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

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ON BEHALF OF THE ICARUS COLLABORATION

THE FIRST EDITION OF THE AFRICAN CONFERENCE ON HIGH ENERGY PHYSICS

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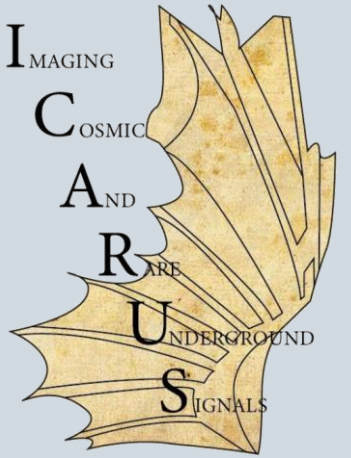
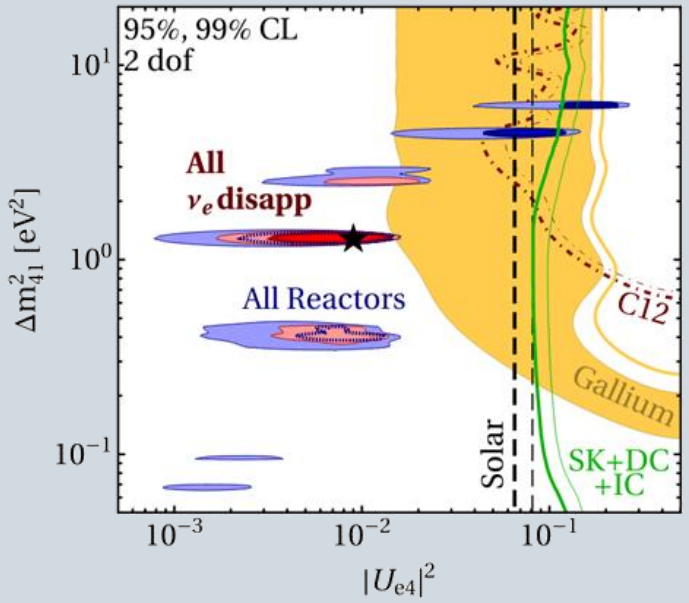


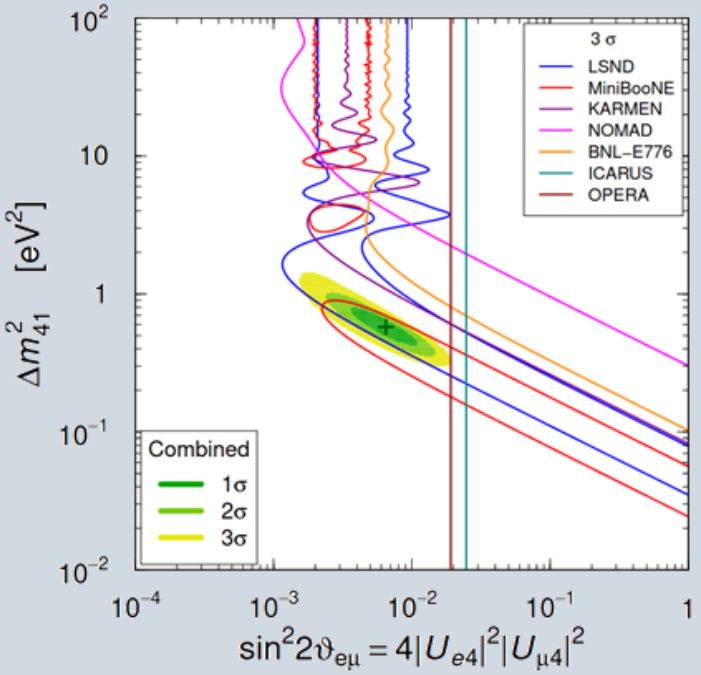
The 3-neutrino anomaly status

Despite the well-established 3-flavour neutrinos mixing picture, such model is being questioned after **anomalies have been reported**

- $\bar{\nu}_e$ appearance - LSND experiment saw a $3.8\ \sigma$ excess of $\bar{\nu}_e$ in the $\bar{\nu}_e \rightarrow e^+ + n$ channel
- ν_e disappearance - SAGE, GALLEX experiments showing an observed/predicted rate $\mathrm{R} = 0.84 \pm 0.05$. Recently confirmed at 4σ by BEST experiment
- $\bar{\nu}_e$ disappearance - in nuclear reactor experiments, $\mathrm{R} = 0.934 \pm 0.024$

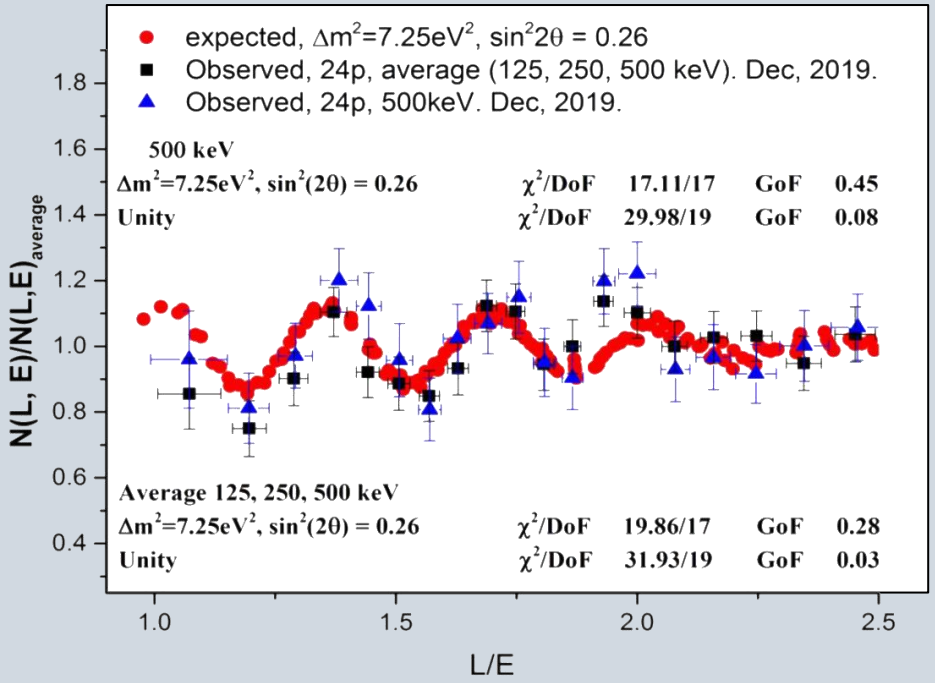
A clear tension between appearance and disappearance experiments, which are characterized by different neutrino energy range and detection technique, is evident.





The 3-neutrino anomalies status

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 $\mathbf{L/E_\nu \sim 1 - 3\ m/MeV}$ modulation

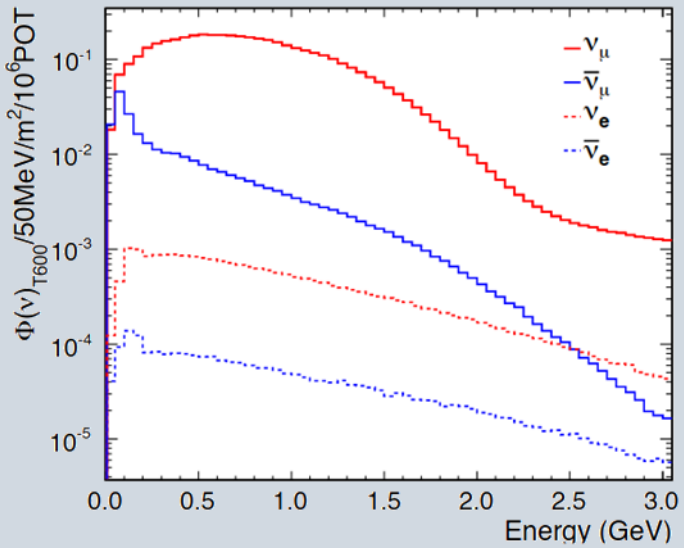


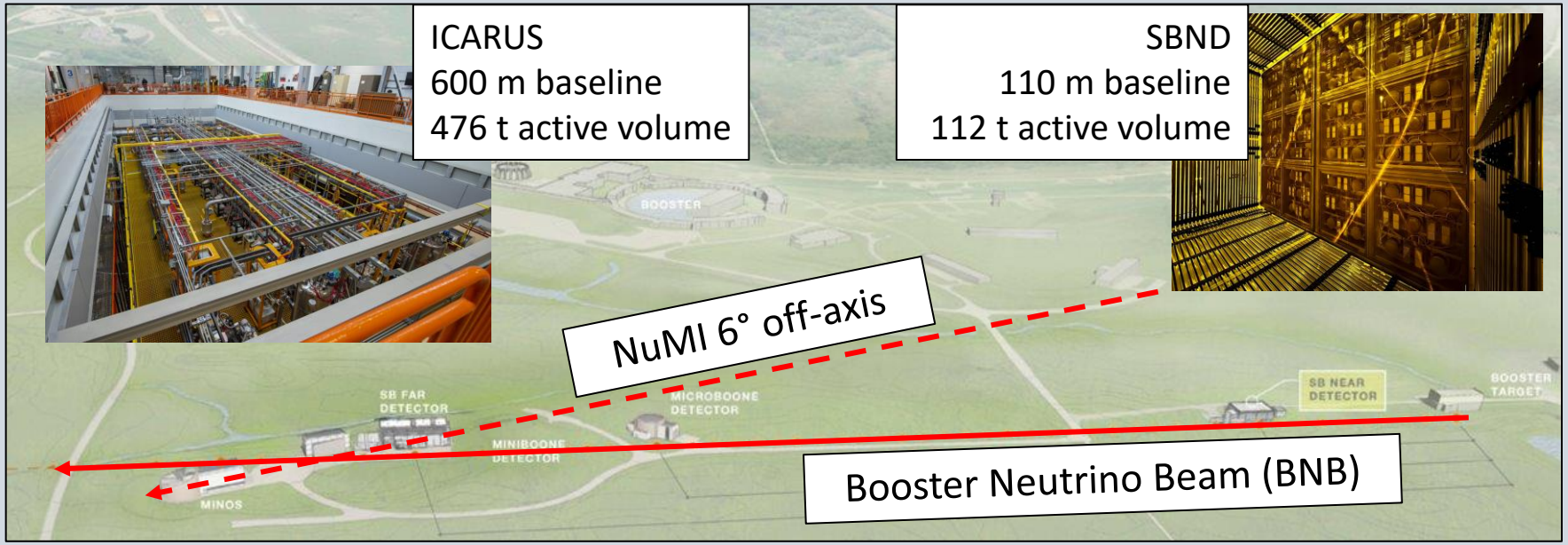
Neutrino signal (blue and black) compared with expectation (red) for $\Delta m^2_{14} = 7.25\ \mathrm{ev}^2$ and $\sin^2(2\theta_{14}) = 0.26$ as a function of L/E

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

THE SBN program at FNAL

BNB is a well-characterized $\nu_\mu(\overline{\nu_\mu})$ beam with low ν_e contamination





- ICARUS and SBND LAr-TPCs are installed at 600 and 110 m from the Booster Neutrino Beam (BNB)
- ICARUS is also exposed 6 degrees off-axis to the NuMI beam, accessing the electron-neutrino-rich component of the spectrum which will grant access to a rich Beyond Standard Model physics program.
- Both appearance and disappearance channels can be observed, granting access to study the nature of the observed anomalies and shed light on the existence of sterile neutrinos

The ICARUS detector

Self-triggering detector, with precise 3D imaging and calorimetric capabilities.

Two identical modules:

- 2 TPCs per module
- Total mass of 760t of Lar
- 476t total active mass

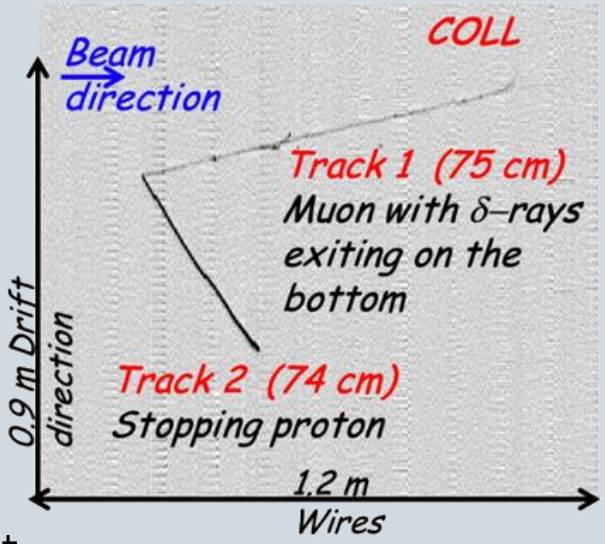
Fully instrumented with 360 PMTs coated TPB and a 4π Cosmic Ray Tagging System (CRT).

ICARUS moved from Gran Sasso (Italy) to FNAL (US) in 2017 after a major upgrade in view of the shallow depth operations [*Eur. Phys. J. C* **83**, 467 (2023)].

The TPC

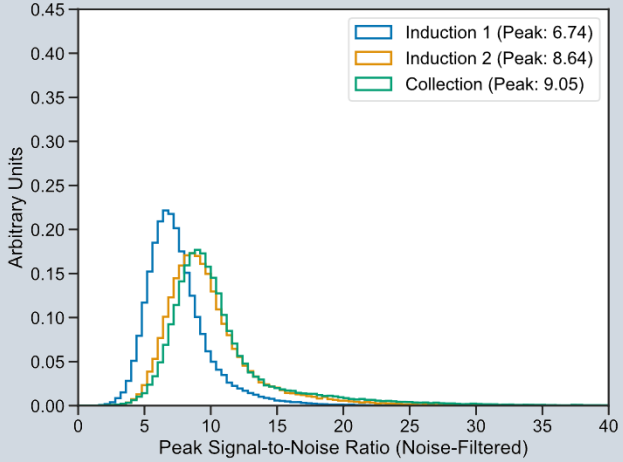
Each module is composed of two TPCs with a common cathode:

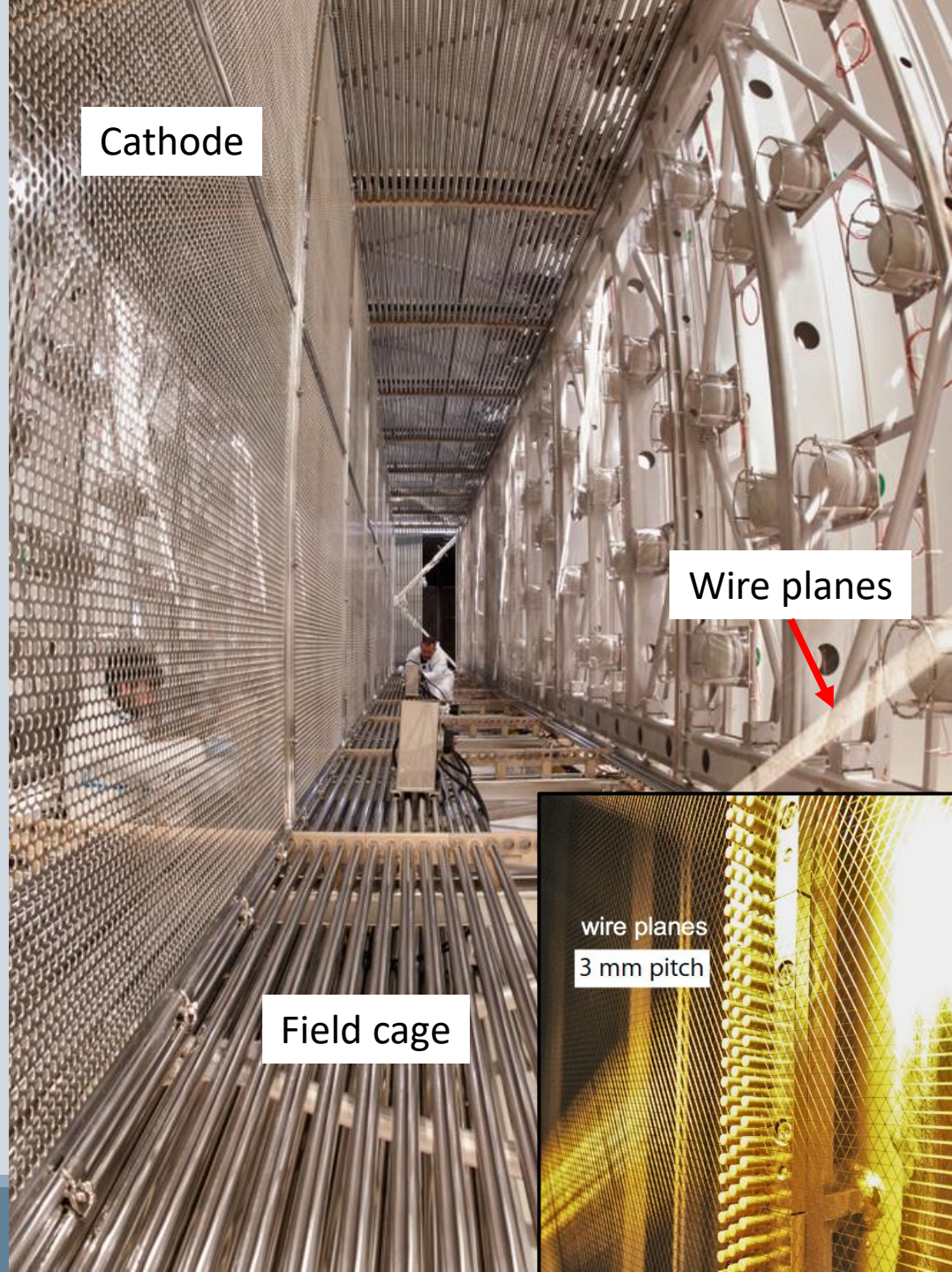
- 1.5 m drift length
- $E_{drift} = 500\ V/cm$
- $T_{drift} \sim 1\ ms$
- $V_{drift} \sim 1.55\ mm/\mu s$



Three readout planes (0°, ± 60° w.r.t. horizontal) are used to continuously read ionization charge:

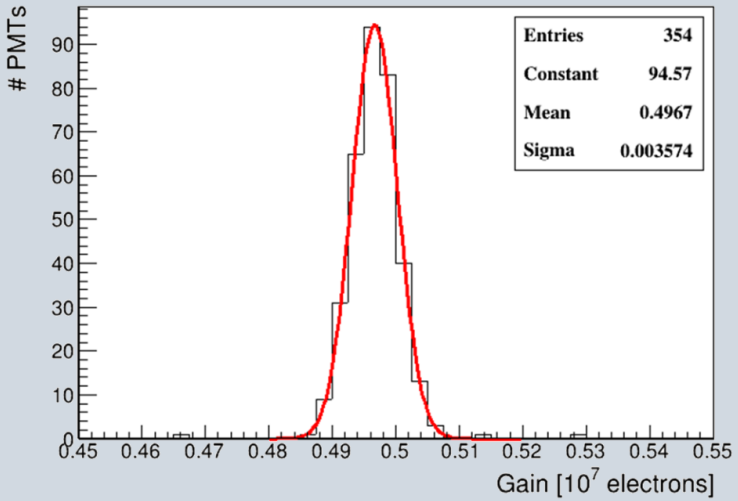
- 54000 total wires
- 400 ns sampling time
- 3 mm pitch

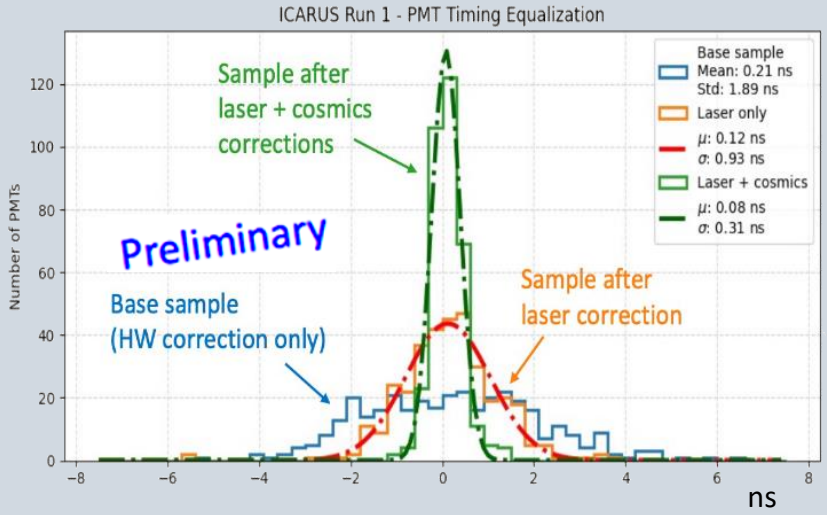




The light collection system

- 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 us acquisition windows)
- a $\lambda \sim 405$ nm laser and cosmic rays are used to calibrate the PMT gain and measure the PMT timing ($\sigma = 0.31$ ns)





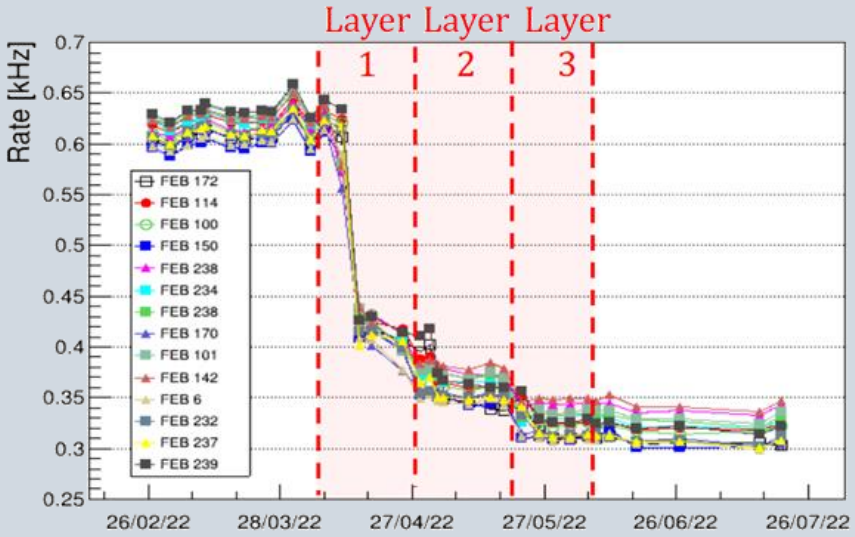
PMT signals are crucial to the trigger logic!

The cosmic ray tagger

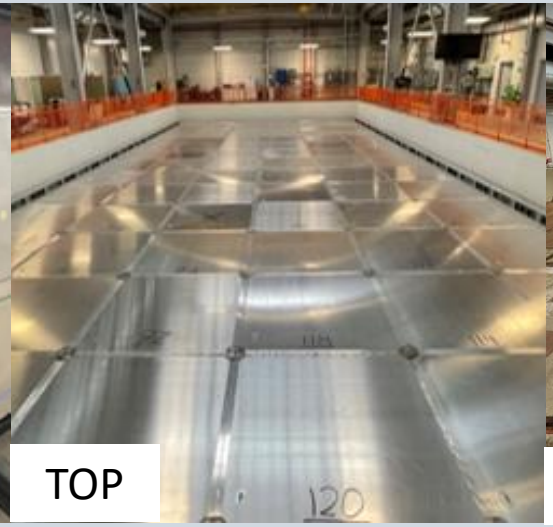
ICARUS is on the surface and hence exposed to a huge comic background activity that would overwhelm the detector

In order to mitigate such contribution, ICARUS is instrumented with

- 4π Cosmic Ray Tagger (CRT): 3 subsystems with double layer scintillation bars equipped with SiPMs tagging incoming cosmics with ~ 95% efficiency, ~cm spatial resolution and ~ns timing resolution
- Coincidence of CRT signal with the light and charge signals in the TPC used for background rejection
- $\sim 3\ m$ concrete overburden placed on top of the detector




SIDE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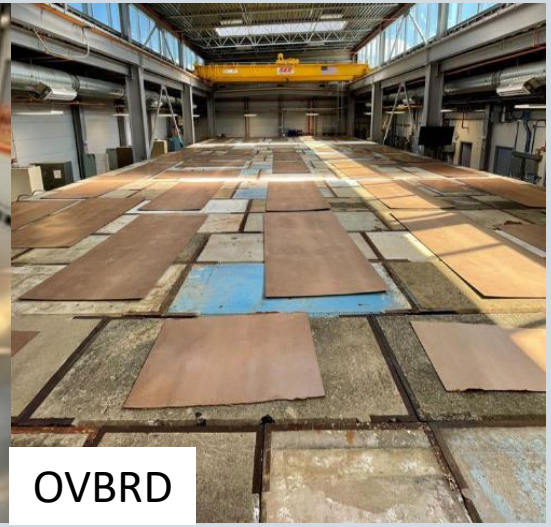
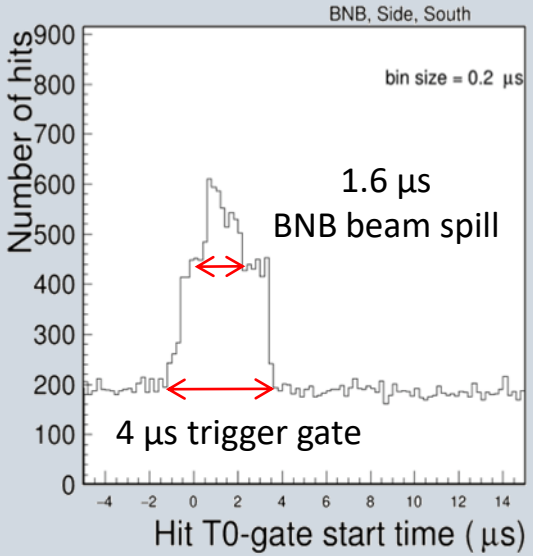
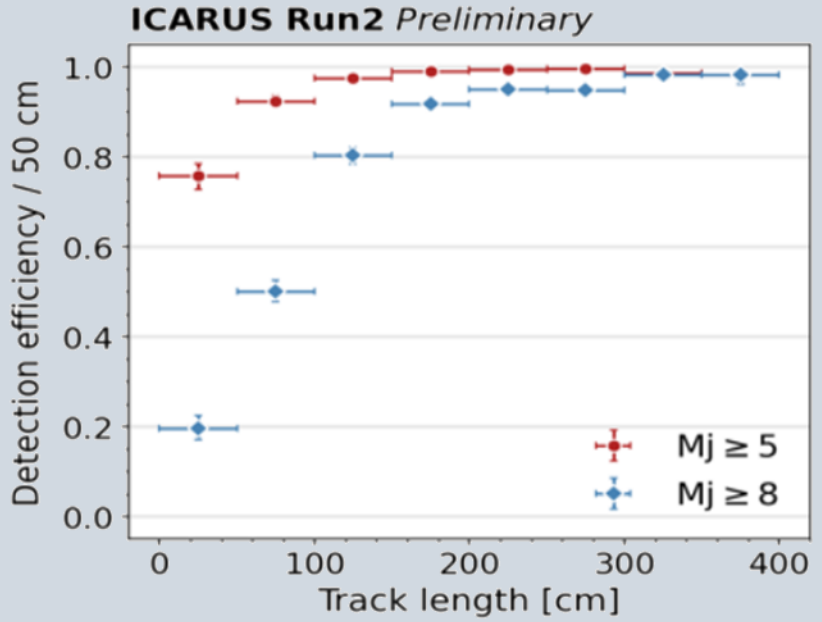
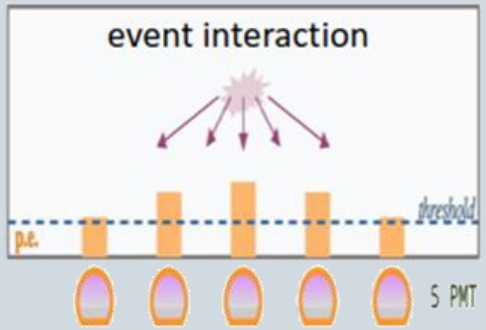

OVBRD



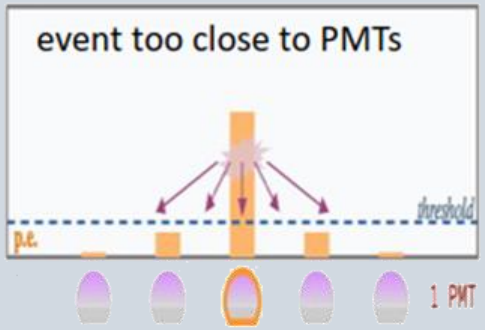
The trigger system

- Trigger system based on the coincidence of the beam spills and the prompt scintillation light detected by the PMTs
- Minimum 5 fired PMT pairs (Mj = 5) inside one of the 6 m longitudinal slices (30 PMTs left + 30 PMTs right)
- PMT and CRT signals also recorded in 2 ms around the trigger to recognize cosmic rays crossing the LAr-TPCs during the 1 ms e-drift time
- The trigger efficiency measured with ~vertical cosmic muons independently selected by TPC tracks matched with CRT signals.





enough light,
enough firing PMTs



plenty of light, not
enough firing PMTs

To improve the trigger performance an additional and independent trigger, based on the scintillation light signal amplitude instead of multiplicity of fired PMTs, is under study.

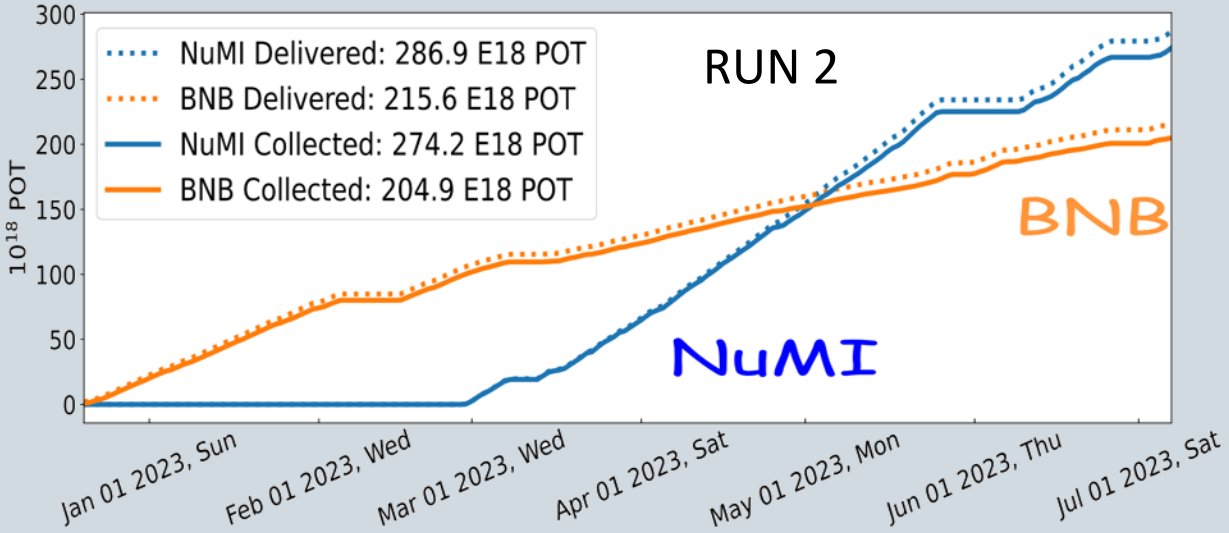
ICARUS Operations

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) $\sim 2.7 \cdot 10^{20}$ POT NuMI
  $\sim 2.0 \cdot 10^{20}$ POT for BNB

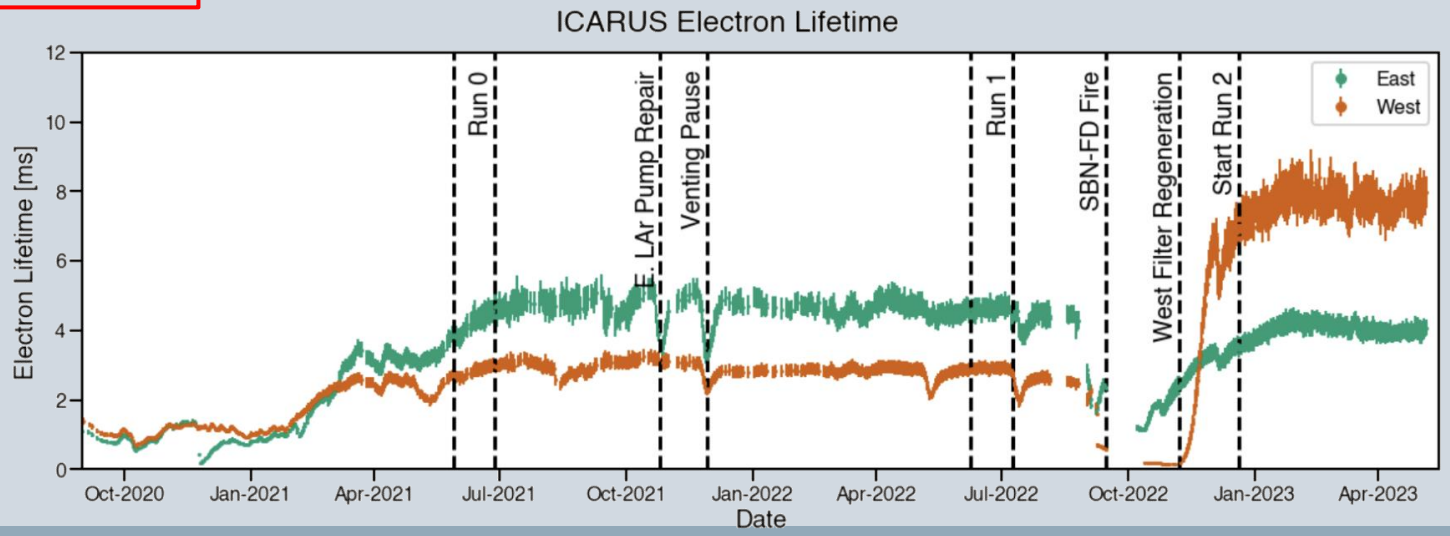
Total event statistic

$\sim 2.46 \cdot 10^{20}$ POT BNB , $\sim 3.42 \cdot 10^{20}$ POT NuMI
with an uptime of 93% and 95% respectively.



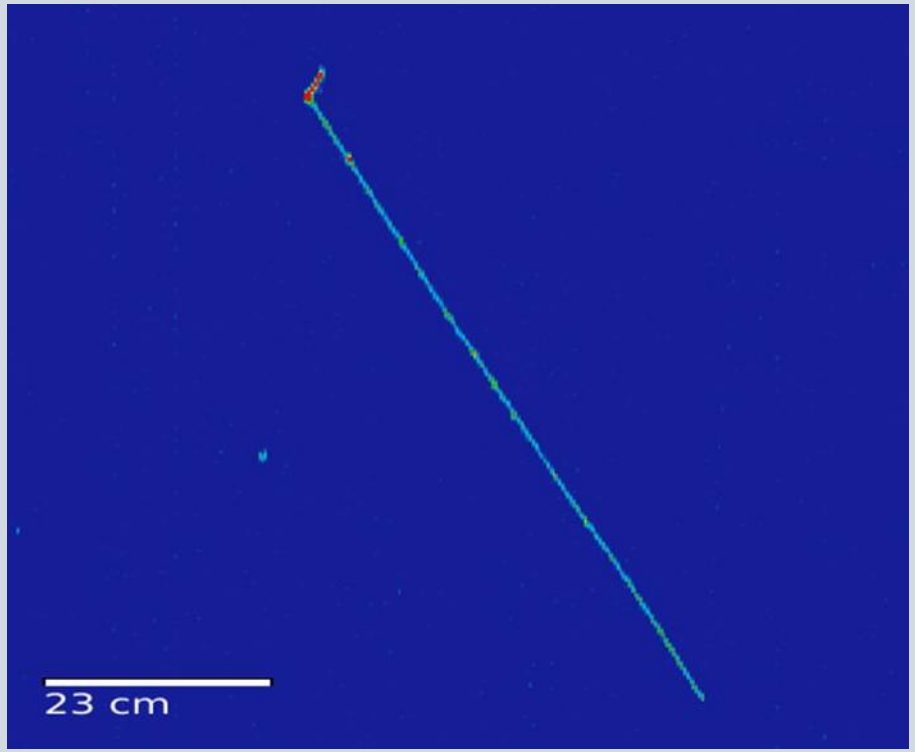
Liquid argon purity level is continuously monitored

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

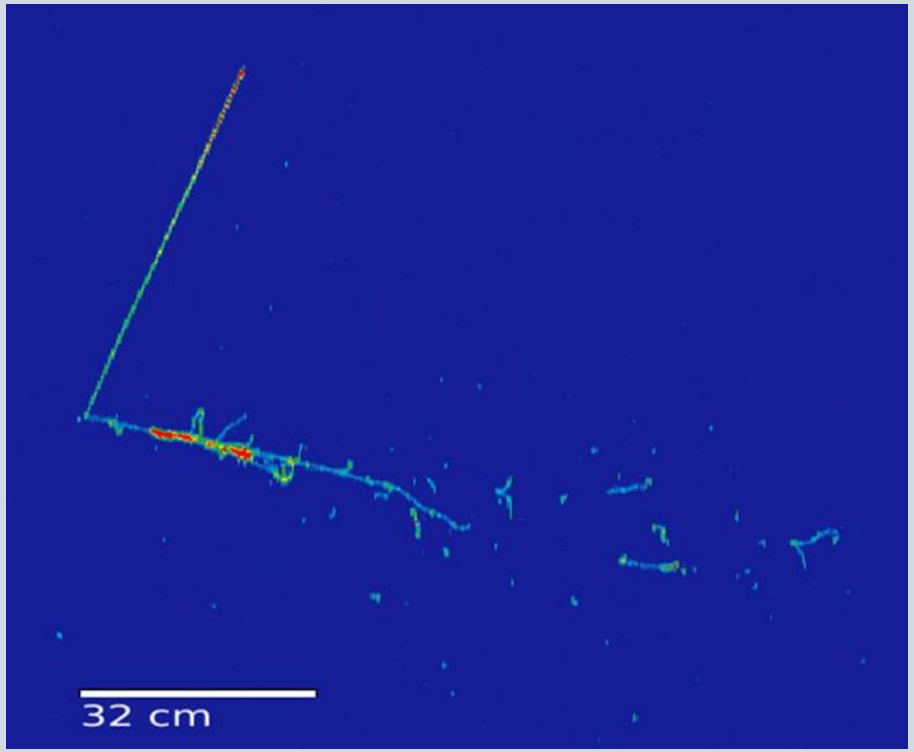


Neutrino event candidates

$\nu_\mu CC$ interaction
from a BNB neutrino



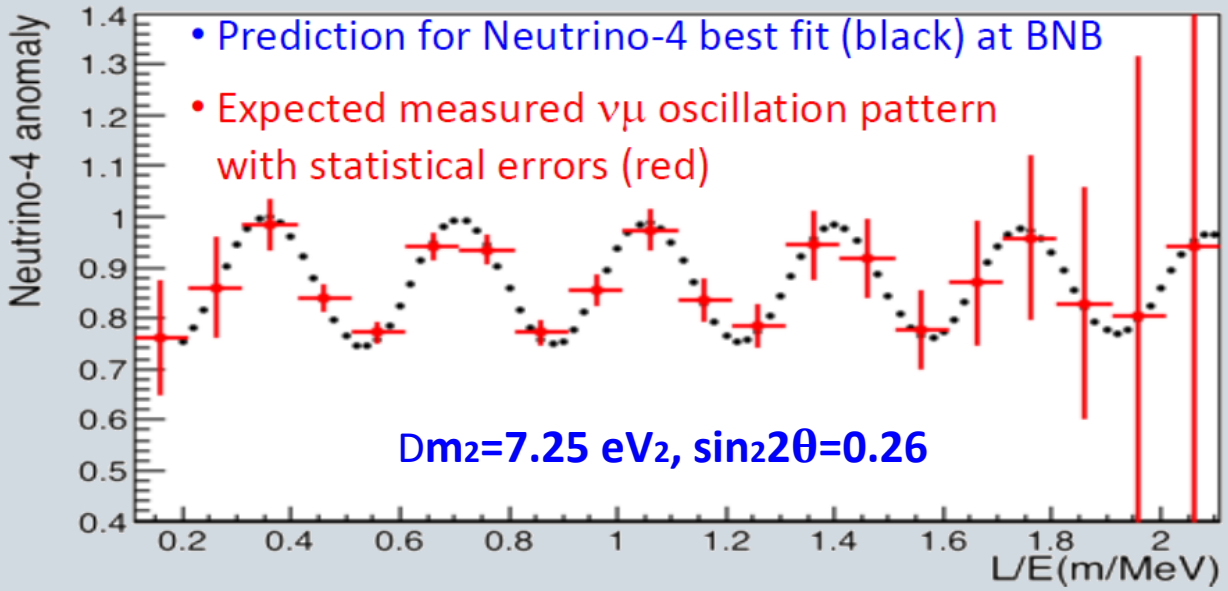
$\nu_e CC$ interaction
from a NuMI neutrino



Toward the Oscillation analysis

ICARUS presents remarkable similarities to NEUTRINO-4 which should allow to settle the NEUTRINO-4 sterile- ν claims in the initial ICARUS-only run with BNB and NuMI in the same L/E ~ 1-3 m/MeV but at ~100 times higher neutrino energy

ICARUS-only run, focusing on well-defined $QECC\ \nu_\mu\ and\ \nu_e$ fully contained events, could verify the NEUTRINO-4 claim.



ν_μ survival oscillation probability at Booster:

- ~ 8500 QE events, >50 cm contained μ track
- $\sim 0.4 \cdot 10^{19}$ POT (Run1+Run2 $\sim 2.4 \cdot 10^{20}$)
- $\Delta E/E \sim 3\%$

Toward the Oscillation analysis

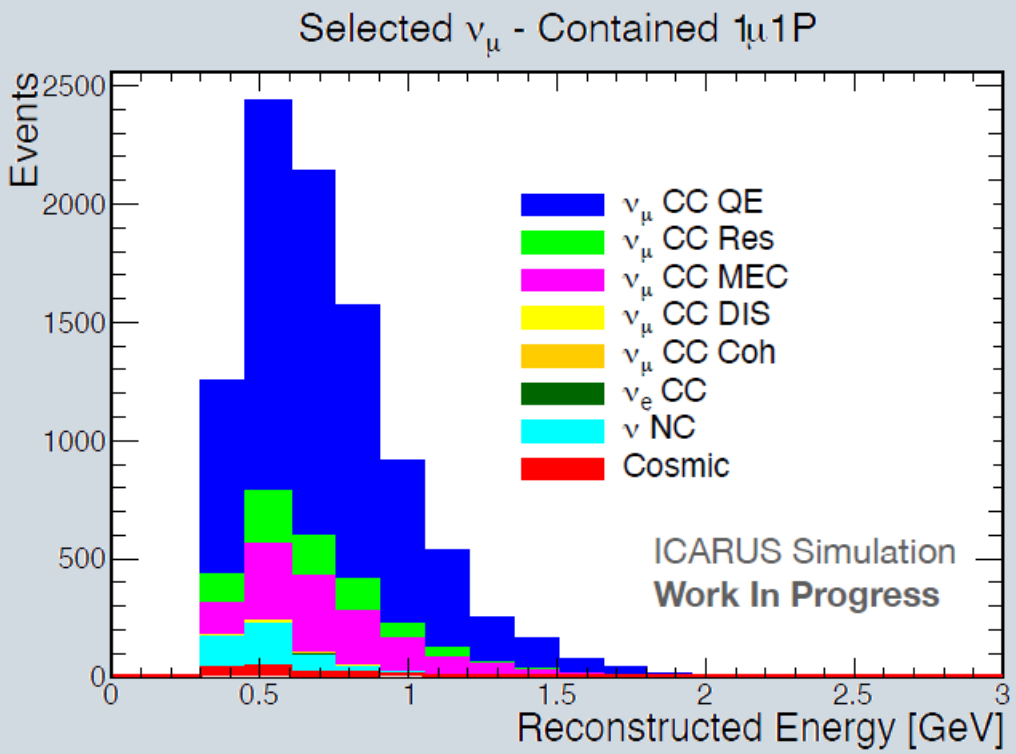
A first automatic procedure for selecting 1μ 1p ν_μCCQE interactions fully contained in the active volume is being prepared starting from MC events to be then applied to data.

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
- Fully contained μ and p candidates with no other particles

Improvement expected from ongoing activities:

- Cosmics rejection exploiting CRT/PMT
- Upgraded calibration and PID
- Improved event reconstruction



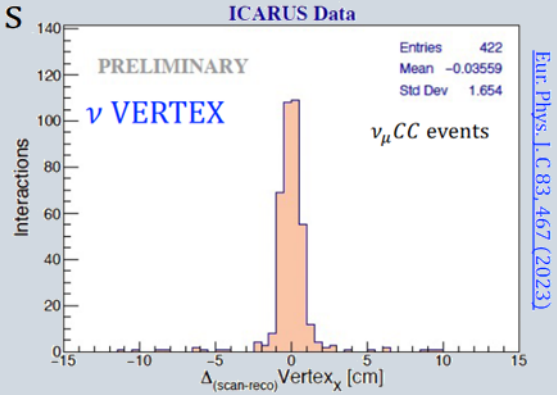
Tuning of events reconstruction

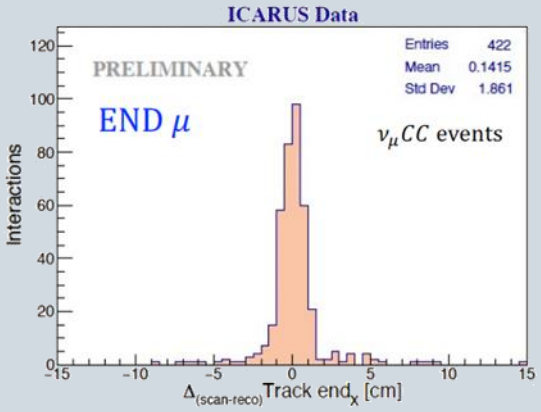
ν_μCCQE candidates have been **visually selected/measured** and are exploited to qualify the automatic event selection

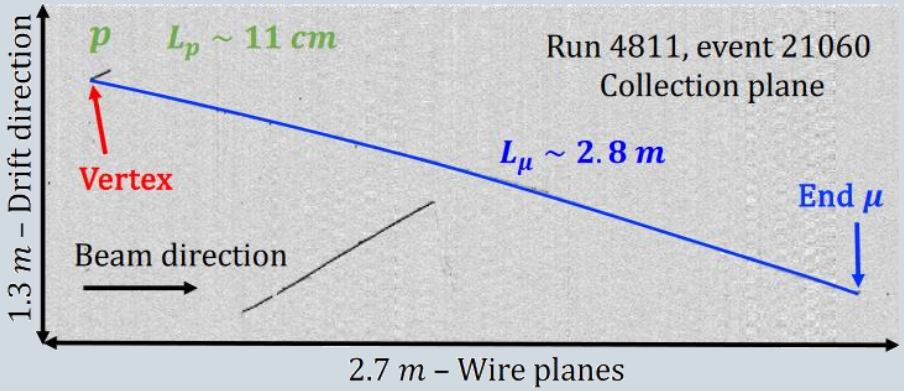
For each visually scanned event the **3D positions of the vertex, end muon and end proton (when present) are saved**

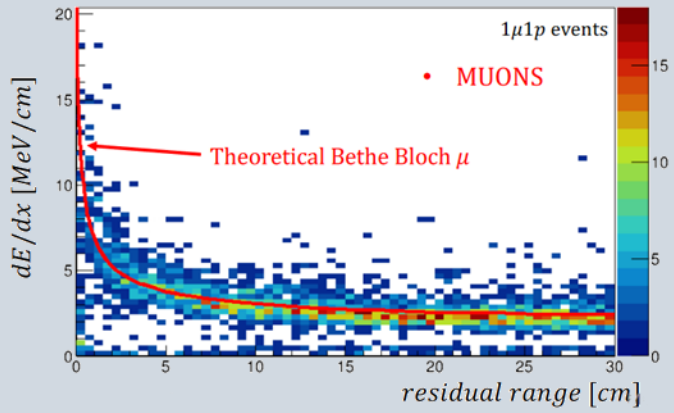
Reconstructed ν interaction vertex and μ end-point is within **~2 cm** from the measured one.

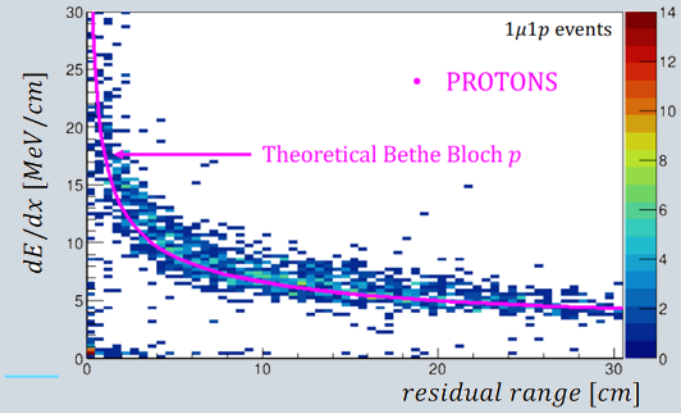
Comparison between the **measured dE/dx vs residual range** along the track with the theoretical profiles from different particles μ, p, K, π allows **PID**











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, search for sub-Gev Dark Matter signals and other BSM physics

Collected data is being actively processed and analyzed.

After the ICARUS-only phase, the SBND detector will join soon as near detector from the BNB target to perform a definitive 5σ analysis of sterile neutrinos search