Short-Baseline neutrino oscillation searches with the ICARUS detector

Bruce Howard – Fermilab
On behalf of the ICARUS Collaboration

PANIC 2021 – 5 September 2021

ICARUS at a glance

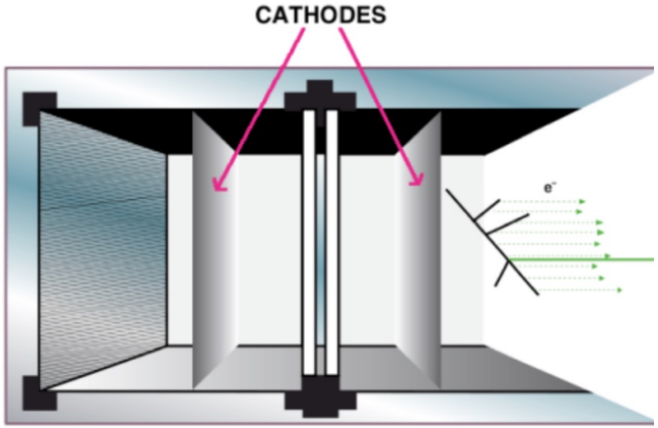
- Liquid Argon (LAr) time-projection chamber (TPC) detector
- First large LAr TPC: still one of the largest in operation
  - 2 modules, each 19.6 x 3.6 x 3.9 m^3
  - Total 760 t LAr, 476 t active.
  - 2 TPCs per module with active drift distance ~1.5 m
- Originally deployed at LNGS, refurbished/moved to FNAL for Short Baseline Neutrino program (sterile ν search)

BNB beam runs along length of detector

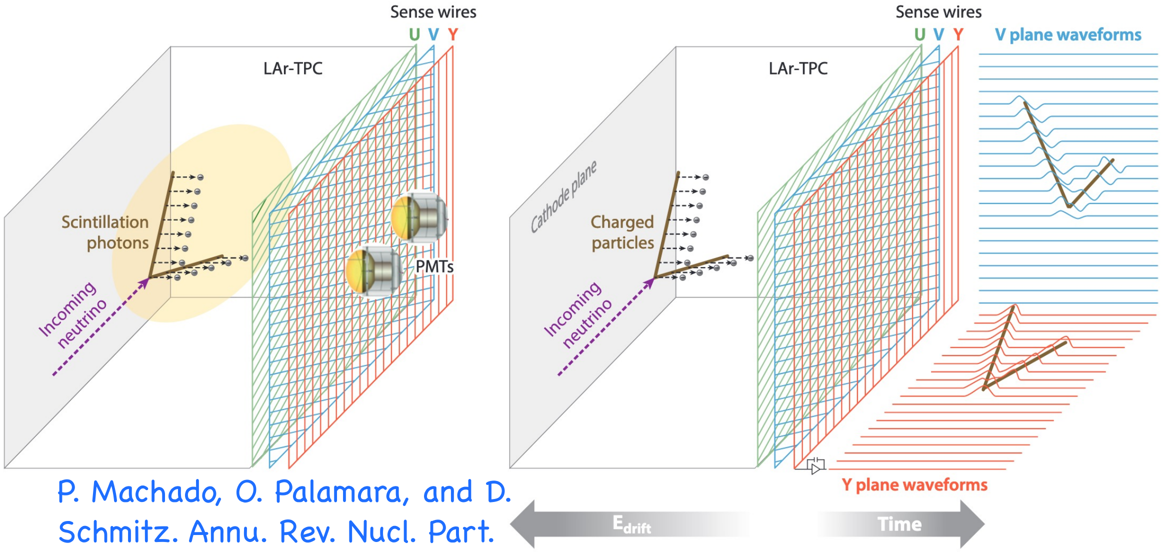
Above: photo of ICARUS being deployed at FNAL (FNAL VMS 18-0150-12). Left: inside the ICARUS detector.

Liquid argon TPCs

- LAr is powerful detection medium: charged particles produce ionization and scintillation
- E-field drifts ionization to wires to measure tracks/showers. Light provides prompt signal: in ICARUS, PMTs provide light detection
- Same detection principle as the future (multi-kt) DUNE experiment



FRONT VIEW OF THE DETECTOR
(C. Rubbia et al. arXiv: 1106.0975)

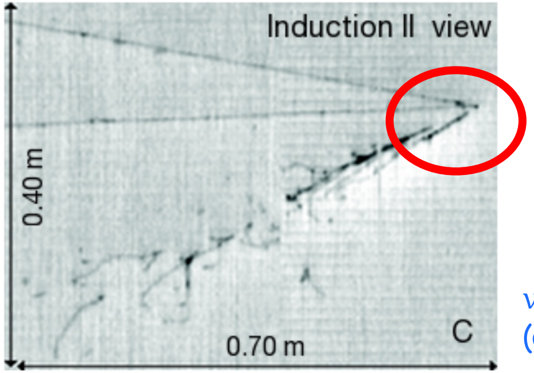


P. Machado, O. Palamara, and D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

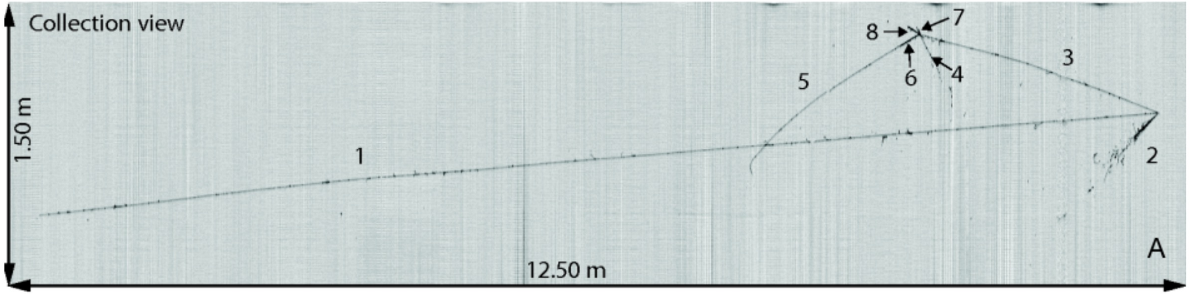
Fermilab

Liquid argon TPCs

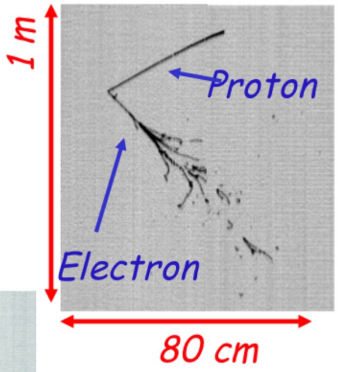
- LAr TPC detectors offer high resolution tracking (multiple planes of wires spaced mm apart) and calorimetry (proportional to amount of signal)
  - Determine properties of tracks (e.g. from muons) and showers (e.g. e/γ separation)

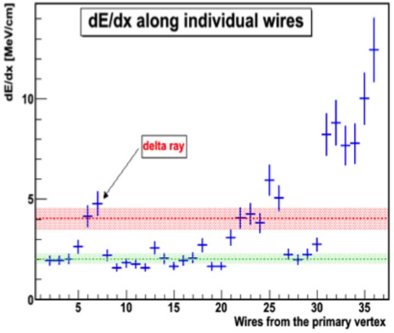


ν_μ CC candidate from CNGS beam
(C. Rubbia et al. arXiv: 1106.0975)



Atmospheric *veCC* event collected @LNGS



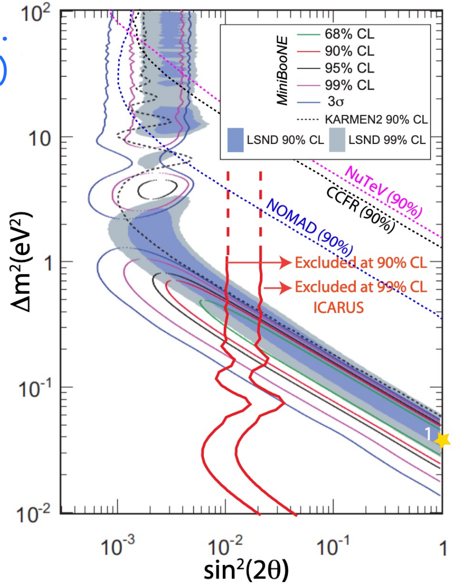


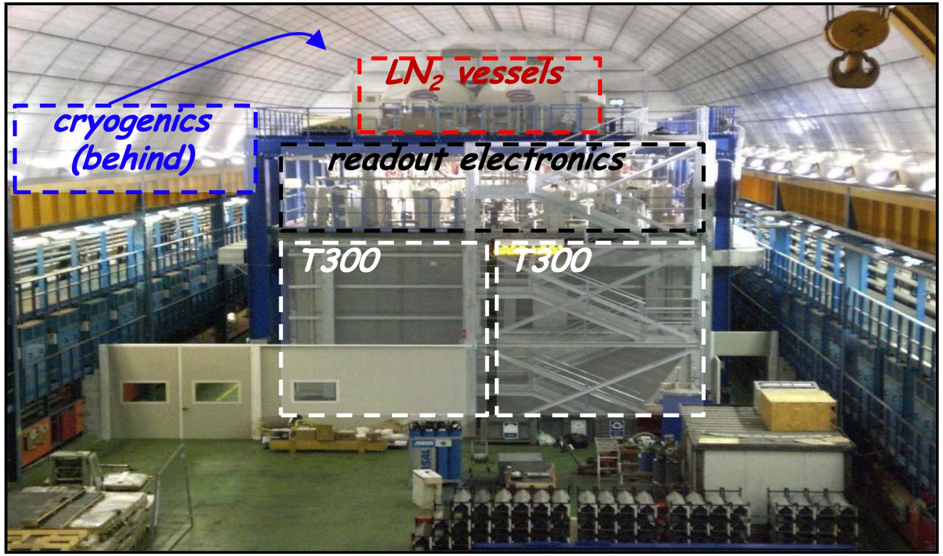
Profile of an electron candidate shower
(Jan 2020 FNAL PAC meeting, D. Gibin and O. Palamara)

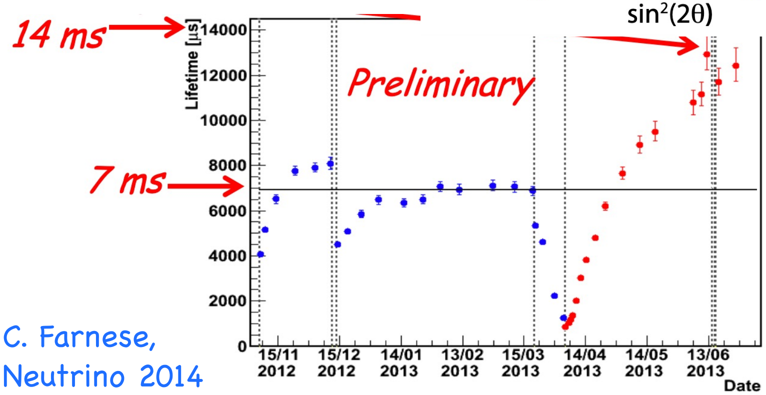
ICARUS at LNGS

- ICARUS T600 run in LNGS spanned several years, with neutrino beam (CNGS from CERN) between 2010-2012
- Tests/demonstrations of many aspects of LAr detector development and analysis techniques
- Analyses e.g. sterile ν search with CNGS (~10-30 GeV)

(M. Antonello et al. arXiv:1209.0122)



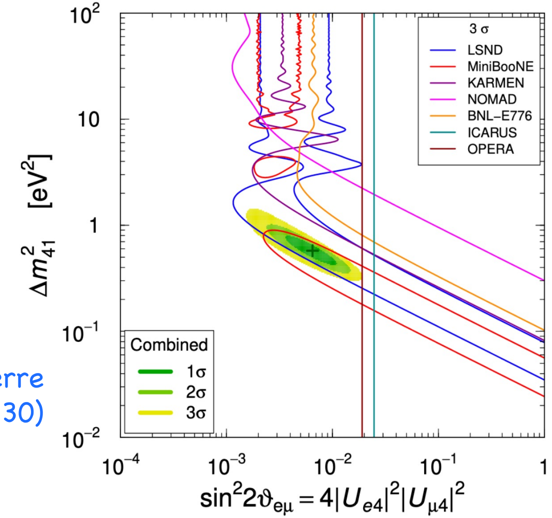




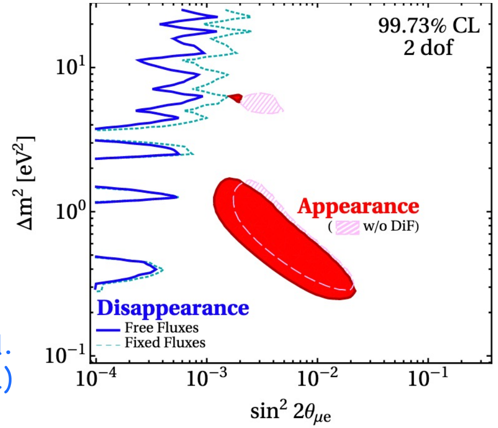
C. Farnese, Neutrino 2014

Sterile neutrinos & SBL anomaly

- LSND and MiniBooNE experiments have found anomalous excess of low energy ν_e candidates at short baseline (SBL), which is outside the scope of 3-flavor oscillation explanation.
  - An interpretation of this signature is oscillation of ν_μ to ν_e via presence of ≥1 sterile ν
- The experimental landscape of other appearance-type experiments have placed limits on allowed sterile osc parameters (including previous iteration of ICARUS) and strong tension w/ ν_μ disappearance channel
- More recently, the Neutrino-4 collaboration has interestingly reported a hint of oscillation signature at higher mass splitting (7.3 eV^2 and $\sin^2 2\theta$~0.36). See A. P. Serebrov et al. Phys. Rev. D **104**, 032003 (2021)
  - More on this in a bit



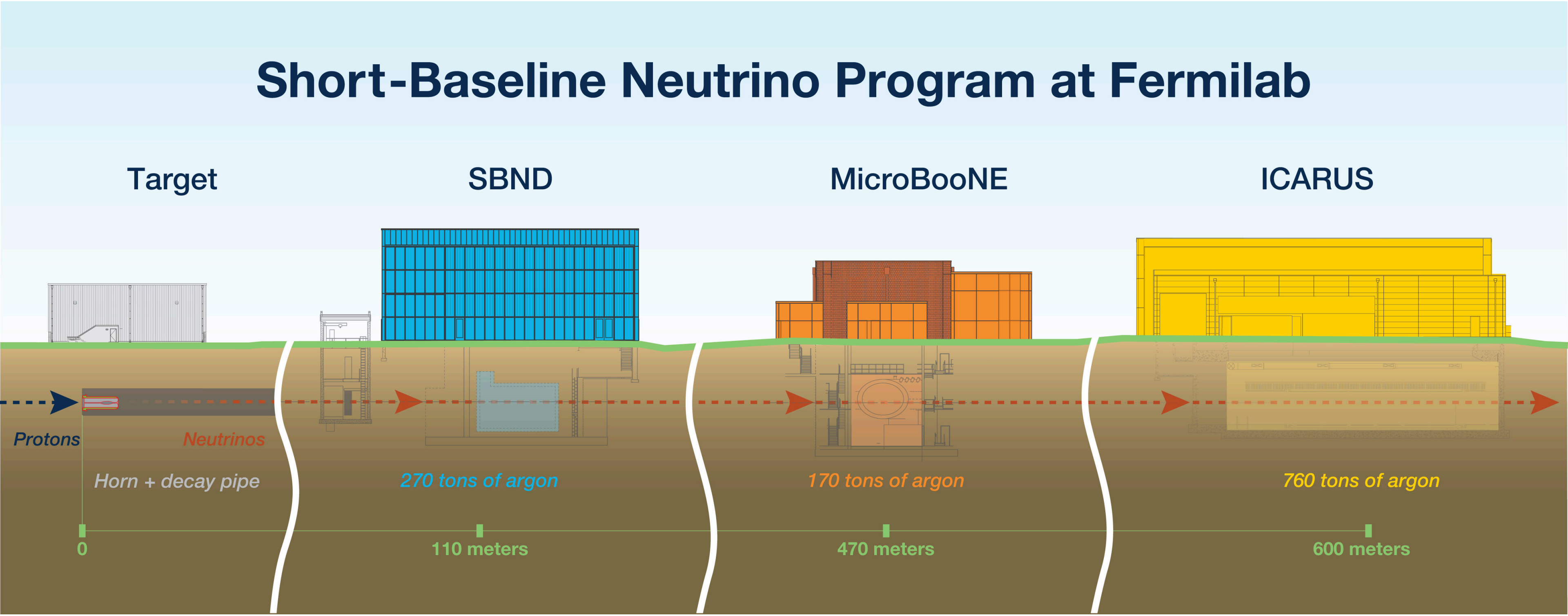
(C. Giunti, T. Lasserre arXiv:1901.08330)



(M. Dentler et al. arXiv:1803.10661)

Fermilab

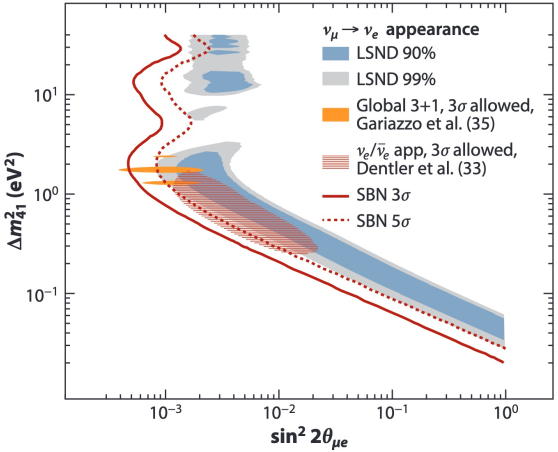
SBN Program at FNAL

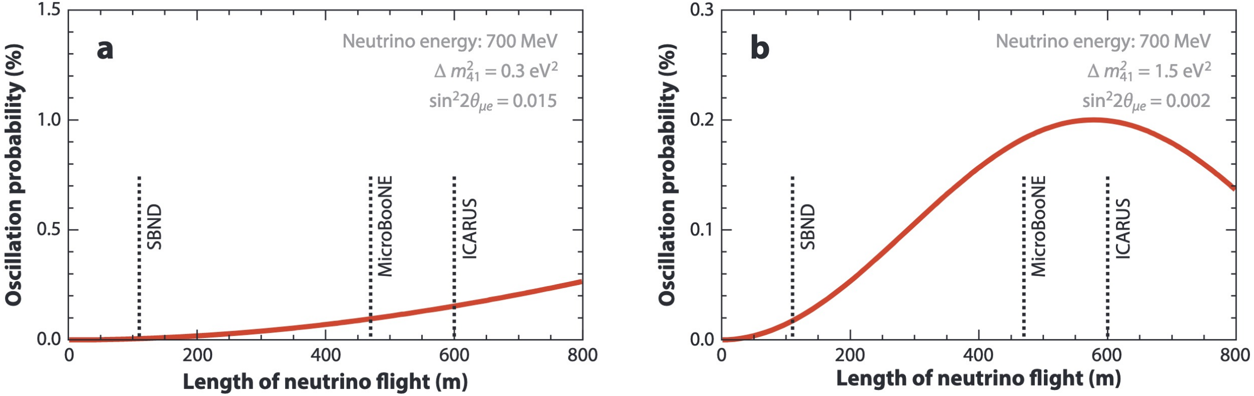


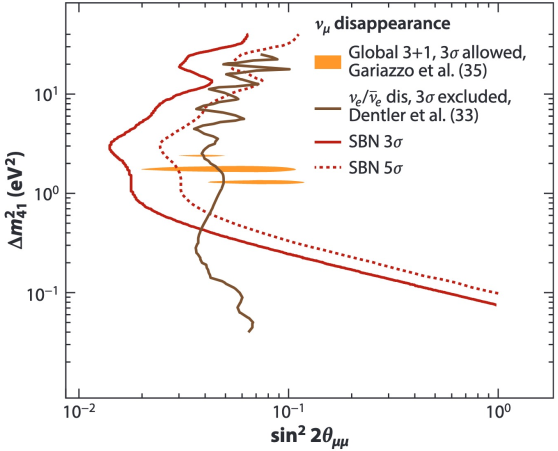
Fermilab VMS, 19-0107-02

SBN Program at FNAL

- ICARUS largest of 3 LAr TPC experiments using BNB beamline and serves as a far detector in the osc study
- SBND will be the closest & serve as near detector
- Studies ν_e appearance and ν_μ disappearance along beam
  - Aim to provide definitive answer on nature of MiniBooNE & LSND excess, and the sterile neutrino question







P. Machado, O. Palamara, and D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

ICARUS at FNAL

- ICARUS T600 moved from Europe to the US and deployed at Fermilab
- Serves as the far detector in the Short Baseline Neutrino (SBN) program searching for definitive answer on this sterile neutrino question
- Able to detect NuMI (120 GeV p on target) at ~6 degrees off-axis – input to another oscillation study, valuable cross-section measurements, light dark matter searches, etc.

BNB beam runs along length of detector

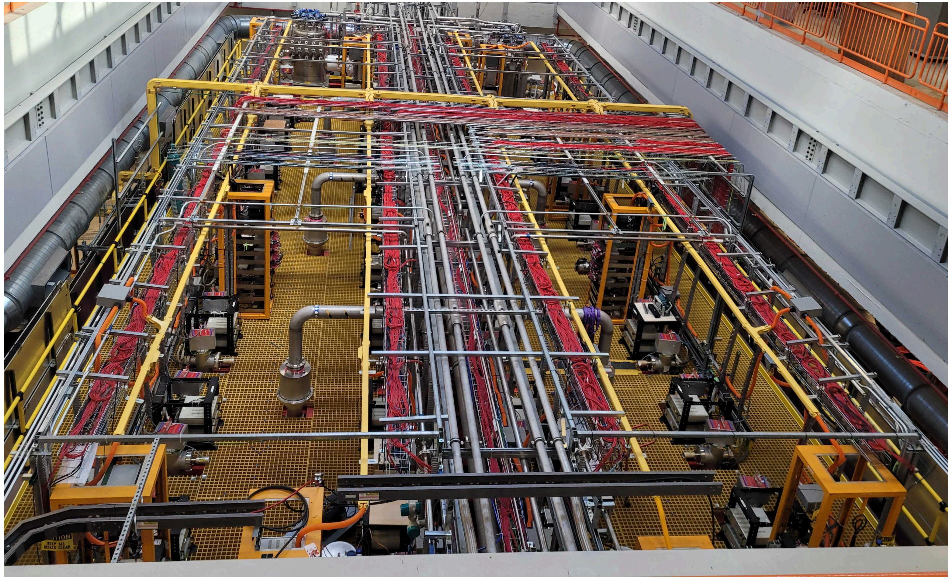
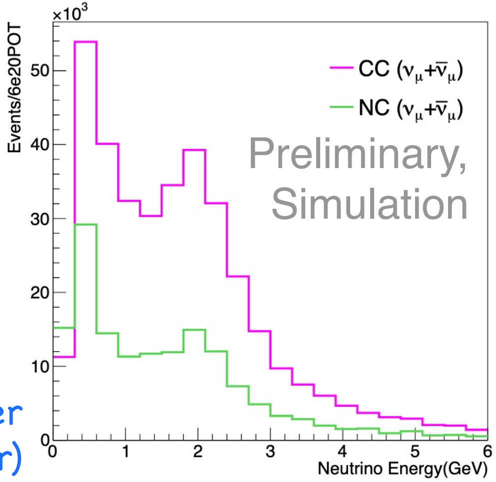
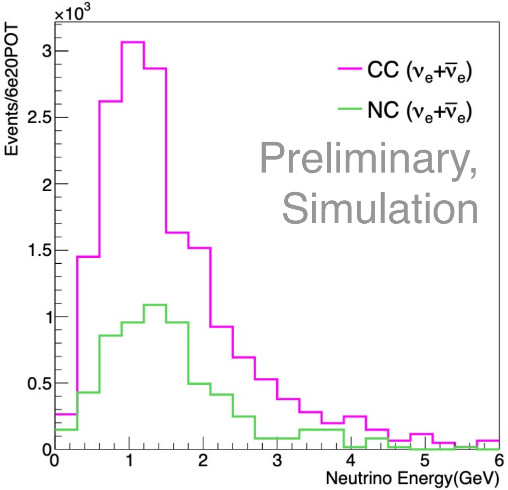


Photo from this spring showing electronics, piping, cables, etc. of the installed ICARUS detector at FNAL

Cross sections with NuMI

- Understanding neutrino interactions with Ar like cross-sections, nuclear effects, final states are important to oscillation measurements and constraining systematics
  - Effects e.g. both the rates/signal efficiency understanding and energy resolution
- The NuMI beam provides ICARUS a wealth of ν_μ and ν_e interactions, from order of a few hundred MeV to multi-GeV (higher energy ν_e from K decays & are more abundant in NuMI)
- Provides both an interesting sample in comparison to BNB oscillation study and also to provide input to DUNE (covers 2nd oscillation maximum and extends well into 1st)
- NuMI off-axis measurements will also include light dark matter searches



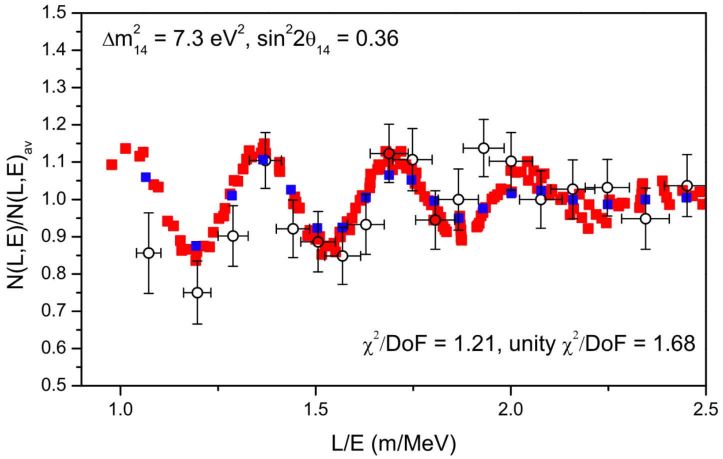


Anticipated NuMI neutrino interactions per 6e20 protons on target (roughly 1 year)

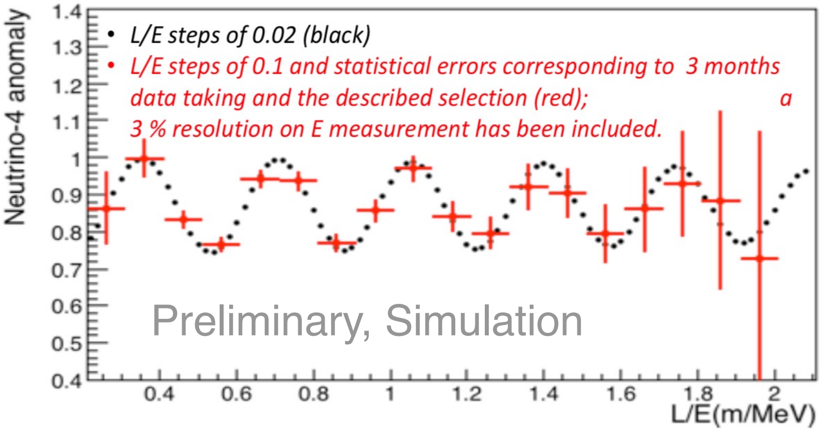
Fermilab

Neutrino-4 study with ICARUS

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



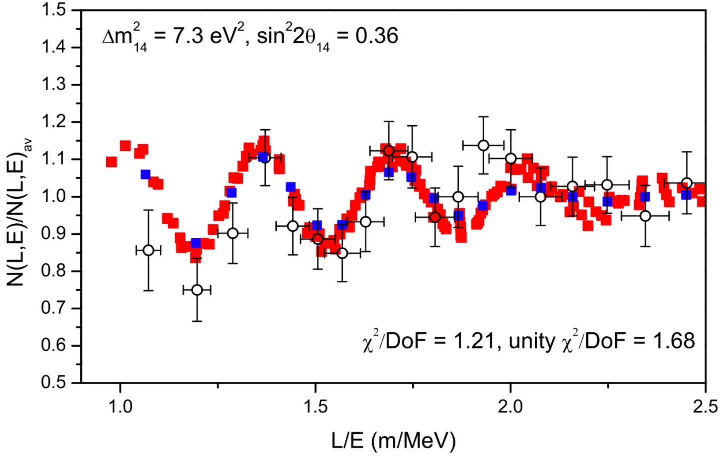
- Neutrino-4 collaboration reported finding a reactor neutrino disappearance signal in the L/E range ~ 1-3
- ICARUS sensitive to similar L/E. Two (separate) samples and beam-off sample can test these findings:
  - ν_μ disappearance in BNB beamline: focus on ν_μ CC QE sample w/ contained μ ≥50 cm
  - ν_e disappearance in NuMI beamline: focus on ν_e CC QE sample w/ contained electron shower



Example ν_μ survival probability at Δm^2 ~ 7.25, $\sin^2 2\theta$ ~ 0.26 in ICARUS and corresponding anticipated measurement assuming 3 months data taking and 3% energy scale resolution.

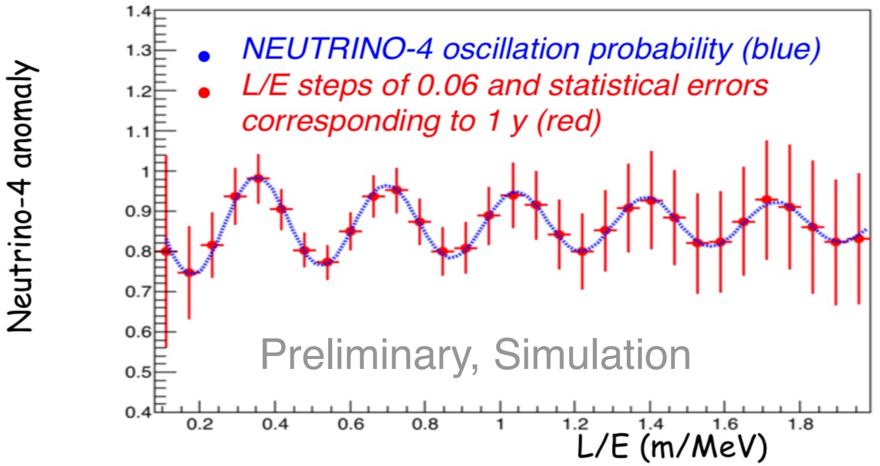
Neutrino-4 study with ICARUS

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



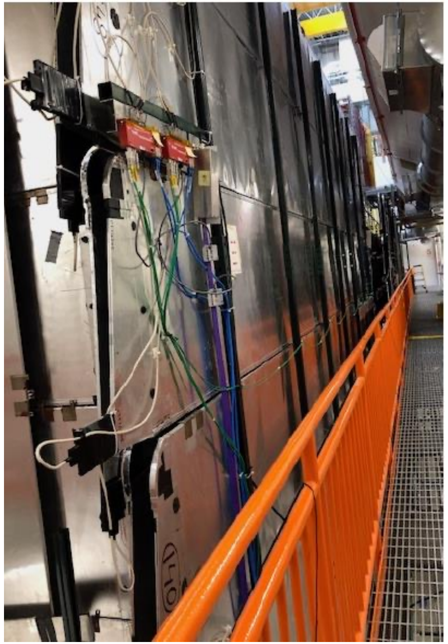
- Neutrino-4 collaboration reported finding a reactor neutrino disappearance signal in the L/E range ~ 1-3
- ICARUS sensitive to similar L/E. Two (separate) samples and beam-off sample can test these findings:
  - ν_μ disappearance in BNB beamline: focus on ν_μ CC QE sample w/ contained μ ≥50 cm
  - ν_e disappearance in NuMI beamline: focus on ν_e CC QE sample w/ contained electron shower

Example ν_e survival probability at Δm^2 ~ 7.25, $\sin^2 2\theta$ ~ 0.26 in ICARUS and corresponding anticipated measurement assuming 1 year data taking (statistical uncertainties only).



ICARUS at FNAL

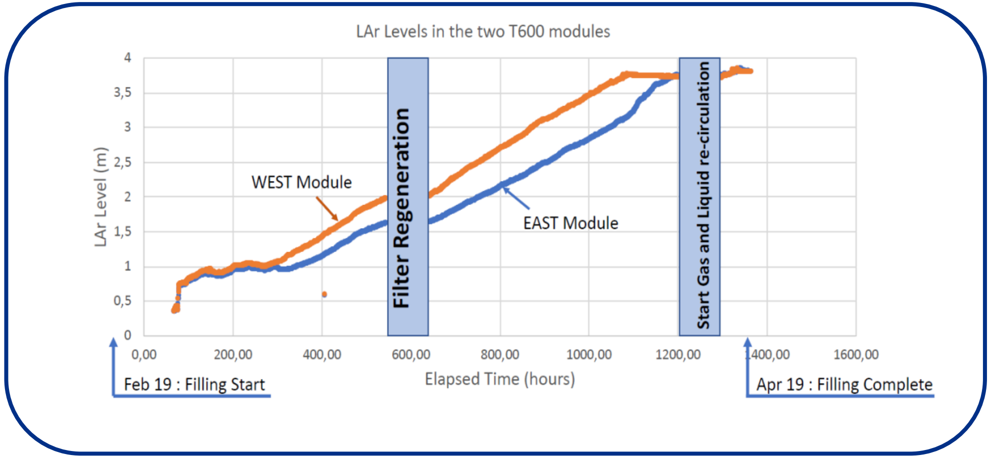
- Because on surface and size, significant cosmic bkg expected (~3 (1-2) cosmic trigger events per 1 from ν in LAr in BNB (NuMI))
- Multi-pronged mitigation strategy:
    - Some cosmic activity can be "clear" (e.g. appear too far outside expected detector bounds given "T=0" beam time)
    - Matching of charge signal from the TPC with the light signals in the PMTs can help determine if depositions are in-time
    - In addition to TPC/PMT systems noted earlier, cosmic ray tagger (CRT) is being installed to help identify cosmic tracks entering detector, especially helpful in-time activity
        - Possibility of CRT-PMT match to distinguish entering/exiting tracks under study
    - An overburden is to be placed above the detector upon the completion of installation

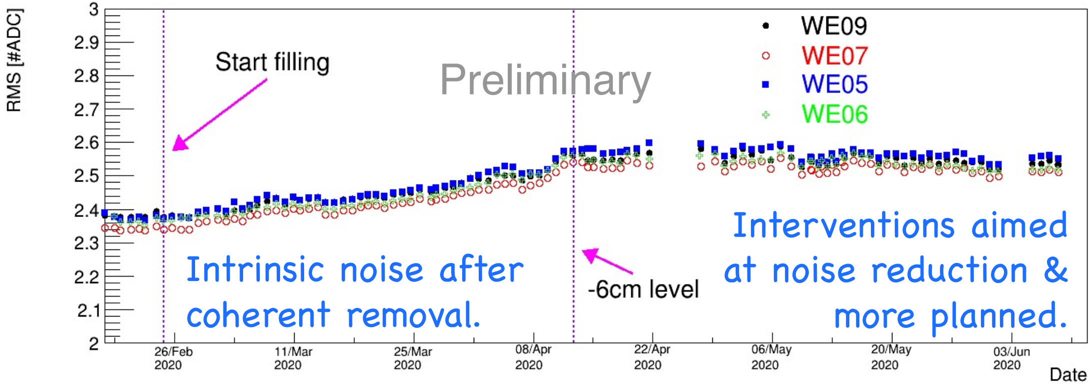


ICARUS Side CRT

ICARUS at FNAL: Activation & Commissioning

- After installation, ICARUS began cooldown and filling Feb 2020
- Taking detector monitoring shifts since then: briefly in person, switching to remote w/ pandemic
- By Fall 2020 detector was activated to the full electric drift field of -75kV (500 V/cm) was reached. PMTs were activated and gain calibration was underway, etc.
  - A few walls of CRT were installed prior to pandemic, other parts of side CRT installed during. Top CRT remains – is upcoming work.

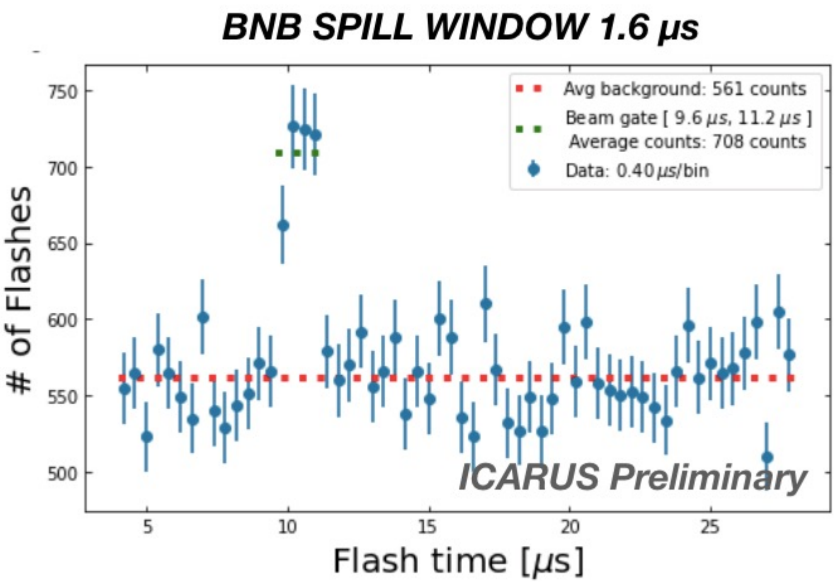


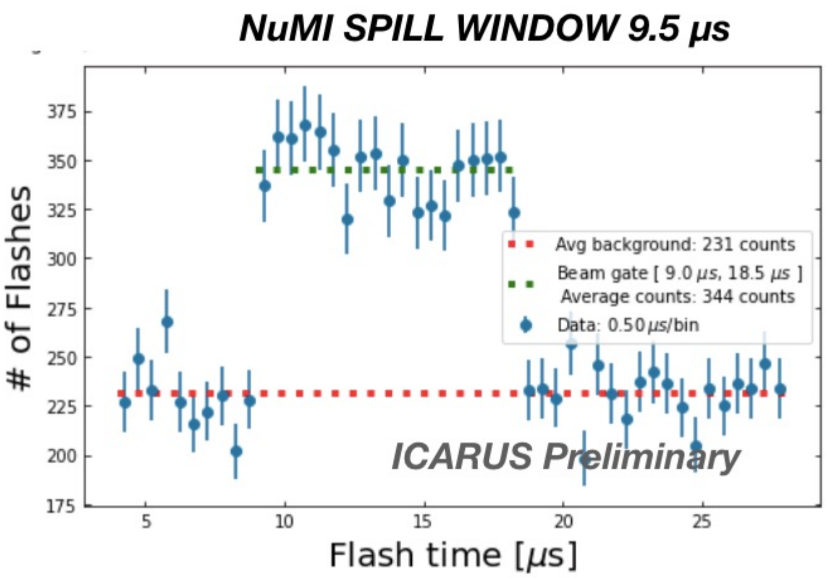


Fermilab

ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam



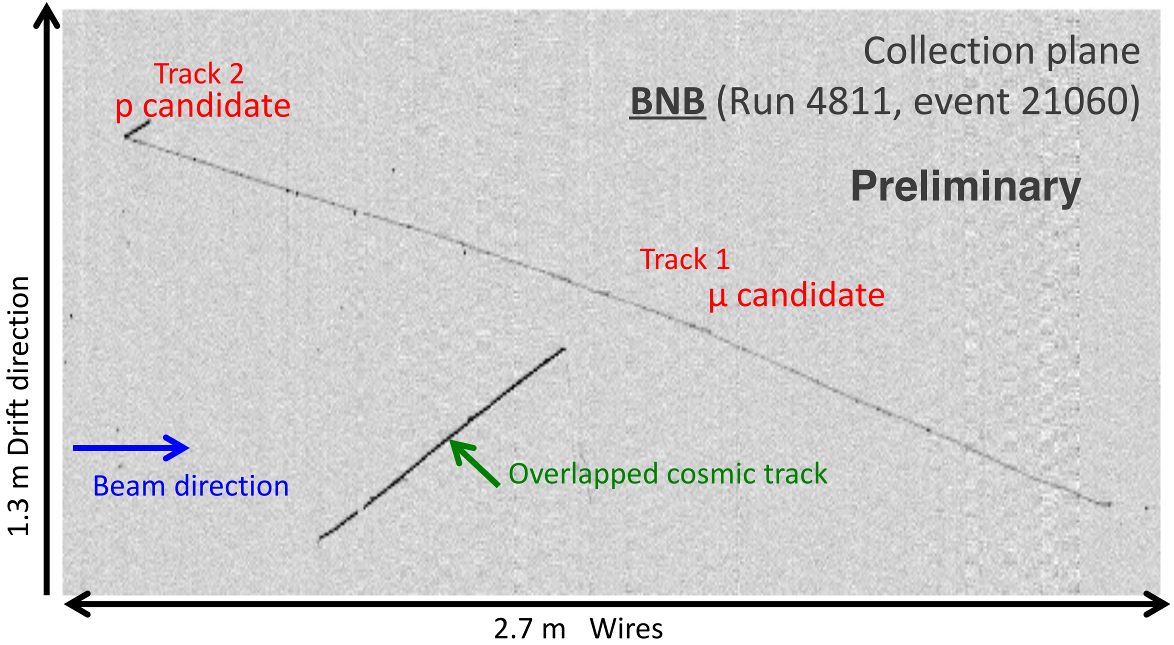


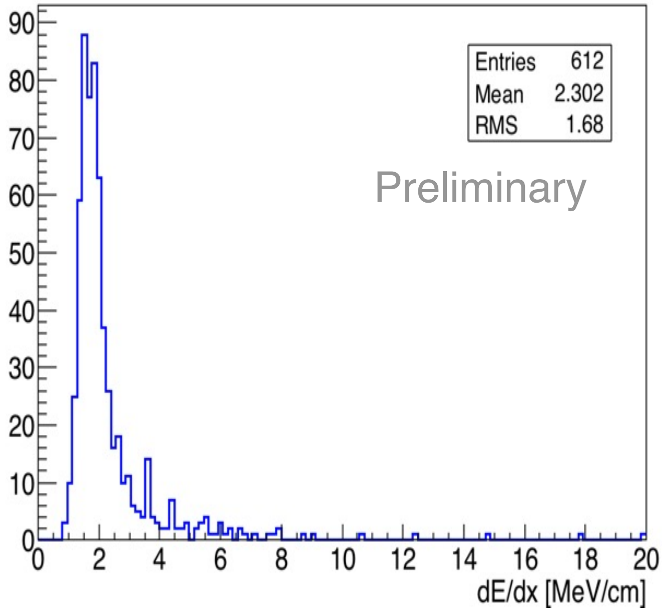
Excess plateaus ~right width correspond to neutrinos interacting in detector from the beams.

Fermilab

ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam
- Visual scanning effort to find neutrino candidates in early collected data





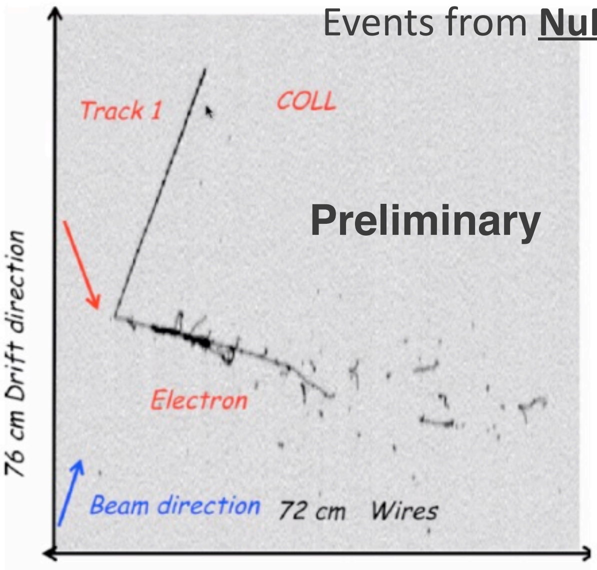
One of the first candidate ν_μ interactions found in BNB. Electron lifetime at this point was ~1.2 ms

Fermilab

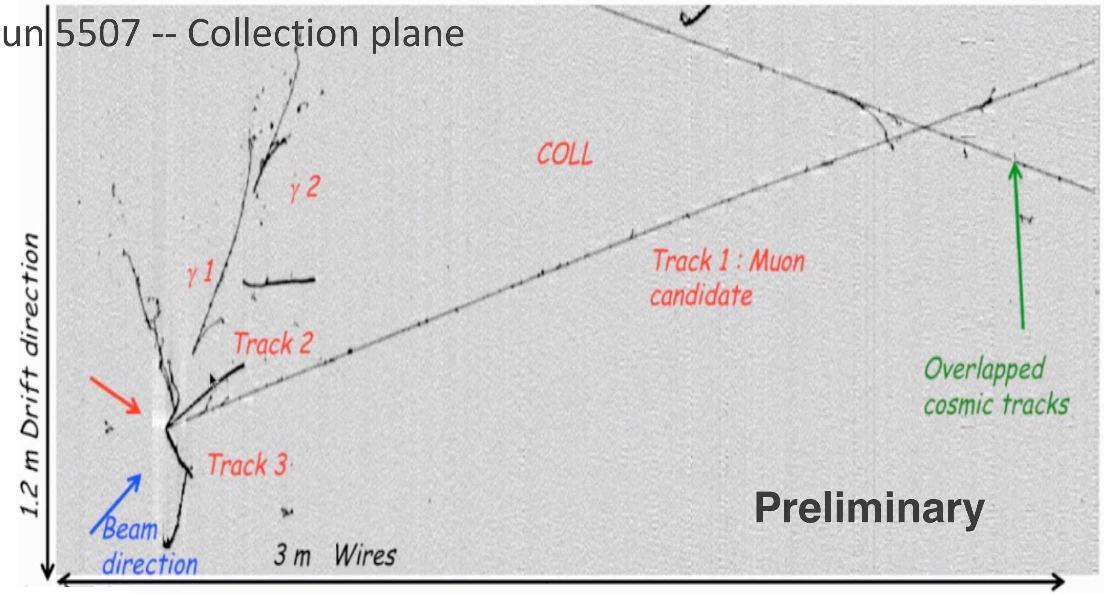
ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam
- Visual scanning effort to find neutrino candidates in early collected data

Events from **NuMI** Run 5507 -- Collection plane



Candidate ν_e interaction from NuMI. Electron lifetime ~3.2 ms

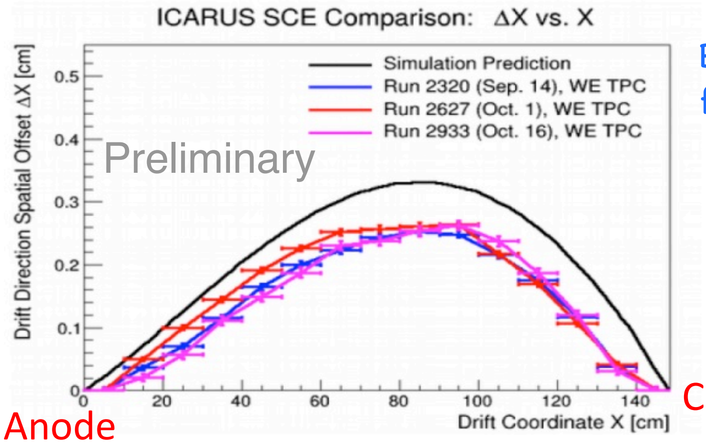


Candidate ν_μ interaction from NuMI.

ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam
- Visual scanning effort to find neutrino candidates in early collected data
  - Input to status of trigger and readout. e.g. fix any TPC channel mis-mapping
  - Provides set of commissioning events that can be studied for their properties
  - Currently using these events to better understand data reconstruction
- Calibration campaign with early data to understand detector effects, calorimetry, etc.

~few mm



Anode

Cathode

Early measurement of space charge effect from tracks extending from anode to cathode

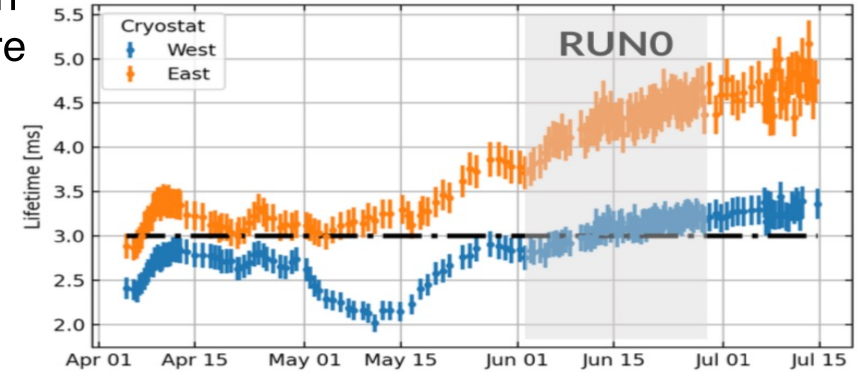
Also drift velocity, calorimetry measurements (i.e. e/ADC), look at recombination, etc.

Fermilab

ICARUS at FNAL: Activation & Commissioning

- Trigger commissioning included confirmation of a peak of excess corresponding to beam
- Visual scanning effort to find neutrino candidates in early collected data
  - Input to status of trigger and readout. e.g. fix any TPC channel mis-mapping
  - Provides set of commissioning events that can be studied for their properties
  - Currently using these events to better understand data reconstruction
- Calibration campaign with early data to understand detector effects, calorimetry, etc.
- Just before summer, a dry run (Run0) was taken as an emulation of physics data mode to prepare for when the beam begins running in fall again

Electron lifetime showed improvement over the course of Run0, above the desired minimum of 3ms. Further improvements to the cryogenic system are planned.



Fermilab

ICARUS at FNAL: Collaborative Effort

P. Abratenko[19], A. Aduszkiewicz[20], J. Asaadi[23], M. Babicz[2], W. F. Badgett[5], L.F. Bagby[5], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], S. Berkmann[5], S. Bertolucci[6], M. Betancourt[5], S. Biagi[11], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], A. Braggiotti[15], J. Bremer[2], S. Brice[5], J. Brown[5], H. Budd[22], H. Carranza[23], S. Centro[15], G. Cerati[5], M. Chalifour[2], A. Chatterjee[21], D. Cherdack[21], S. Cherubini[11],T. Coan[18], A. Cocco[14], M. Convery[17], S. Copello[8], A. De Roeck[2], L. Di Noto[8], C. Distefano[11], M. Diwan[1], S. Dytman[22], S. Dolan[2], L. Domine[17], R. Doubnik[5], F. Drielsma[17], V. Fabbri[6], C. Fabre[2], A. Falcone[13], C. Farnese[15], A.Fava[5], A. Ferrari [12], F. Ferraro[8], N. Gallice[12], M. Geynisman[5], D. Gibin[15], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], C. Hilgenberg[4], B. Howard[5], R. Howell[23], C. James[5], W. Jang[23], D. H. Kao[17], W. Ketchum[5], U. Kose[2], J. Larkin[1], G. Laurenti[6], Q. Lin[17], G. Lukhanin[5], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D. P. Mendez[1], G. Meng[15], A. Menegolli[16], O. G. Miranda[3], D. Mladenov[2], N. Moggi[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], M. Nessi[2], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[21], R. Pappaleo[11], L. Pasqualini[6], L. Patrizii[6], G. Petrillo[17], C. Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6], M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], R. Rechenmacher[5], G. Riccobene[11], F. Resnati[2], A. Rigamonti[2], G.L. Raselli[16], M. Rossella[16], C. Rubbia[9], P. Sala[12], P. Sapienza[11], G. Savage[5], A. Scaramelli[16], A. Scarpelli[1], D. Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], A. Soha[5], L. Stanco[15], J. Stewart[1], C. Sutera[7], H. Tanaka[17], M. Tenti[6], K. Terao[17], F. Terranova[13], D. Torretta[5], M.Torti[13], F. Tortorici[7], Y.T. Tsai[17], S. Tufnali[2], T. Usher[17], M. Vicenzi[8], B. Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M. Worcester[1], M. Wospakrik[5], H. Yu[1], J. Yu[24], F. Varanini[15], S. Ventura[15], C. Vignoli[10], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemover[5], S. Zucchelli[6], M. Zuckerbrot[5]

a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi (AQ), Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
17. SLAC National Accelerator Lab., USA
18. Southern Methodist University, USA
19. Tufts University, USA
20. University of Chicago
21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington), USA

11 INFN groups, 11 USA institutions, 1 Mexican institution, CERN

Spokesperson: C. Rubbia, GSSI

2

Summary

- ICARUS is a liquid argon TPC originally operated at LNGS in Italy
- After a successful refurbishment and upgrade, it was moved to Fermilab in the USA where it will see neutrinos from both the BNB and NuMI neutrino beams at Fermilab
- Question of sterile neutrinos remains open, both related to the previous measurements of LSND and MiniBooNE and the more recent claim of oscillation signature from Neutrino-4
  - Short Baseline Neutrino Program at FNAL will use the BNB beam to probe the LSND and MiniBooNE excess. ICARUS serves as the Far Detector of this study.
  - ICARUS is well situated to probe the Neutrino-4 parameters using NuMI and BNB
- ICARUS also able to measure cross-sections, search for light dark matter, etc.
- ICARUS was filled and the TPC activated in 2020 and has been continuing toward full installation/commissioning of all systems since
- A set of commissioning neutrino candidates have been visually identified and work on the various pieces leading towards analysis are ongoing
- No beam at moment (summer shutdown) but excited to collect neutrinos again ~October