The Short Baseline Neutrino Program at Fermilab

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Neutrino-related anomalies?

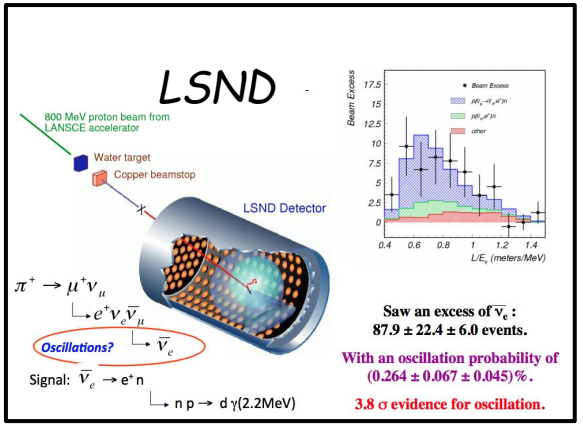
- Neutrino masses and oscillations represent today a main experimental evidence of physics beyond SM. Being some of their fundamental properties still unknown, they are naturally one of main portals towards beyond-Standard Model physics.

- Despite the well-established 3-flavour neutrino mixing and oscillation picture, several anomalies have been collected so far hinting to existence of additional neutrino states:

  - Anti-νe appearance in anti-$\nu\mu$ accelerator LSND experiment (3.8σ effect).

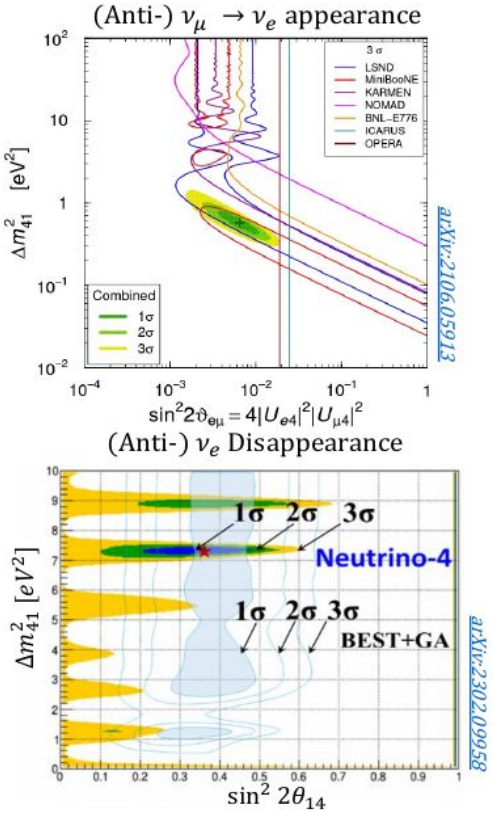
  - νe disappearance: SAGE, GALLEX experiments with Mega-Curie radioactive sources showing an observed/predicted rate R = 0.84±0.05, recently confirmed at 4σ by BEST experiment.

  - Anti-νe disappearance in nuclear reactor experiments, initially R = 0.934 ±0.024 (but recently reconsidered).



The puzzle of short baseline neutrino oscillations

- Anomalies from accelerator experiments (LSND and MiniBooNE), reactors and radioactive source have been reported in the last 20 years, unable to fit inside the 3-flavor oscillation scheme
- Results point towards a new sterile ν flavor at $\Delta m^2 \sim eV^2$ and a small mixing angle, thus driving short distance oscillations.
- The Neutrino-4 collaboration (reactor experiment) also reported a hint of oscillation signature at higher mass splitting arXiv:2005.05301:
  - Reactor anti νe disappearance with $\Delta m^2 \sim 7\ eV^2$ and $\sin^2 2\theta \sim 0.26$
  - Combining Neutrino-4 results with data from GALLEX, SAGE,and BEST experiments the confidence in previously claimed results has increased to 5.8σ CL arXiv:2302.09958



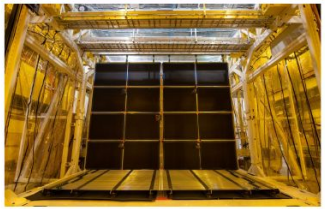
Short Baseline Neutrino Program at Fermilab

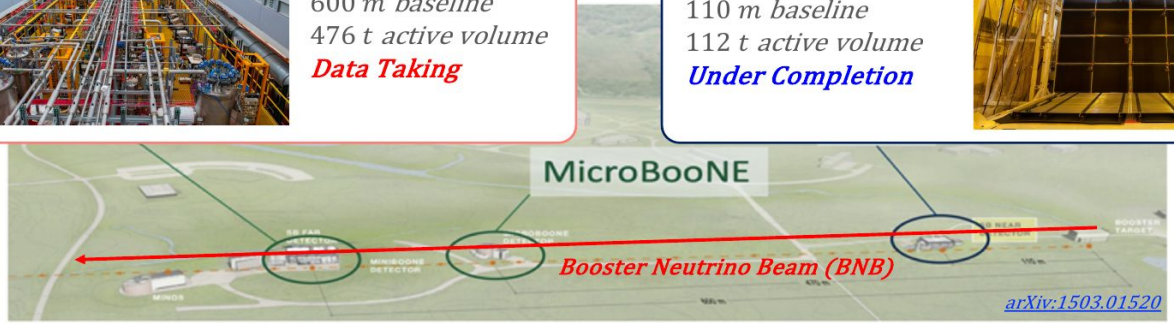
ICARUS

600 *m baseline*
476 *t active volume*
Data Taking

SBND

110 *m baseline*
112 *t active volume*
Under Completion

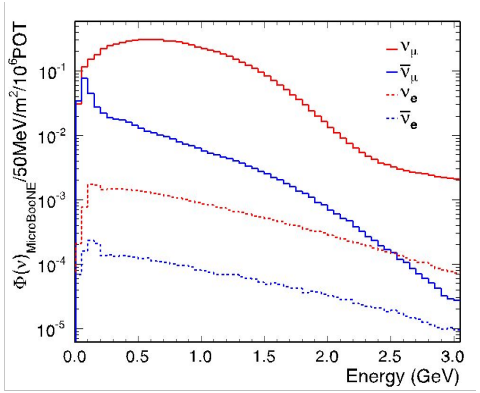


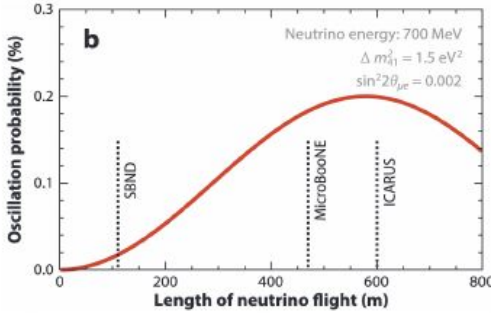


- Short Baseline Neutrino Program (SBN) main goal: search for sterile neutrino oscillations both in appearance and disappearance channels (at ~eV mass scale) to solve the sterile neutrino puzzle.
- Consists of LArTPCs sampling the Fermilab Booster Neutrino Beam (BNB) at different distances
- ICARUS is the SBN Far Detector at 600 m from the BNB target, while SBND at 110 m from the BNB target is used to measure the beam before neutrino oscillation takes place.

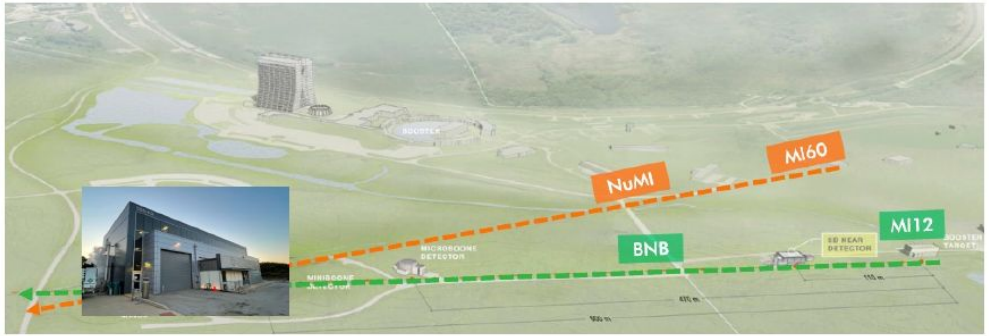
Short Baseline Neutrino Program at Fermilab

- BNB is a well characterized ν_μ beam, able to produce ν and $\bar{\nu}$ beams with low ν_e contamination (0.5 % ν_e content)
- ICARUS is also exposed off-axis to the NuMI beam and can access the ν_e rich component of the spectrum (up to 3 GeV)





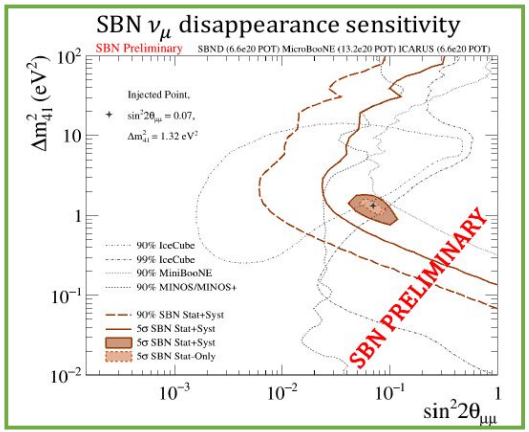
Possible oscillation signature under a set of parameters. P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

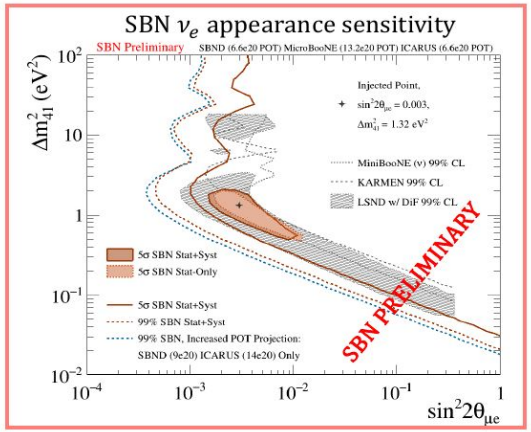


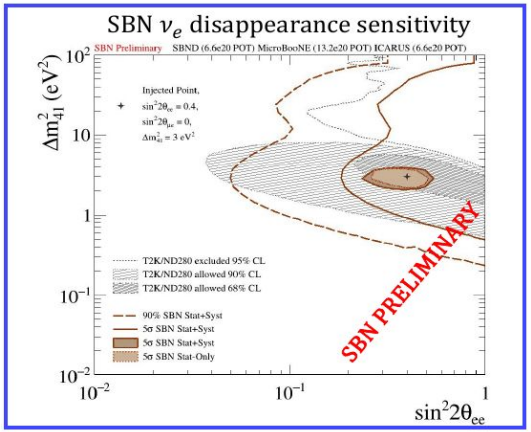
- Measuring the cross-sections neutrino-Argon and understanding the nuclear effects/final states are key elements for oscillation analysis and systematic constraints.
- Independent cross check to BNB oscillation results with NuMI beam.

Short Baseline Neutrino Program at Fermilab

- The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels in 3 years of data taking (6.6 10^{20} POT)



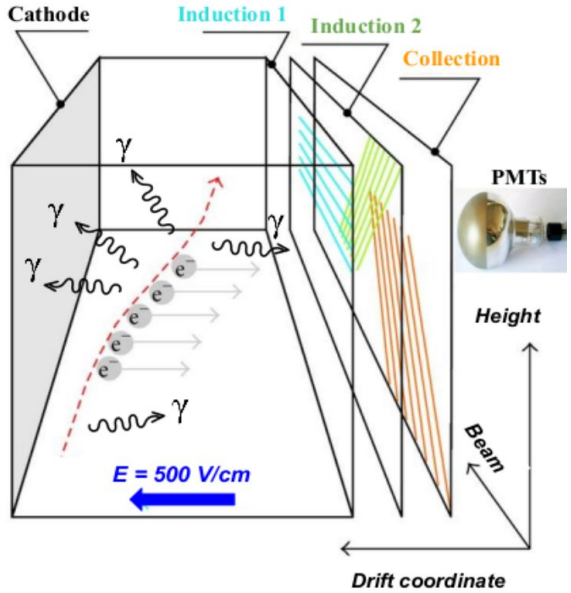




- The adopted liquid argon time-projection chamber technology will greatly reduce systematic errors:
  - Near detector helps providing the initial beam composition and spectrum.
  - The clear electron neutrino identification capability highly reduces backgrounds.

Liquid Argon TPC detector technique

- Very well suited for the experimental study of Neutrino Physics, pioneered by ICARUS Collaboration.
- Massive yet homogeneous target, excellent tracking and calorimetric capabilities.



λ = 128 nm scintillation light:

- 40000 γ/MeV without electric field.
- Response time ≈ 6 ns ÷ 1.6 μs.
- Used for trigger and timing of events.
- Need WLS to convert to visible light.

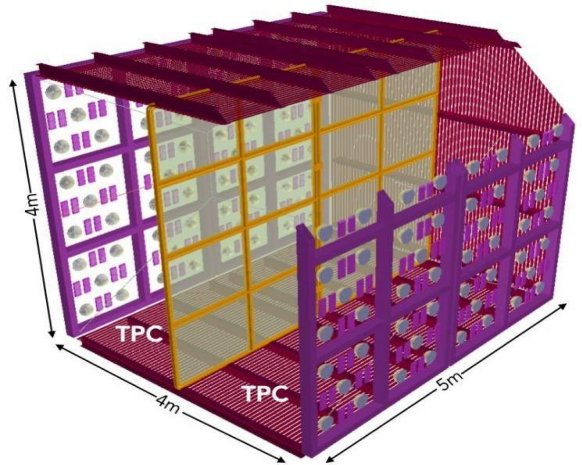
Ionization electrons:

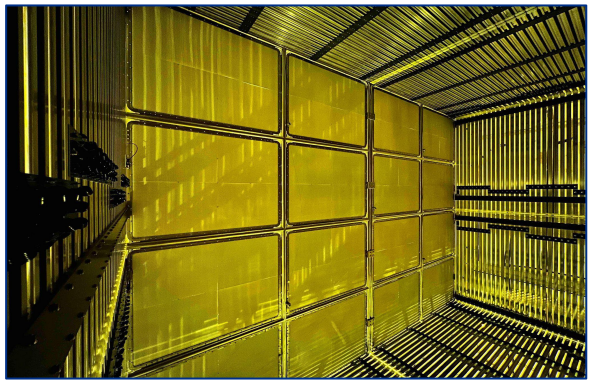
- 42000 e^-/MeV.
- Drifted (E) toward planes of wires on which they induce a signal.
- Response time = drift time (~ ms).

- At E = 500 V/cm both ionization and scintillation occur, roughly with the same weight.
- 3D image reconstruction by combining coordinates on different wire planes at the same drift time.

SBND detector

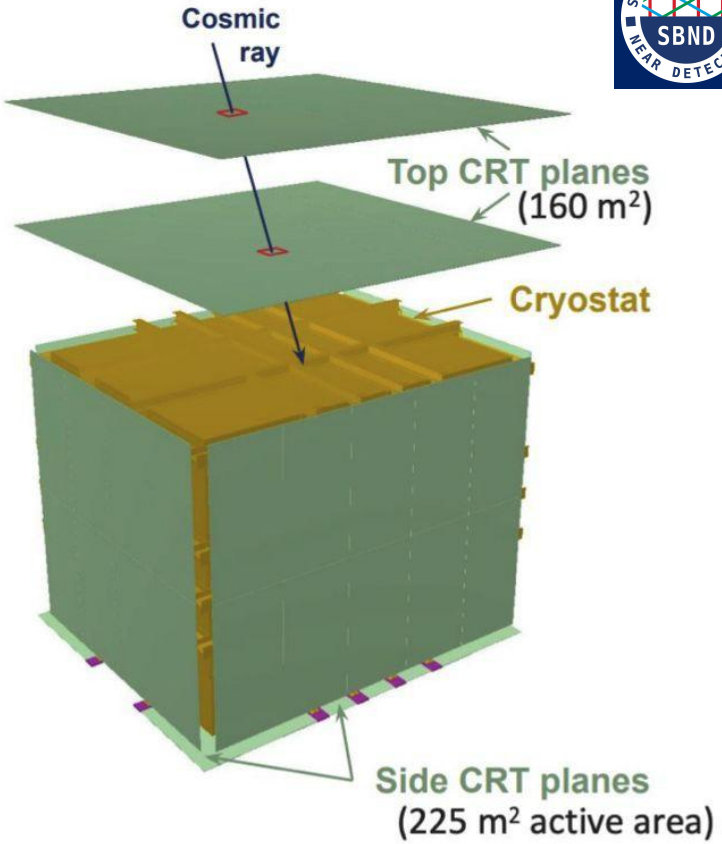
- Two TPC regions that share a central HV cathode
  - 5m (L) x 4m (H) x 2m (drift)
- Drift HV = -100 kV
- 3 wire planes
  - 1 collection (vertical)
  - 2 induction (±60°)
- TPC cold electronics
  - shaping, amplification, and digitization in cold
  - **11,264 wire channels read out by 88 FEMBs** mounted directly to the wire plane frames



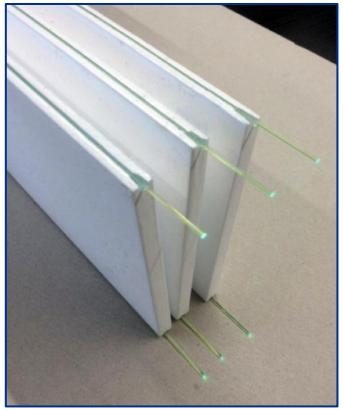


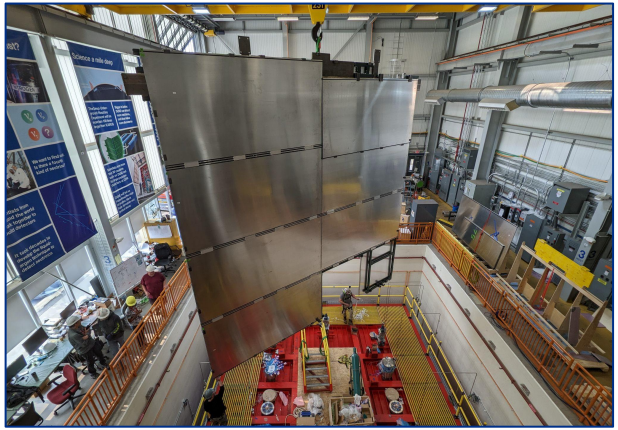
SBND: cosmic ray tagger

- CRT system will surround the SBND cryostat on all 6 sides – double layer telescope on top
- **142 CRT modules** built from 112mm wide scintillator strips. Two WLS fibers per strip read out at the end with MPPC photo-diodes. **Built in BERN.**
- CRT being installed.



Installation of CRT North Wall, May 2023

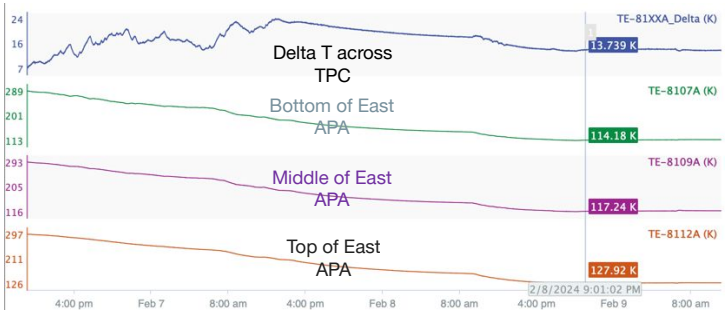


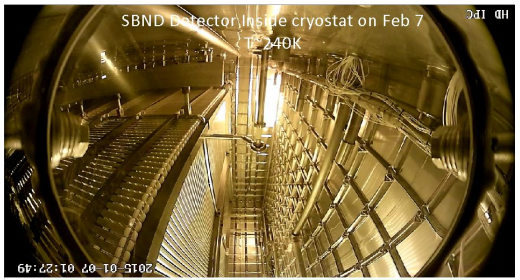


SBND commissioning

Cryogenics System completed and cooldown started!

Liquid Argon Delivery

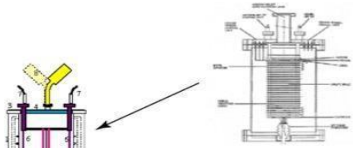




ICARUS: a path towards the kton mass

- With the continuing effort of ICARUS Collaboration and INFN LAr-TPC technology has been taken to full maturity with the T600, the largest LAr-TPC ever built, 0.76 kt of LAr mass.

The path to larger LAr detectors



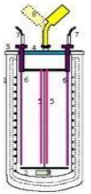
24 cm drift wires chamber (1)

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

CERN (2)

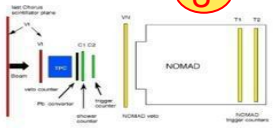
3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



CERN

50 litres prototype
1.4 m drift chamber (3)



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

Pavia-Italy

(4)

10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

LNGS Hall-B (2010-2013)

(5)

CERN

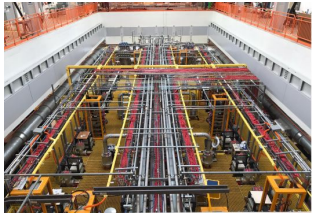
(6)

2014-2017 Detector overhauling at CERN

(7)

2017 Detector transportation to FNAL

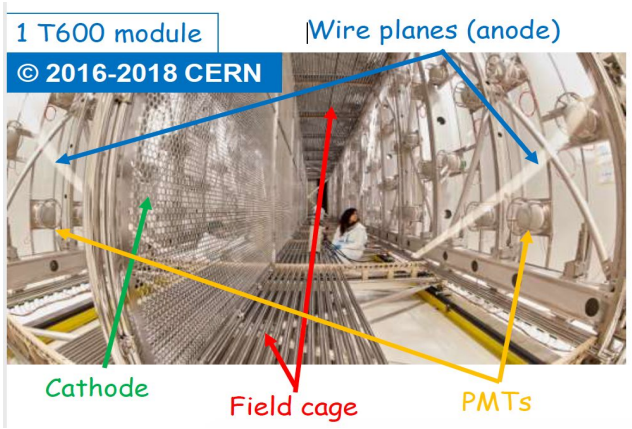
FNAL

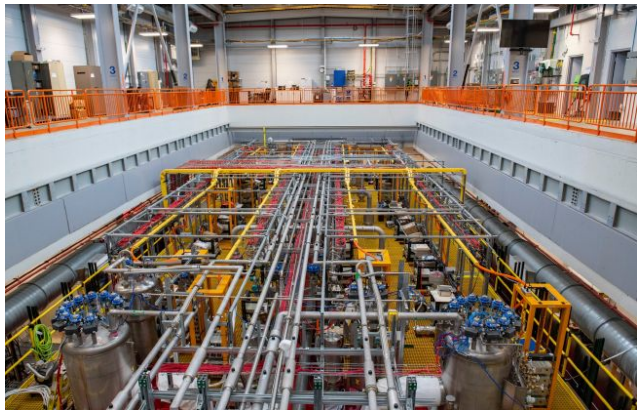


(8)

ICARUS @ Fermilab

- 2 TPCs per module with central cathode, 1.5 m drift, E_D= 0.5 kV/cm, $\Delta t \approx 1$ ms.
- 3 readout wire planes (2 Inductions + Collection) per TPC, ≈54000 wires at 0^0, ± 60^0, 3 mm pitch.
- 360 8” PMTs + TPB wavelength-shifter coating: detection of scintillation light for trigger and event selection:
  - Precise identification of interaction time, ~ 300 ps time resolution.
  - Localization of events with spatial resolution < 50 cm
- LAr/GAr purified by copper filters and molecular sieves for water absorption.





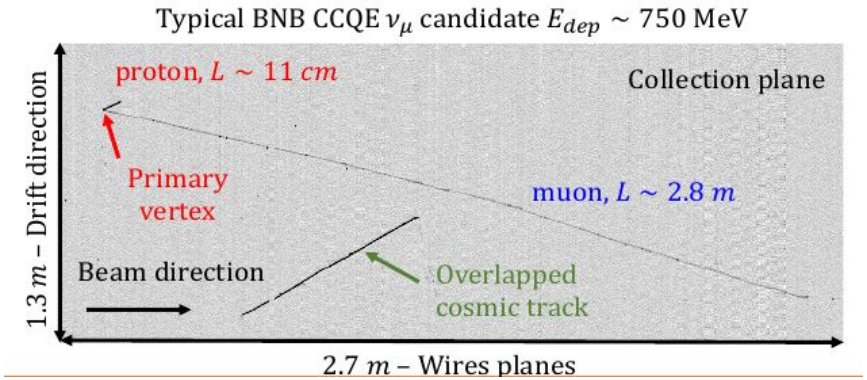
2015-17: overhauling at CERN.
2018: transportation to FNAL and start of installation.
2020: filling with LAr and start of commissioning.
2022: start of physics data taking.

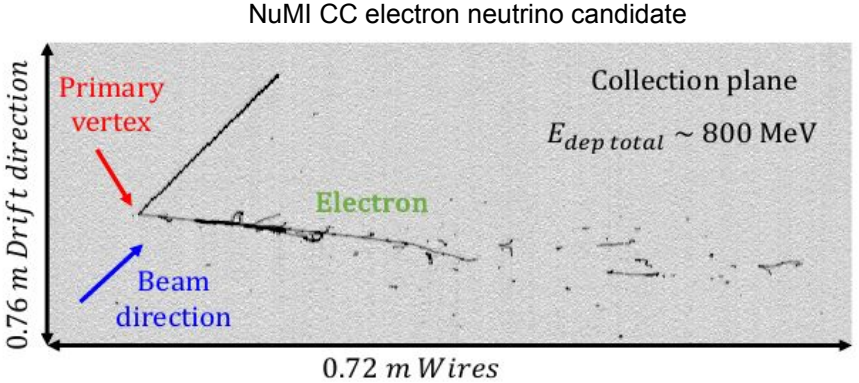
ICARUS: cosmic background mitigation

- 4π Cosmic Ray Tagger (CRT) detector surrounding LAr-TPCs to tag the incoming cosmic muons.
- ~ 3m concrete overburden to suppress cosmic primary γ's and mostly of neutrons.
- Coincidence of CRT signal with the light and charge signals in the TPC allows for a mitigation of cosmic background

ICARUS commissioning and run

- ICARUS first operation activities can be found in our recently published article [Eur. Phys. J. C 83, 467 (2023)]
- Data with both BNB and NuMI beams was collected during Run 1, from June 9th to July 10th (2022) triggering on the scintillation light detected in coincidence with the proton beam extraction.
- Overall efficiency of ~ 93 % and excellent stability on long runs.





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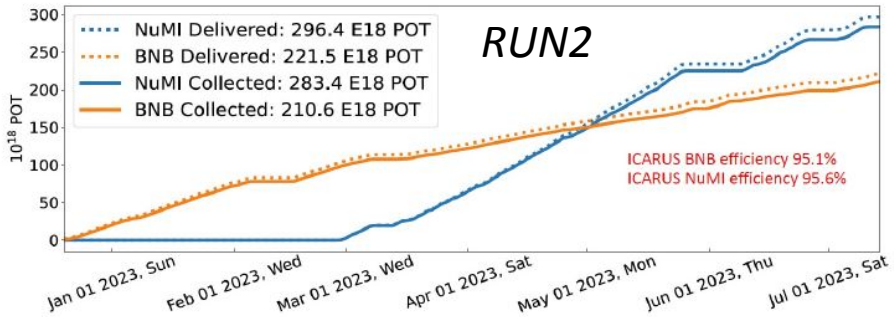
- Overall efficiency of ~ 93 % and excellent stability on long runs.
- After detector improvements during the 2022 summer beam shut down, ICARUS has recently completed its 2nd round of physics data taking from December 20th, 2022 to July 14th, 2023.

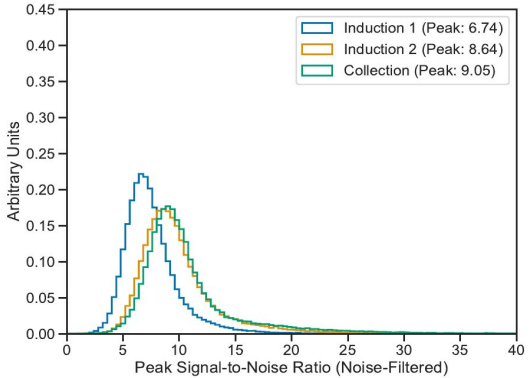


ICARUS statistics (RUN1 + RUN2):

- BNB: 4.1 10^{19} + 2.1 10^{20} POT
- NuMI: 6.8 10^{19} + 2.8 10^{20} POT

ICARUS: first performance

S/N ratio > 10 in Collect./Ind-2 views for mip vertical μs tracks



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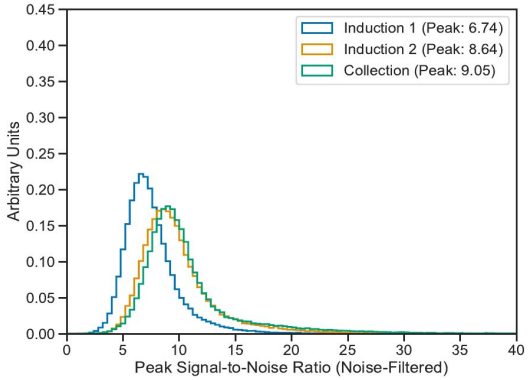
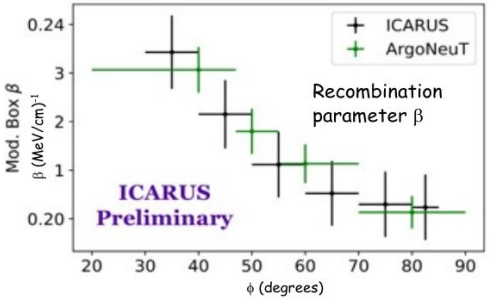
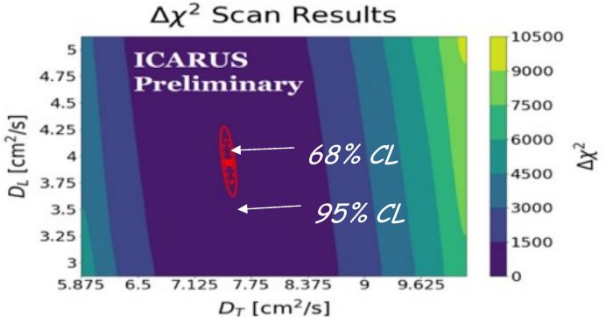


Electron recombination



Drift electron diffusion



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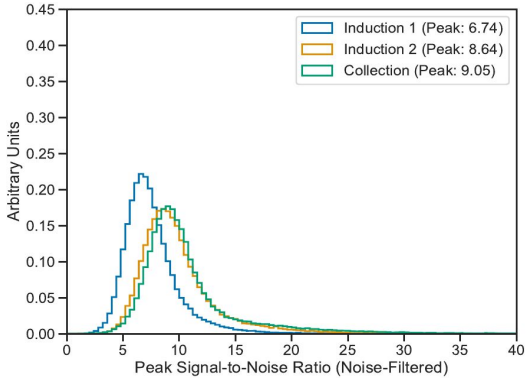
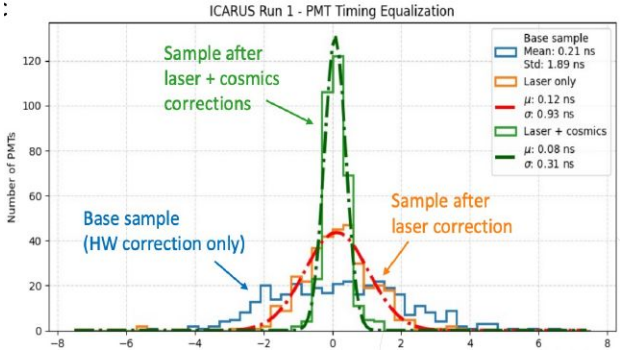


PMT timing ~ 300 ps



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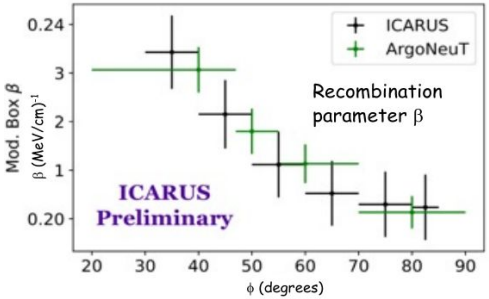

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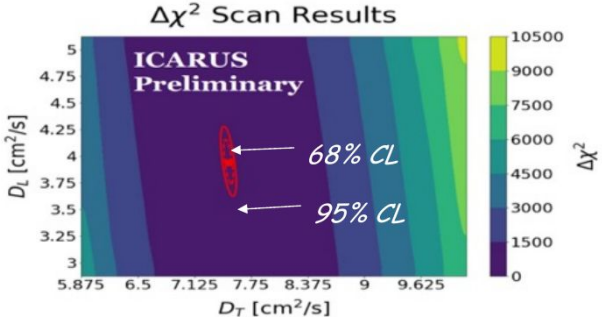

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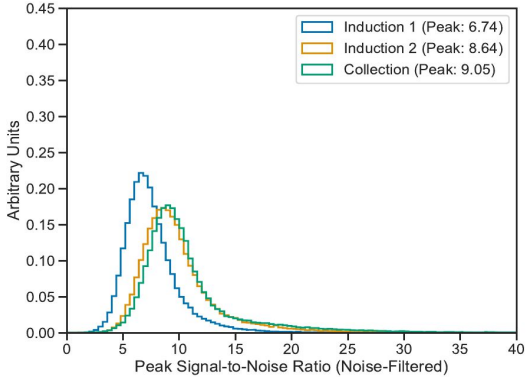

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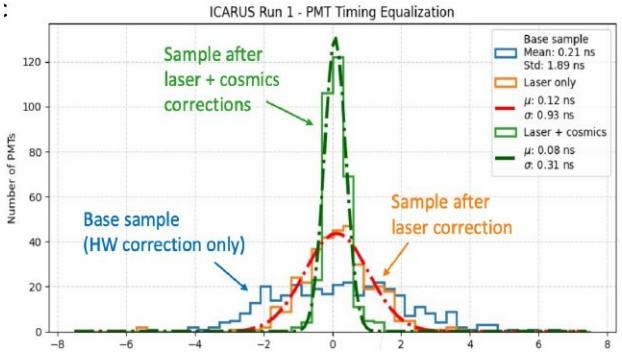
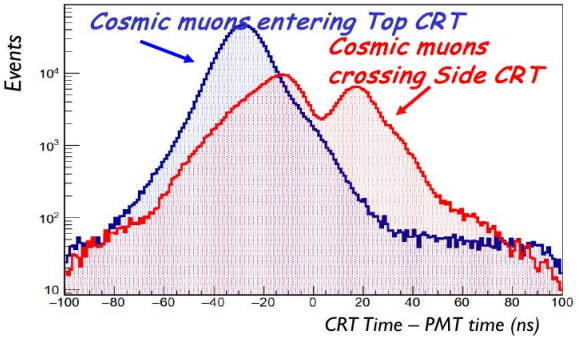
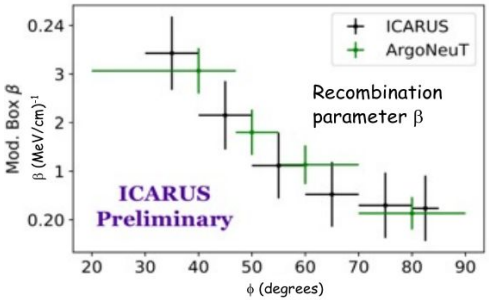


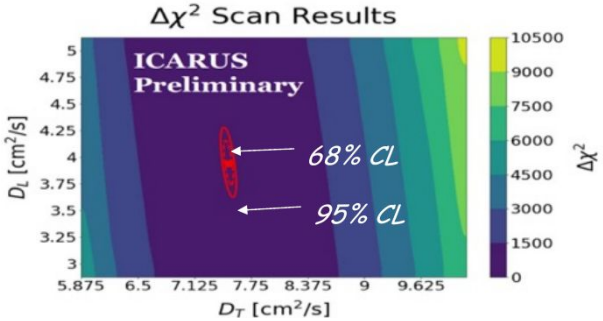
Time difference between CRT Hits and the matched PMT signals.

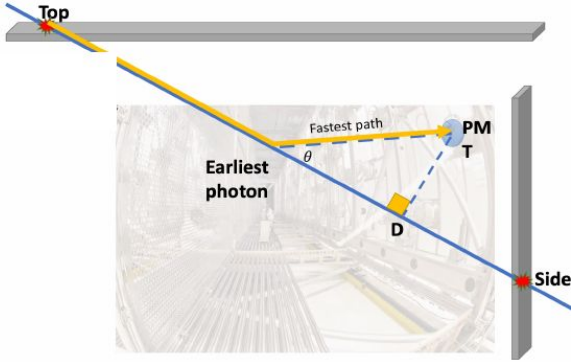


Electron recombination



Drift electron diffusion





ICARUS: first event reconstruction studies

- While SBND is preparing to join the SBN program, ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation hypothesis in the same L/E range (~ 1-3 m/MeV), but collecting ~ 100 times more energetic events: ν_μ disappearance channel from BNB: focusing on contained quasi-elastic ν_μ CC interactions.

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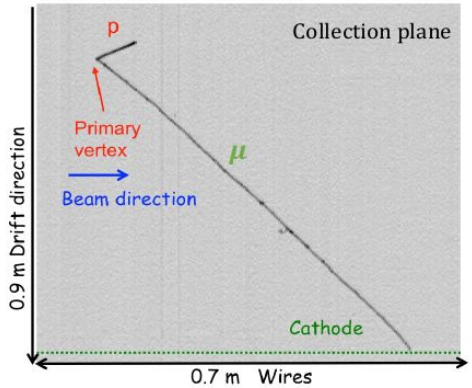

- Strategy to automatically select a pure sample of well reconstructed ν event topology.

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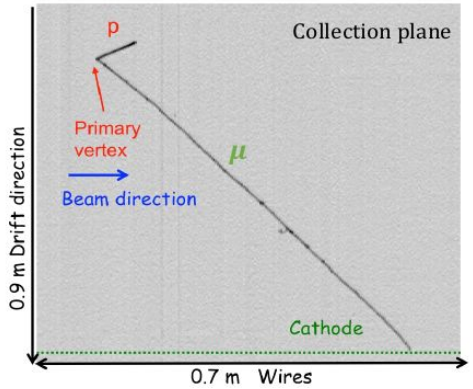
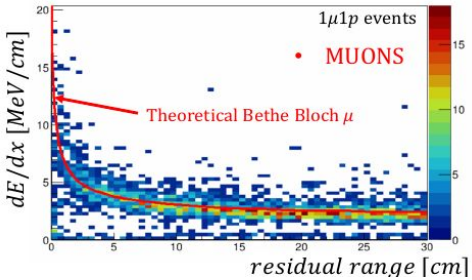
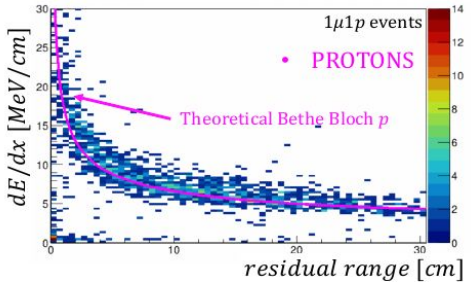


Particle identification by range





- Strategy to automatically select a pure sample of well reconstructed ν event topology.
- Demonstrate the particle identification tool performance → unambiguously recognition of stopping muons and protons.

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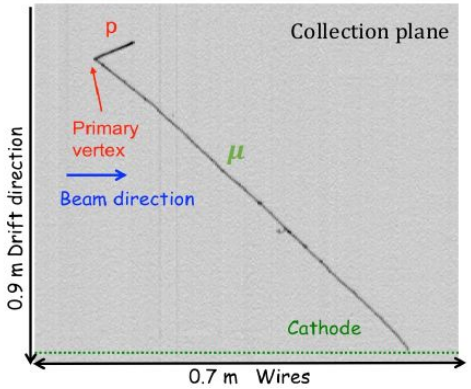

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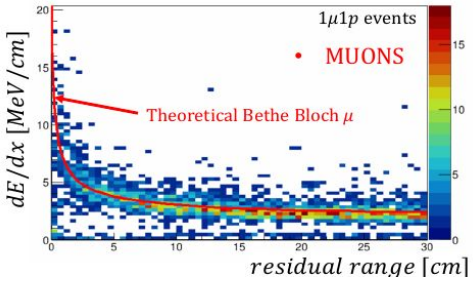
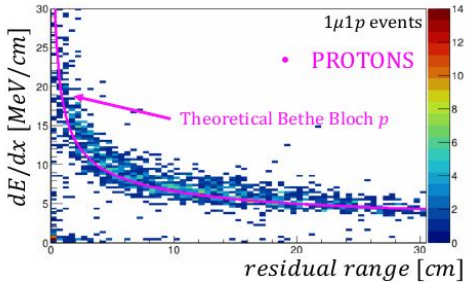
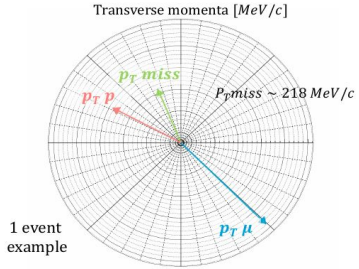
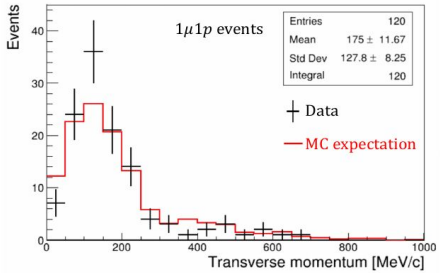




- Strategy to automatically select a pure sample of well reconstructed ν event topology.
- Demonstrate the particle identification tool performance → unambiguously recognition of stopping muons and protons.
- Evaluate the kinematic reconstruction capability in the transverse plane.

Data/MC comparison of transverse momentum





Conclusions

- ICARUS installation and commissioning was completed by mid 2022. Run 2 has smoothly finished collecting data from both Booster and NuMI beams. Run 3 is starting by March 2024.
- SBND is beginning its commissioning phases. Filling with LAr is expected very soon!
- ICARUS early phase primary focus: study of the Neutrino-4 claims searching for ν_μ disappearance with BNB ⟶ data collected are being actively analysed, first physics results expected soon.
- The comparison between near (SBND) and far (ICARUS) detector data will allow to exploit the full capabilities of the SBN program, verifying the currently allowed region in sterile neutrino parameter space with 5σ sensitivity.

Thank you!