Investigating Short-Baseline Neutrino Anomalies with ICARUS

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Introduction

The Short-Baseline Neutrino program (SBN) is comprised of three liquid argon time-projection chambers (LAr TPCs) located along the Booster Neutrino Beam (BNB) at Fermilab. The SBN program seeks to definitively investigate the anomalous results reported by the LSND and MiniBooNE experiments. SBN also provides an opportunity to study neutrino-nucleus interactions at the GeV scale and testing of various LAr TPC technologies ahead of the DUNE long-baseline neutrino experiment.

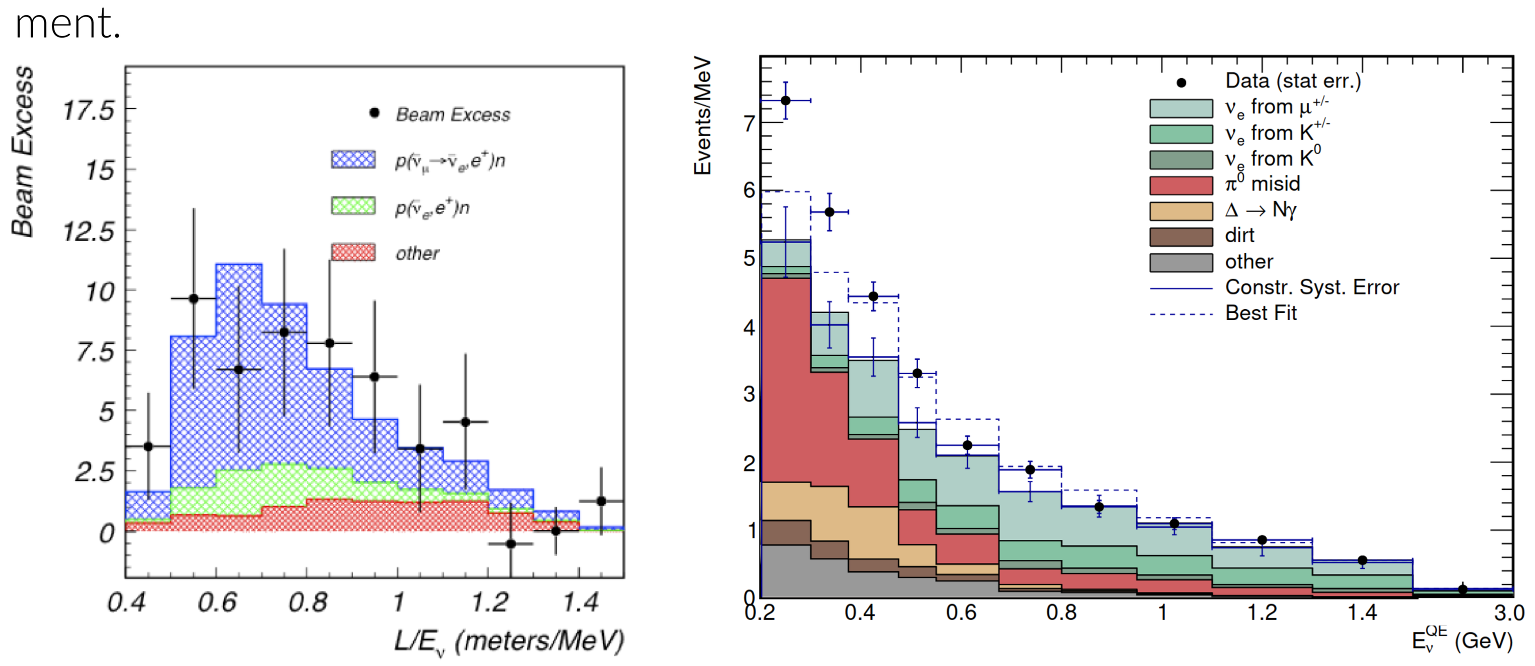


Figure 1. Left: The electron antineutrino excess observed at LSND [1] Right: Electron neutrino excess observed at MiniBooNE [2]

The ICARUS T600 Detector

The ICARUS detector was originally designed, built, and operated in Italy as the world's first hundred-ton-scale LAr TPC. The ICARUS collaboration designed the detector as two separate volumes comprising the single T600 detector. Each of the T300's is further subdivided into identical drift volumes by a common central cathode.

The T600 was operated at Laboratori Nazionali del Gran Sasso (LNGS) located in L'Aquila, Italy where it operated from 2010 to 2013 in the CERN Neutrinos to Gran Sasso (CNGS) high-energy neutrino beam. During the LNGS run, ICARUS successfully demonstrated the maturity of the LAr TPC technology and set limits on the sterile neutrino oscillation phase space.

Upgrades at CERN

After the successful LNGS run, ICARUS was transported to CERN where it underwent refurbishment during the 2016-2017 time frame.

Figure 2. An inside view of one of the chambers during upgrades at CERN

New TPC electronics

- A front-end based on an analogue low noise/charge sensitive pre-amplifier
- More compact design - analogue and digital electronics mounted in a single flange

Upgrades to light collection system including 360 8" PMTs

- Allows for nanosecond resolution of ionizing events in the TPCs
- Events localized with <50 cm spatial resolution
- Sensitivity to low-energy events (down to $\sim$ 100 MeV)

Commissioning at Fermilab

After extensive upgrades at CERN, ICARUS was transported to Fermilab, arriving in 2018. In early 2019, the cold vessels were installed in the outer warm vessel. Throughout the remainder of 2019 the supporting electronics and cryogenics were placed, allowing for the cold commissioning to commence in February 2020. The detector was completely filled in late April 2020 after two months of continuous LAr filling

By August 2020, the TPC was fully connected for readout and the cathode high voltage was raised to 75 kV for the first time. During this commissioning phase of the experiment the Side CRT was finalized, and the first cosmic event and first BNB neutrino was observed. The Top CRT installation began in December 2021 and was followed soon after by the installation of the overburden in early 2022. Regular data taking has continued since June 2021 and will soon be transitioning to physics data taking.

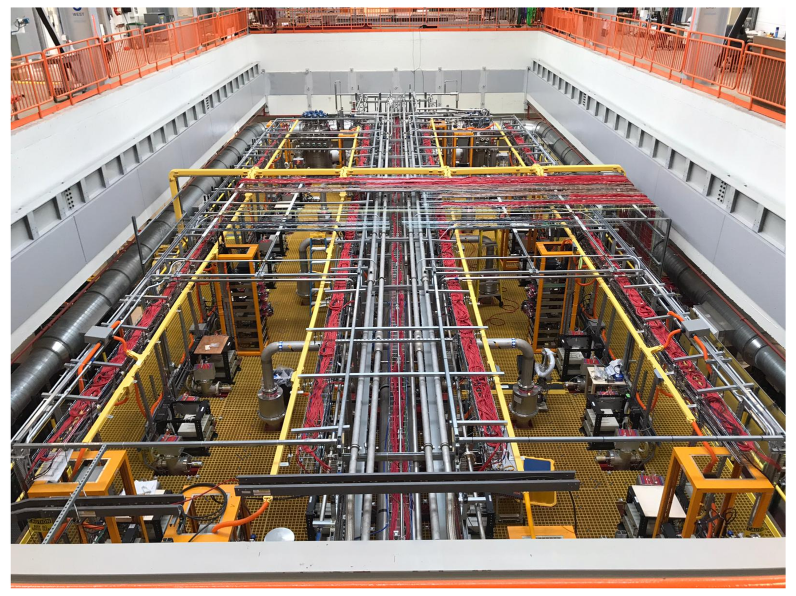


Figure 3. ICARUS as it appeared before cold commissioning and Top CRT installation

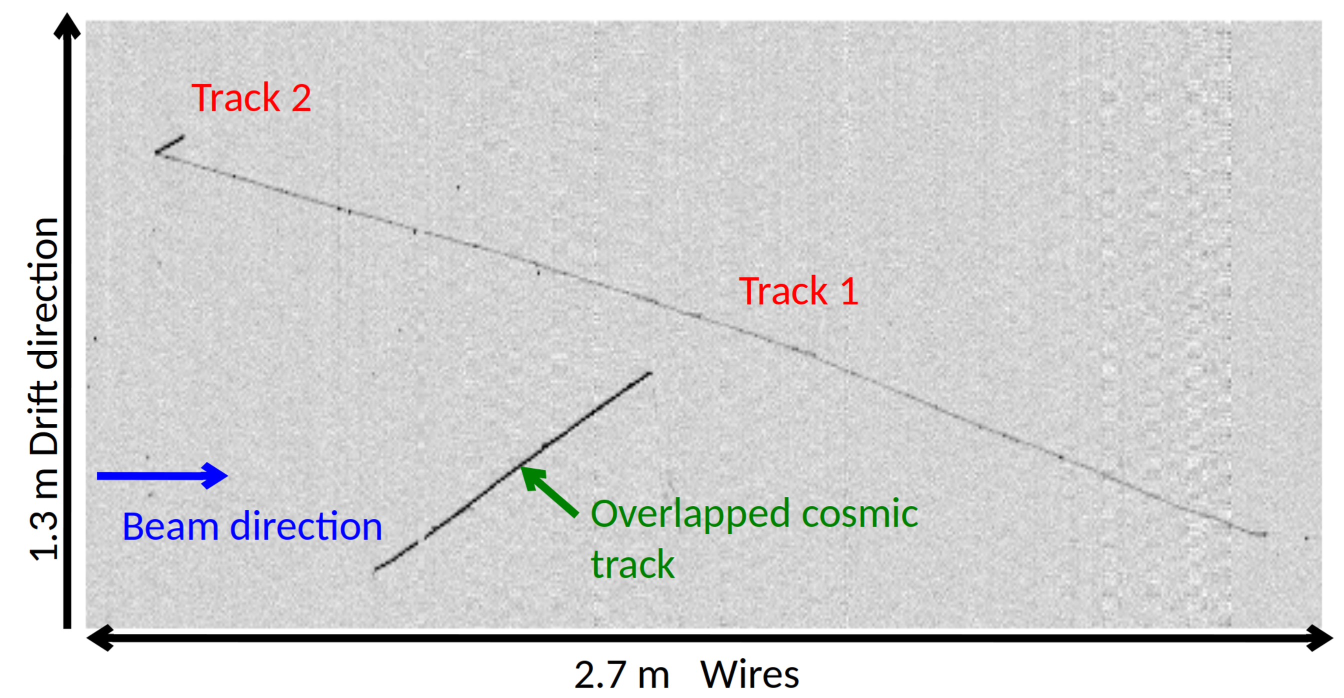


Figure 4. A BNB ν_μ CC Candidate: ν_μ n $\rightarrow \mu$ p from first neutrino data

The past year of data taking has provided opportunities to validate and study detector performance. A sample of cathode-crossing stopping muons was used for dE/dx validation and provided an initial detector gain calibration. The signal-to-noise ratio was extracted from a sample of almost-vertical anode-to-cathode crossing cosmic tracks. Only hits near the anode wire planes were selected to avoid electron lifetime effects.

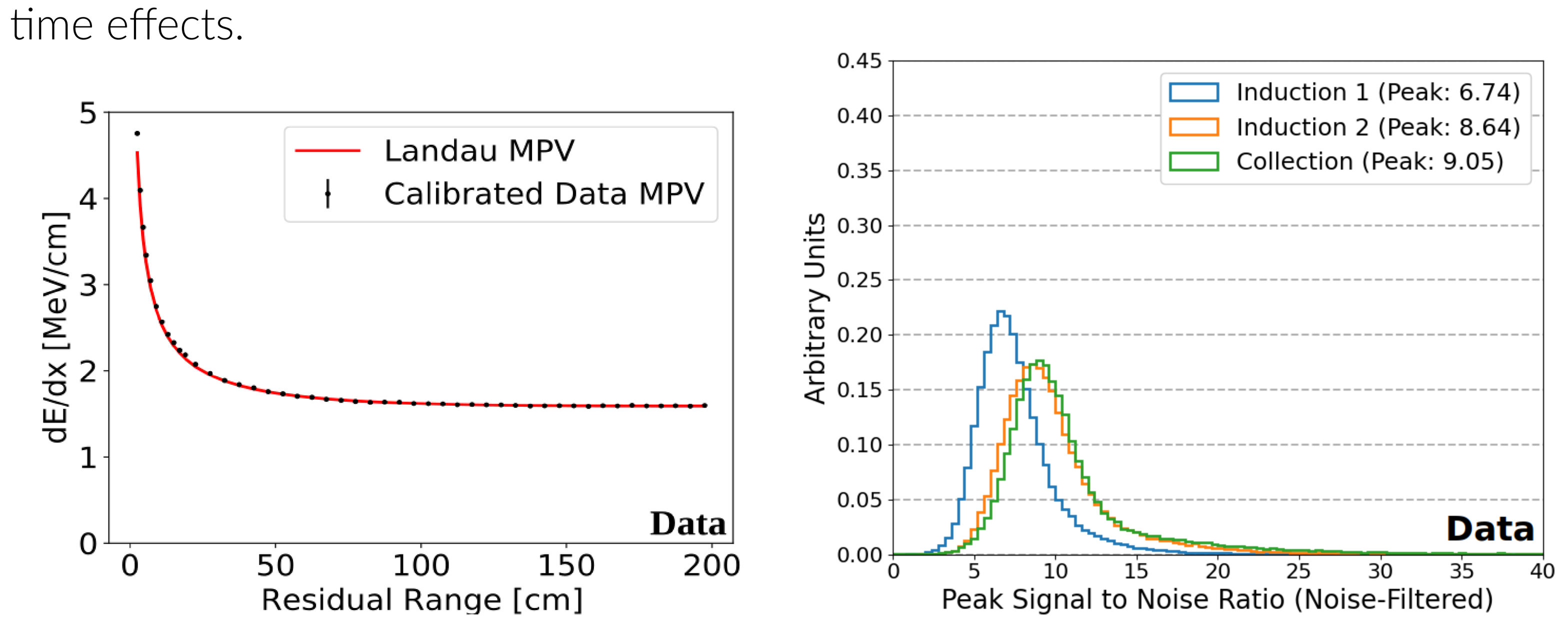
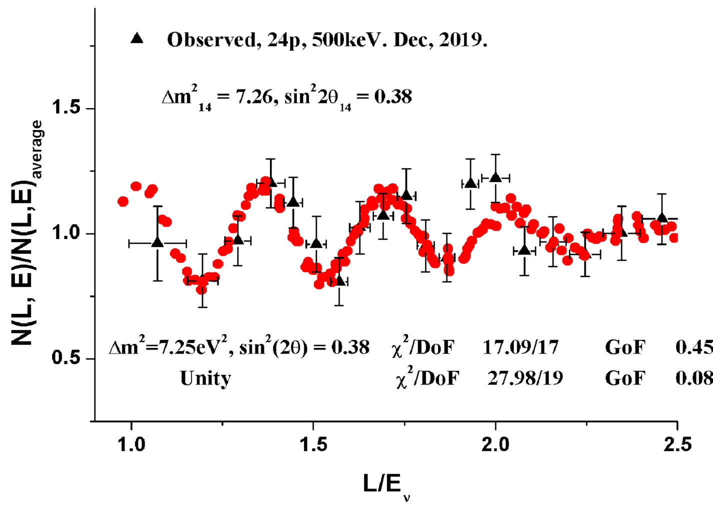


Figure 5. Left: Stopping muon dE/dx vs. Residual Range and Right: Signal-to-Noise Ratio per plane.

Short-Baseline Neutrino Anomalies

The Neutrino-4 Anomaly

The Neutrino-4 collaboration reported a reactor neutrino disappearance signal with a clear modulation with an L/E $\sim$ 1-3 m/MeV.



Due to its location and size, ICARUS will be able to perform a single-detector oscillation analysis using data taken in the coming year with two independent channels and different beams: ν_μ disappearance using the BNB and ν_e disappearance using the NuMI beam

Figure 6. Antineutrino disappearance as reported by Neutrino-4 [3]

The LSND and MiniBooNE Anomalies

Both LSND and MiniBooNE observed significant excesses of electron-like events (Figure 1), which could be interpreted as originating from light sterile neutrinos. The design of SBN is intended to leverage consistent detector technologies at different baselines along the same neutrino beam to provide a definitive answer to the LSND and MiniBooNE anomalies.

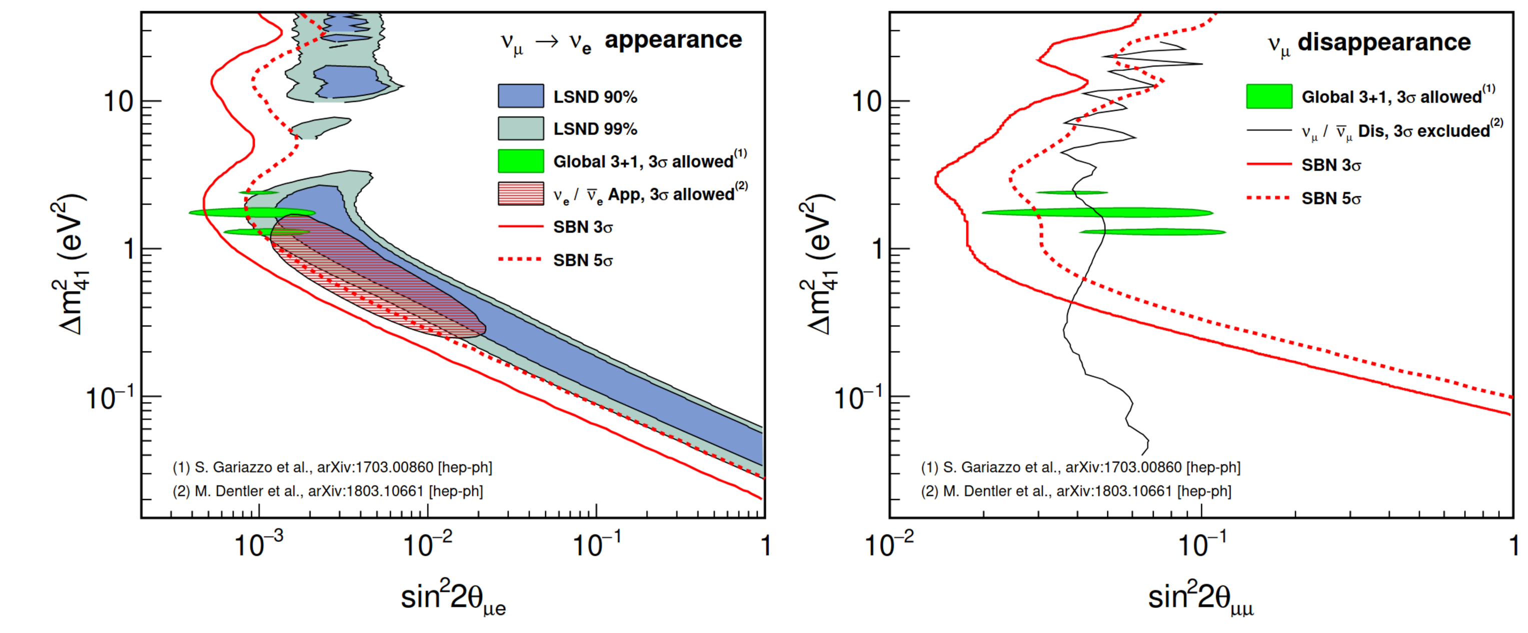


Figure 7. Left: SBN sensitivity in the $\nu_\mu \rightarrow \nu_e$ appearance channel and Right: SBN sensitivity in the ν_μ disappearance channel [4]

References

[1] LSND Collaboration. Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam. *Physical Review D*, 64(11), Nov 2001.

[2] MiniBooNE Collaboration. Updated MiniBooNE neutrino oscillation results with increased data and new background studies. *Physical Review D*, 103(5), Mar 2021.

[3] A. P. Serebrov et al. First observation of the oscillation effect in the neutrino-4 experiment on the search for the sterile neutrino. *JETP Letters*, 109(4):213–221, Feb 2019.

[4] Pedro A.N. Machado, Ornella Palamara, and David W. Schmitz. The short-baseline neutrino program at fermilab. *Annual Review of Nuclear and Particle Science*, 69(1):363–387, Oct 2019.

Acknowledgements

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