Short-Baseline neutrino oscillation searches with the ICARUS detector at Fermilab

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on behalf of the ICARUS Collaboration

Imaging Cosmic And Rare Underground Signals

SBN Program

INFN Istituto Nazionale di Fisica Nucleare

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ICARUS Collaboration

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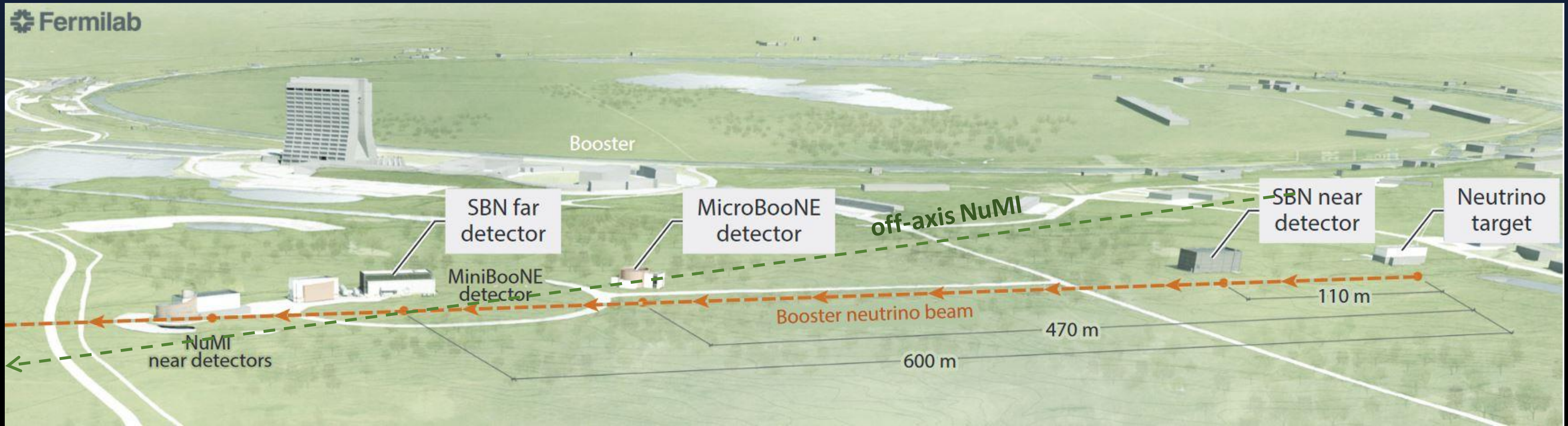
The Short Baseline Neutrino Program

- Three Liquid Argon Time Projection Chambers (**LAr TPCs**) located at different positions along the ν_μ Booster Neutrino Beam (E_ν ~ 1 GeV) at Fermilab
- The SBN Far Detector, ICARUS T600, is on axis on BNB and 6° off axis on NuMI
- Main goal: search for sterile neutrinos at the eV mass scale (1st year of ICARUS run to investigate the Neutrino-4 anomaly)
- Additionaly, ν-Ar cross-section measurements and exploration of New Physics scenarios

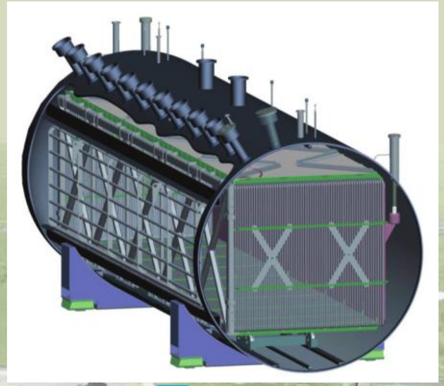


Annual Rev. Nucl. Part. Sci. 2019.69:363-387

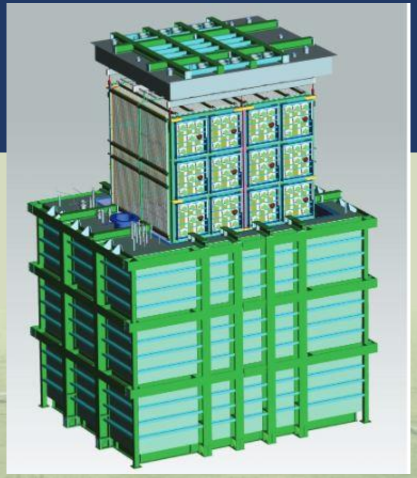
The SBN detectors

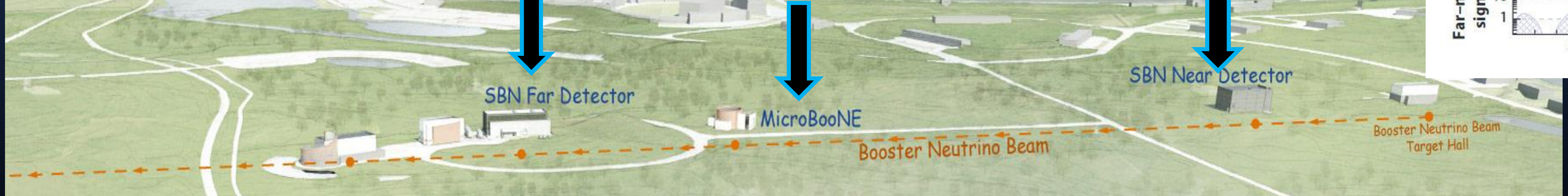
ICARUS T600 at 600 m with 476 ton active LAr mass

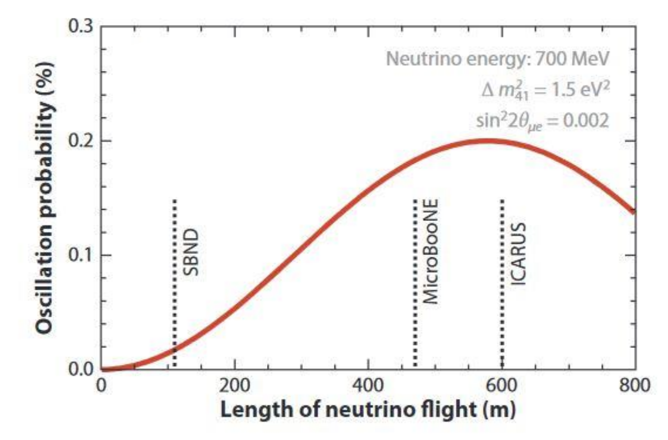
Already existing MicroBooNE at 470 m with 89 ton active Lar mass

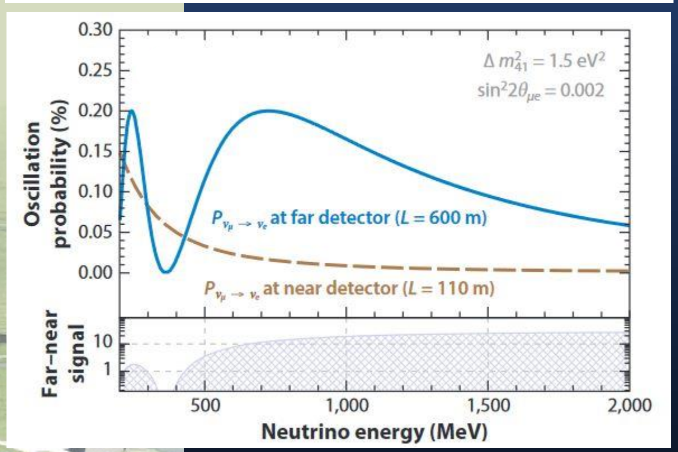


SBND at 110 m with 112 ton active LAr mass









ICARUS in data taking since 2020 and completed its commissioning

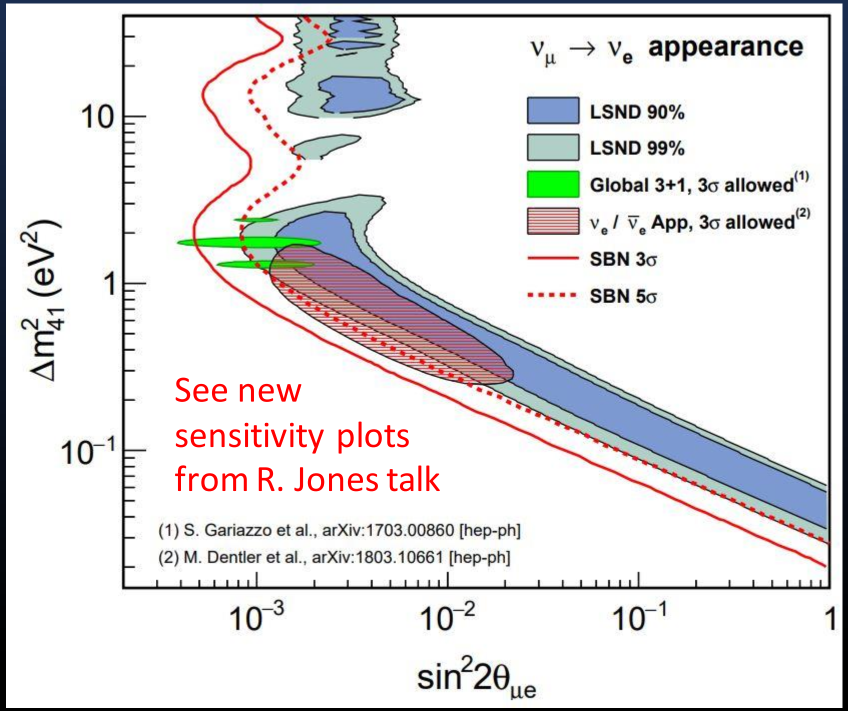
Recent MicroBooNE results disfavour the MiniBooNE low energy ν_e excess but don't exclude the sterile neutrino ipothesis

SBND is in construction and will be completed in 2023

PHYS. REV. Lett. **128**, 241802 (2022)

The SBN sensitivity

- Unique capability of measure both the ν_e **appearance** and the ν_μ **dissapearance** oscillation channels with BNB
- SBN will cover most of the parameter regions allowed by past experimental anomalies
- Expected 5σ sensitivities to a light sterile neutrinos in 3 year of data taking (6.6 x 10^{20} pot)



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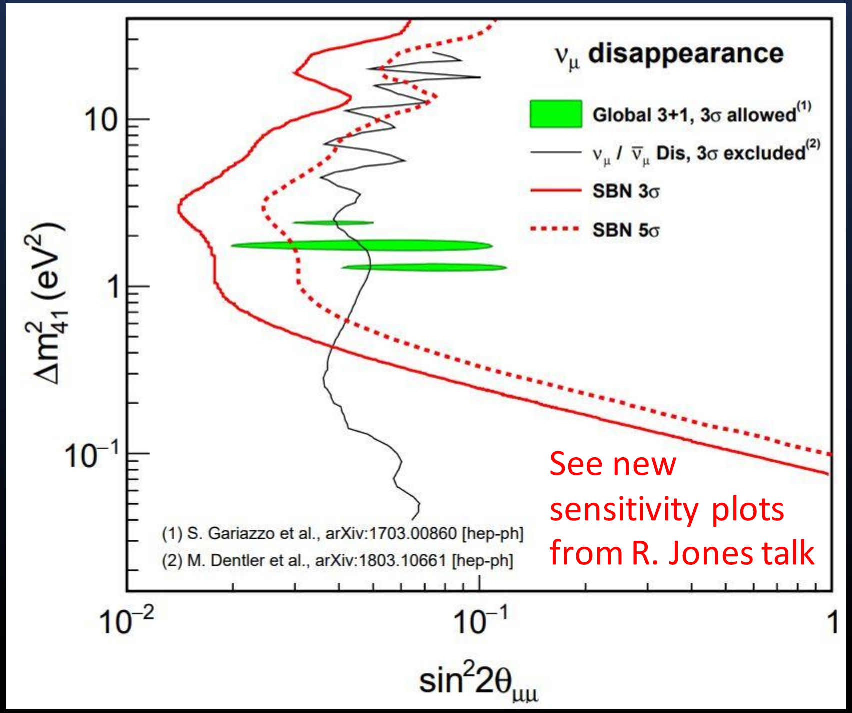
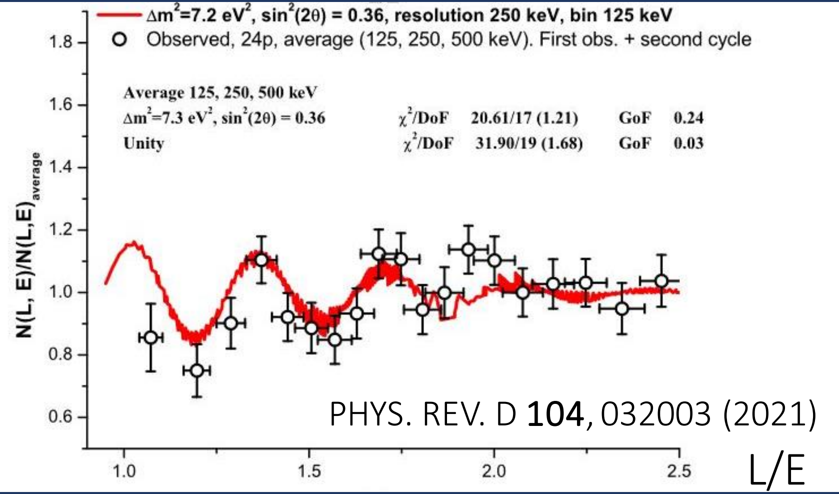


Search for Neutrino-4 anomaly

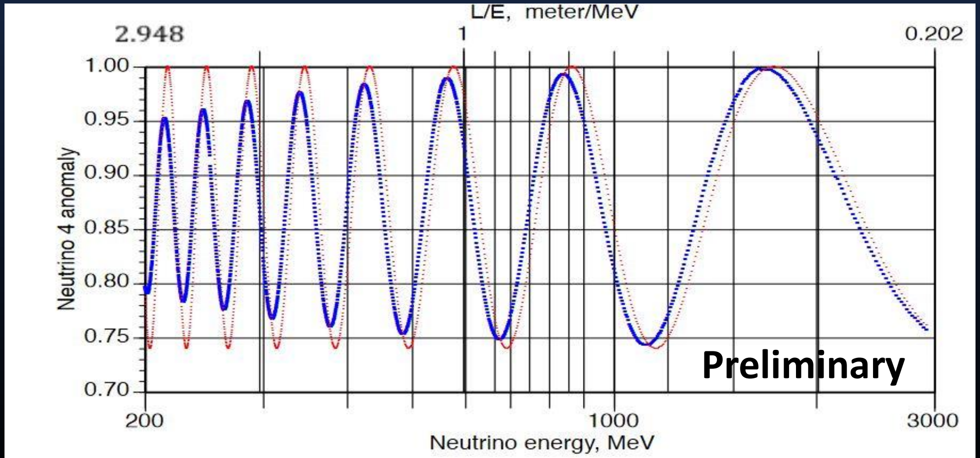


PHYS. REV. D **104**, 032003 (2021)

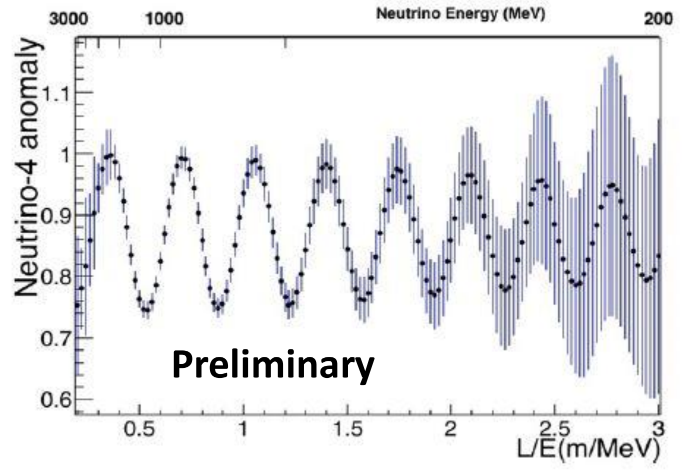
Neutrino-4 experiment claimed a reactor neutrino disappearance signal with a clear modulation with L/E ~ 1-3 m/MeV resulting in Δm^2_{14} = (7.3 ± **1.17)** eV^2 and $\sin^2 2\theta$ = 0.36 ± 0.12 with 2.7σ significance

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

- disappearance of ν_μ from BNB, focusing on contained QE ν_μ CC interactions (~11500 events in 3 months)
- disappearance of the ν_e from NuMI beam, selecting contained QE ν_e CC events (~5200 events per year)



ICARUS expected Neutrino-4 ν_μ disappearance signal for L averaged position (blue) and at center (red)



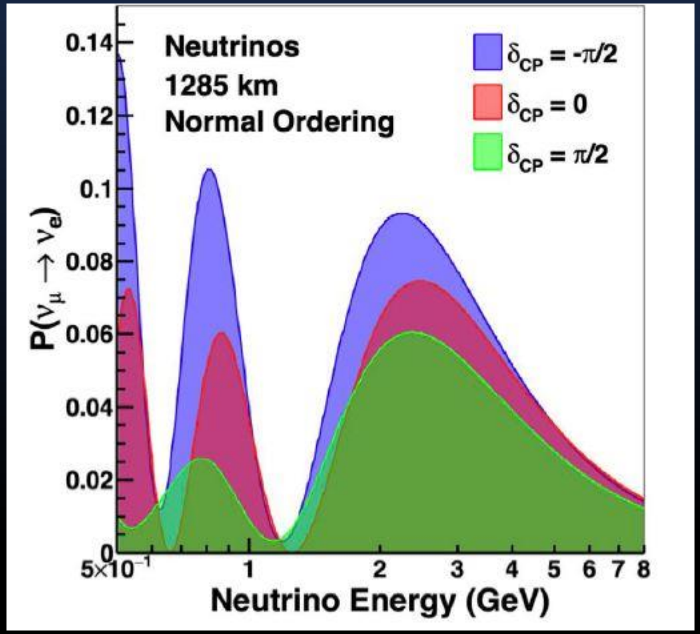
Survival oscillation probability in 3 years considering Neutrino-4 best fit (only stats)

Physics searches with NuMI

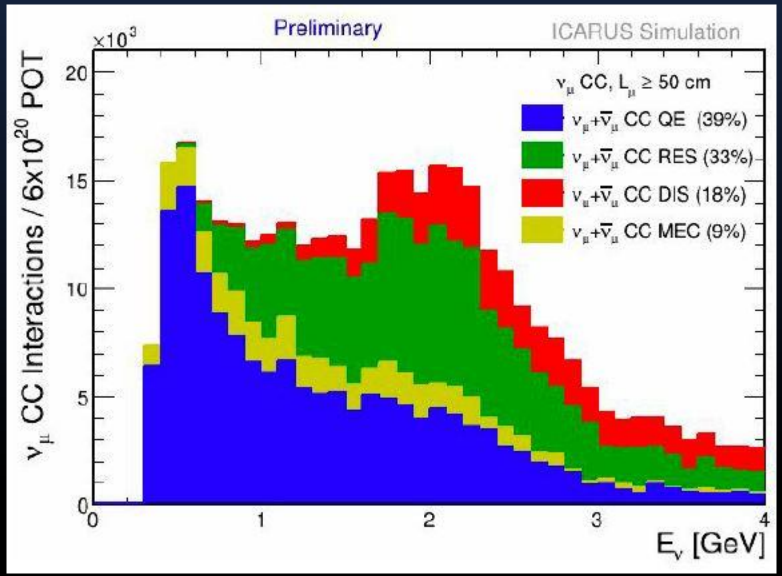
- ICARUS will collect a high-statistic sample of the off-axis ν_e NuMI component (10^5 events / year) to perform high precision measurements of ν Argon cross section and test interaction models in the few hundred MeV to few Gev energy range extremely useful for SBN oscillation analysis and for the upcoming DUNE experiment

- Rich BSM Physic program: Higgs portal scalar, neutrino tridents, light dark matter, heavy neutral leptons, millicharged particles ....

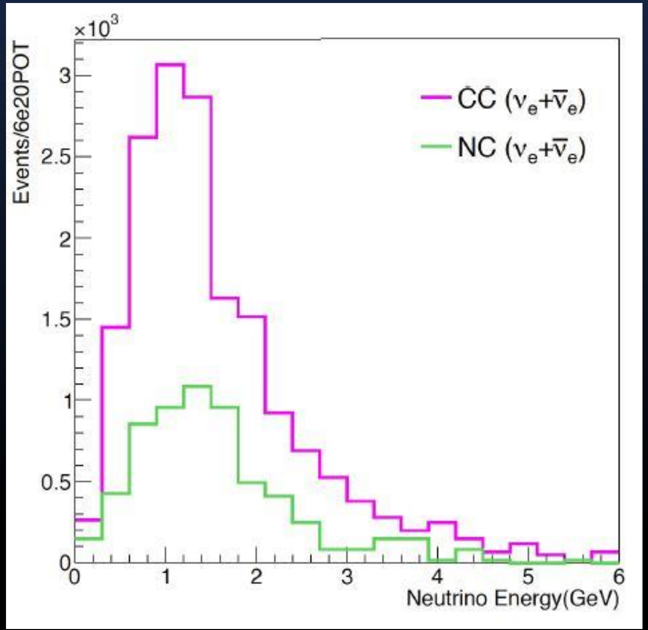
oscillation probability at DUNE



ν_μ from NuMI at ICARUS

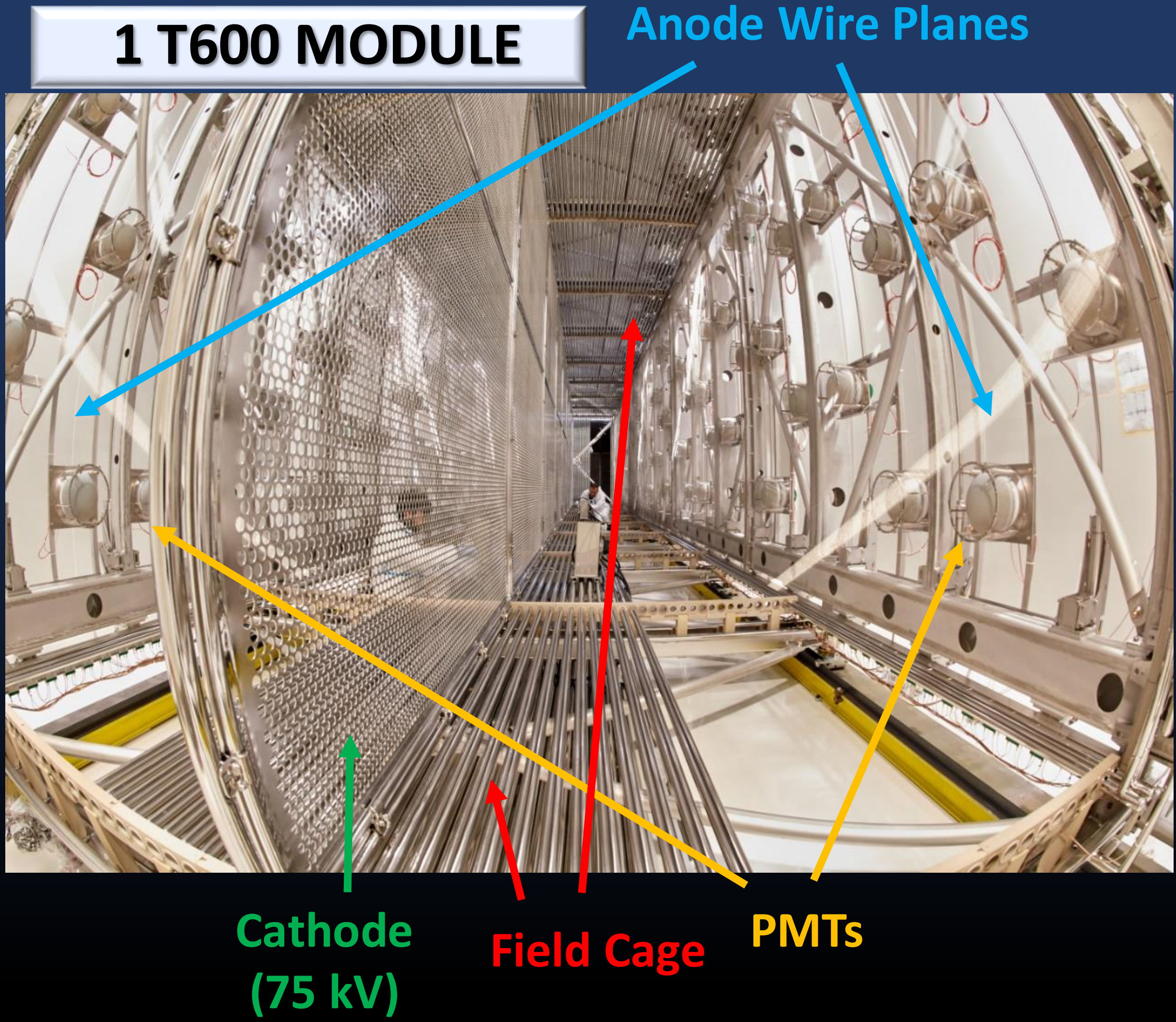


ν_e from NuMI at ICARUS



The ICARUS T600 detector

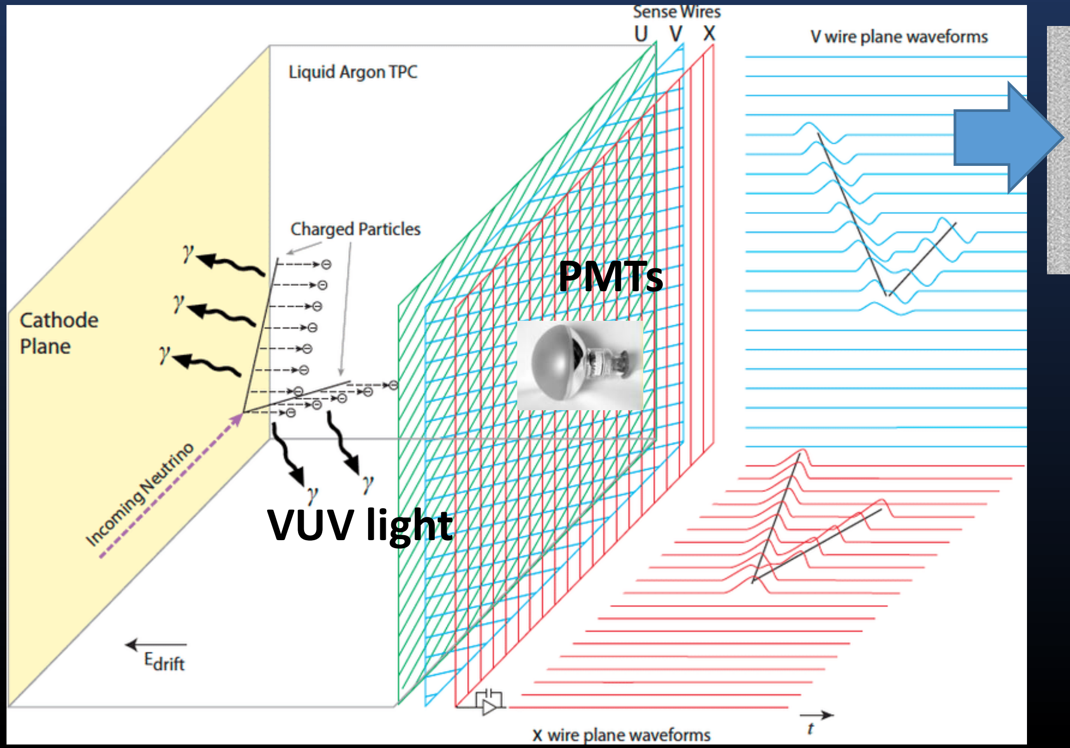
- ICARUS is a self-triggering detector successfully operated at LNGS from 2010 to 2013 as the first and largest LArTPC ever operated collecting 8.6×10^{19} POT statistics from the CNGS neutrino beam
- Two identical modules 19.6 (L) x 3.6 (W) x 3.9 (H) m^3 each with a total (active) LAr mass of 760 (476) tons
- Each module is divided in 2 TPCs with a common central cathode:
  E_D = 500 V/cm and 1.5 m drift length ($v_D \sim$ 1.6 mm/µs)
- Each TPC has three parallel anode wires planes at different orientations (0°, ± 60°) w.r.t. horizontal to readout ionization charge: Collection, Induction1 and Induction2
- 360 PMTs coated with PTB



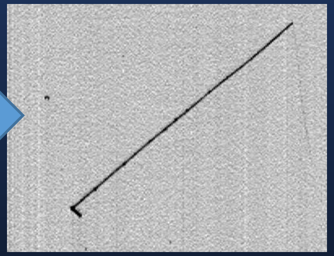
The Liquid Argon TPC detection technique

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

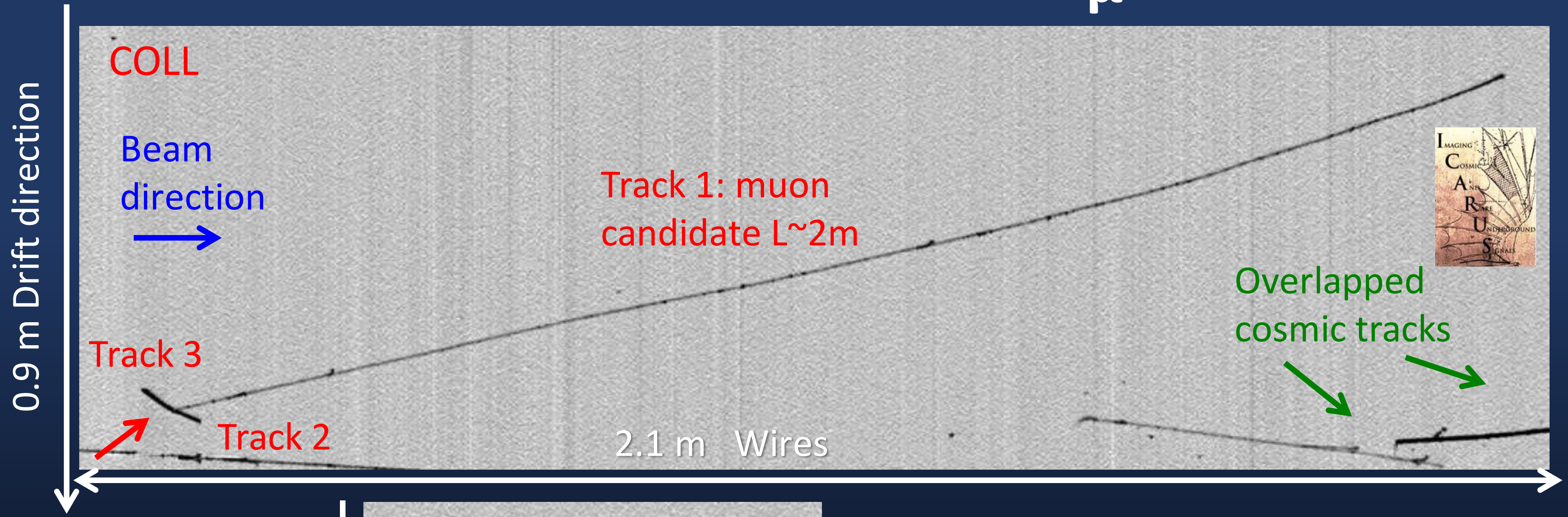
- scintillation light (40000 γ/MeV at λ = 128 nm and E_D = 0 V/cm) detected by PMTs to provide the event time and trigger
- charged particles from neutrino interactions ionize the LAr producing ionization electrons (42000 e^- / MeV) drifting in 1 ms towards readout sense wires
  - combining wire coordinates at same drift time → 3D track reconstruction with resolution of ~ mm
  - dE/dx measurements to perform PID

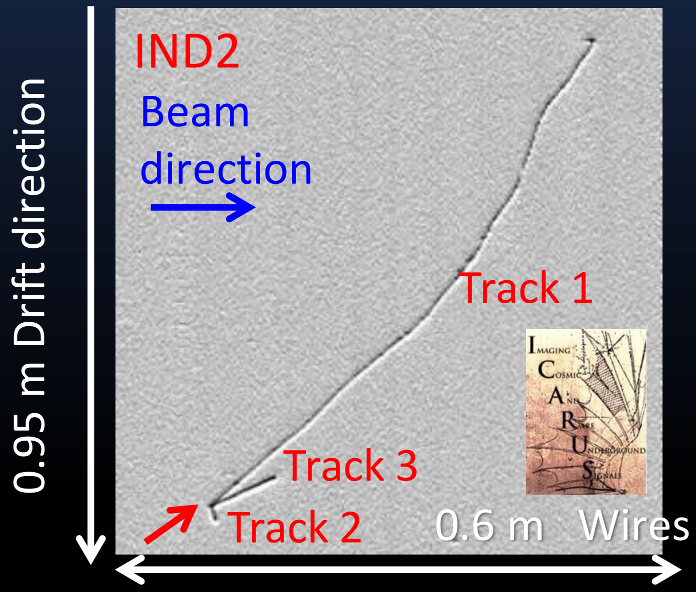


Reconstructed image on a plane



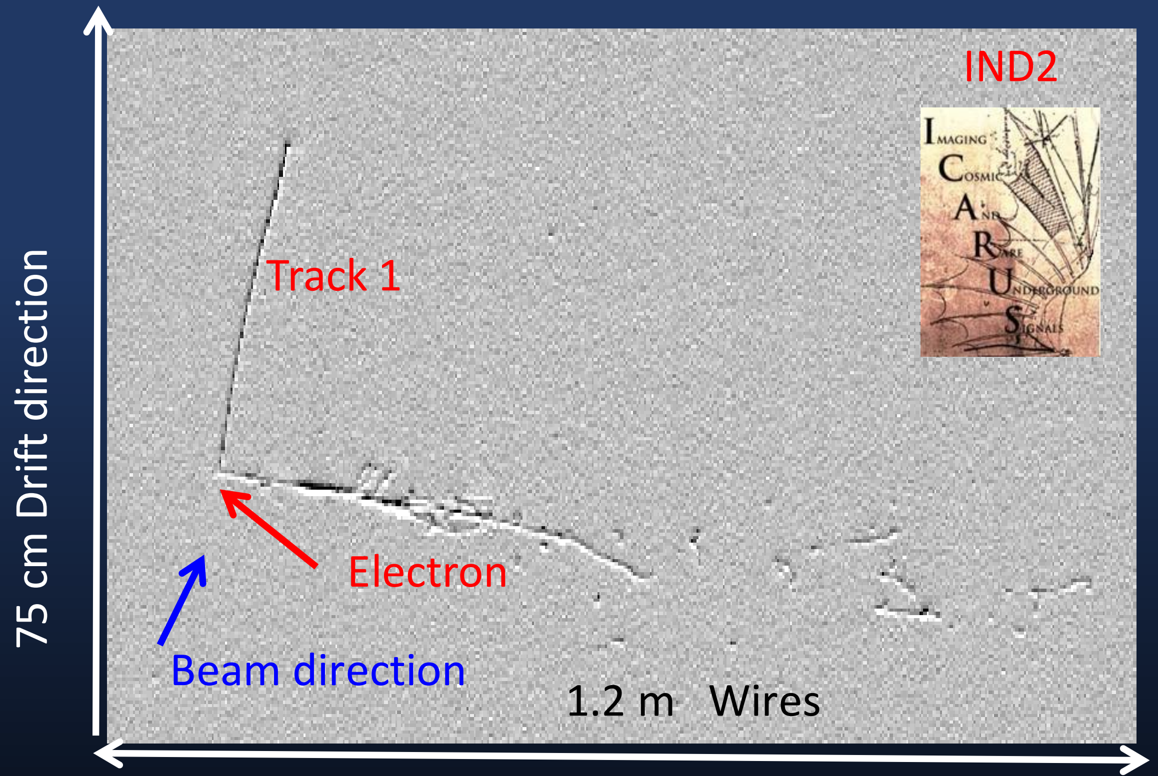
Neutrino Events – BNB ν_μ CC candidate

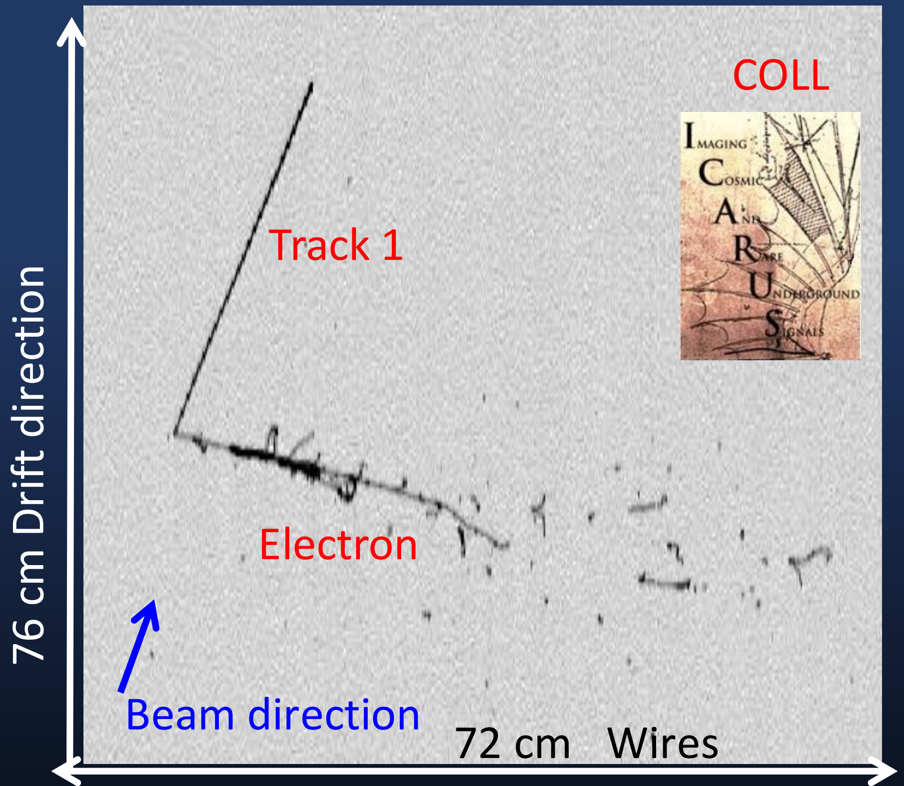




Neutrino candidates identified by visual scanning procedure

Neutrino Events – NuMI ν_e CC Q.E. like candidate

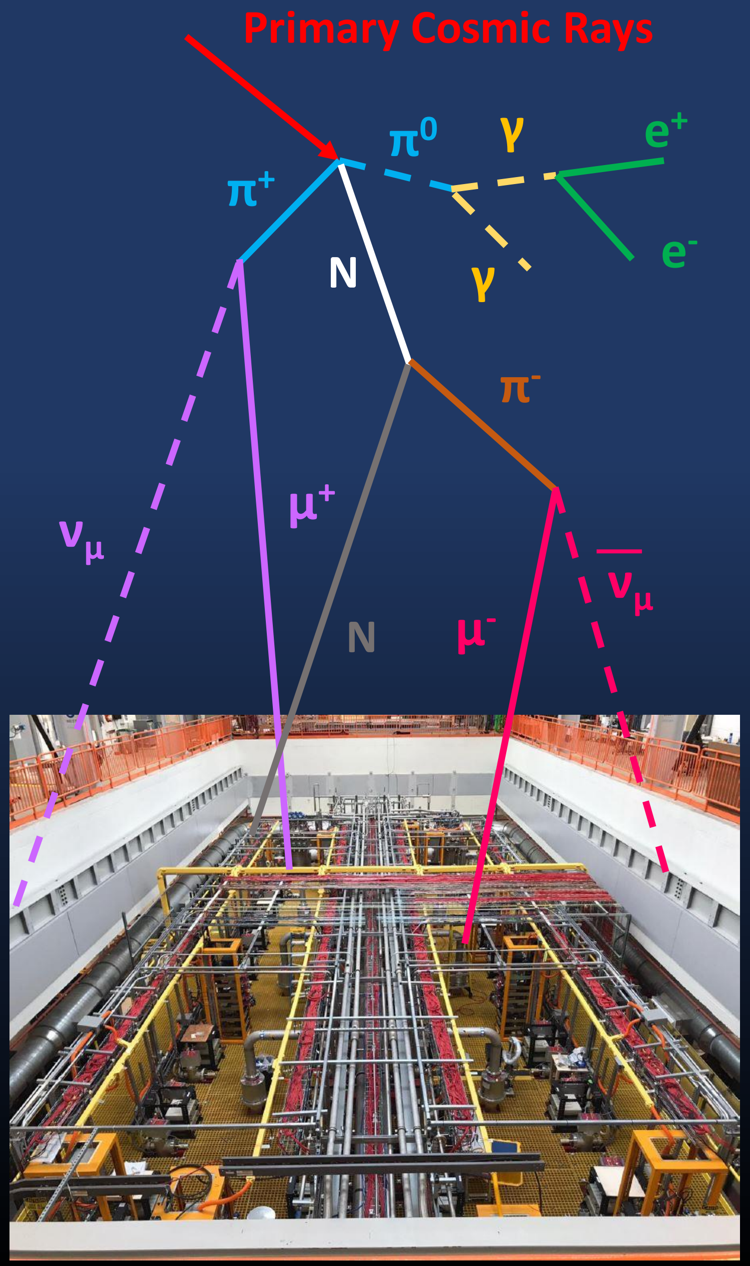




High spatial resolution in combination with dE/dx measurement at the beginning of the shower ensures e/γ showers separation → very good ν_e identification

The Cosmic Ray Background: a new experimental challenge

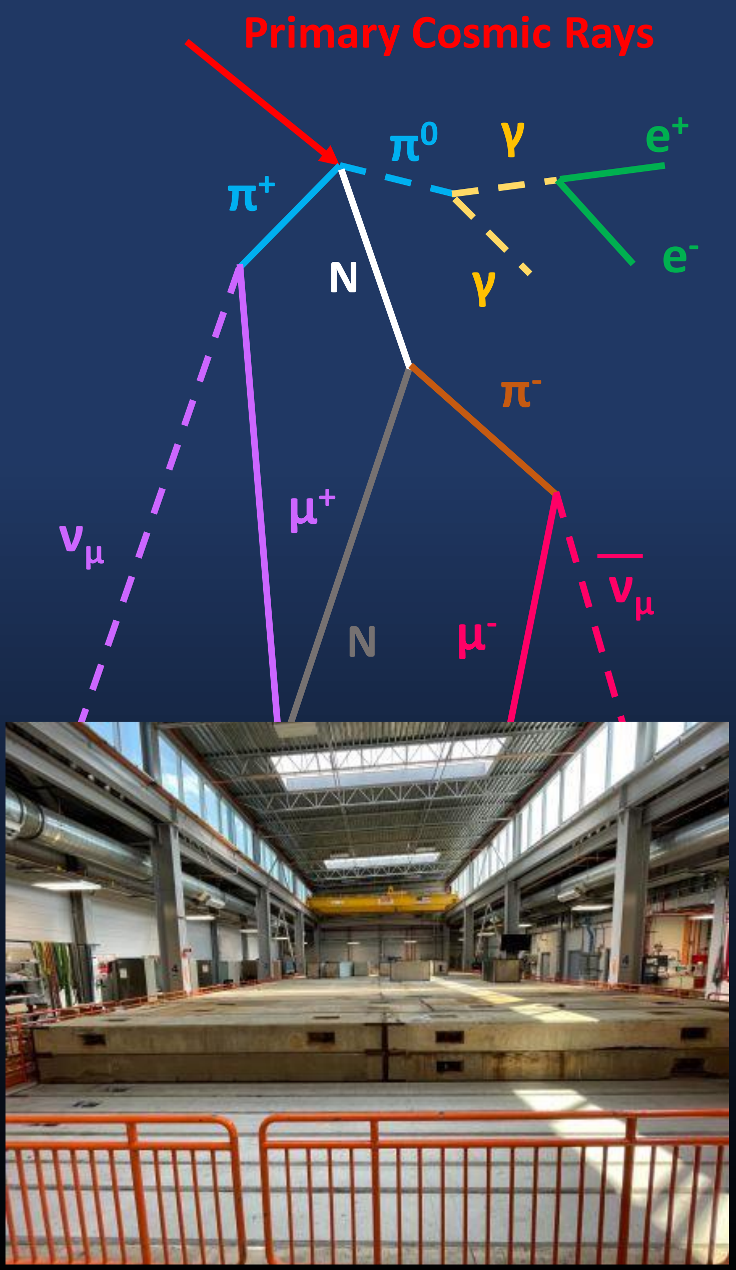
- ICARUS at Fermilab operates at surface and the cosmic ray induced signal is mitigated by:



The Cosmic Ray Background: a new experimental challenge

- 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%



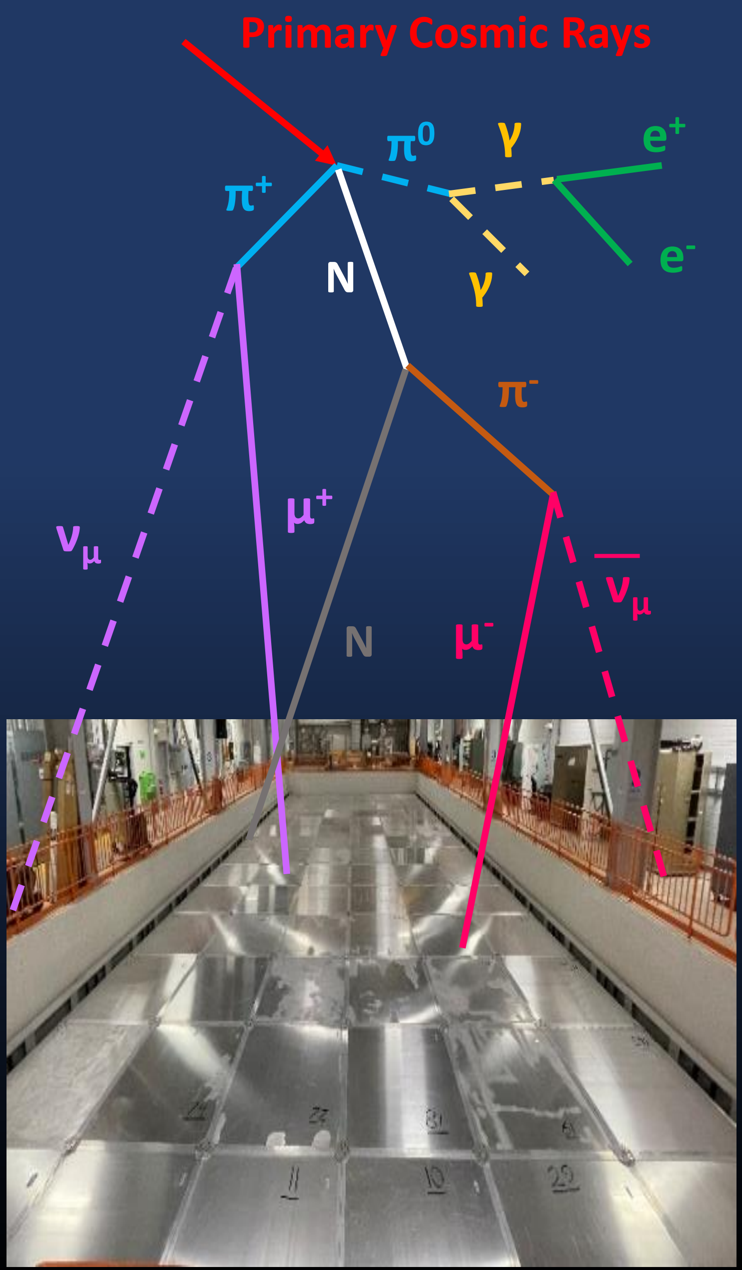
The Cosmic Ray Background: a new experimental challenge

- 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 estimated as ~ 11 muon tracks in 1 ms TPC readout is identified by a Cosmic Ray Tagger (CRT)* system ensuring a 4π coverage of the detector with 95 % tagging efficiency and few ns time resolution

  - Particulary crucial for background rejection of gammas produced by muon interactions in the sorrounding materials that can generate e.m. showers miming a ν_e signal

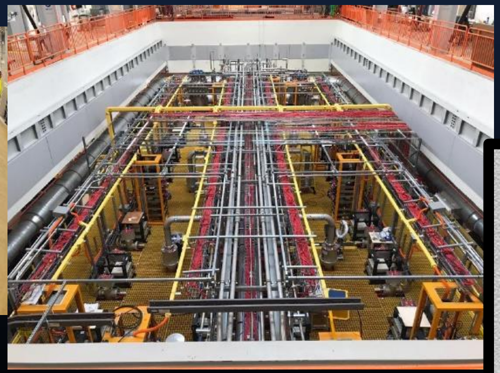


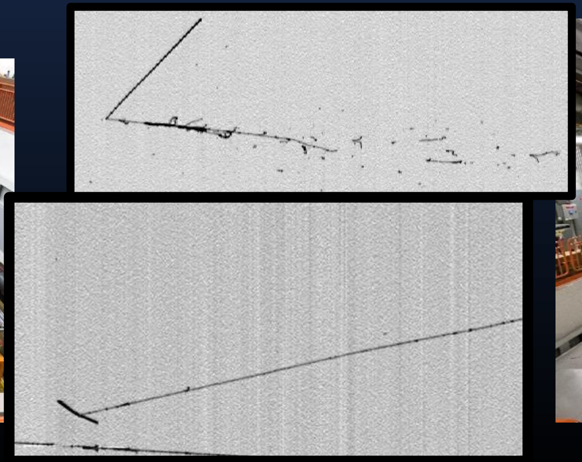
* See F. Poppi's talk

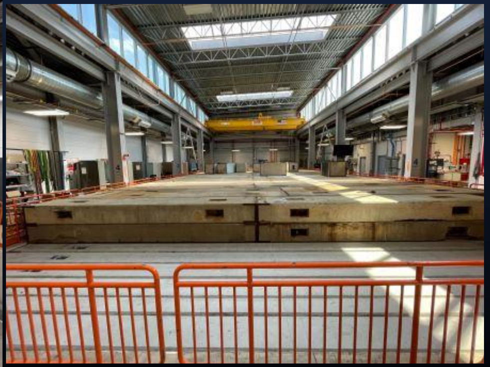
The ICARUS journey at Fermilab

After detector refurbishment at CERN during 2016-2018 …

August 2018	August 2020	March 2021	June 2021	December 2021	May 2022	June 2022
start of installation at FNAL	detector activation	First BNB and NuMI detected neutrinos	Run-0 taking data 24/7 with beam	Installation of CRT system completed	End of overburden installation	Beginning of Run-1

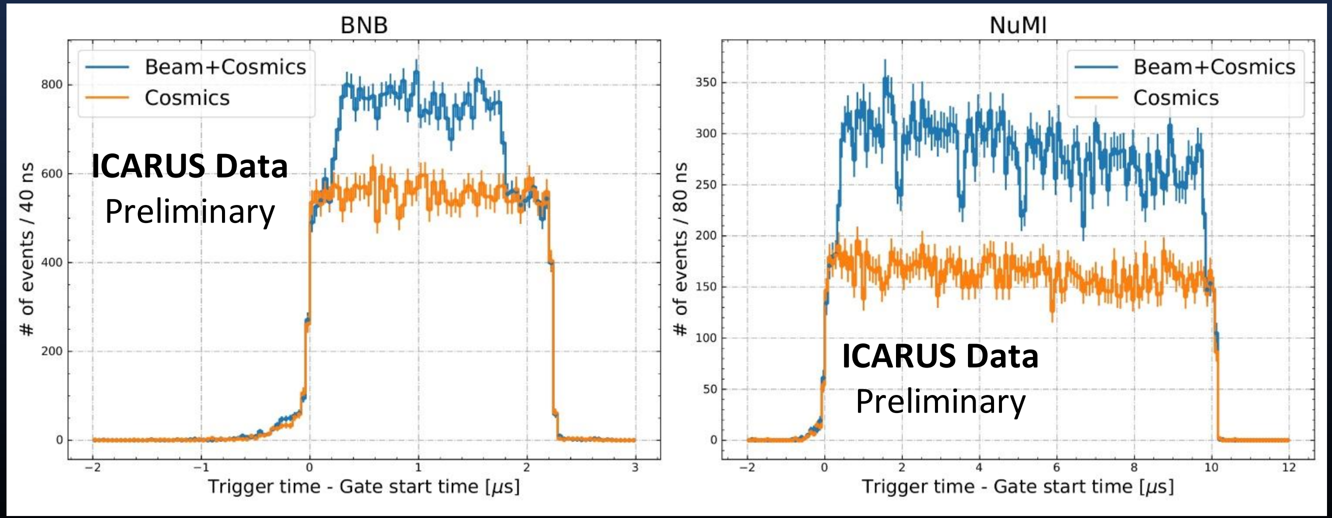






Trigger system

- ICARUS main trigger signal is generated by majority of discriminated pairs of PMT signals (> 13 p.e.) in coincidence with BNB and NuMI beam spill gates
- PMT light and CRT signals are recorded for 2 ms and 25 ms, respectively, around the trigger time to recognize and tag cosmics crossing the detector during 1 ms drift time
- Additional triggers in correspondance of a subset of beam spills without any request on PMT signals and outside beam spills to detect cosmic ray interactions for calibration studies



Beam	Spill gates (μs)	Main trigger rates [mHz]	Offbeam trigger rates [mHz]
BNB	1.6	164	123
NuMI	9.6	187	119

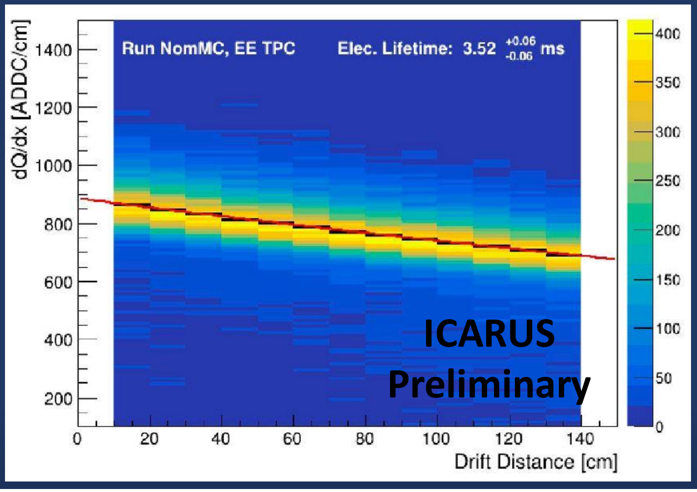
Total trigger rate < 1 Hz

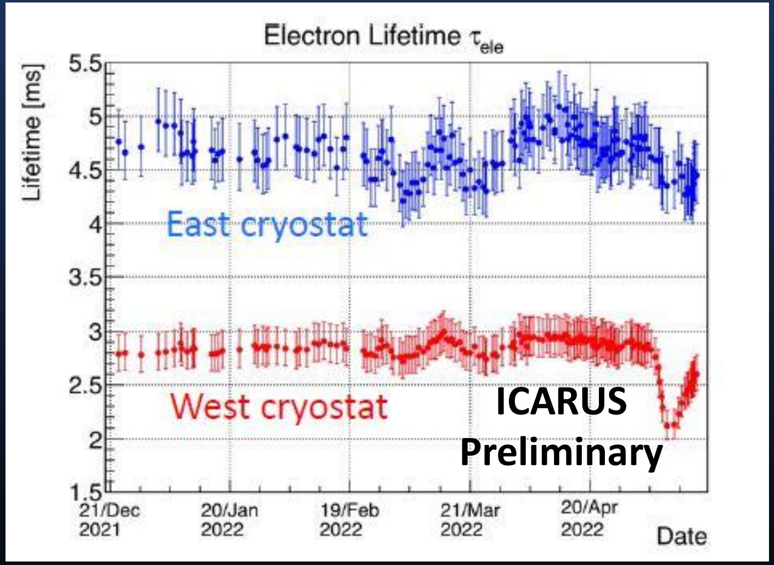
Verification of correct timing of beam signals by looking for excess of PMT light flash over comic background rates

Detector Calibration

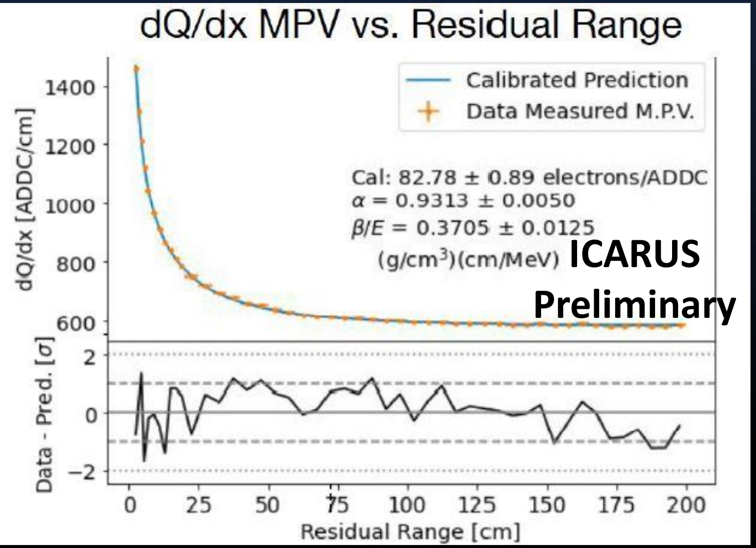
- Free electron lifetime τ_{ele} (purity) in LAr measured by the attenuation of ionization along the drift path for cosmic muon tracks crossing both anode and cathode

Attenuation of ionization along μ track



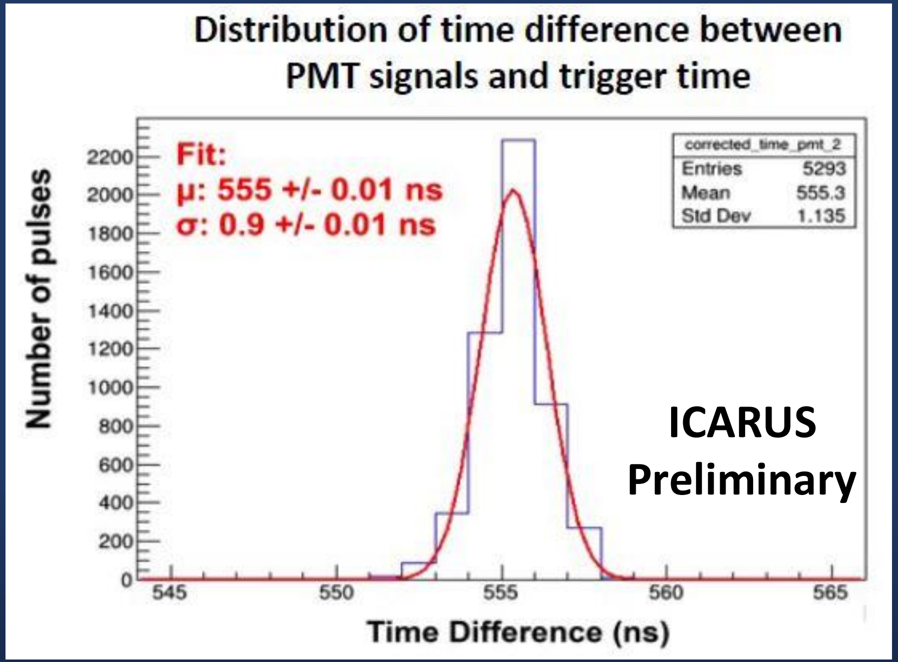


- TPC wire signal gain calibration based on the study of ionization (dQ/dx) vs residual range for cosmic μ crossing the cathode, stopping/decaying in the active LAr and identified by the reconstruction tools

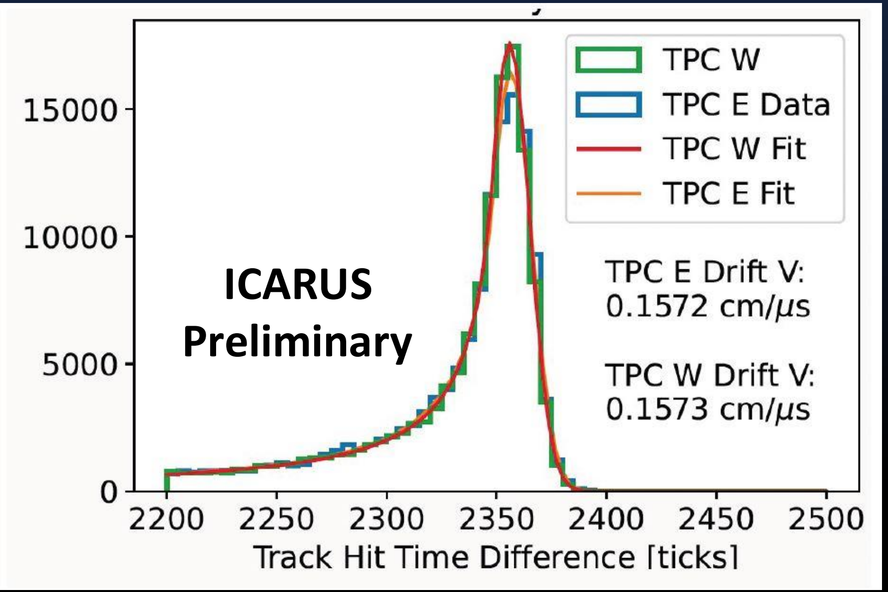


Detector performance

- Scintillation ligth detection system:
  - PMT timing resolution measured 1 ns allows to precisely determine the absoulte timing of collected events
- TPC:
  - anode-cathode crossing cosmic muon tracks used to measure drift velocity by maximum drift time of charge associated with tracks



Drift velocity in West Cryostat



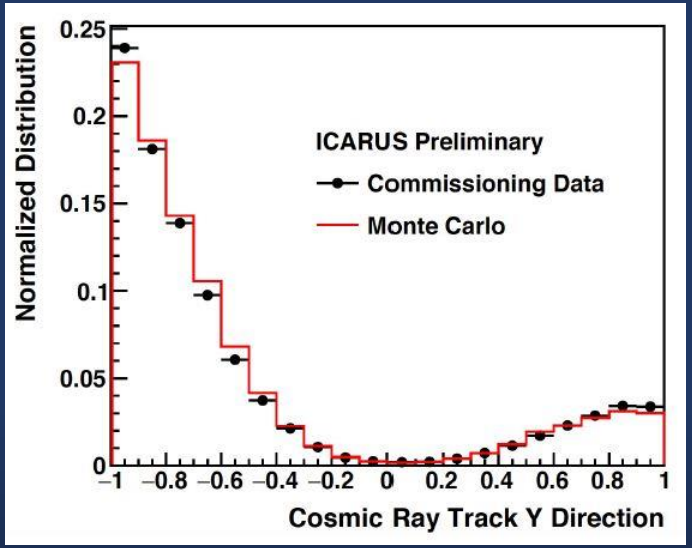
Reconstruction tools

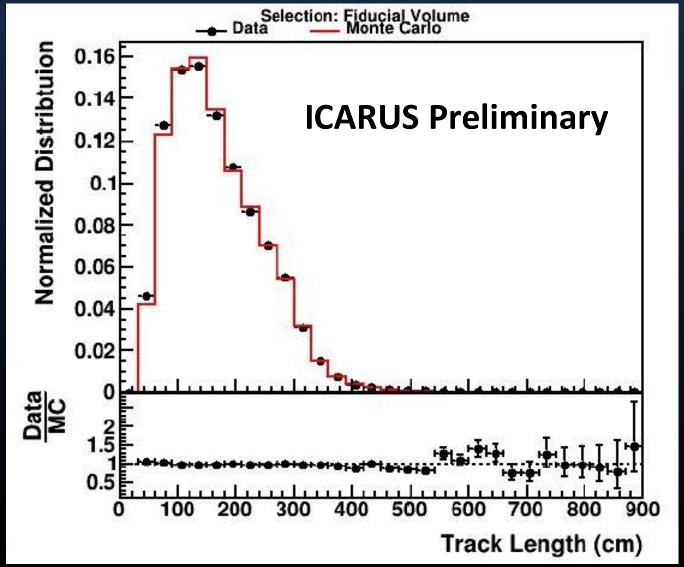
TPC tracks reconstruction algorithm is based on multi-steps: 1) pre-processing; 2) wire signals identification/reconstruction (hits); 3) track/shower reconstruction

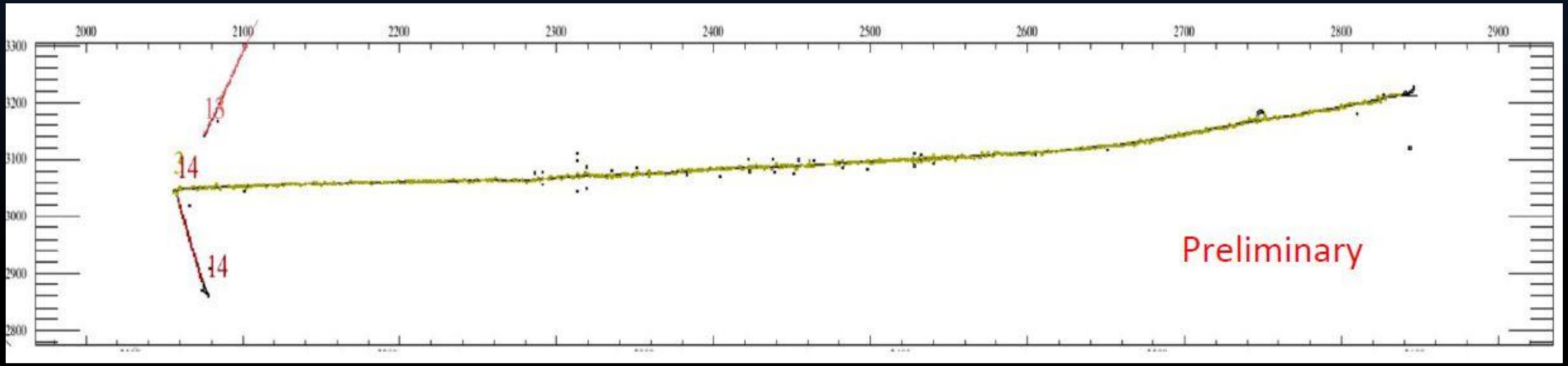
Pandora pattern recognition software tool for LArTPCs:

- clusters the objects together into reconstructed particles in 3D by joining together info from the wire planes;
- reconstructs vertex (common point where particles originate);
- forms reconstructed particle hierarchy (parent/child particles)
- classifies particles as track-like (e.g. μ, p, π±, K±) or shower-like (e.g. e, γ)

Neutrino events selected by visual scanning of collected data used to test and tune automated software tools and compare data/MC







Conclusions

- The SBN program at Fermilab is expected to clarify the sterile neutrino puzzle in 3 years of data taking by measuring ν_e appearance and ν_μ disappearance oscillation channels

- ICARUS operated staedily since summer 2020 and data collected with cosmics and with beam neutrinos allowed accurate detector calibration and tuning of simulation and reconstruction tools

- The detector commissioning was completed on May 2022 and ICARUS is currently taking data 24/7 with both BNB and NuMI beams starting its searches for new Physics Beyond the Standard Model

Thank you for your attention!