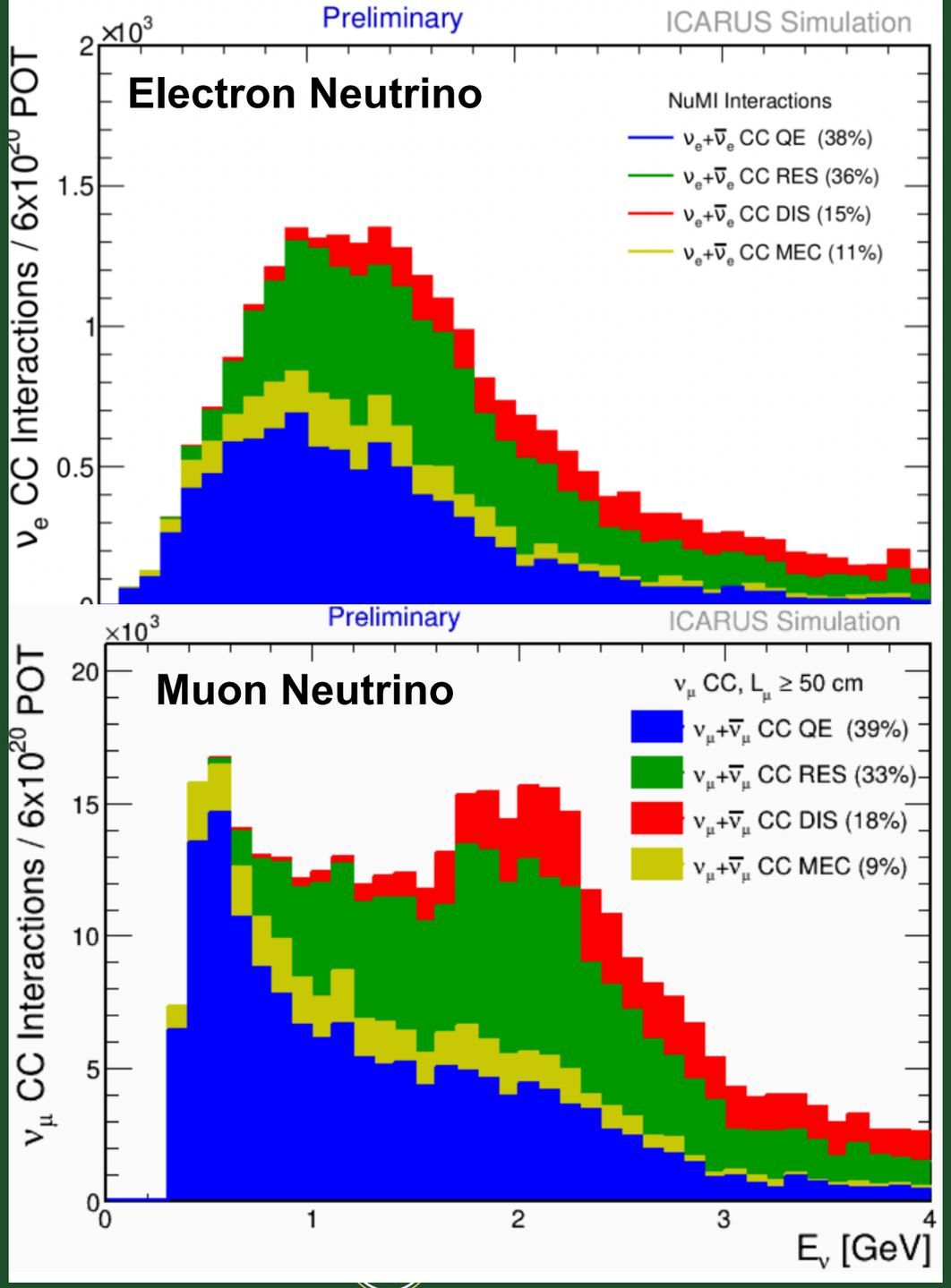
SBN sensitivities for 6.6e20 BNB protons on target (POT); actual dataset will be larger for both SBND and ICARUS

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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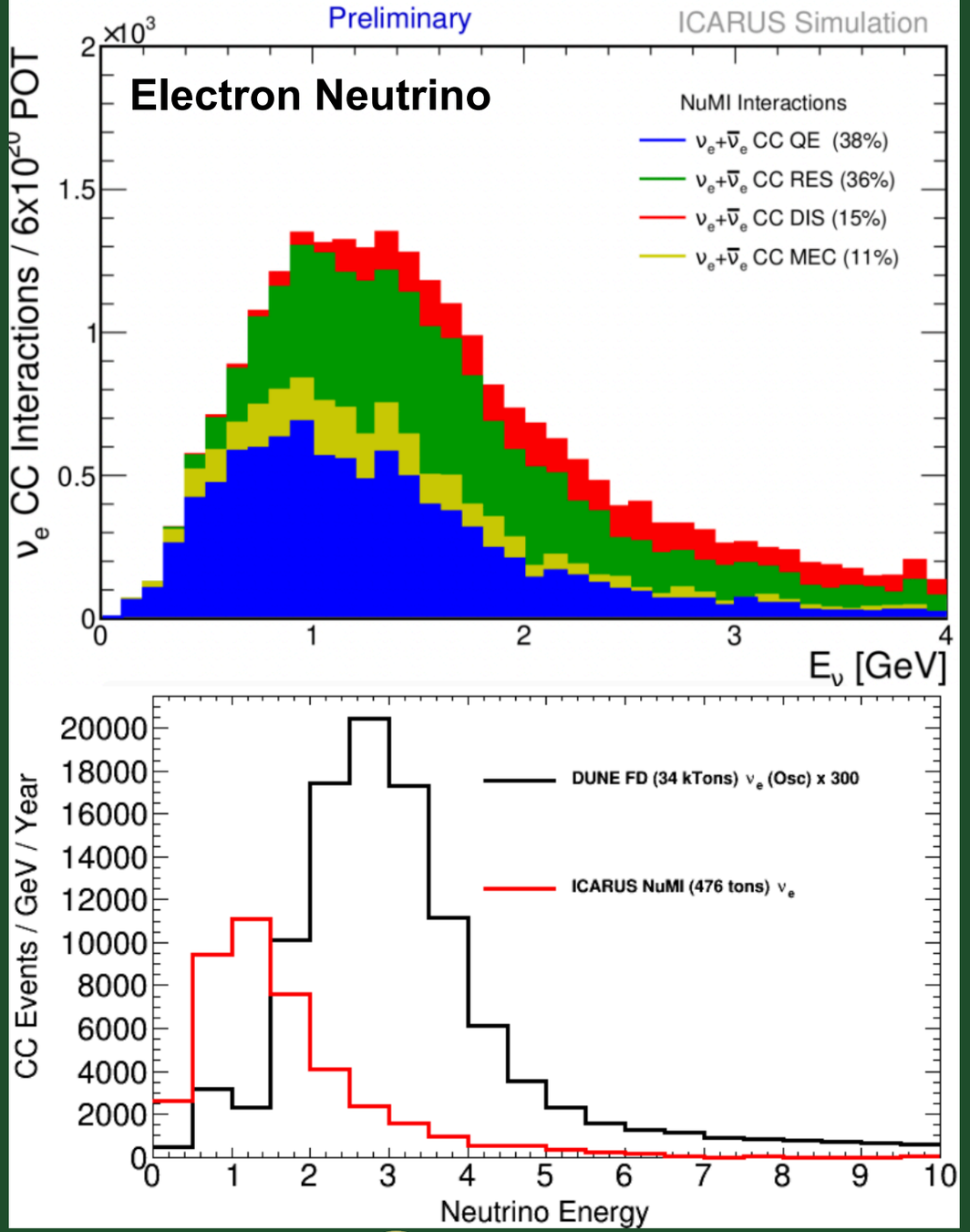

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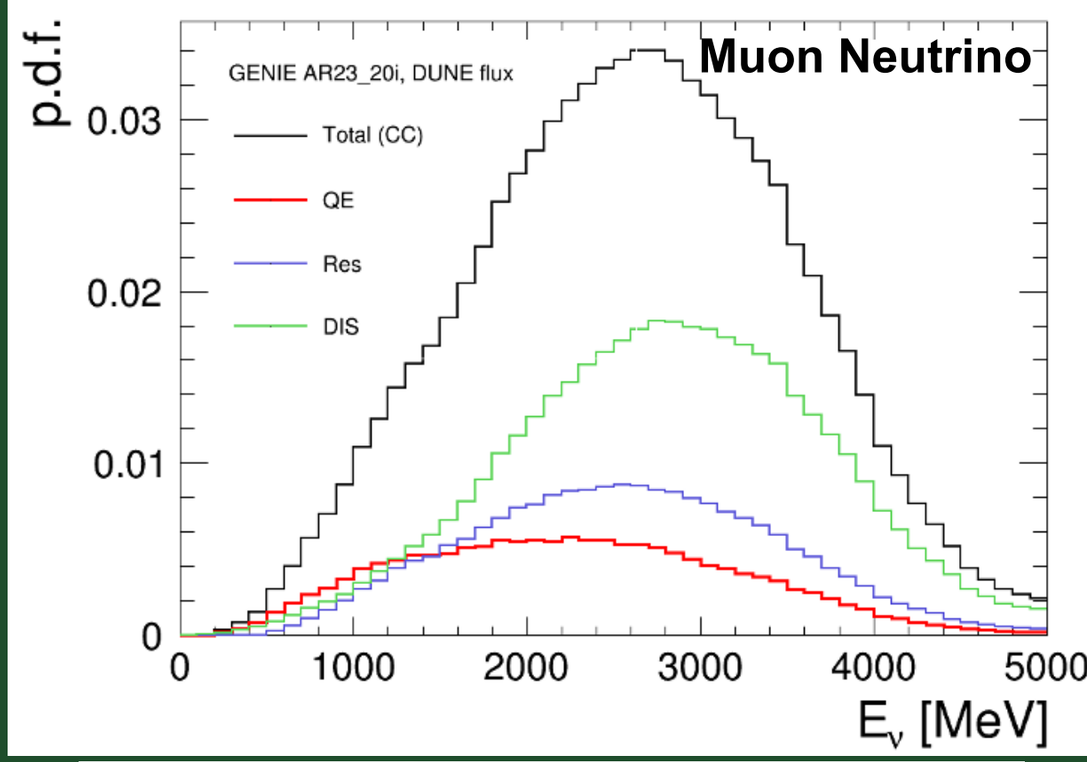
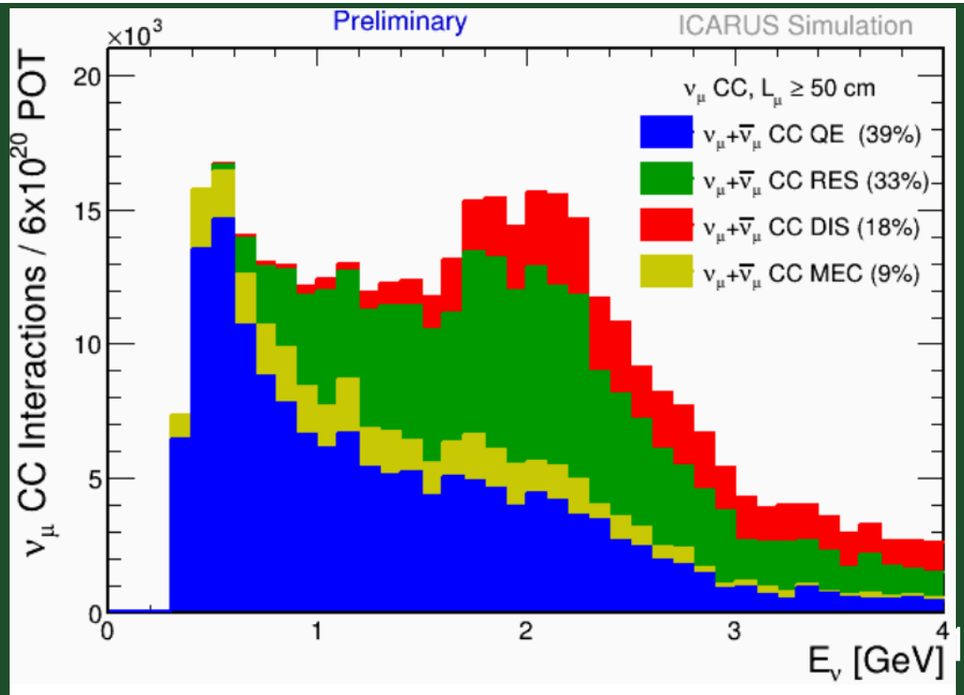


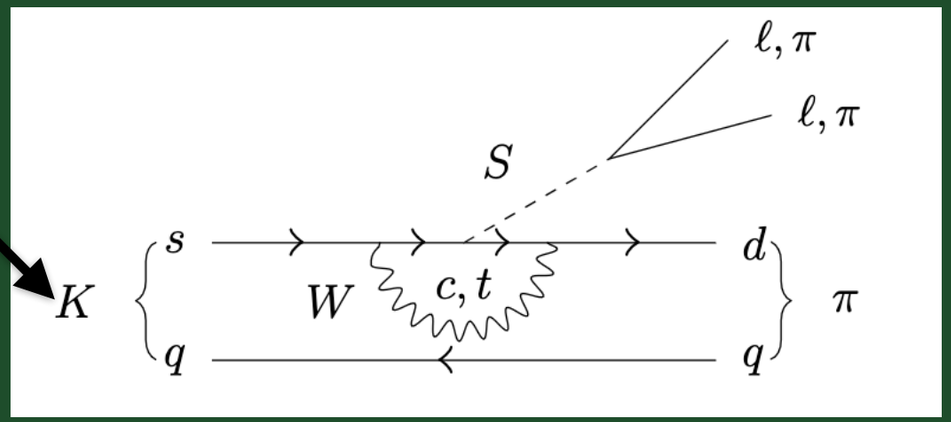


Higgs Portal Scalar

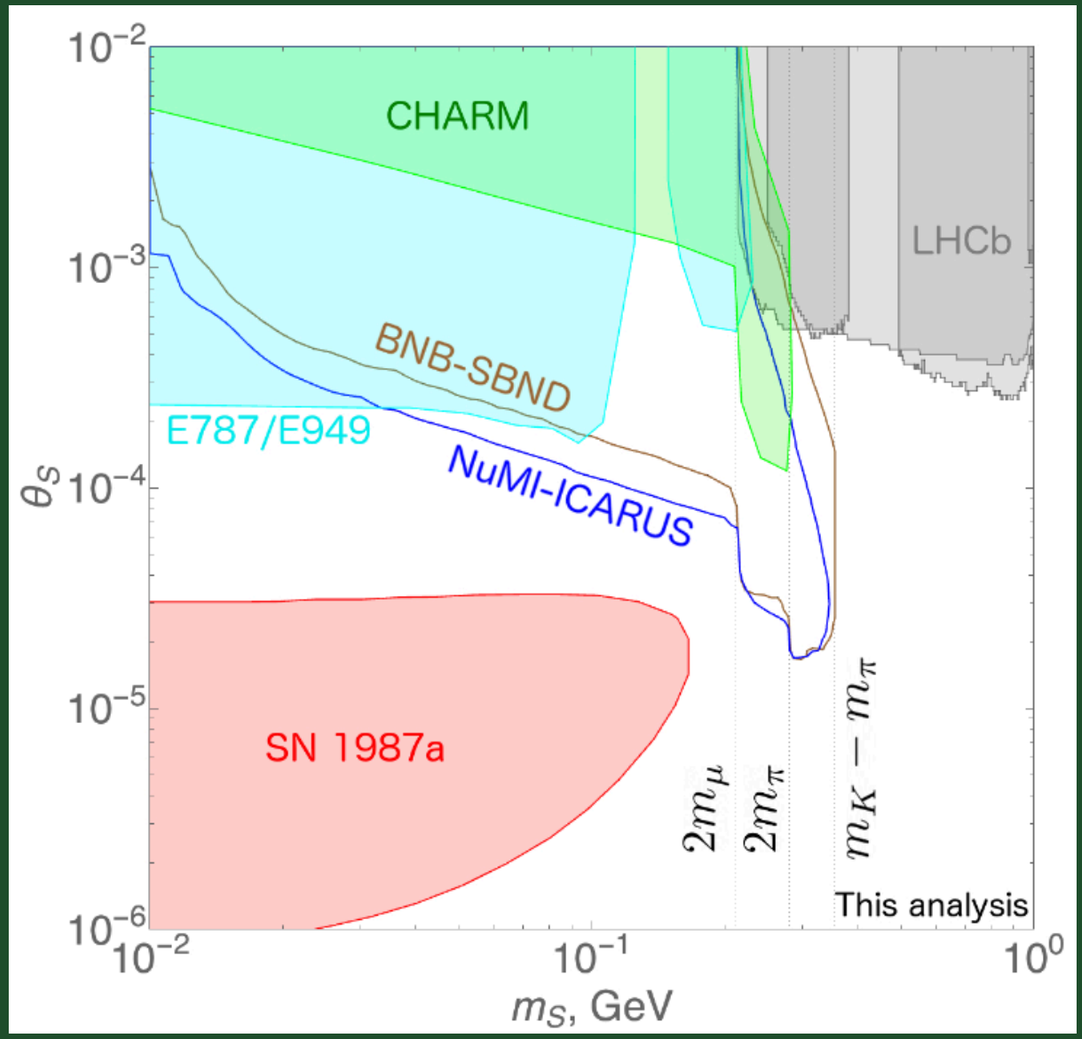
- The extension of the Standard Model to include a dark scalar S, which interacts via the Higgs portal, is testable using NuMI @ ICARUS

Dominant production and interaction modes

Kaon production in NuMI



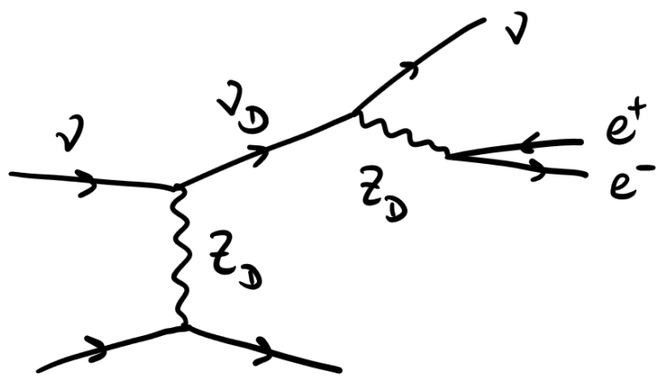
- Experimental signatures in ICARUS are pairs of collinear e^+/e^- showers, μ^+/μ^-, and π^+/π^- with a common vertex
  - A cut on the angle with respect to the beam may also help with background rejection (decay at rest)

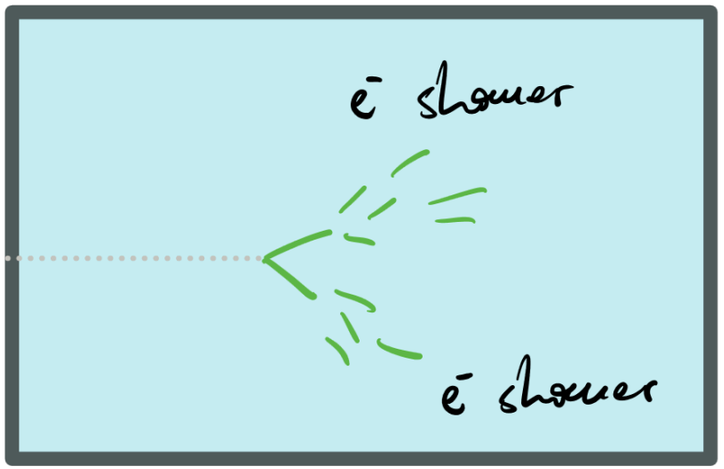


arXiv:1909.11670
B. Batell, J. Berger, A. Ismail

Other BSM Explanations for ν-Anomaly

Model in a nutshell
Dark neutrinos with light Z_D





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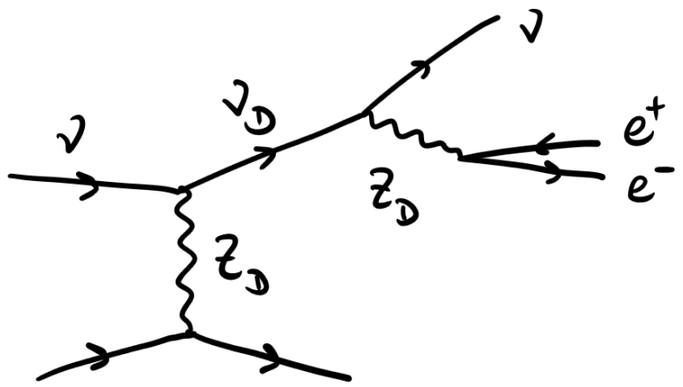
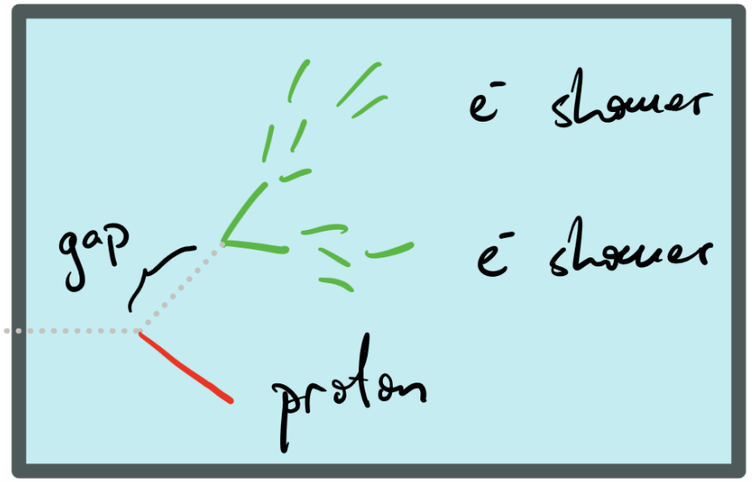


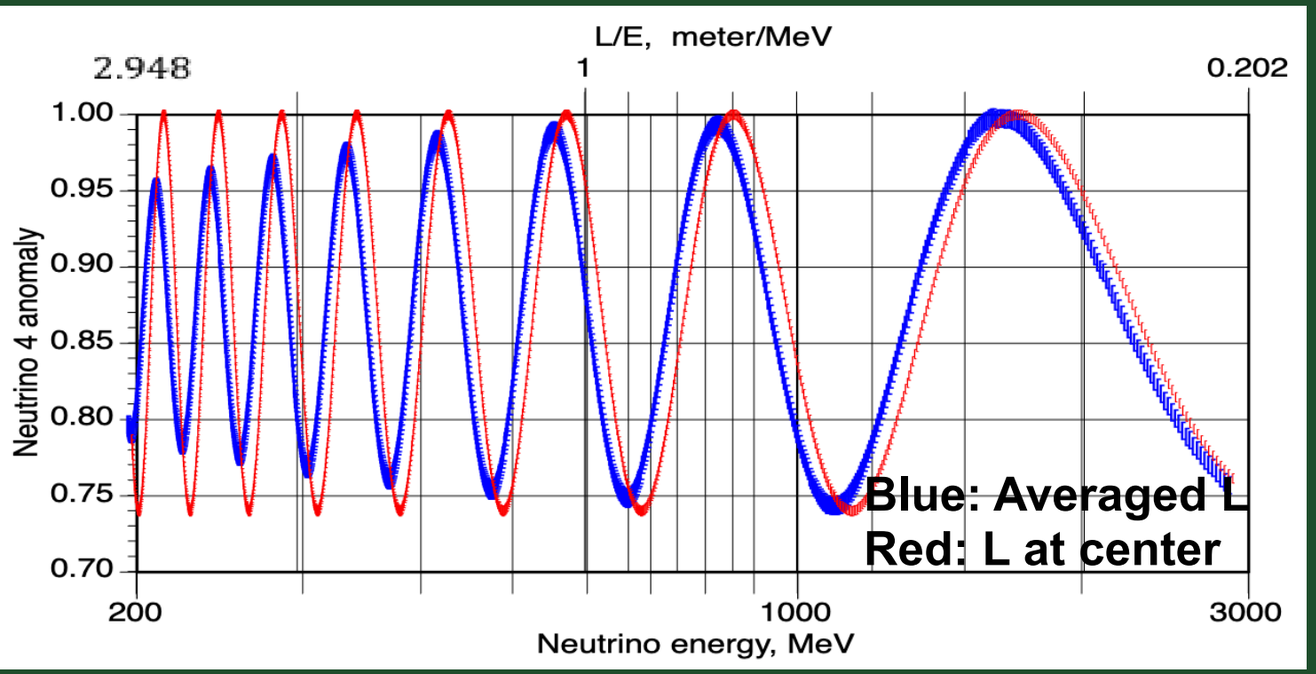


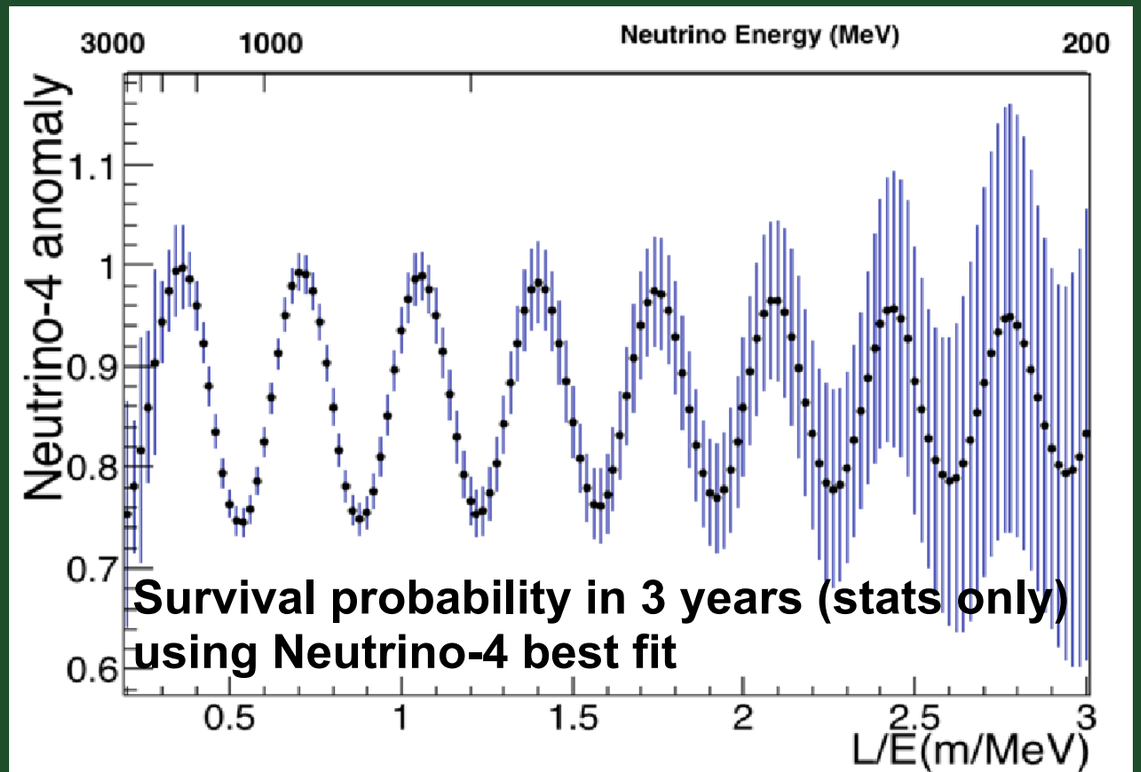
There are many additional theorized models that one could test in LArTPCs

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

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

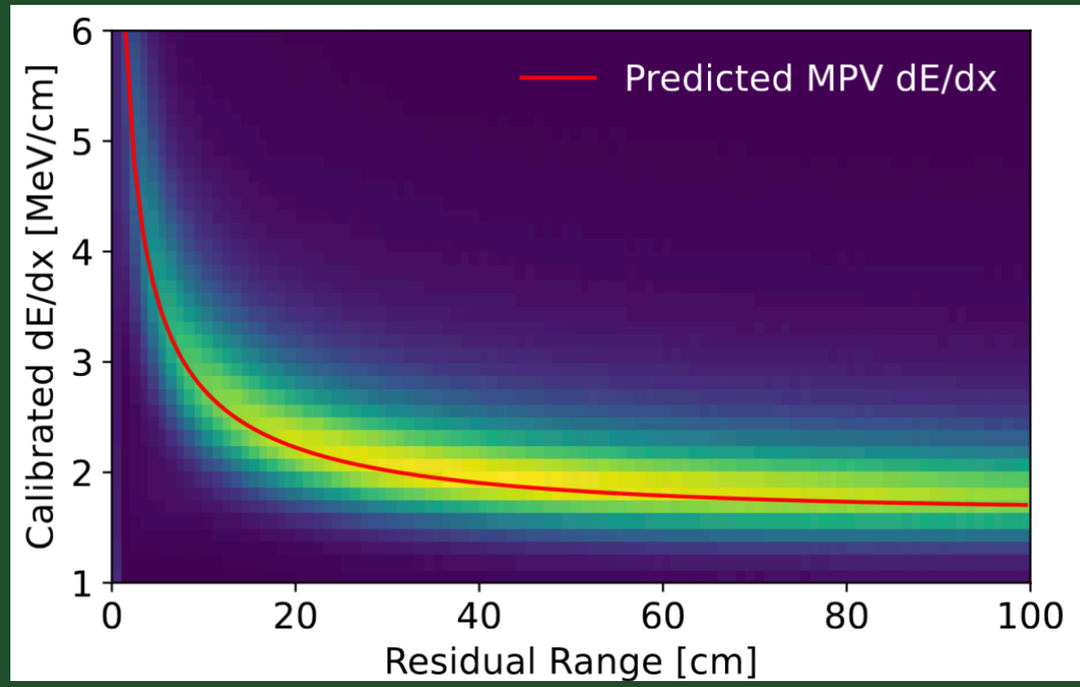


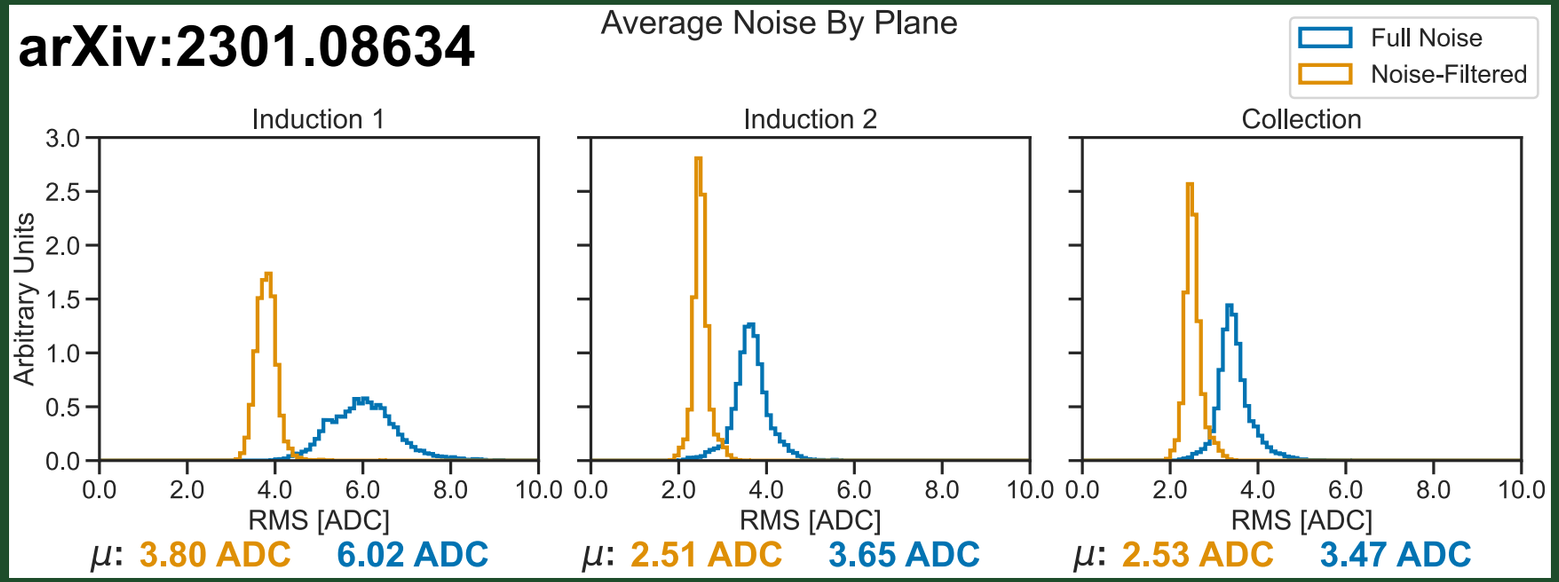


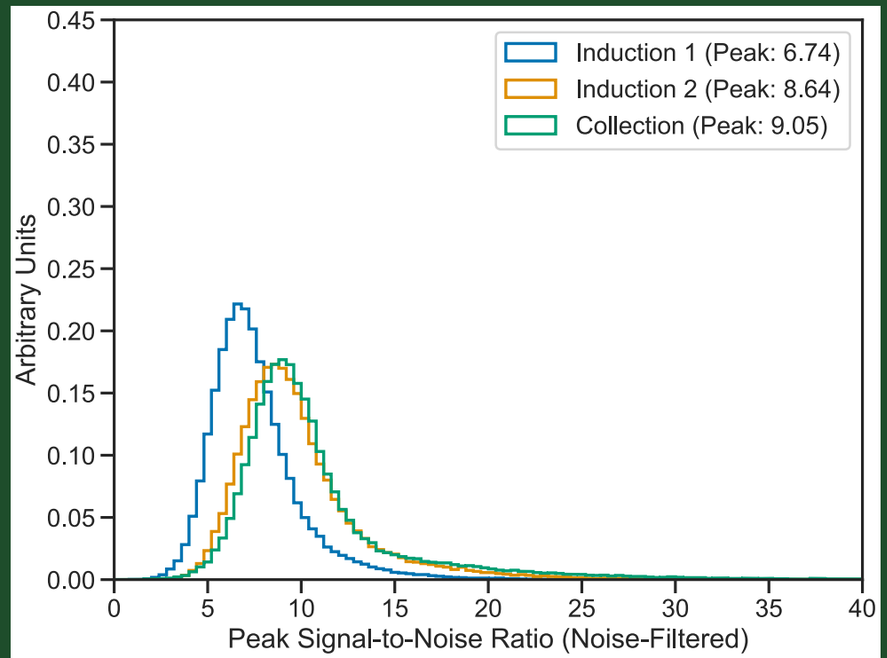
Detector Performance

- 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

Detector performance paper recently accepted by the **European Physical Journal C** (arXiv: 2301.08634)

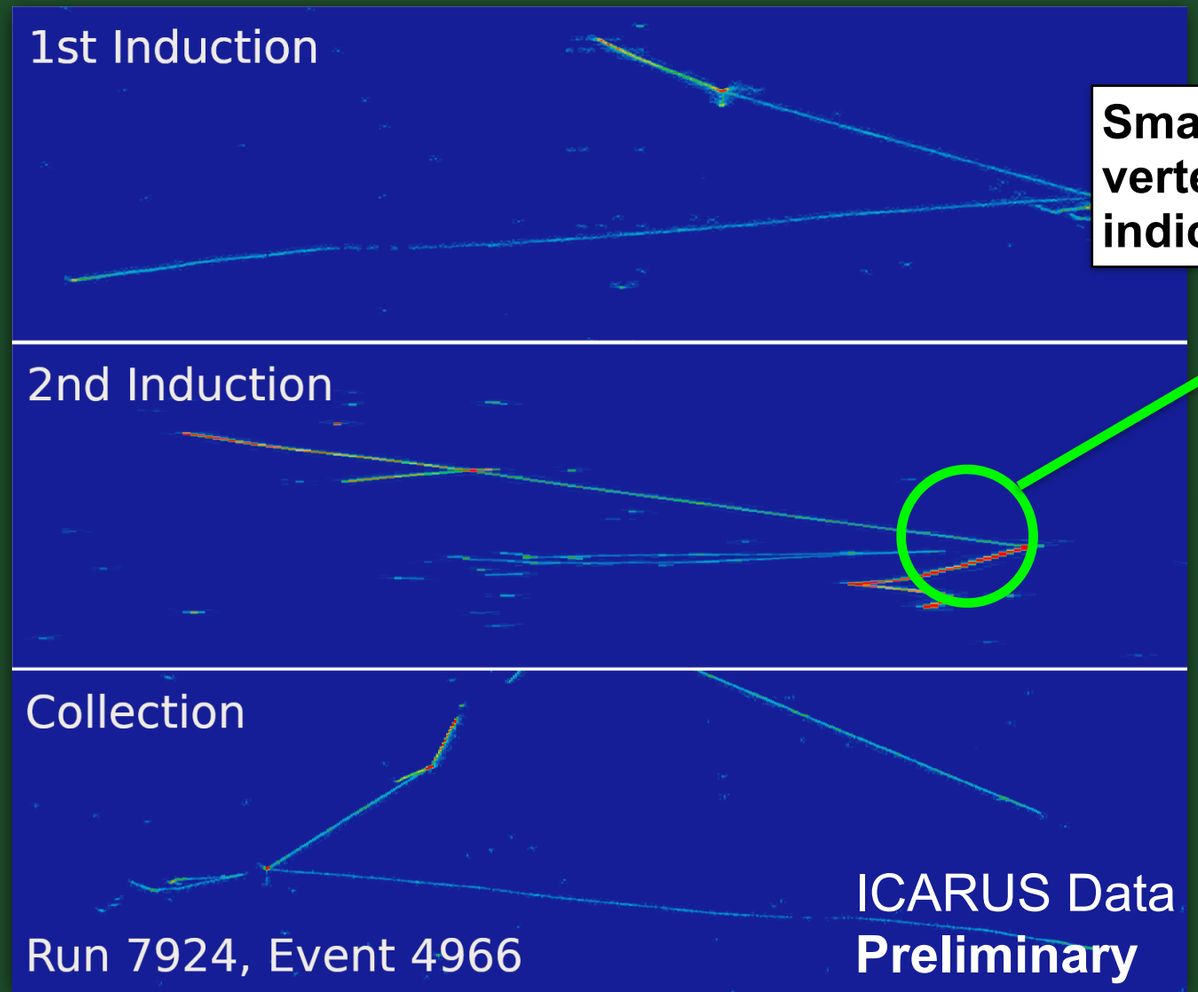




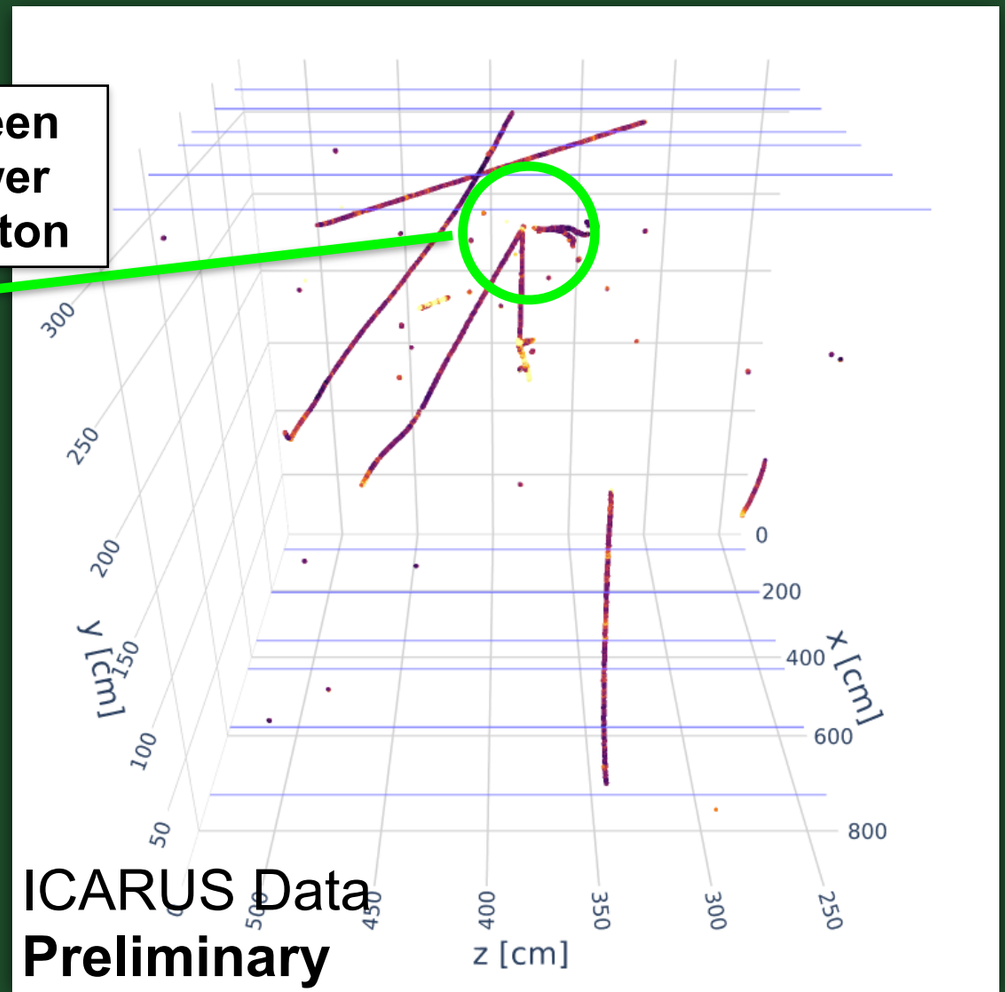


Neutrino Interactions in ICARUS!

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

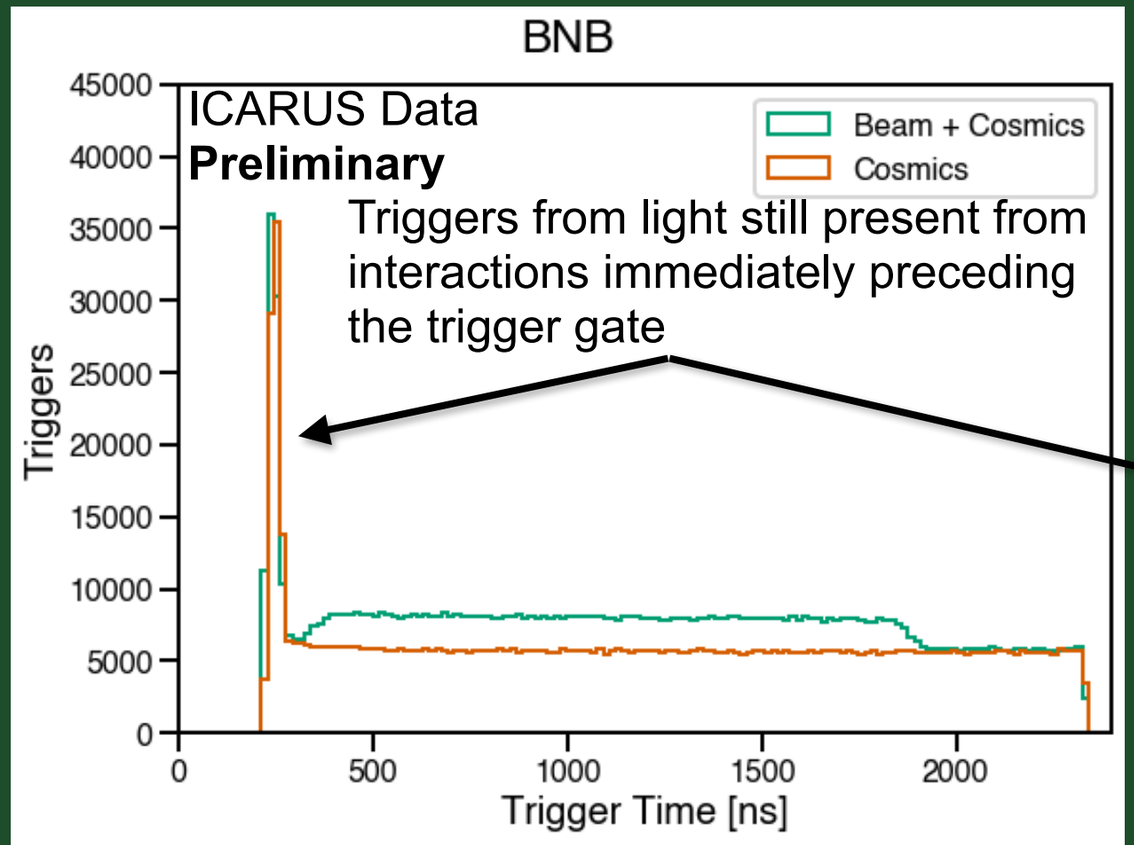


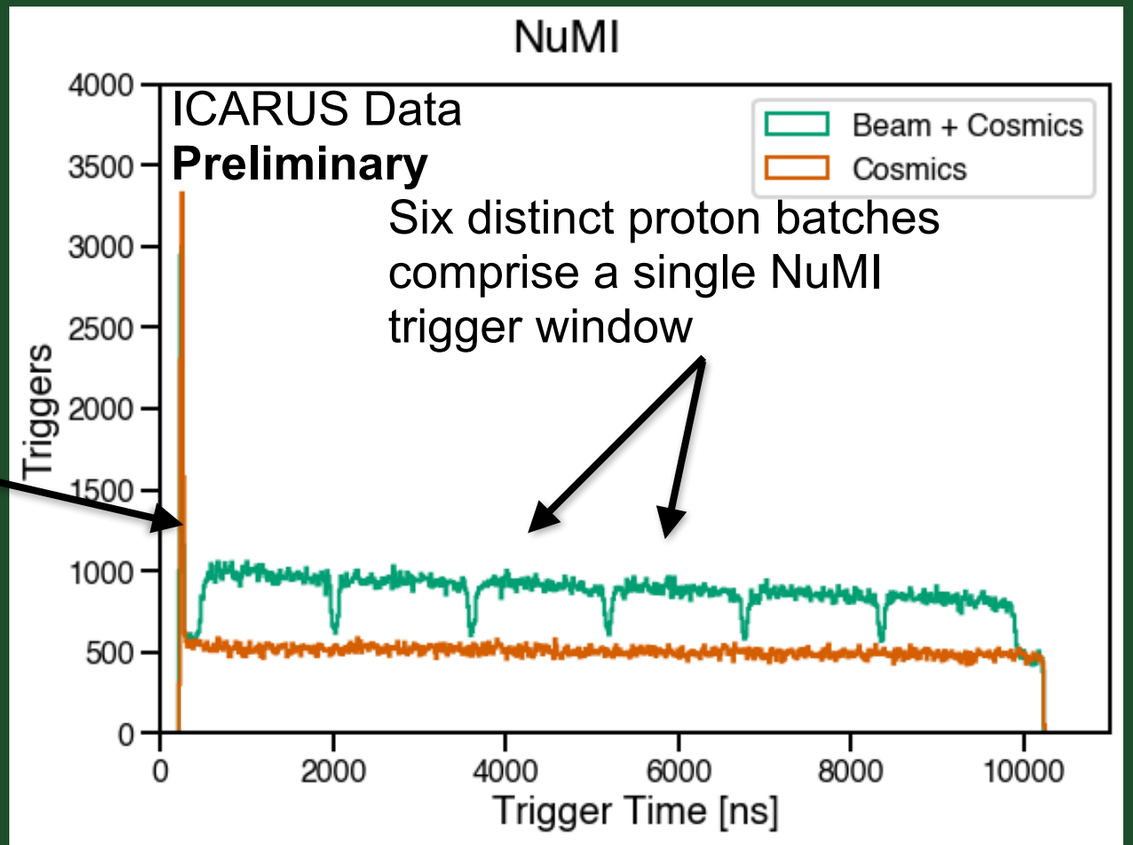
Small gap between vertex and shower indicating a photon



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

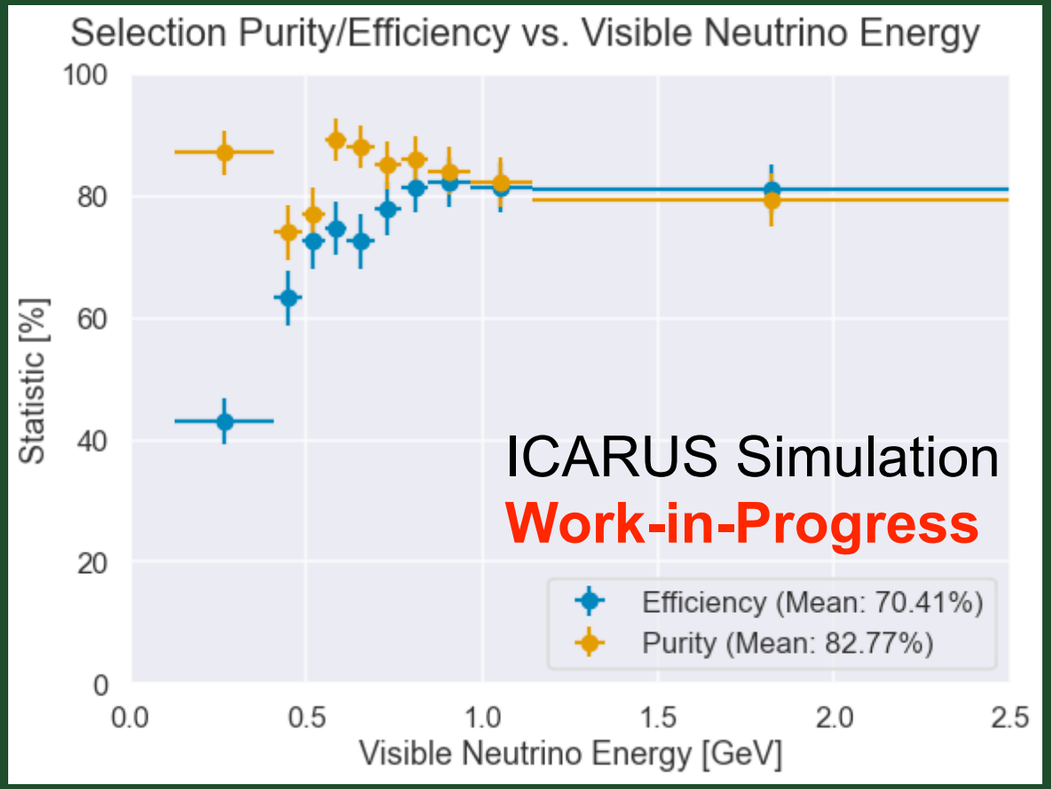




Neutrino Reconstruction

- In addition to more traditional reconstruction algorithms, an end-to-end machine learning-based reconstruction is being developed within ICARUS
- This framework takes as input the list of 3D hits in the event and produces a set of distinct particles/interactions with predictions for the particle ID and interaction vertex (amongst other information)
- An example selection using a 1μ1p signal definition achieves promising purity and efficiency with **major paths for improvement identified** (very near future)

The $1\mu1p$ channel is a CC QE-like signature that will be a major component of first analyses (Neutrino-4, cross section, low-energy excess)



Purity: Percent of selected interactions which are true 1μ1p

Efficiency: Percent of true 1μ1p selected

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
- Commissioning was completed in June 2022, marking the beginning of the first physics run
- The second physics run started in December 2022 and is currently ongoing

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	1.63e20	1.88e20	95.2%	96.1%

****Run 2 still in progress!**

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
- ICARUS is able to probe the Neutrino-4 anomaly using both NuMI ν_e disappearance and BNB ν_μ disappearance
- Commissioning of the ICARUS detector was completed in June of 2022
  - Physics-quality data taking is ongoing!

This work is supported by the US Department of Energy

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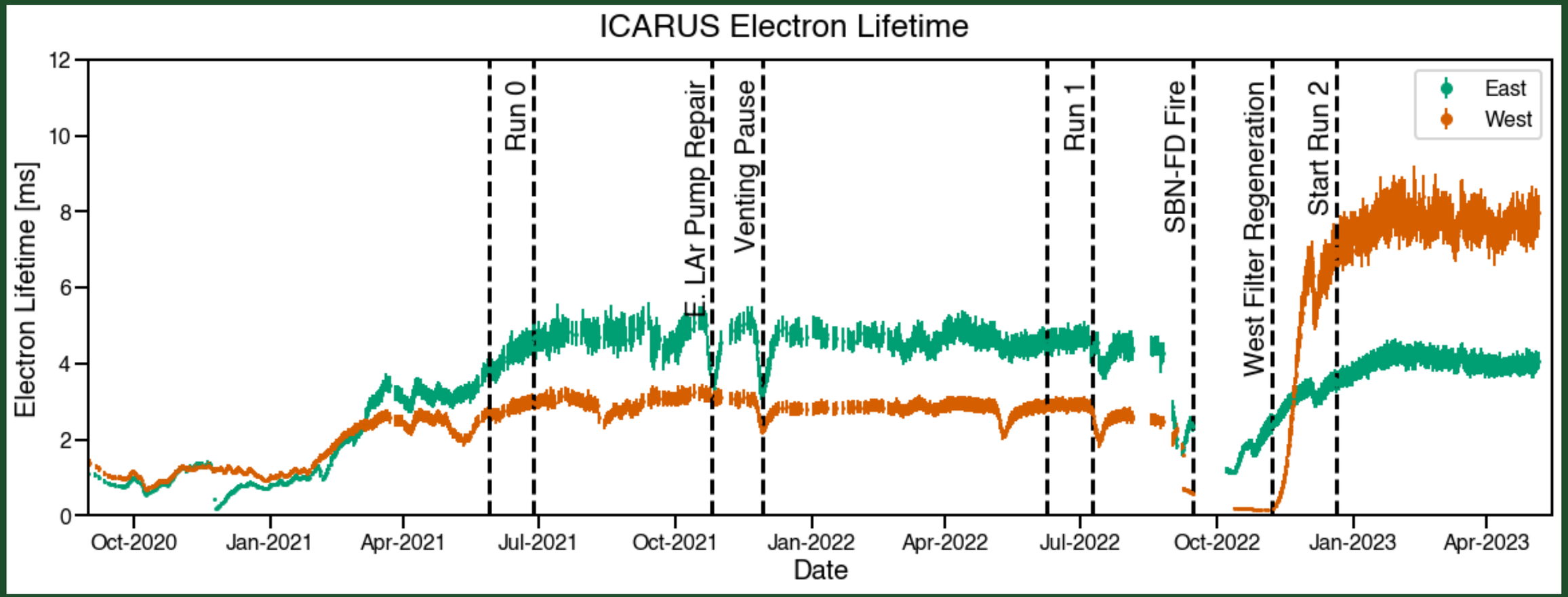
Backup

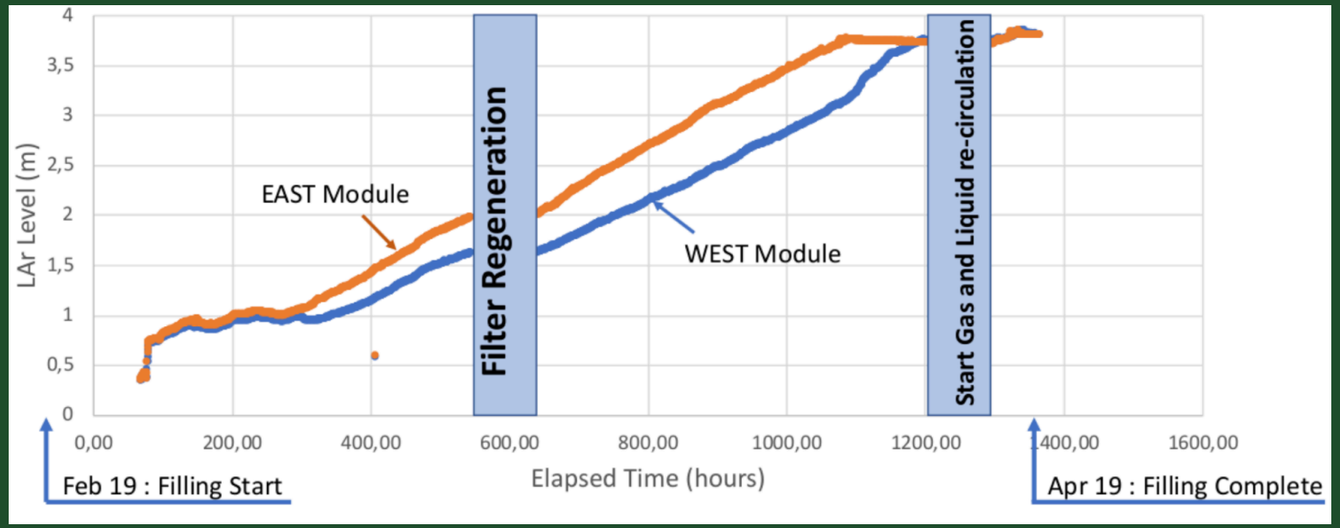
Electron Lifetime at ICARUS

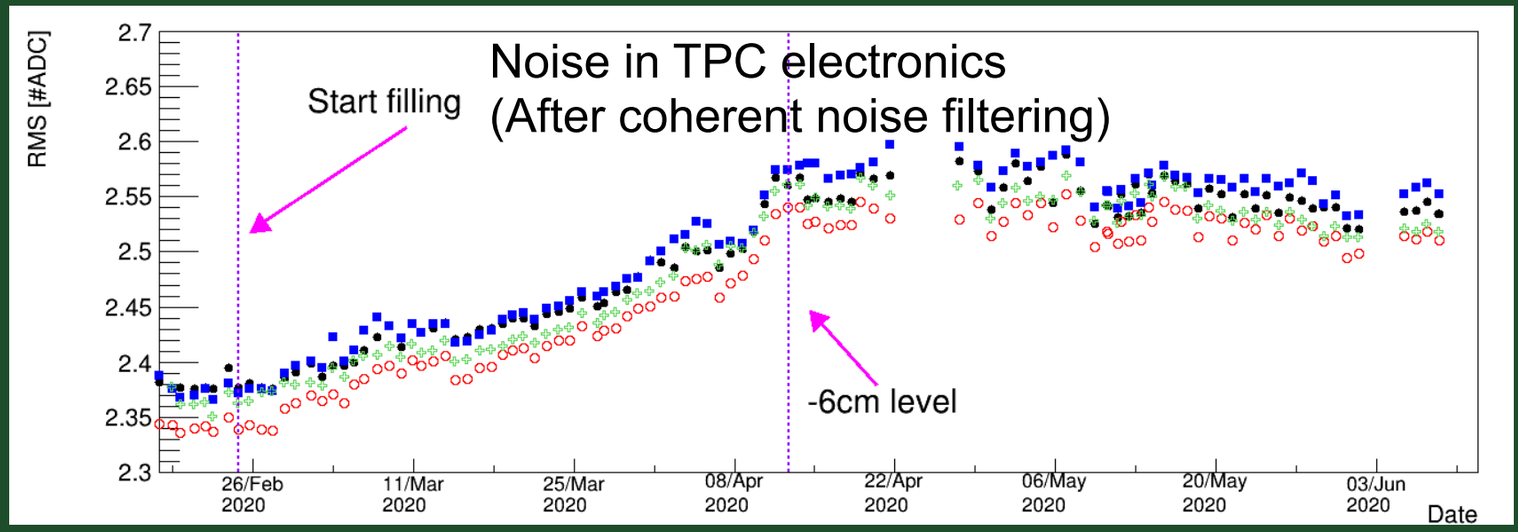
Electron Lifetime: measure of LAr purity from electronegative impurities — describes the 1/e time for ionization loss during the drift



Commissioning

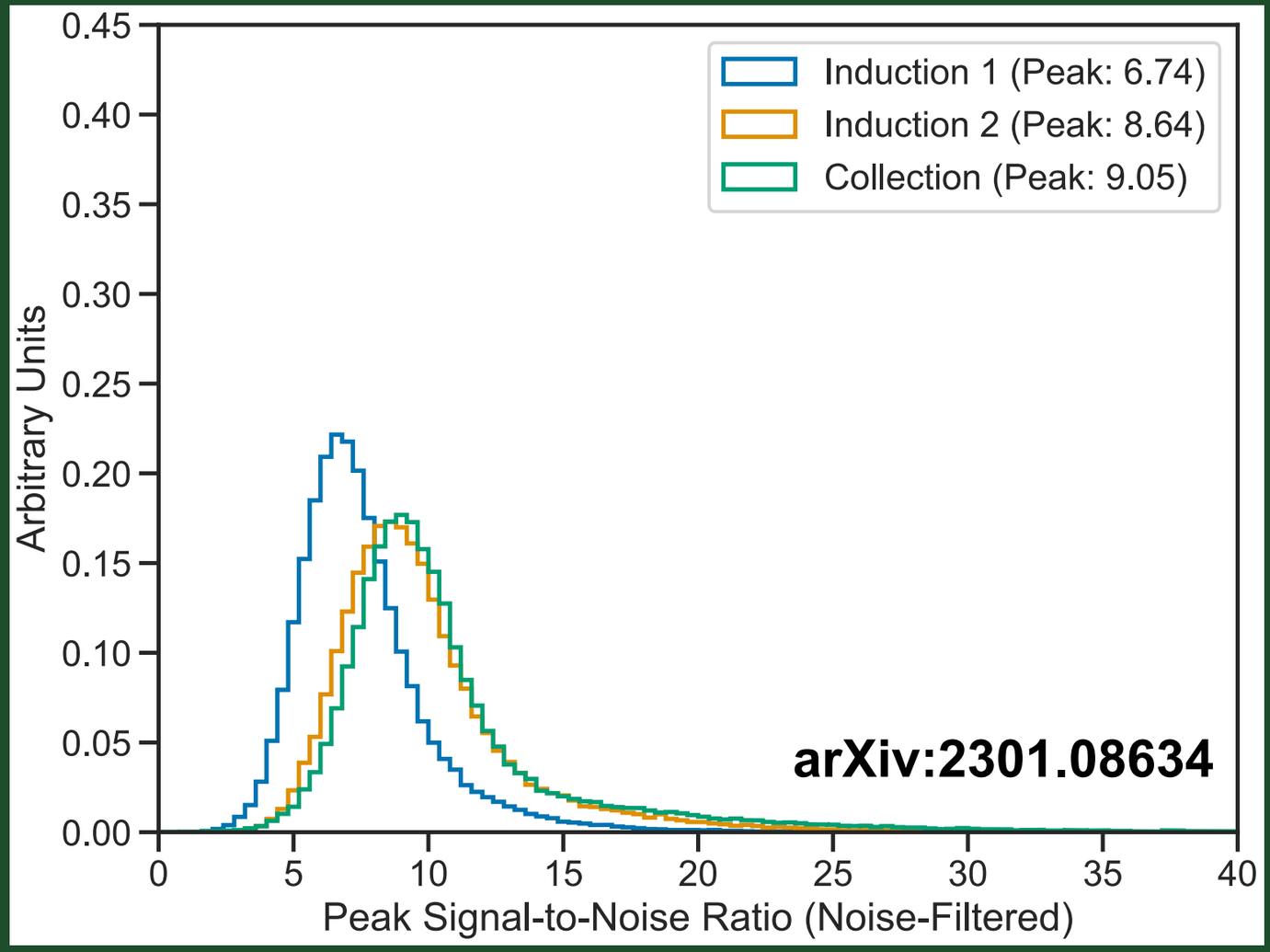
- After the main installation, ICARUS began cooldown/filling with LAr in February of 2020
- A portion of our TPC readout was enabled during the filling and showed an increase in noise due to increased wire capacitance
- By Fall 2020 full TPC readout was achieved at nominal drift field (500 V/cm), PMTs were activated and gain calibration underway, and trigger commissioning started





Improving Noise in TPC Electronics

- After achieving full detector readout there was period study dedicated to characterizing and reducing TPC noise
- Several major sources of noise were identified and mitigated:
  - Resistive Temperature Devices (RTDs) disconnected and grounded
  - Individual readout boards replaced
  - Readout board baseline setting optimized
- This major effort resulted in significant improvements to our signal-to-noise ratio



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