Status and perspectives of the ICARUS experiment at the Fermilab Short Baseline Neutrino program

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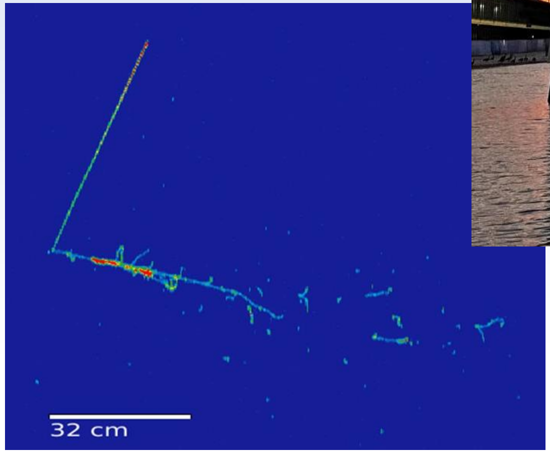
on behalf of the ICARUS Collaboration



Istituto Nazionale di Fisica Nucleare

Imaging Cosmic And Rare Underground Signals

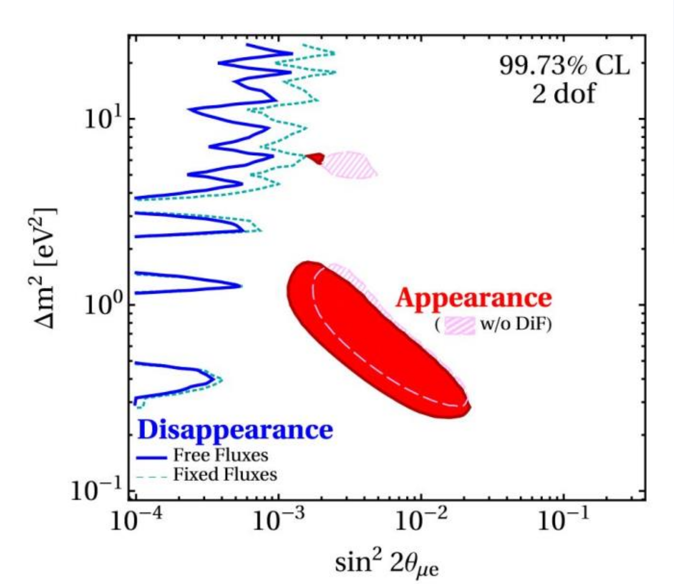
16th International Conference on Heavy Quarks and Leptons
HQL 2023, Mumbai, India
28 November – 2 December 2023

The Sterile Neutrino Puzzle

3-neutrino oscillations paradigm well established but some experimental anomalies may indicate the existence of sterile neutrinos at eV mass scale:

- $\bar{\nu}_e$ appearance – LSND experiment reported a 3.8 σ excess of $\bar{\nu}_e$ in the $\bar{\nu}_e \rightarrow e^+ + n$ channel
- ν_e disappearance – SAGE and GALLEX experiments with radioactive sources showing an observed/predicted rate R = 0.84 ± 0.05, recently confirmed at 4 σ by BEST experiment
- $\bar{\nu}_e$ disappearance – in nuclear reactor experiments R = 0.943 ± 0.024 at ~ 3 σ
- Further test at accelerators experiments:
  - MinBooNE: electron-like excess in ν and $\bar{\nu}$ mode observed at 4.7 σ (Phys. Rev. Lett. **121** (2018) 221801)
  - MicroBooNE: no evidence of sterile neutrinos (Phys. Rev. Lett. **130** (2022) 011801)

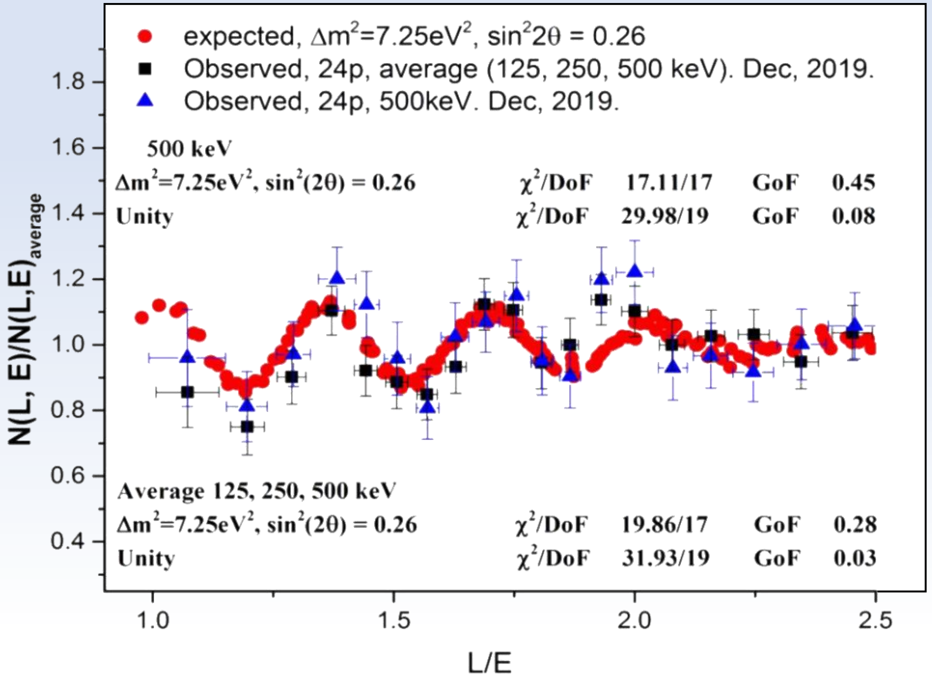
A clear tension between appearance and disappearance experiments which are characterized by different neutrino energy range and detection technique is evident.



JHEP 08 (2018) 010
Dentler et al.

The Sterile Neutrino Puzzle

In 2019 Neutrino-4 experiment (A.P. Serebrov et al.) at Dimitrovgrad SM-3 reactor gave evidence of neutrino oscillation into sterile neutrinos **showing a disappearance signal** with a clear **L/E ~ 1-3 m/MeV modulation**



Neutrino signal (blue and black) compared with the expectation (red) for $\Delta m^2_{14} = 7.25\ eV^2$ and $sin^2(2\theta_{14}) = 0.26$ as a function of L/E

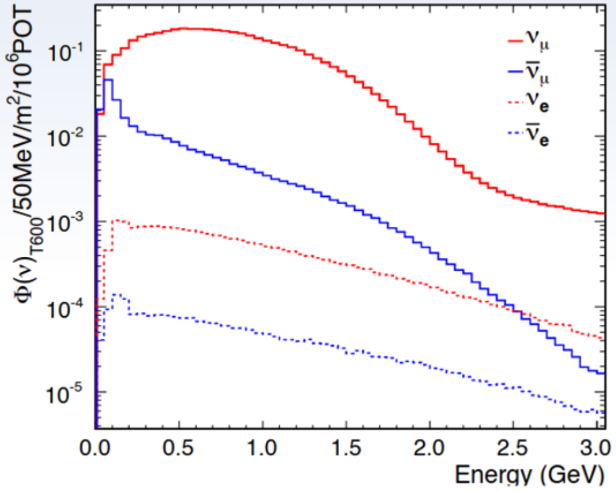
Combined analysis of Neutrino-4 with GALLEX, SAGE, BEST (P.R.D. 104, 032003, 2021) results in a best fit of $\boldsymbol{\Delta m^2_{14} = 7.3\ eV^2}$ **and** $\boldsymbol{sin^2(2\theta_{14}) = 0.36}$ **at 5.8 σ**

The Short Baseline Neutrino Program at Fermilab

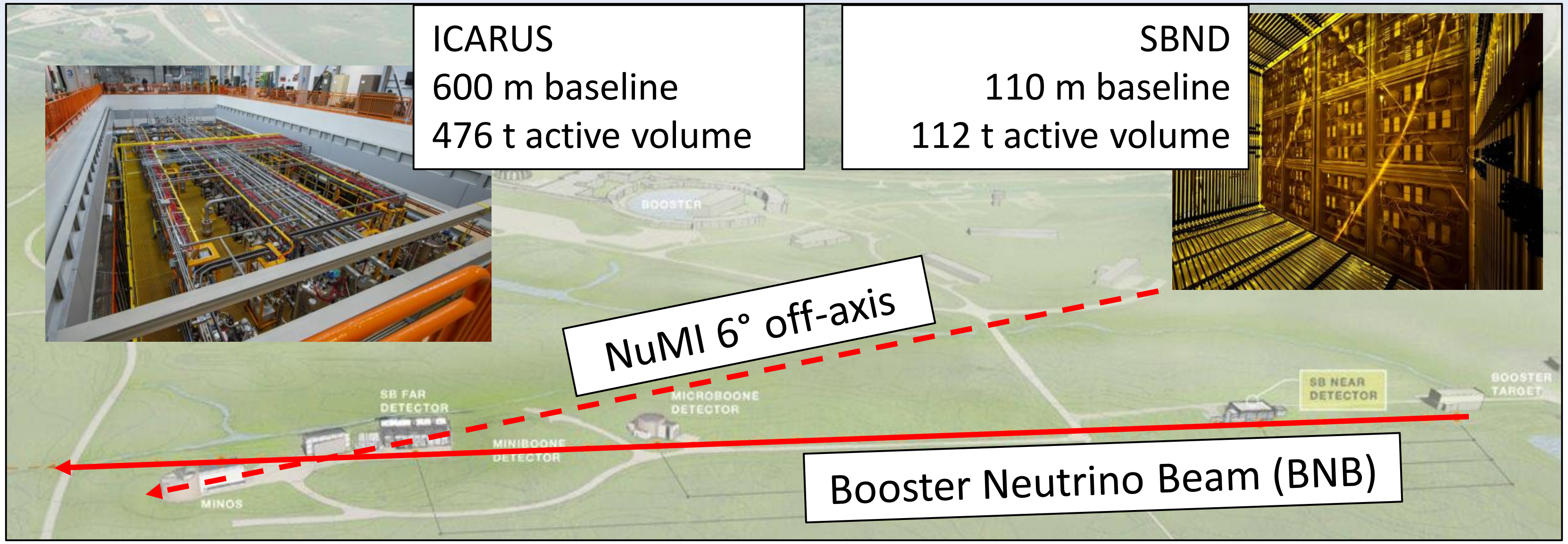
- ICARUS and SBND Liquid Argon Time Projection Chambers are installed at 600 and 110 m from the Booster Neutrino Beam (BNB) at Fermilab

- The SBN Far Detector, ICARUS T600, is on axis on BNB and 6° off axis on NuMI, accessing the electron-neutrino-rich component of the spectrum which will grant the exploration of Beyond Standard Model physics

- Both ν_e appearance and ν_μ disappearance channels can be observed in the same experiment using detectors with optimal neutrino identification, allowing to confirm or definitively ruled out the existence of sterile neutrinos at eV mass scale



BNB is a well-characterized ν_μ $(\bar{\nu}_\mu)$ beam with low ν_e contamination



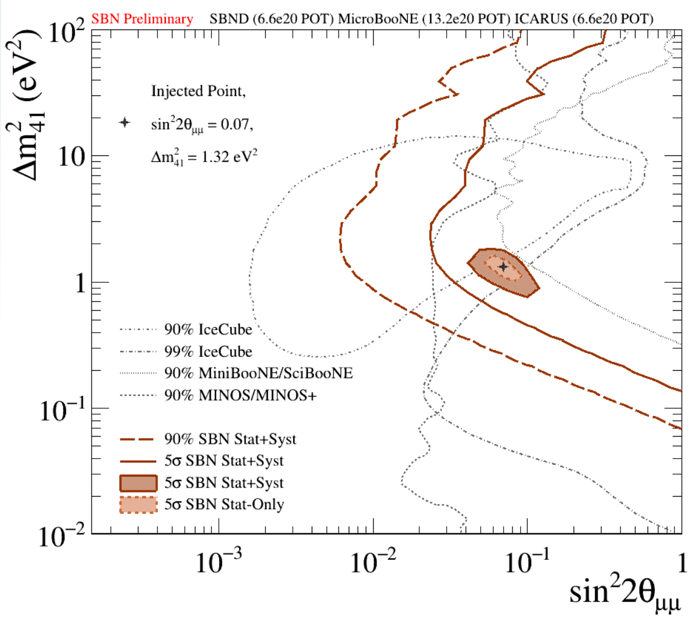
The SBN sensitivity in 3 years (6.6 x 10^{20} pot)

Combined analysis of events collected by ICARUS (far detector) and SBND (near detector) using the same Lar-TPC event imaging technology greatly reduces the expected systematics:

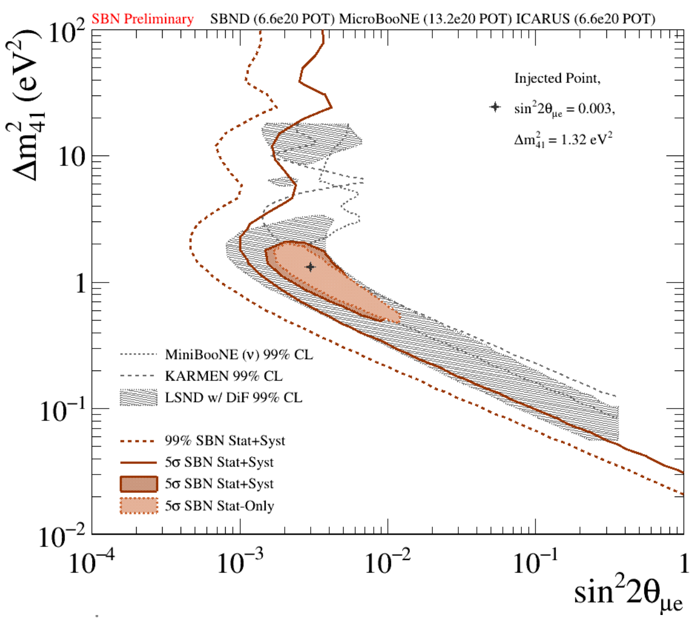
- High identification capability of LArTPCs rejecting NC event background;
- Initial BNB beam composition and spectrum provided by the near detector;
- Sharing of recontruction/analysis tools between near and far detectors reduces systematics.

5σ coverage of the parameter area relevant to LSND anomaly

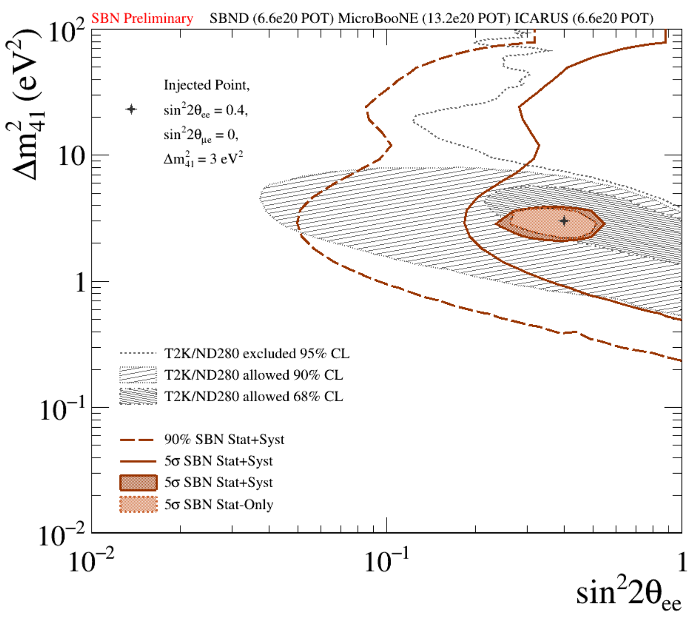
ν_μ disappearance



ν_e appearance



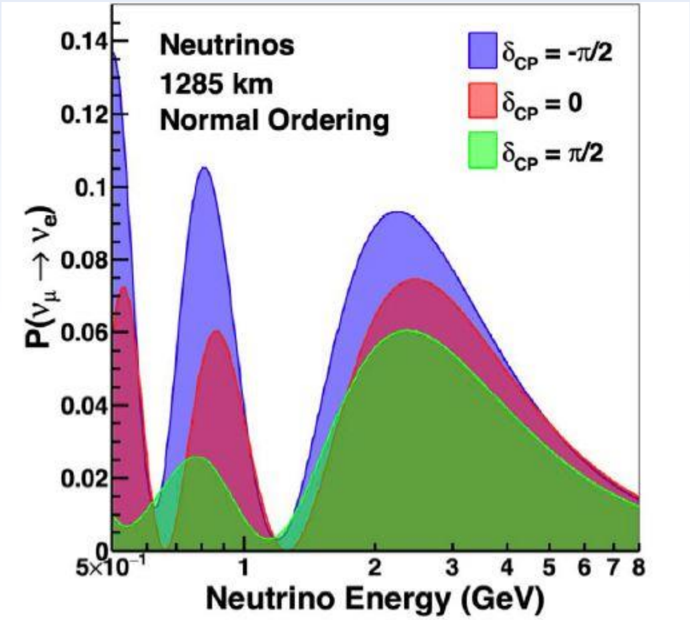
ν_e disappearance



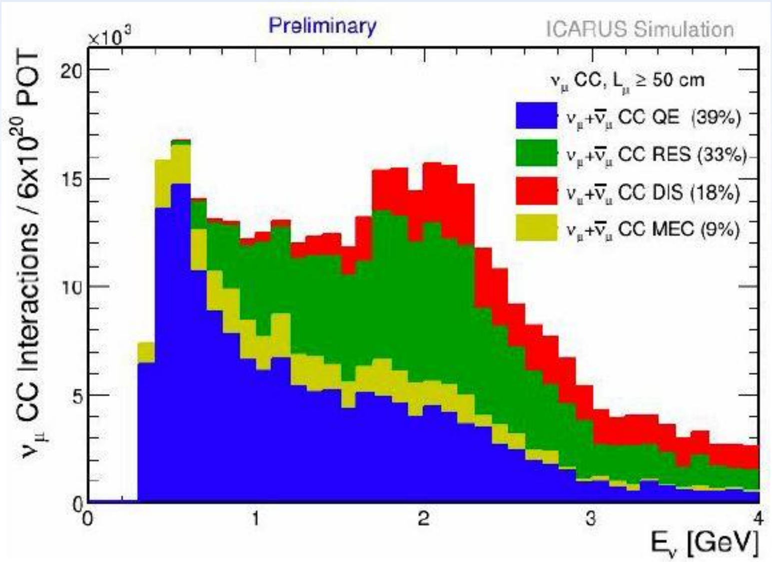
Physics searches with NuMI

- ICARUS is collecting a high-statistic sample of the off-axis ν_e NuMI component to perform high precision measurements of ν Argon cross sections (10^4 ν_e events / year) and test interaction models in the few hundred MeV to few Gev energy range extremely useful for SBN oscillation analysis and for the upcoming DUNE experiment
- Rich BSM Physic program: Higgs portal scalar through di-muon final states (advanced analysis), neutrino tridents, light dark matter, heavy neutral leptons, millicharged particles ….

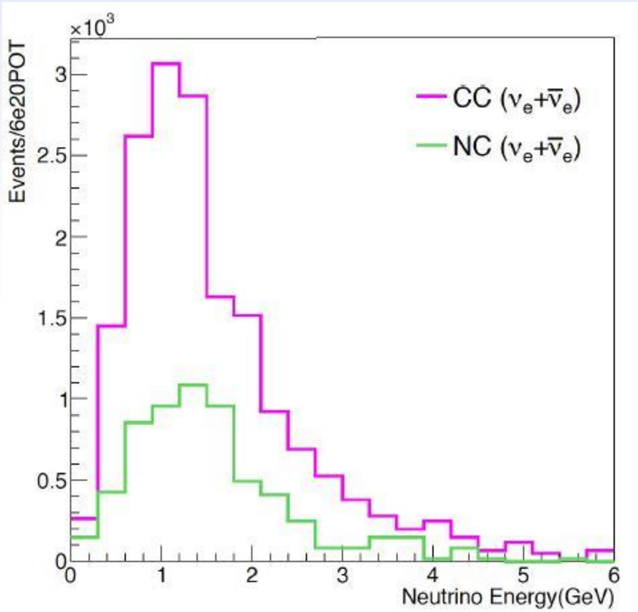
oscillation probability at DUNE



ν_μ from NuMI at ICARUS



ν_e from NuMI at ICARUS



The Liquid Argon TPC detection technique

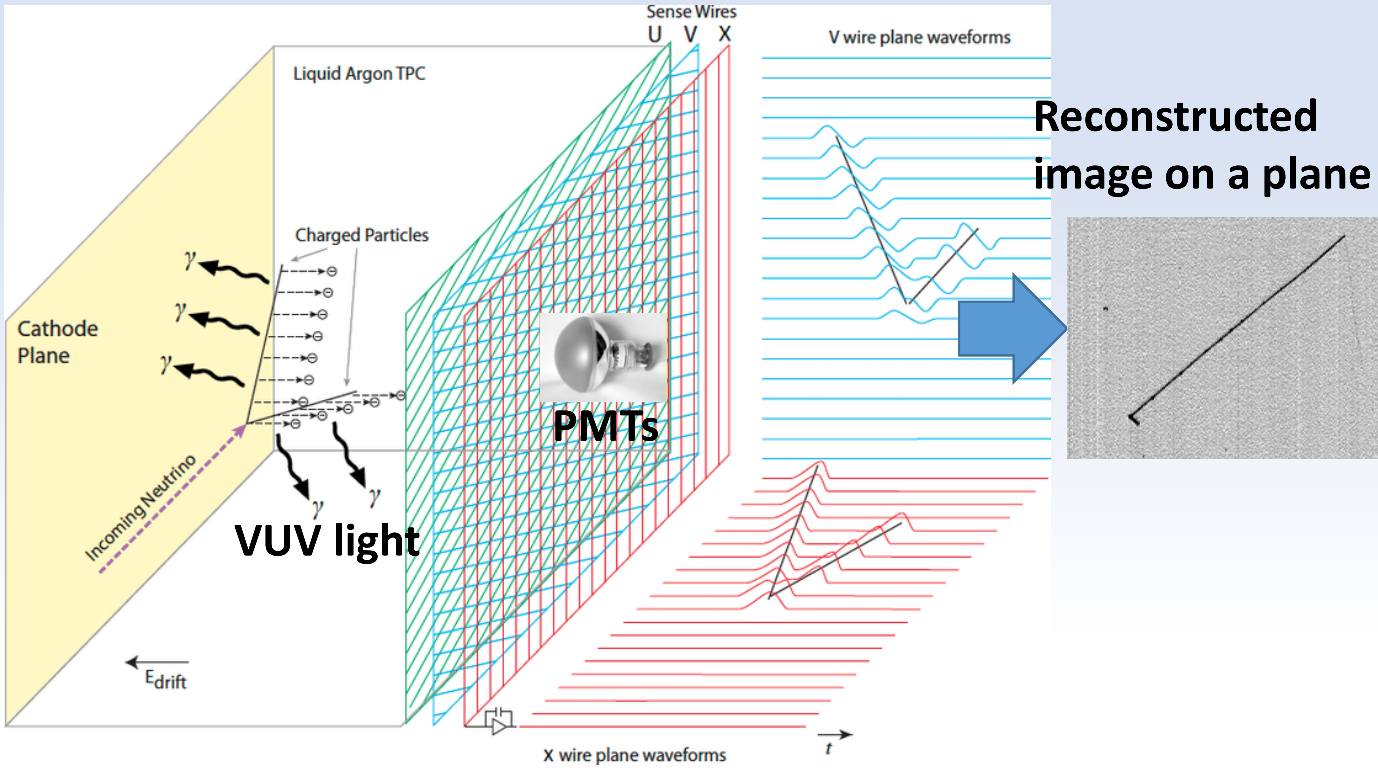
Ideal detector for ν Physics with excellent imaging and calorimetric capabilities allowing to reconstruct events with complex topologies

- scintillation light (40000 γ/MeV at λ = 128 nm and E_D = 0 V/cm) detected by PMTs to provide the event time and trigger

- charged particles from neutrino interactions ionize the LAr producing ionization electrons (42000 e^- / MeV) drifting in 1 ms towards readout sense wires

  - combining wire coordinates at same drift time → 3D track reconstruction with resolution of ~ mm

  - dE/dx vs range measurements to perform PID



The ICARUS T600 detector

- ICARUS is a self-triggering detector successfully operated at LNGS from 2010 to 2013 as the first and largest LArTPC ever operated collecting 8.6×10^{19} POT statistics from the CNGS neutrino beam
- Two identical modules (19.6 (L) x 3.6 (W) x 3.9 (H) m^3) with 2 TPCs each with a total (active) LAr mass of 760 (476) tons
- Fully instrumented with 360 PMTs coated with TPB
- An external Cosmic Ray Tagger (CRT) system ensuring a 4π coverage to reject cosmic background

- ➢ 2015-2017: overhauling at CERN
- ➢ 2018: transportation to FNAL and start of installation
- ➢ 2020: filling with LAr and start of commissioning
- ➢ 2022: start of physics data taking

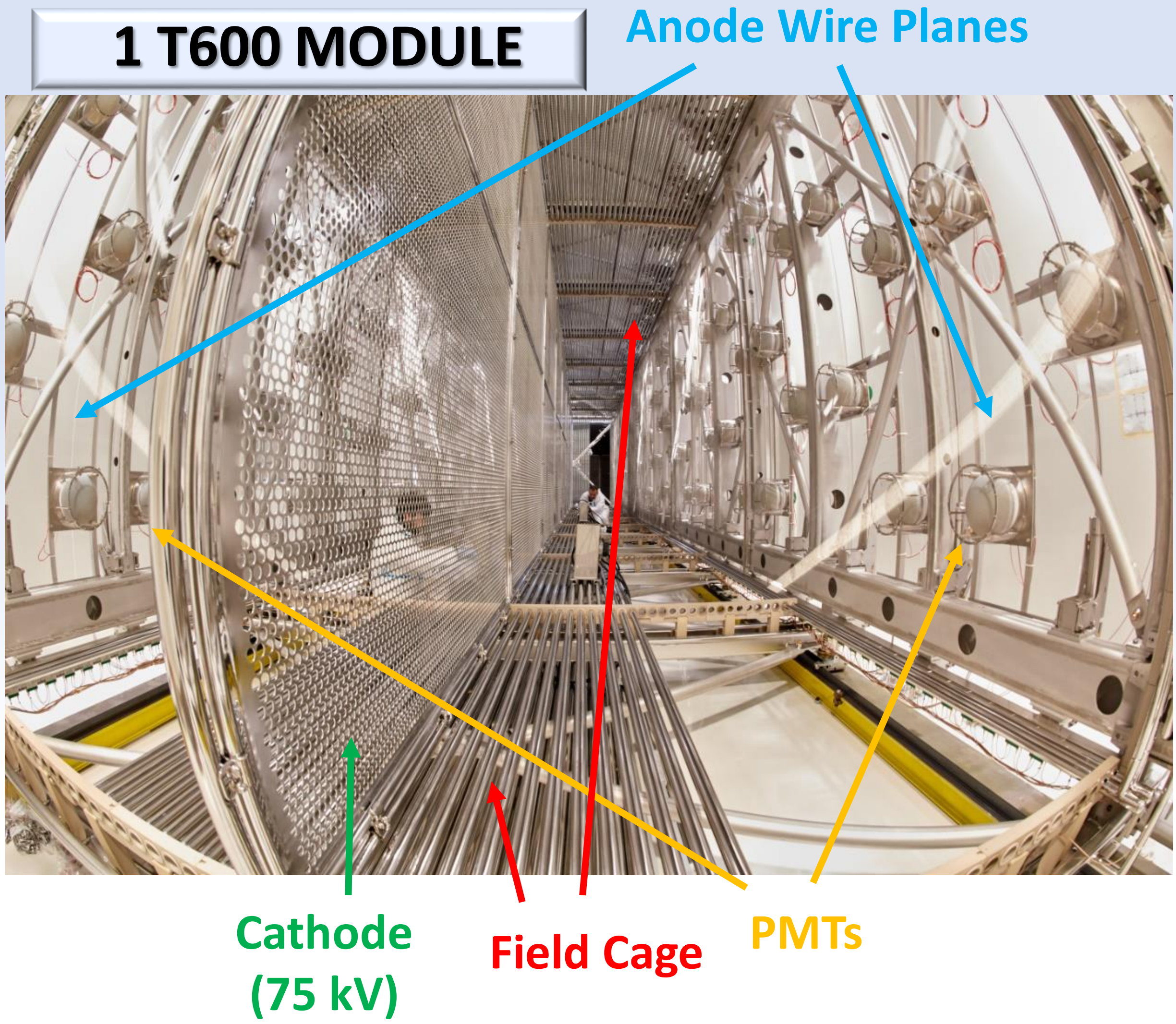
The ICARUS Time Projection Chamber

Each module is divided in 2 TPCs with a common central cathode:

- E_{DRIFT} = 500 V/cm
- 1 ms drift time
- v_{DRIFT} ~ 1. 55 mm/µs

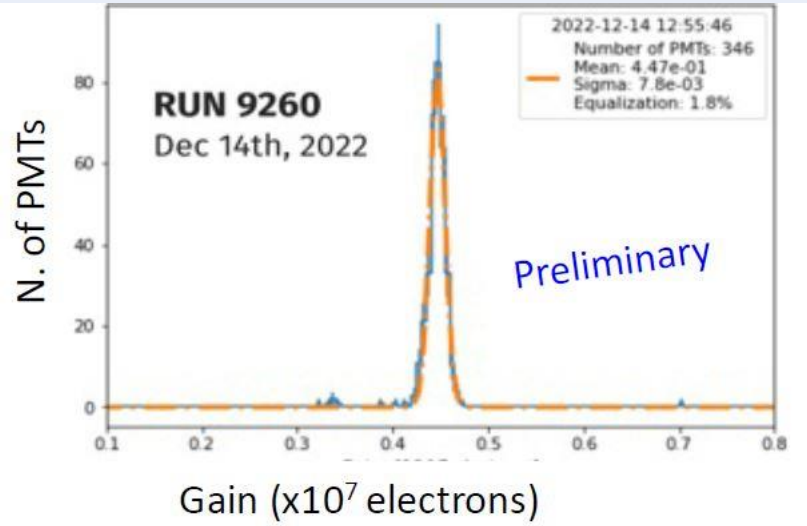
Each TPC has three parallel anode wires planes at different orientations (0°, ± 60°) w.r.t. horizontal to readout continuously ionization charge: Collection, Induction1 and Induction2:

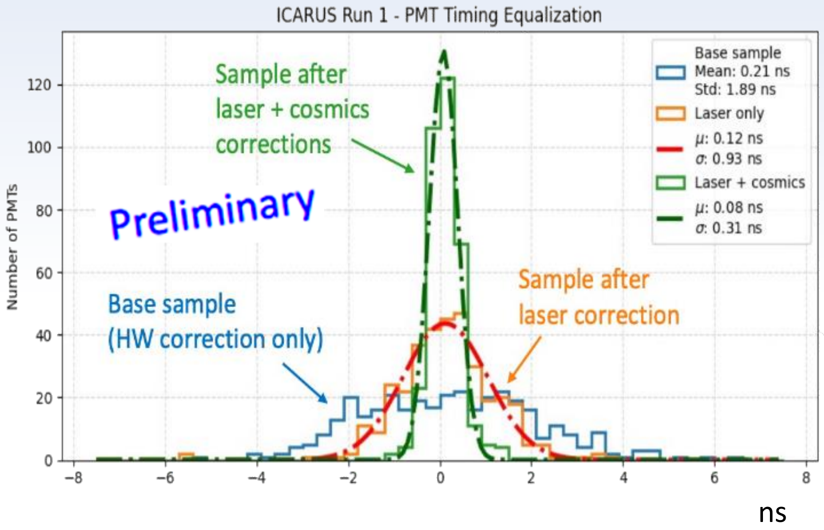
- 54000 total wires
- 400 ns sampling time
- 3 mm pitch



The light collection system

- 360 Hamamatsu 8“ PMT (5% coverage, 15 phe/MeV) installed behind the wire planes, 90 PMTs per TPC chamber
- Continuous read-out, digitization, discrimination and waveform recording of PMTs signals (2 ns sampling in 10 µs acquisition windows)
- a $\lambda \sim 405$ nm laser source and cosmic rays are used to calibrate the PMT gain and measure the PMT timing (σ = 310 ps)





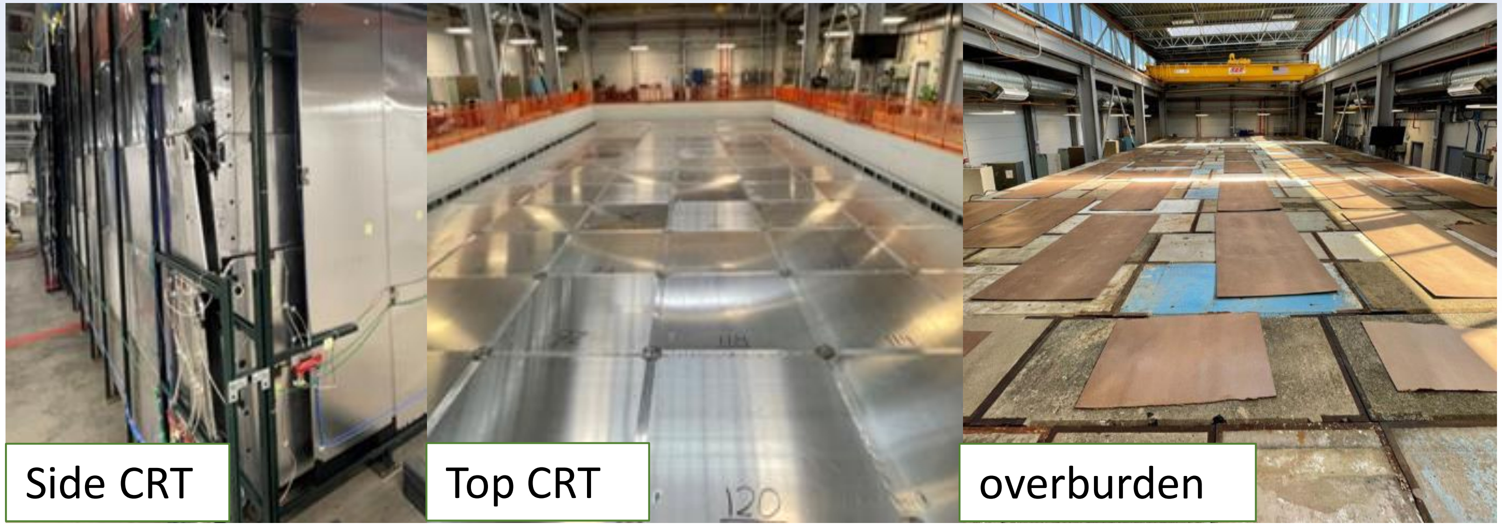
The Cosmic Ray Tagger (CRT)

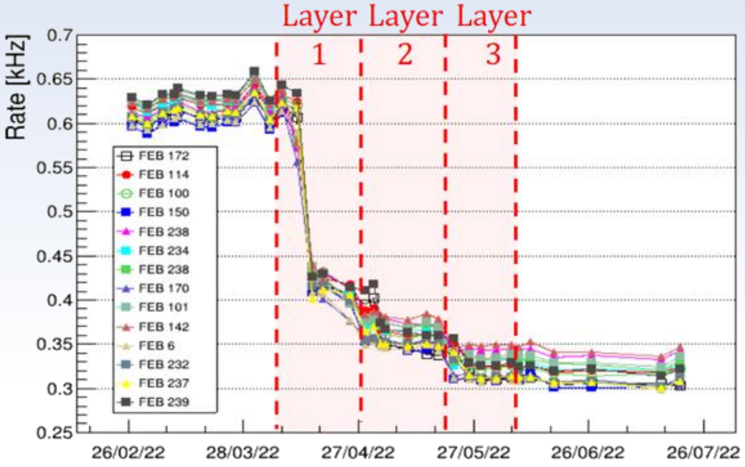
ICARUS at Fermilab operates at surface and the cosmic ray induced signal is mitigated by:

- 3 m concrete overburden reducing the rate of cosmic neutrons and γ by a factor 200 and muons by 25%
- the residual cosmic activity is rejected by a Cosmic Ray Tagger system made of plastic scintillator strips with 95 % tagging efficiency, few ns time resolution and ~ cm spatial resolution

Coincidence of CRT signal with the light signal in PMTs and matching with TPC tracks ensures cosmic background rejection

- Crucial for rejection of γs produced by μ interactions in the sorrounding materials that can generate e.m. showers miming a ν_e signal





Rates of cosmics measured by Top CRT modules during overburden installation

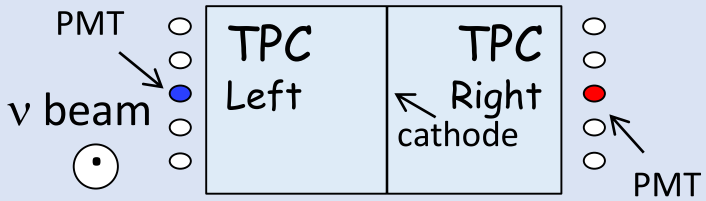
The trigger system

- ICARUS main trigger signal is generated by **majority of discriminated pairs of PMT** signals in **coincidence** with BNB (1.6 μs) and NuMI (9.5 μs) **beam spill gates**

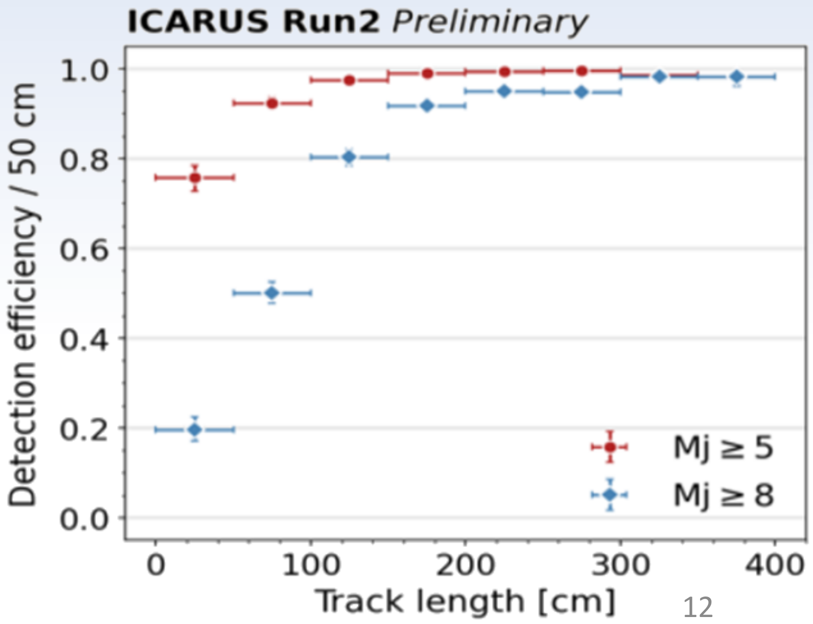
- Beam events are collected requiring at least **5 fired PMT pairs** inside one of the 6 m longitudinal slices (30 PMTs left + 30 PMTs right)

- **PMT light and CRT signals** are recorded for 2 ms around the trigger time to **recognize and tag cosmic rays** crossing the detector during 1 ms drift time

- Trigger efficiency measured with almost vertical cosmic muons independently selected by TPC tracks matched with CRT signals



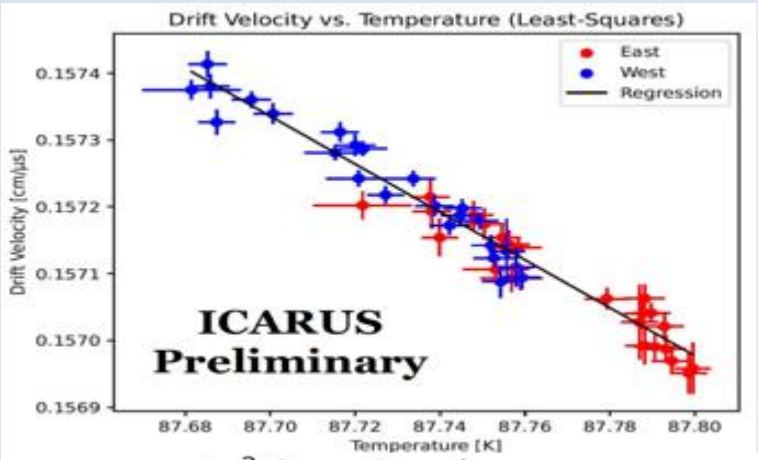
Total trigger rate < 1 Hz



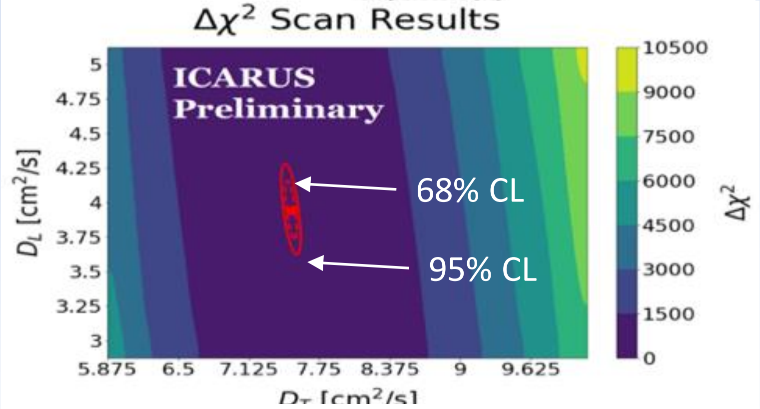
Detector physics measurements

Accurate measurements of main detector parameters with cosmic rays are needed for calibration of energy response and efficient PID:

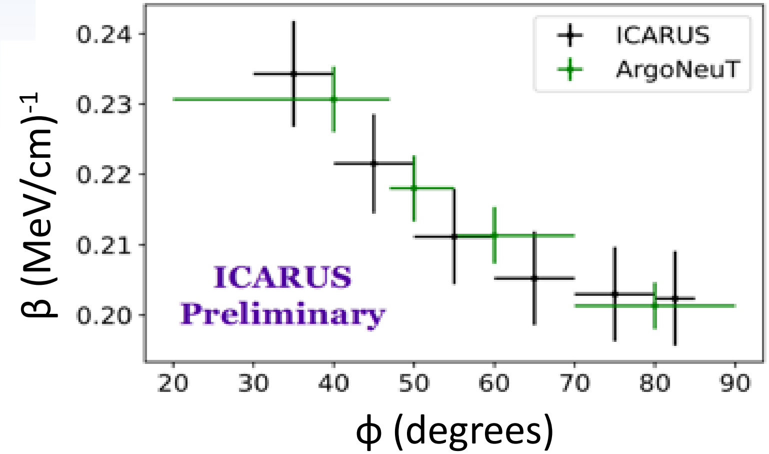
- electron drift velocity as a function of cryogenic temperature in Lar



- TPC signal widths from cosmic tracks have been used to measure ionization diffusion coefficients in the directions transverse (D_T) and longitudinal (D_L) to the drift electric field



- Observed dependence of electron recombination on track angle ϕ w.r.t. drift coordinate for high dE/dx (proton tracks), consistent with ArgoNeut LArTPC

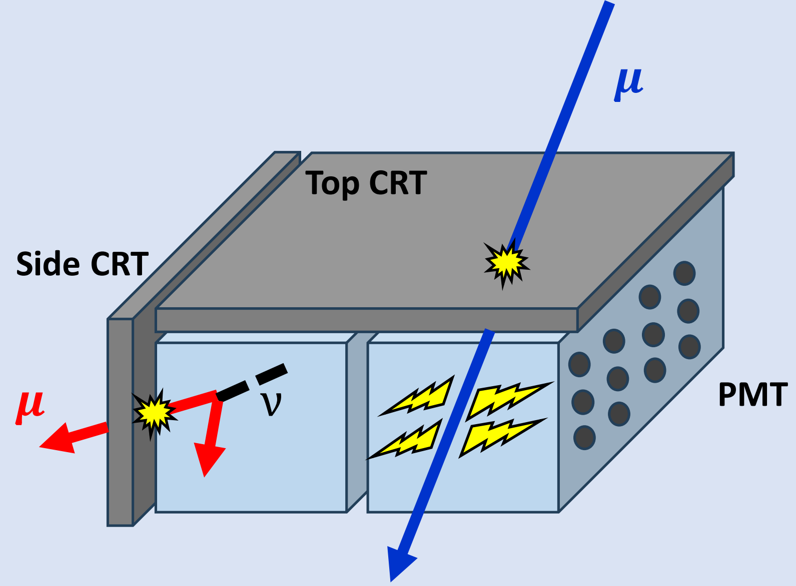


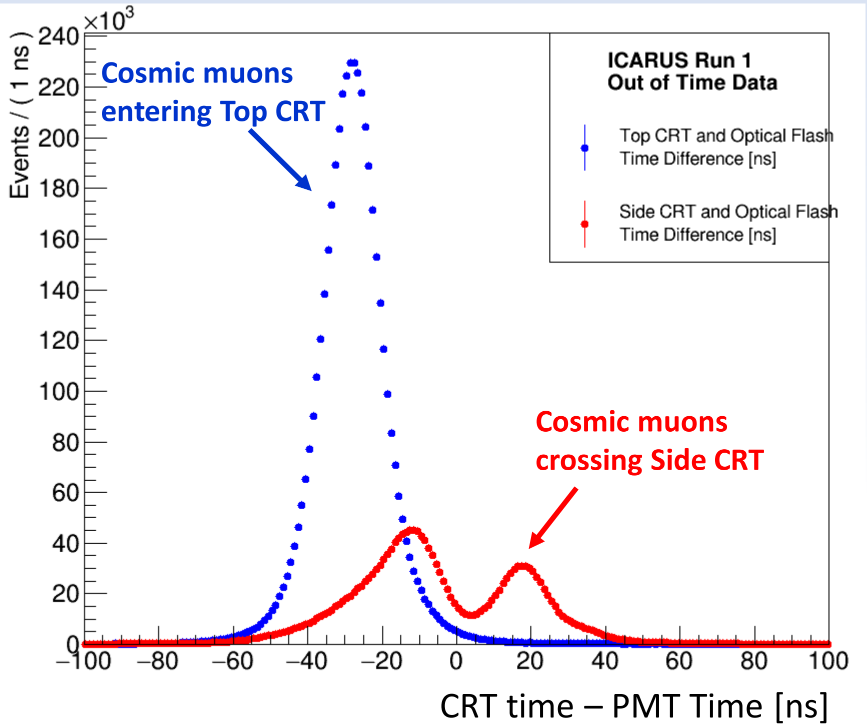
Cosmic background rejection

- Cosmic rays entering/exiting the detector can be identified by the relative timing between CRT and PMT signals

- This requires:
  - Accurate timing synchronization of PMT and CRT system through a global trigger signal
  - Modeling of scintillation and light propagation in LAr

- The CRT system can also be used for vetoing non-contained tracks from beam neutrino interactions: the absence of CRT hits allows to select a subsample of contained events



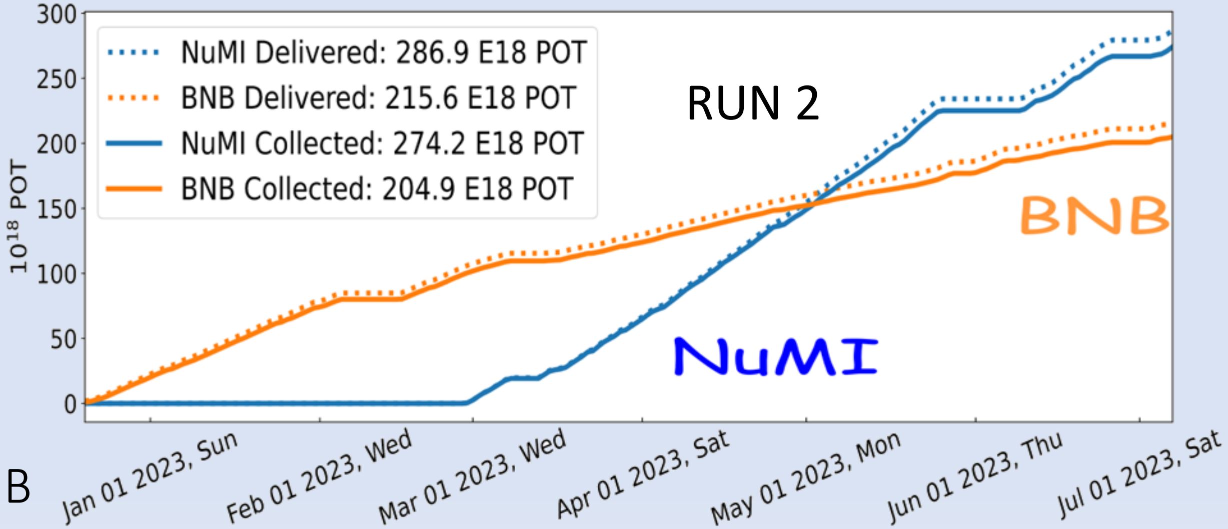


Icarus operations

Commissioning runs started in March 2021

Physics quality data started in June 2022:

- Run 1 (9 June – 9 July 2022) $\sim 6.8 \cdot 10^{19}$ POT NuMI
  $\sim 4.1 \cdot 10^{19}$ POT BNB
- Run 2 (2 Dec 22 – 16 Jul 23) $\sim 2.74 \cdot 10^{20}$ POT NuMI
  $\sim 2.05 \cdot 10^{20}$ POT for BNB

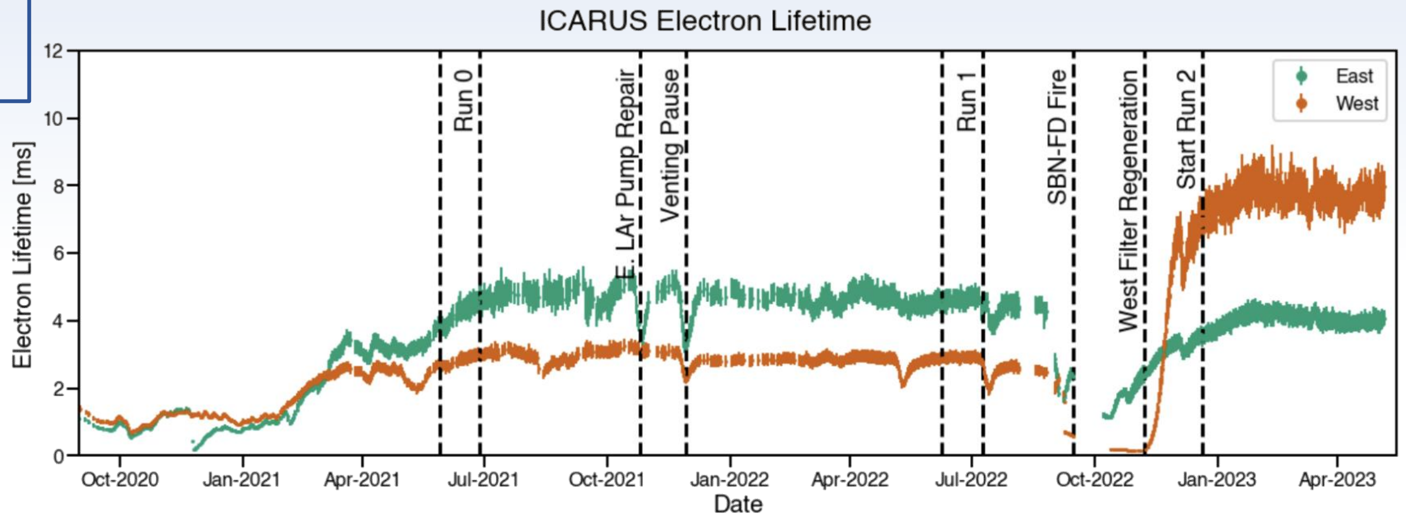


Total event statistic

$\sim \mathbf{2.46 \cdot 10^{20}}$ POT BNB , $\sim \mathbf{3.42 \cdot 10^{20}}$ POT NuMI with a detector live-time of 93% and 95% respectively.

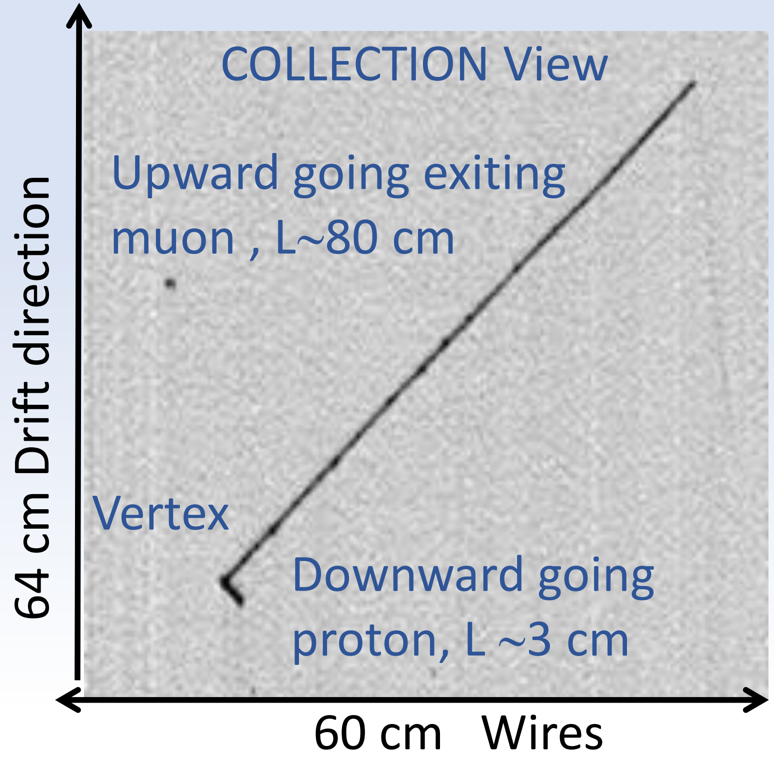
Liquid argon purity level is continuously monitored

- West LAr purity filters were regenerated during the 2022 summer shutdown.
- The East LAr purity filters regenerated this summer and will increase electron lifetime and improve uniformity.

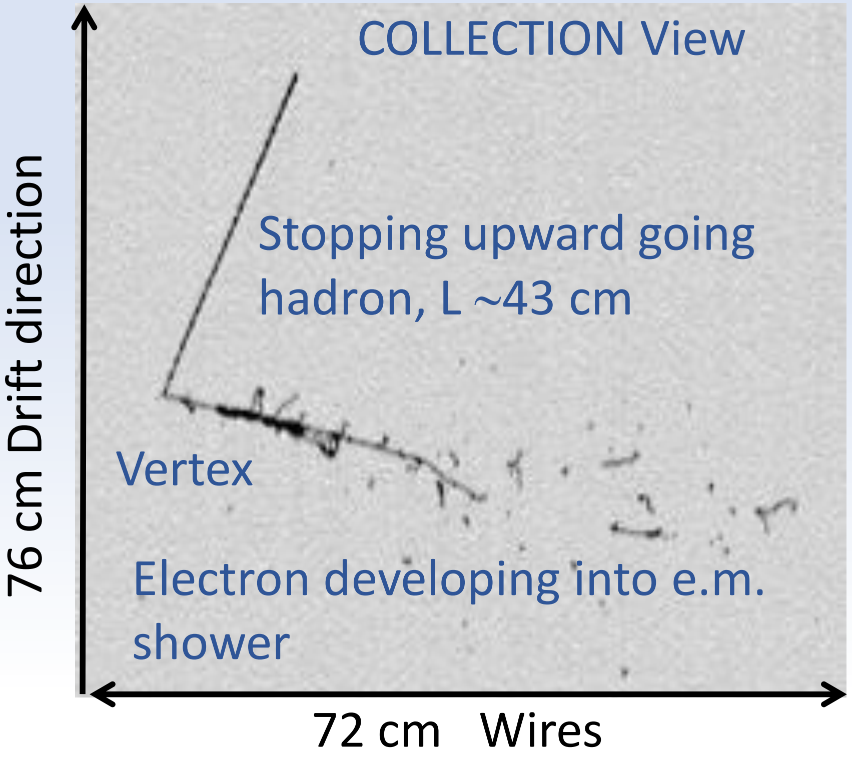


Neutrino events candidates

Typical BNB CCQE ν_μ candidate, E_{DEP} ~ 200 MeV



Contained NuMI CCQE ν_e candidate, E_{DEP} ~ 800 MeV



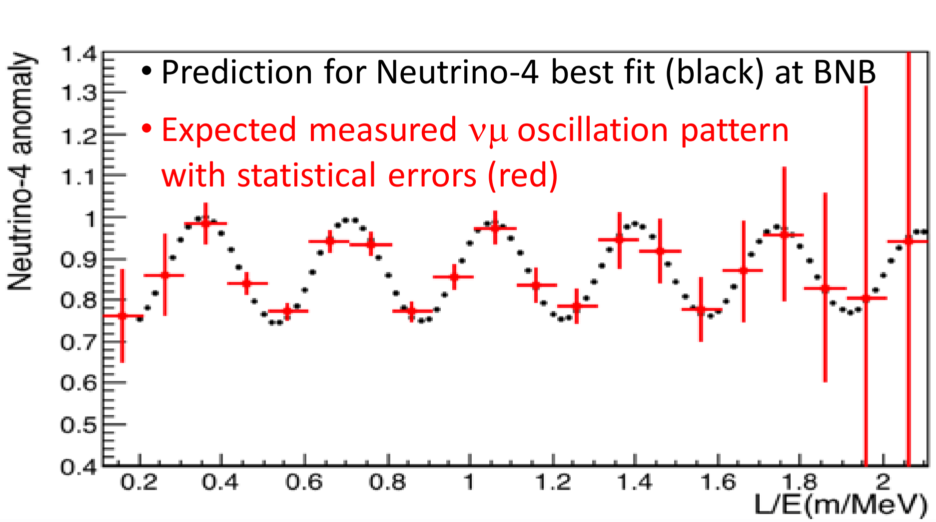
High spatial resolution in combination with dE/dx measurement at the beginning of the shower ensures e/γ showers separation → very good ν_e identification

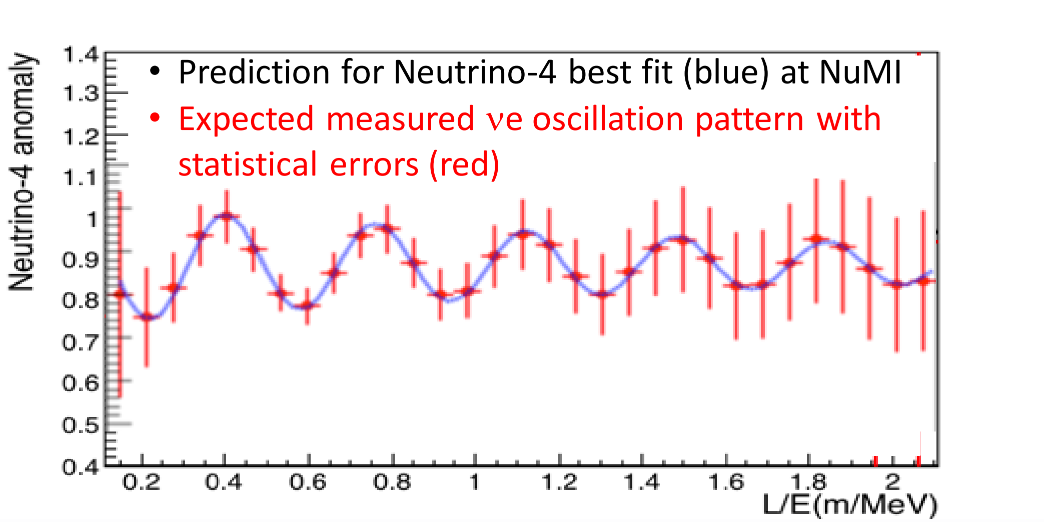
Study of Neutrino-4 anomaly

BNB and NuMI neutrinos at ICARUS are characterized by an L/E ~ 1-3 m/MeV as Neutrino-4 experiment but in a different energy range

ICARUS can confirm or exclude the Neutrino-4 oscillation signal by measuring:

- disappearance of ν_μ from BNB, focusing on fully contained QE ν_μ CC interactions (high statistic already available)
- disappearance of ν_e from NuMI beam, selecting fully contained QE ν_e CC events (more direct comparison with Neutrino-4 results)





ν_μ survival oscillation probability at BNB:

- ~ 8500 QE events, >50 cm contained μ track
- $\sim 8.4 \cdot 10^{19}$ POT (Run1+Run2 $\sim 2.4 \cdot 10^{20}$)

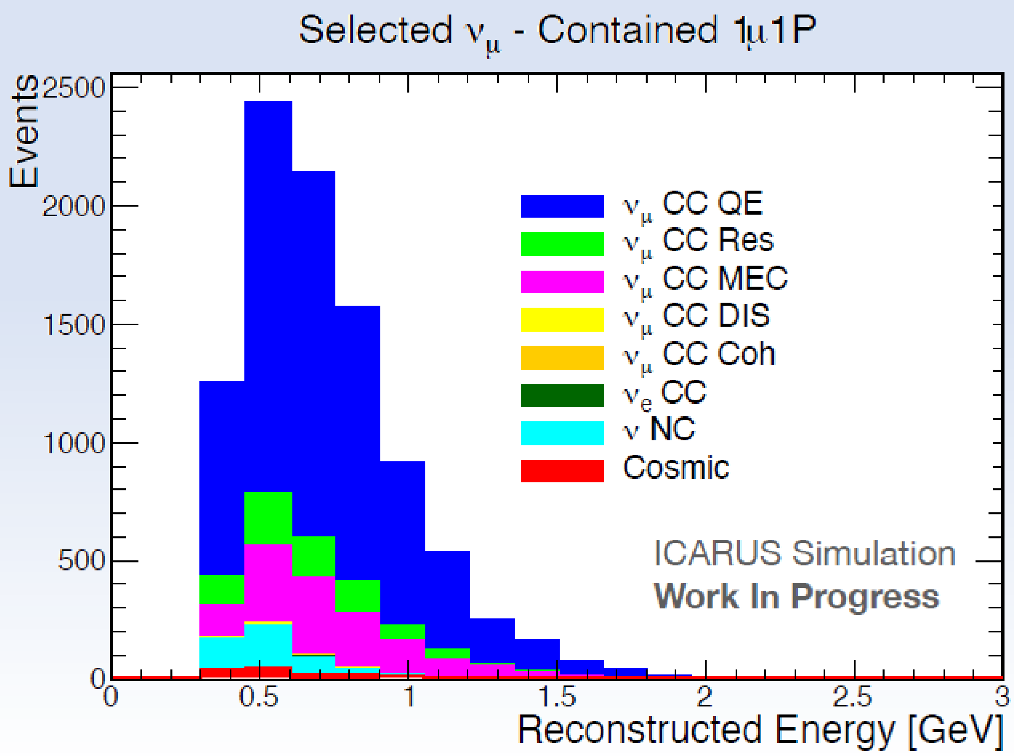
ν_e survival oscillation probability at NuMI:

- ~ 5200 QE events with contained e.m. shower
- $\sim 9 \cdot 10^{20}$ POT (Run1+Run2 $\sim 3.3 \cdot 10^{20}$)

Comparison with a beam-off event sample will allow to observed Neutrino-4 modulation

Status of event selection for oscillation analysis

- A first automatic procedure for selecting 1μ 1p ν_μCCQE interactions fully contained in the active volume is being prepared starting from MC events to be then applied to data.
- From MC simulation, the selection of true fully contained ν_μCCQE contained is based on:
  - TPC-PMT match within a beam-spill
  - Direction-based rejection of cosmics
  - Interaction vertex in the fiducial volume
  - Fully contained μ candidate with L > 50 cm and a single contained proton with no other particles in the event

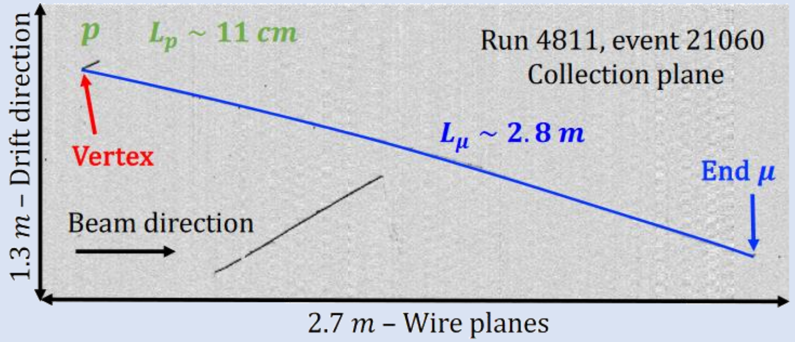


Improvement expected from ongoing activities:

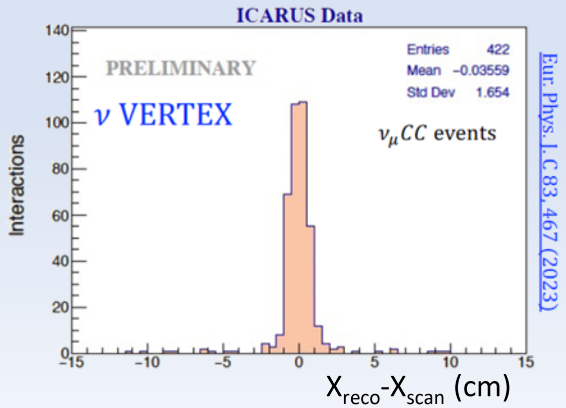
- Cosmics rejection exploiting CRT/PMT matching
- Upgraded calibration and PID
- Improved event reconstruction
- Include events with multiple protons in the selection

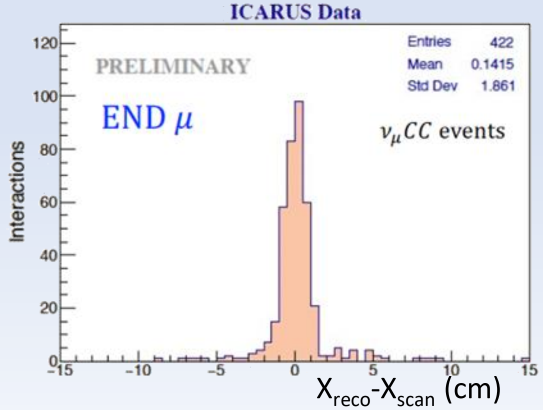
Tuning of event reconstruction

ν_μCCQE candidates have been visually selected/measured and are exploited to qualify the automatic event selection

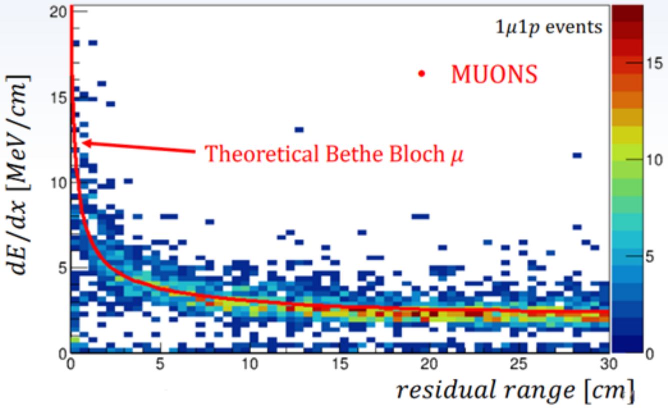


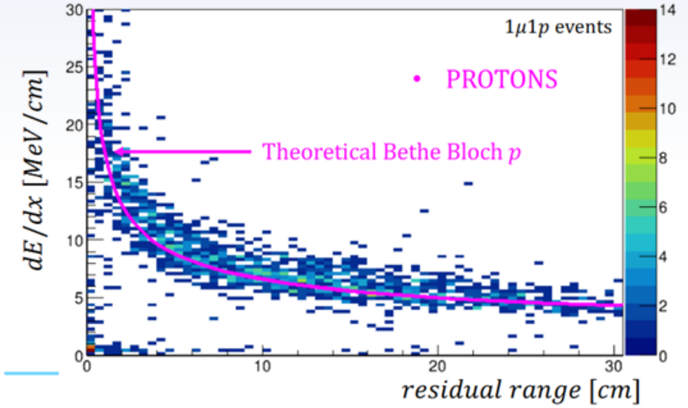
- For each visually scanned event the 3D positions of the vertex, end muon and end proton (when present) tracks are saved
- Reconstructed ν interaction vertex and μ end-point is within ~2 cm from the measured one.





- Comparison between the measured dE/dx vs residual range along the track with the theoretical profiles from different particles μ, p, K, π allows PID





Conclusions

- ICARUS has been taking high-quality physics data in stable conditions, with both BNB and NuMI beams, since June 2022

- Neutrino candidates have been successfully collected and are being used to further develop and tune automatic selection and reconstruction software tools

- First ICARUS physics measurements will be standalone: study of the Neutrino-4 claims via ν_μ disappearance with BNB, then ν_e disappearance with the NUMI off-axis beam.

- More studies ongoing: ν-Ar interaction cross-sections in a range of interest for DUNE and search for BSM physics

- After the ICARUS-only phase, the SBND detector will join soon as near detector from the BNB target to confirm or exclude definitively the existence of light sterile neutrino in 3 years of data taking with 5σ sensitivity

Thank you for your attention!