The Fermilab Short Baseline Neutrino Program

Filippo Varanini
INFN Padova

on behalf of the ICARUS and SBND collaborations

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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-SM physics.

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

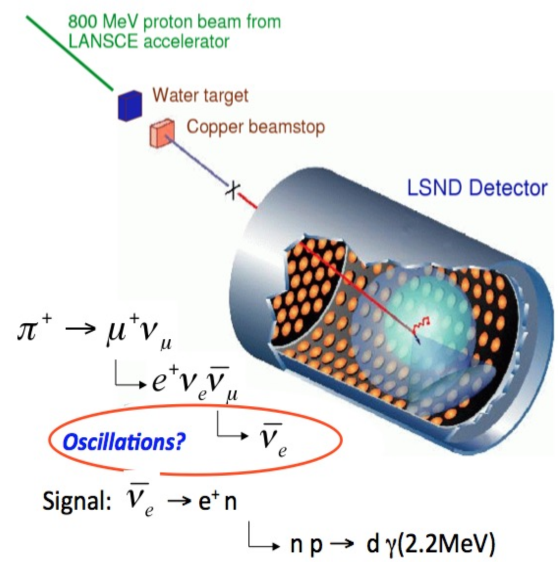
➢ *anti–ve appearance:* *in anti-$\nu\mu$ accelerator LSND experiment where anti-ve -> e+ + n with neutron resulting n + p into d + γ.*

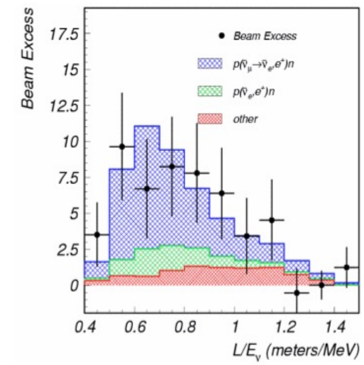
➢ *ve disappearance:* *SAGE, GALLEX experiments Mega-Curie radioactive sources showing an observed/predicted rate R = 0.84±0.05, recently confirmed at 4σ by BEST experiment*

➢ *anti-ve disappearance* *in nuclear reactor experiments, initially R = 0.934±0.024 but now mostly explained*

Possibly hinting to sterile neutrinos hypothesized by Bruno Pontecorvo in 1957

The LSND Anomaly





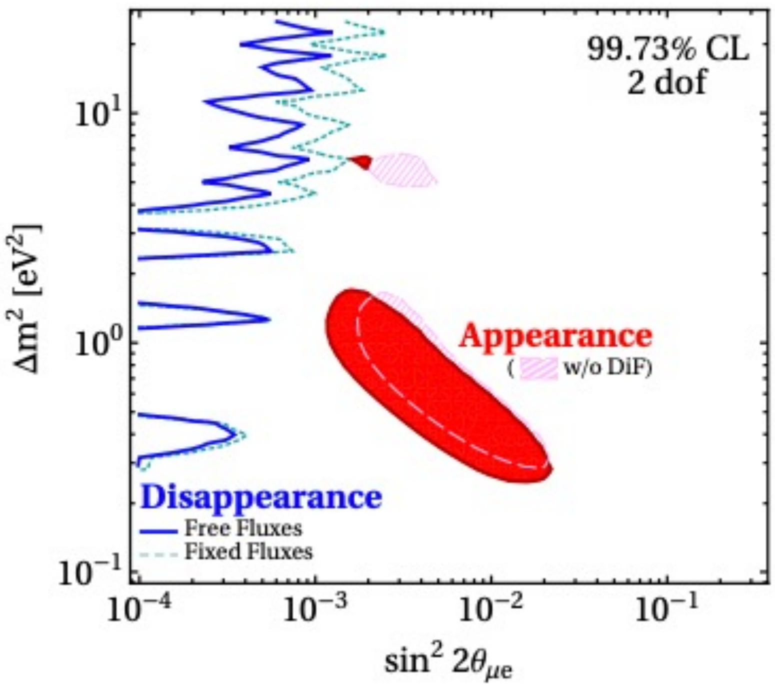
Saw an excess of $\bar{\nu}_e$: 87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

The sterile neutrino puzzle

- Several experiments performed at reactors and accelerators to study neutrino anomalies, e.g. MiniBooNE (arXiv:1805.12028) and MicroBooNE (arXiv:2210.10216), but:
  - A clear tension between (anti-)νe appearance and (anti-)νμ appearance/disappearance results which are characterized by different neutrino energy range and detection technique is evident.



JHEP 08,010 (2018)
Dentler et al.

✓ *Measuring both νe appearance and νμ disappearance in the same experiment using a detector with optimal neutrino identification and background rejection is mandatory to disentangle the physics scenario;*

✓ *Far to near detector neutrino spectra comparison is crucial for the control of background and beam/detector systematics.*

New evidence for oscillations of sterile neutrinos at reactor ?

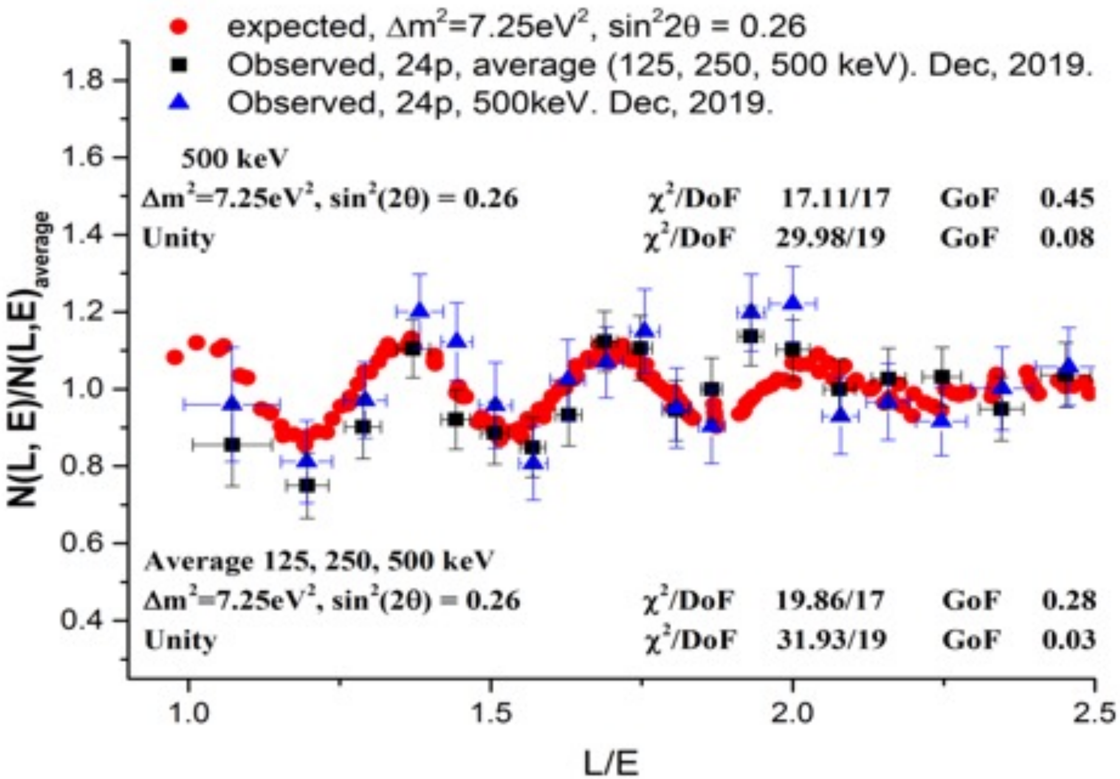
- In 2019 Neutrino-4 experiment *(A.P. Serebrov et al.)* at Dimitrovgrad SM-3 reactor gave evidence of neutrino oscillation into sterile-νs showing a disappearance signal with a clear L/Eν ~ 1-3 m/MeV modulation

Neutrino signal (blue ▲ and black ■) compared with expectation (red ●) for Δm^2, $\sin^2 2\theta$ values as a function of L/E

Reactor On - Off : 223 events/day with Signal/Background ~ 0.54

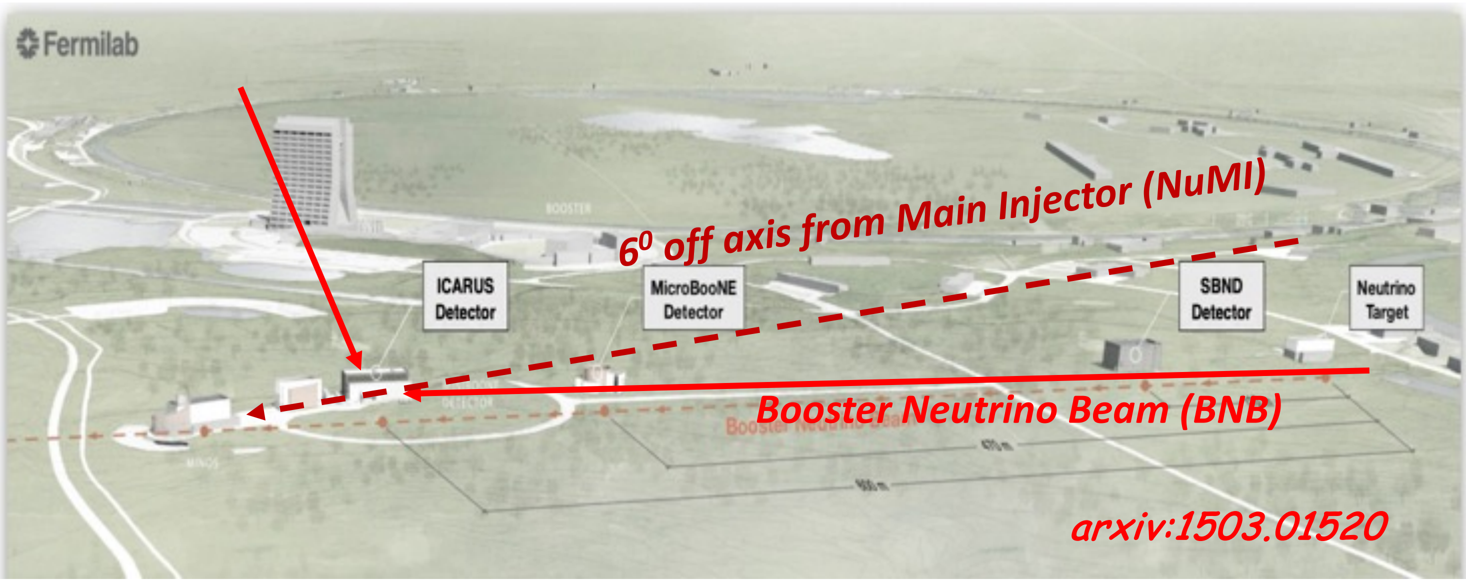
$\Delta m_{41}^2 = 7.25 \pm 1.09\ eV^2$ with $\sin^2(2\theta_{14})$ =

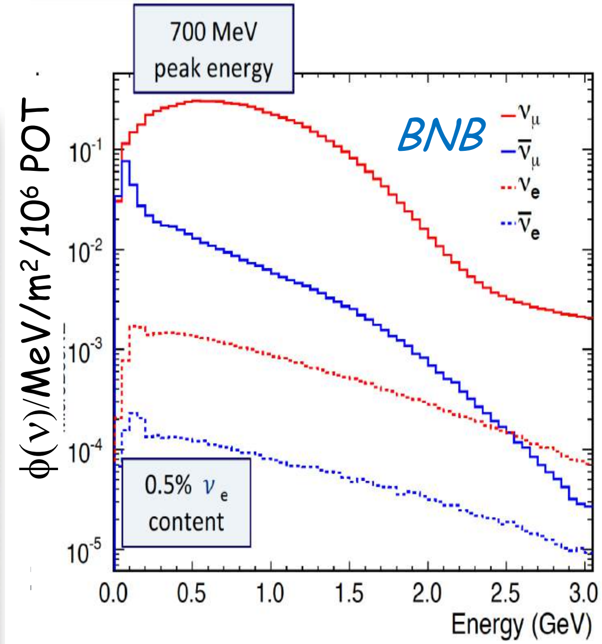
$0.26 \pm 0.08\ stat \pm 0.05$



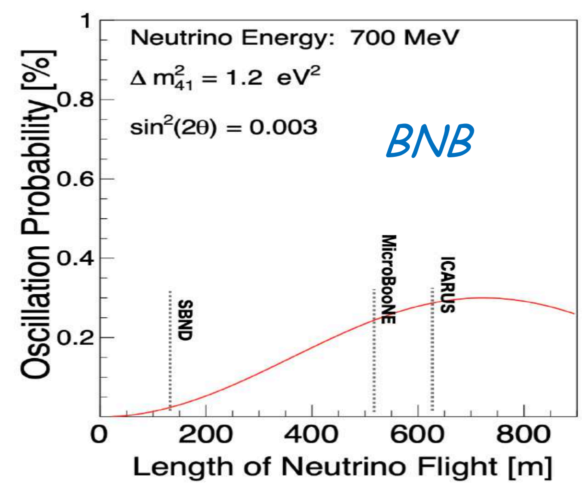
- Combined analysis of Neutrino-4 with GALLEX, SAGE, BEST (*P.R.D 104, 032003, 2021*) results in a best fit of $\Delta m_{41}^2 = 7.3\ eV^2$ $\sin^2(2\theta_{14}) = 0.36$ at 5.8 σ C.L

SBN program at FNAL: a definitive answer to sterile neutrinos?





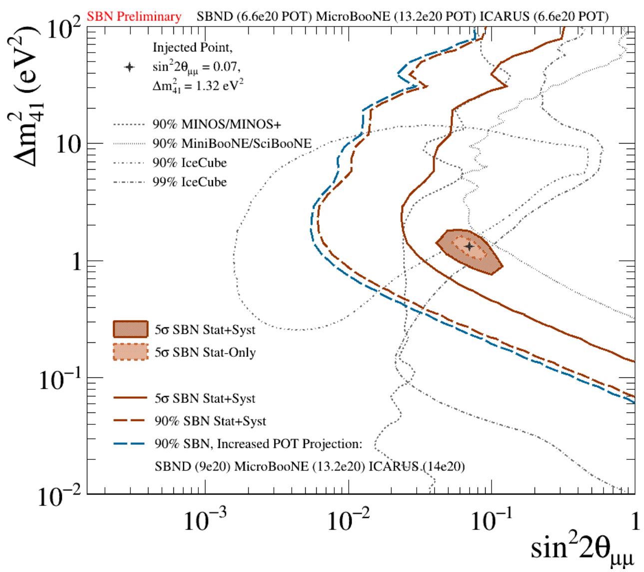
- ICARUS and SBND LAr-TPC's installed at 600 and 110 m from Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels.
- Furthermore, high-statistics ν-Ar cross-section measurements and event identification/reconstruction studies:
  - ~10^6 events/y in SBND < 1 GeV from Booster
  - ~10^5 events/y in ICARUS > 1 GeV from off-axis NuMI beam.



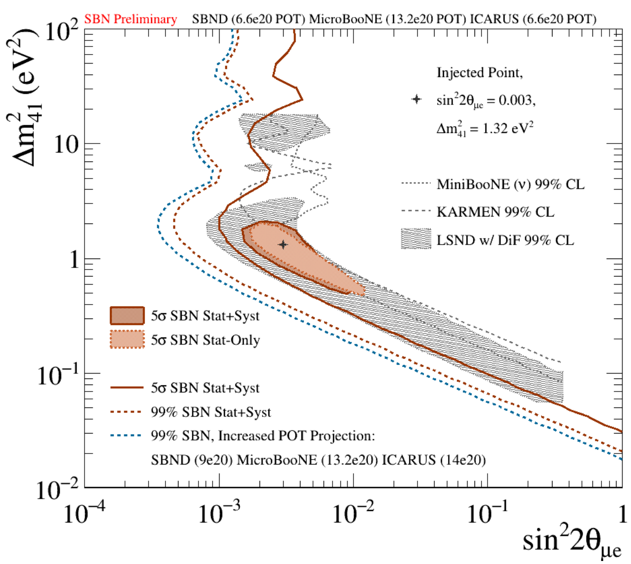
SBN Program: sterile neutrino sensitivity, 3 years (6.6 $\times 10^{20}$ pot)

- Combined analysis of events collected ICARUS (far detector) and SBND (near detector) using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPCs rejecting NC event background;
  - "Initial" BNB beam composition and spectrum provided by SBND detector.
  - Sharing of reconstruction/analysis tools between near and far detector reduces systematics

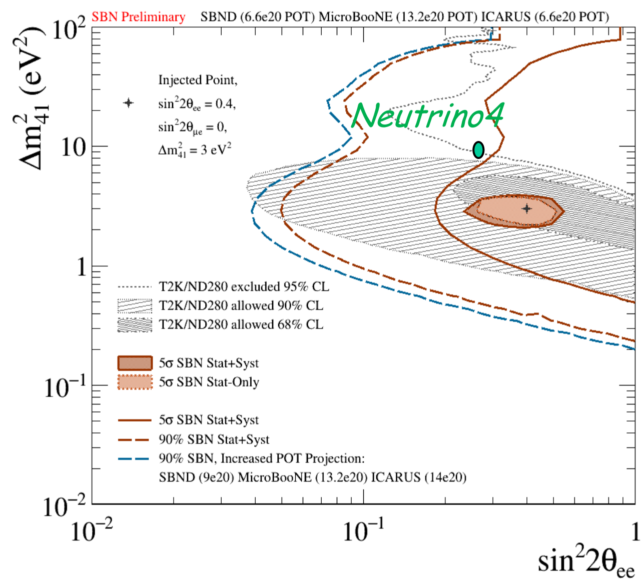
νμ disappearance



νe appearance



νe disappearance



5σ coverage of the parameter area relevant to LSND anomaly

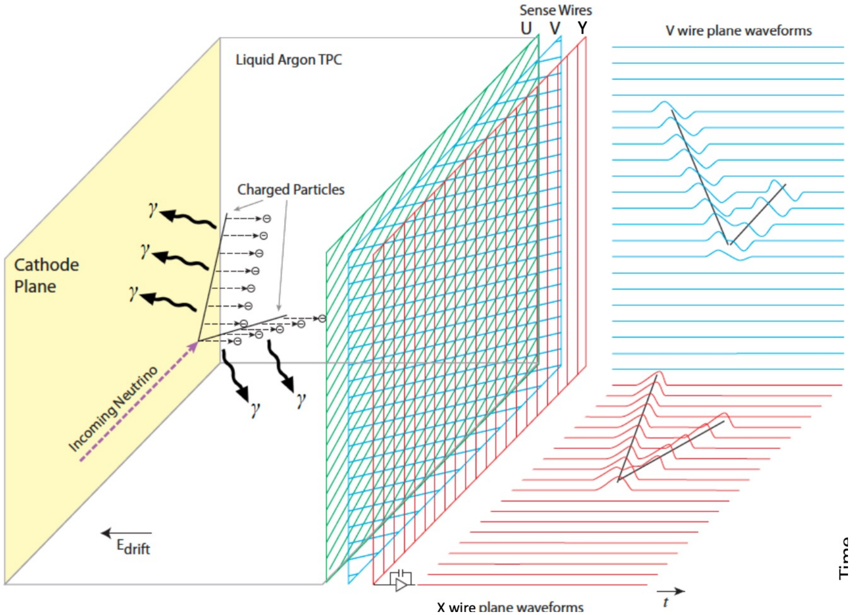
Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study neutrino appearance and disappearance simultaneously

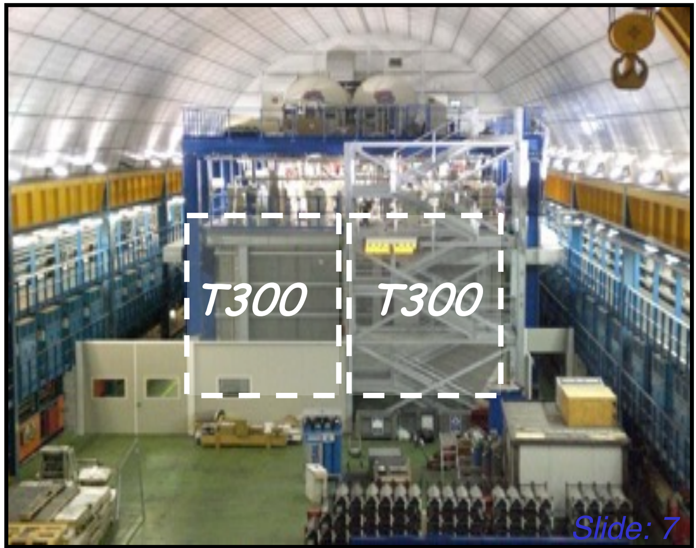
The evolution of the LAr-TPC

Liquid Argon TPC (LAr-TPC) technology was first proposed by C. Rubbia in 1977 as an alternative to Cherenkov detectors: an electronic bubble chamber to reconstruct a large variety of complex neutrino interactions

- **3D Tracking** with $\Delta x \sim mm^3$:ionization e- can drift for meters if LAr is sufficiently pure (E~500 V/cm)
- **Full sampling homogeneous calorimeter:** Energy measurement by e- charge signal integration;
- **Measurement of local energy deposition dE/dx:** remarkable e/γ separation, 0.02 X_0 sampling, X_0=14 cm, a powerful PID by dE/dx vs range.
- **Scintillation light** by charged particles provides fast signals for timing/triggering.

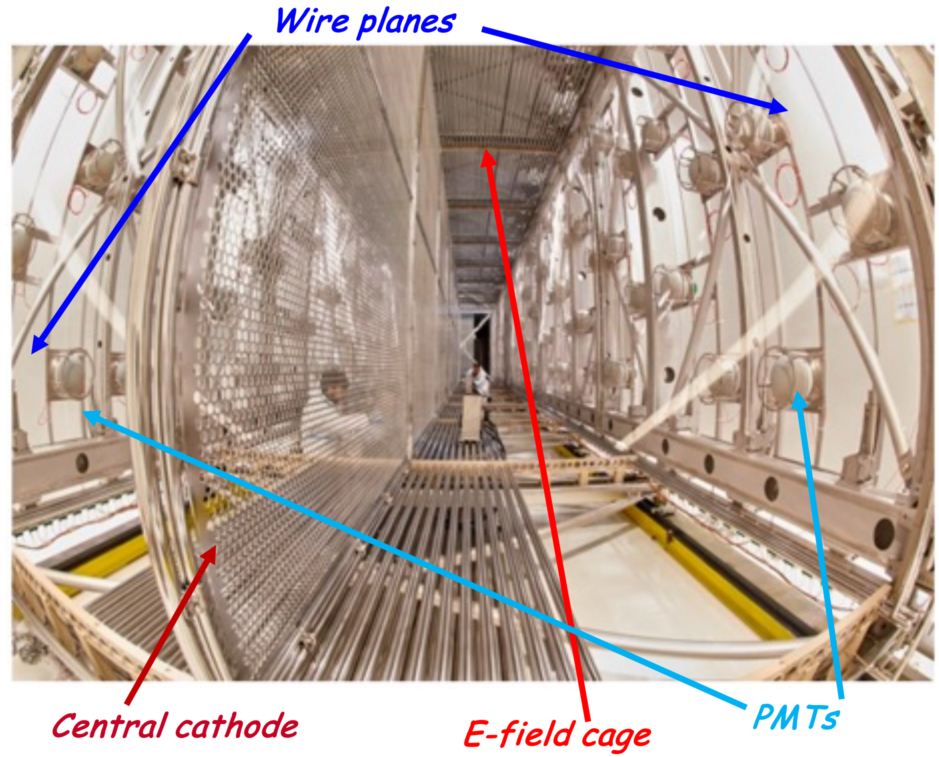


- *A long R&D culminated in ICARUS-T600, 0.76 kt LAr at LNGS exposed to CNGS neutrino beam.*
  - *ICARUS produced significant results in sterile neutrino searches (EPJ C 73, 2013)*
  - *It also confirmed the viability of LAr-TPC technology, paving the way for DUNE*



The ICARUS detector at FNAL

- Combined 2 modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
- 3 readout wire planes per TPC (2 Inductions+1 Collection). 54000 wires in total at 0, ± 60^0, 3 mm pitch;
- S/N > 10 for MIP tracks in Induction2 and Collection planes;
- 360 photomultipliers, TPB coated, to detect the scintillation light produced in LAr;



2015-17: overhauling at CERN

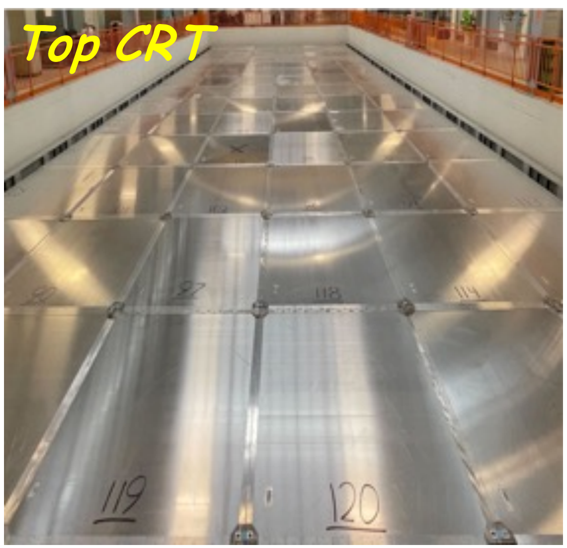
2018: transportation to FNAL and start of installation

2020: filling with LAr and start of commissioning

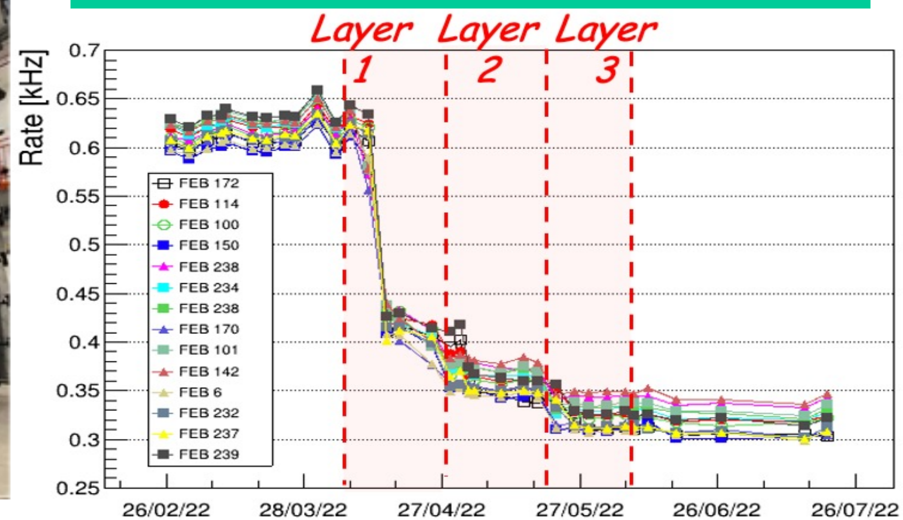
2022: start of physics data taking

Cosmic-ray background mitigation in ICARUS

- ICARUS is installed in a pit exposed to cosmic rays where electrons produced by Compton/pair-production photons can mimic a genuine ν_e CC interaction
- In order to reduce this background specific strategies had to be developed
  - Installation of a Cosmic Ray Tagger (CRT): double layer of scintillator bars covering the TPC at 4π (~1000 m^2 total surface) read out by SiPMs
  - CRT allows to identify incoming cosmics in position and time with ~95% efficiency, and match this information with PMT and TPC data
  - Installation of a concrete overburden (~2.85 m thick) suppressing EM component of cosmic rays and most neutrons.

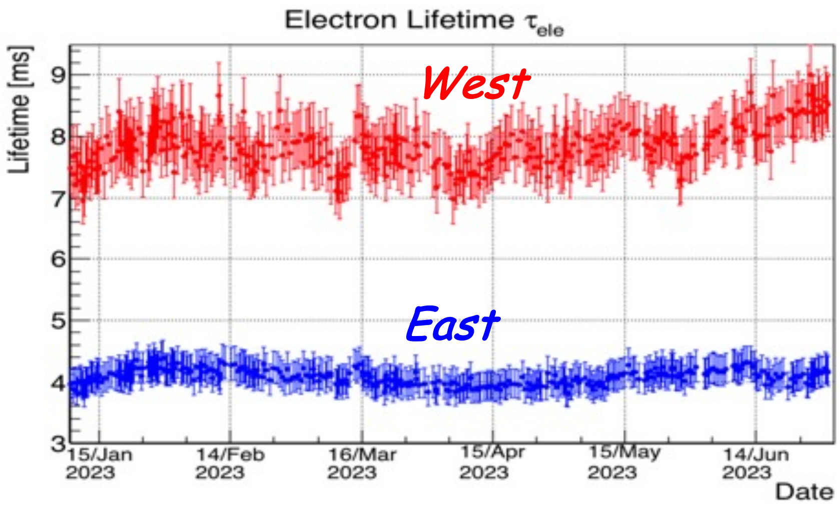


Rate of cosmics measured by top CRT modules during the overburden installation

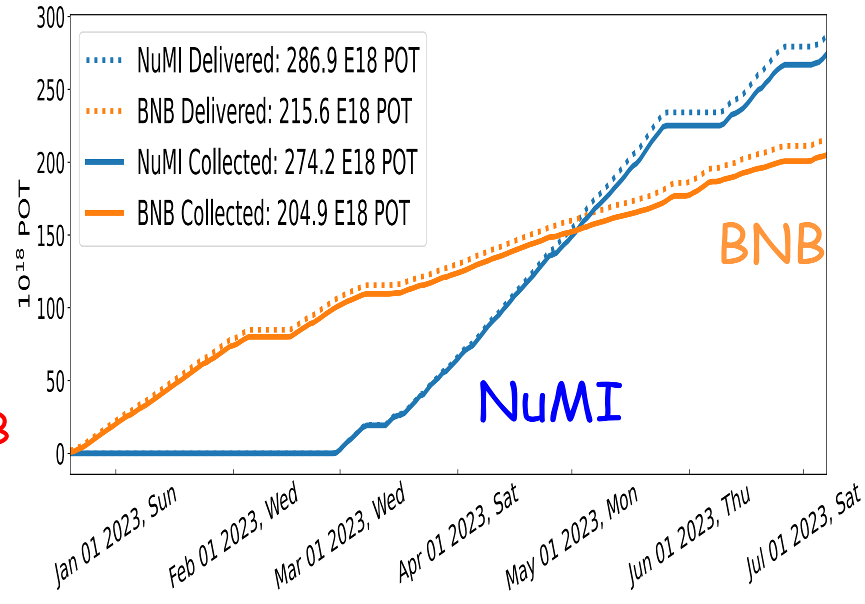


ICARUS physics runs

- The first ICARUS run (Run 1) started after the completion of the overburden. ~6.8 10^{19} POT were collected for NuMI and ~4.1 10^{19} POT for BNB, with a good detector live-time (>93%) in 1 month run (June 9 to July 9, 2022).
- Detector improvements and calibration with cosmic rays, followed by the LAr filter regeneration in the West cryostat, were performed during summer 2022



- Run-2 officially started on December 20, 2022 with BNB only. Due to horn magnet issues, NuMI only started on February 28, 2023
- Electron lifetime was stable and adequate for physics during all Run2 (~4ms East, ~8ms West). Regeneration of the East filters will allow increase to ~8ms for Run 3
- Better control of detector conditions allowed to improve the live-time to >95%
- ~2.7 10^{20} POT collected for NuMI, ~2.0 10^{20} POT for BNB

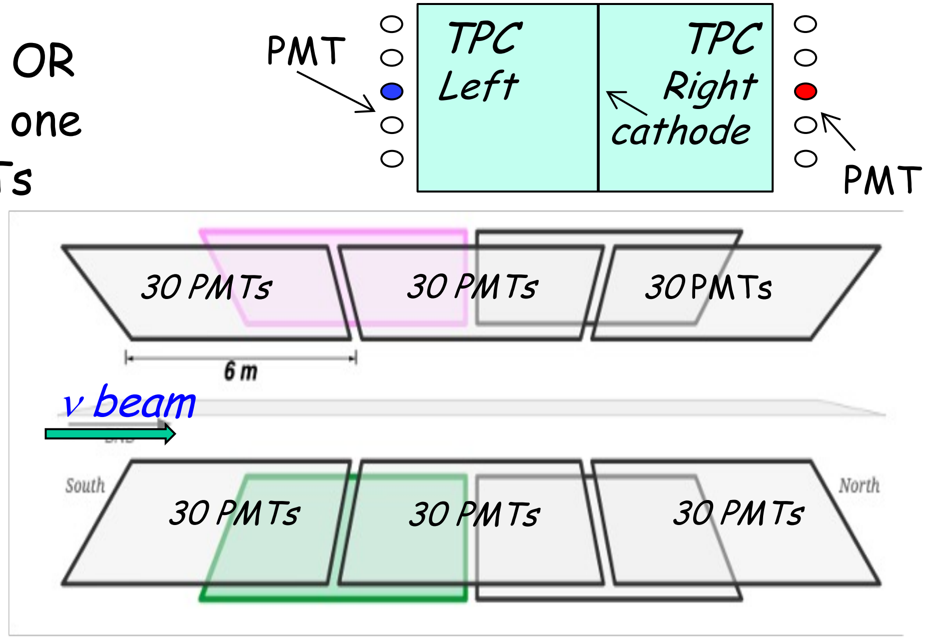


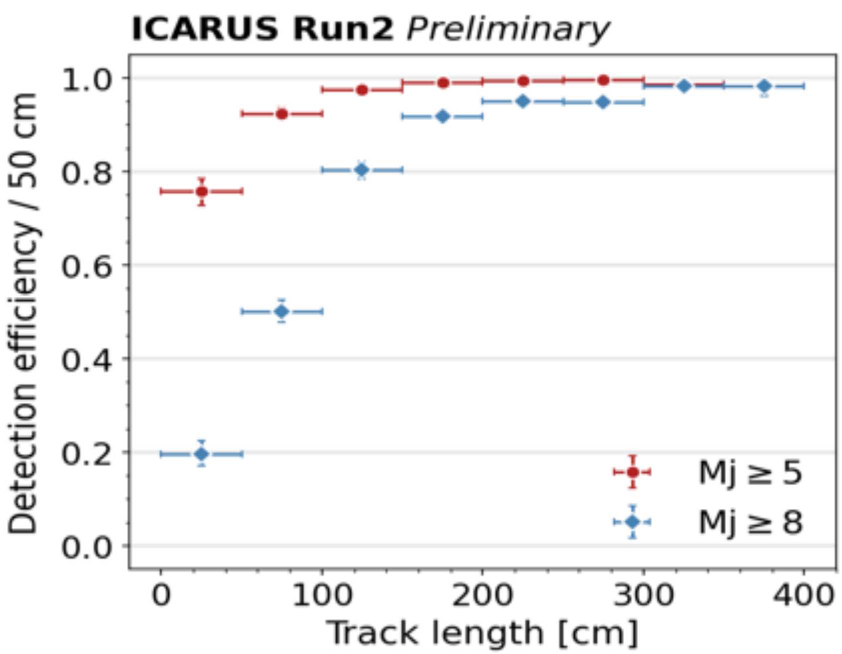
ICARUS at the Fermilab SBN program: initial operation

Eur. Phys. J. C (2023) 83:467

Triggering the neutrino events

- **ICARUS trigger system** relies on PMT light in coincidence with the beam spills, 1.6 μs for BNB and 9.5 μs for NuMI, using the Early Warning signals of proton beam extractions:
  - Beam events are collected requiring at least 5 OR signals from adjacent PMT pairs (*Mj =5*) inside one of 6 m longitudinal slices equipped with 30 PMTs left + 30 PMTs right;
  - PMT and CRT signals also recorded in 2 ms around the trigger to recognize cosmics crossing LAr-TPCs in 1 ms drift time

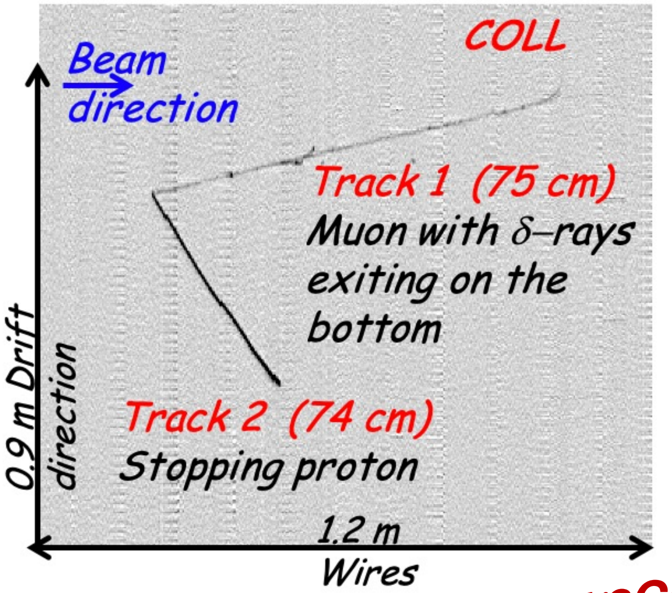




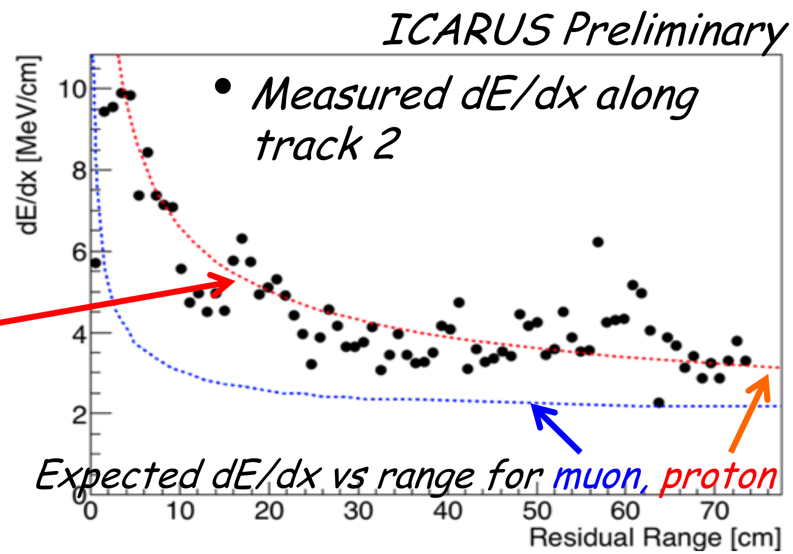
- The trigger efficiency as measured with ~ vertical cosmic muons *independently* selected by TPC tracks matched to CRT signals.
  - An almost full efficiency is found for in-spill events above 1 m track length (E_{DEP}~ 200 MeV),
  - Out-of-spill cosmics are recognized with 90% eff. for L > 1.5 m requiring >= 8 fired PMT pairs.

Some example neutrino events

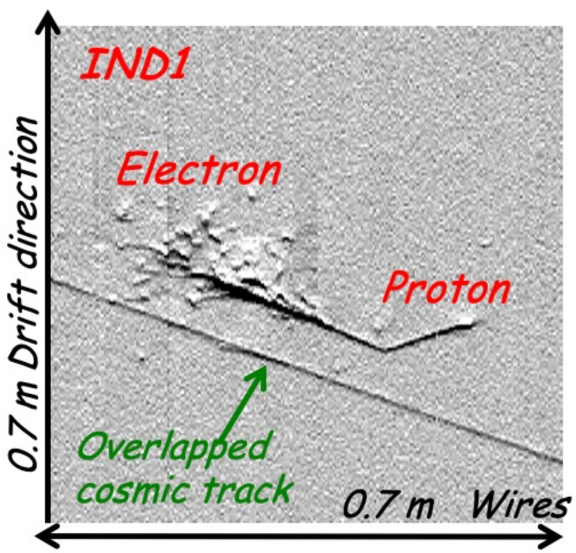
νμCC interaction from a BNB neutrino

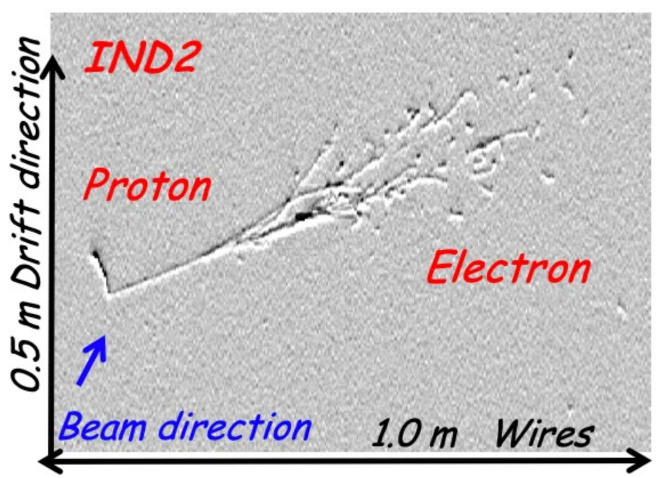


The study of dE/dx *vs* range confirms Track 2 is compatible with a proton (E_{DEP}~ 340 MeV)



νeCC interaction from a NuMI neutrino

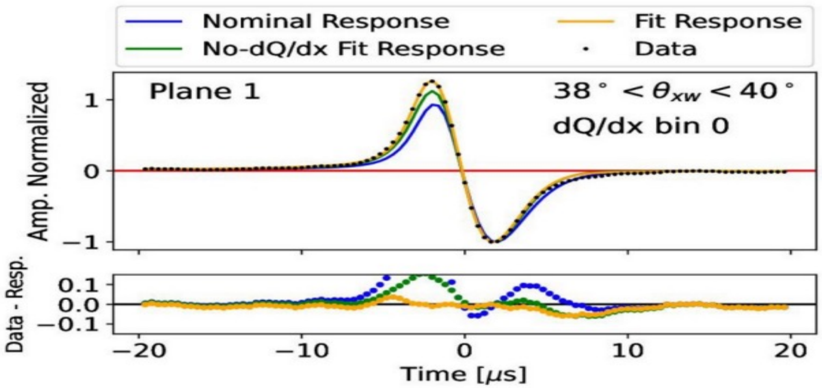




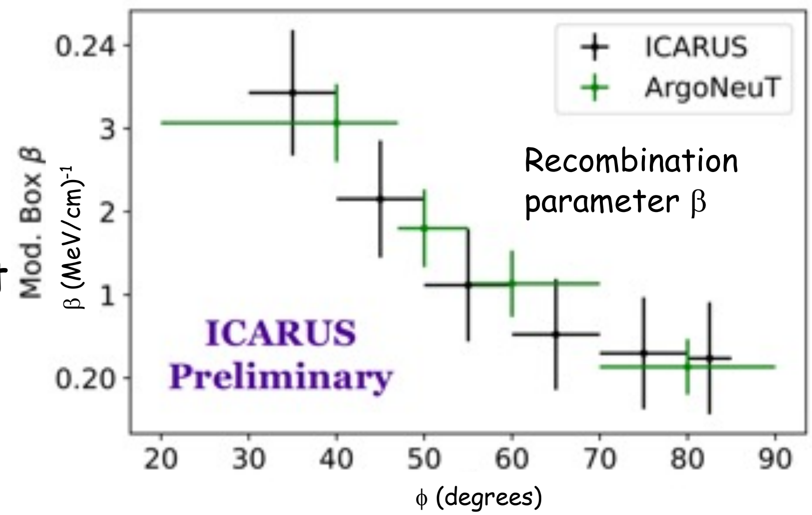
- QE νe CC event contained candidate, E_{DEP}~870 MeV:
  - ✓ proton candidate is upward going/stopping L= 13 cm;
  - ✓ e-shower is downward going.

Detector Physics measurements

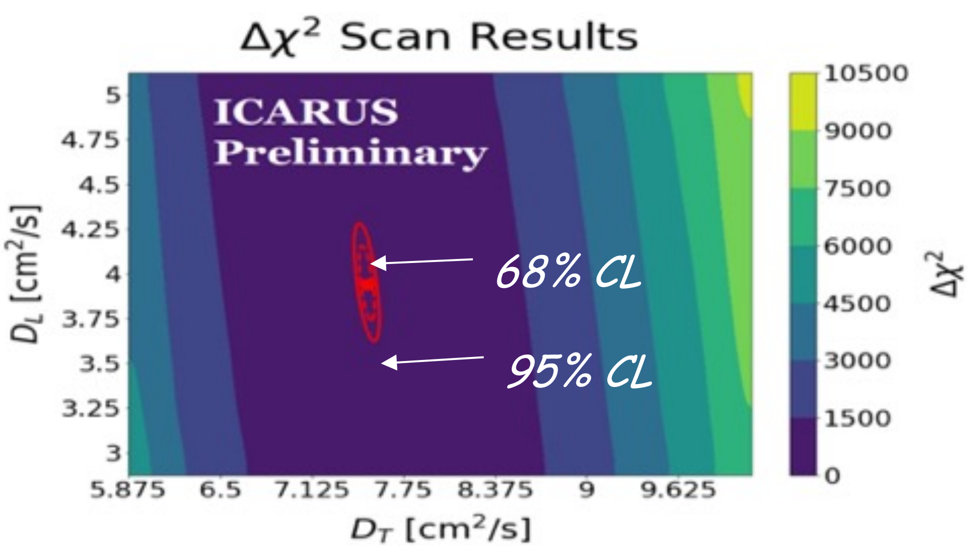
- Accurate measurements of detector parameters and characterization of detector effects are needed for calibration/equalization of energy response and efficient particle ID



- Data-driven fit of TPC field response allows better description of signal shapes in all planes, including for possible non-transparency effects



- Observed dependence of electron recombination on track angle ϕ wrt drift coordinate for high dE/dx (proton tracks). Consistent with ArgoNeut



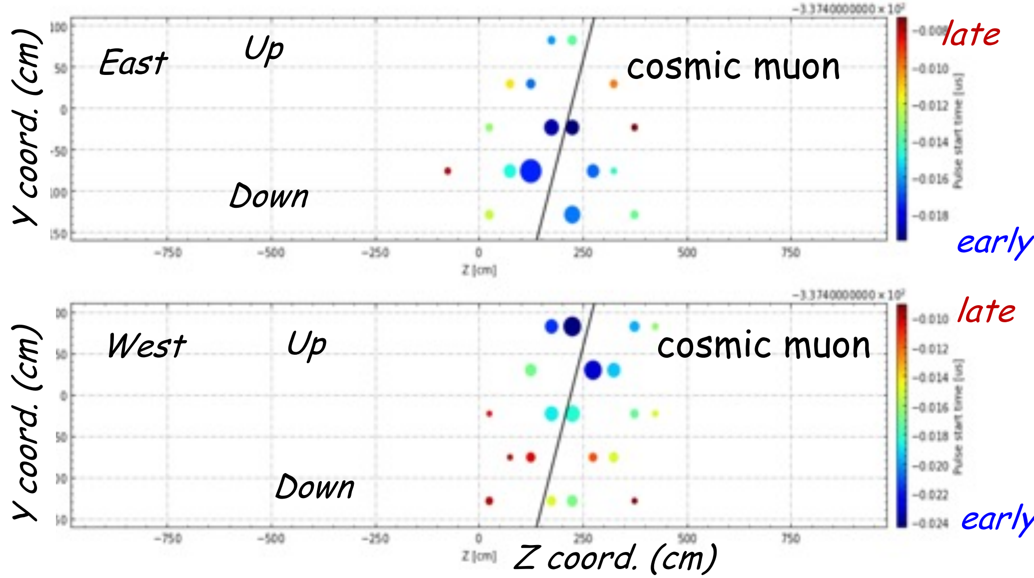
- Longitudinal (D_L) and transverse (D_T) electron diffusion coefficients in LAr measured by observing the dependence of average signal width on drift coordinate.

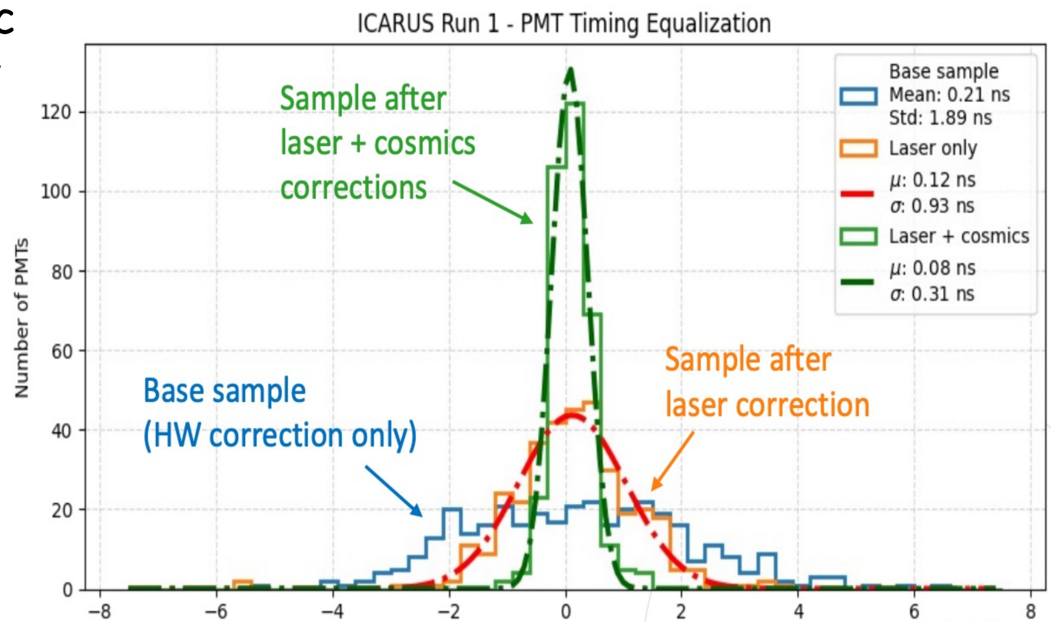
first D_T measurement in this E-field range!

PMT timing calibration

- A good PMT timing is crucial to ensure accurate matching with TPC and CRT information and resolve the BNB bunch structure
- PMT relative timing is regularly calibrated with both laser pulses and cosmic ray data
- The expected linear relationship between the vertical position of a PMT and the corresponding signal time for crossing cosmic muons allows to tune the timing of each PMT
- As a result, the PMT timing is equalized with a resolution of ~300 ps (Run1)
- A significant stability of PMT timing was observed in Run2, with a similar time resolution

Times of fired PMTs in a cosmic muon event

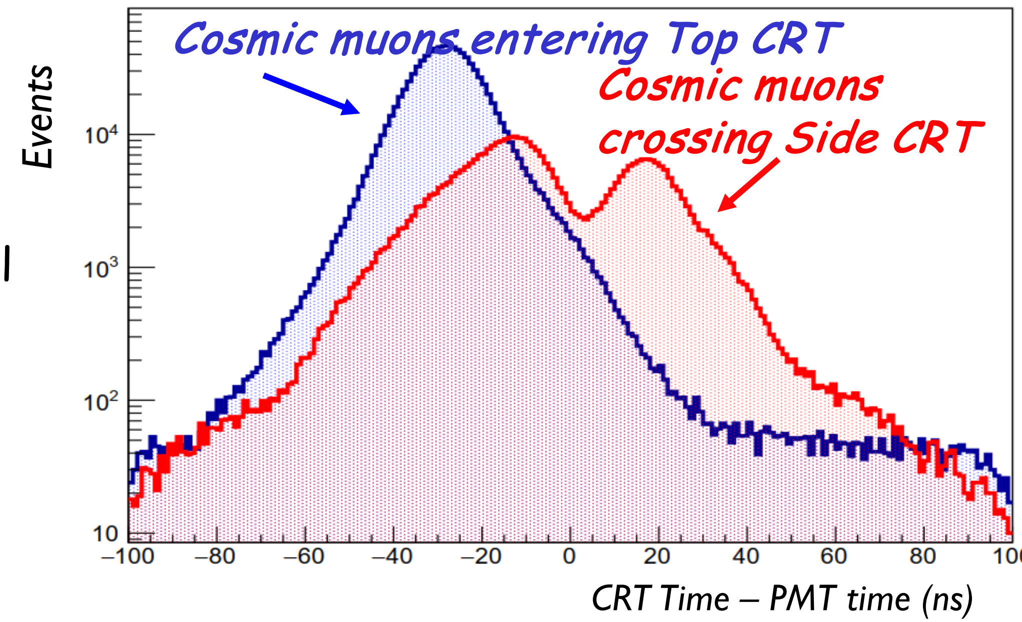


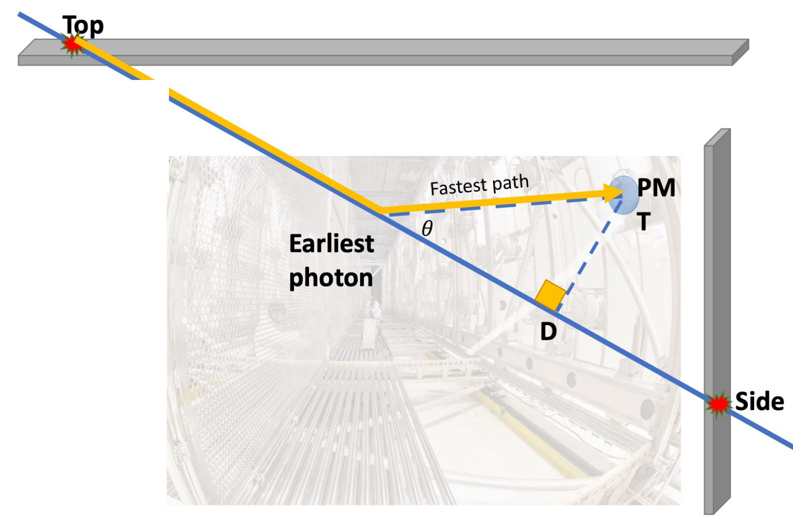


Time of flight measurements with CRT

- Cosmic ray muons entering/exiting the detector can be identified by the relative timing between PMT and CRT signals
- This requires:
  - Accurate relative synchronization of PMT and CRT systems through a global trigger signal
  - Modeling of the scintillation and light propagation in LAr
- CRT 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
- The study of top-side CRT crossing muons allows to estimate the resolution on CRT-PMT matching (convolution of both systems) in a few ns (<4ns Top, <5ns Side)

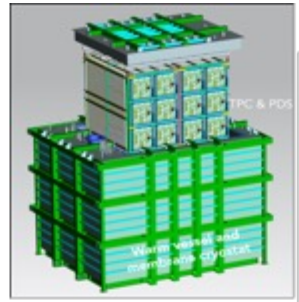
Time difference between CRT Hits and the matched PMT signals.

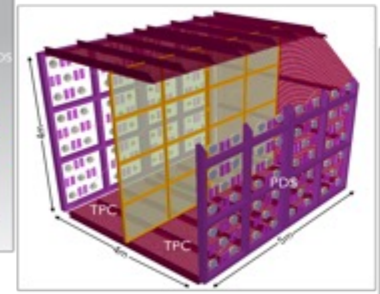




SBN Near detector: SBND at 110 m from target

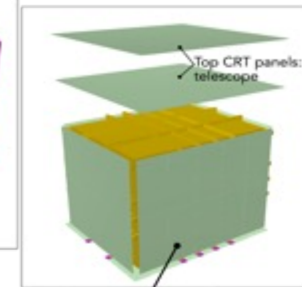
- Two LAr-TPCs with central Cathode, 112 t LAr active volume equipped with cold electronics;
- Scintillation light detected by PMTs and X-Arapucas (partly coated with TPB, partly not). Cathode coated with TPB
- The cryostat is surrounded by a Cosmic Tagger system for cosmic ray rejection.





Two Time Projection Chambers and Photon Detection systems

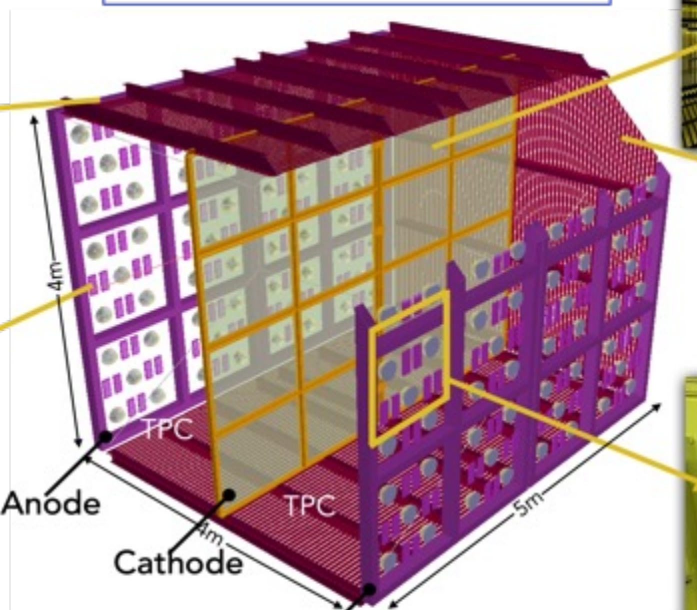
Cryostat surrounded by a Cosmic Ray Tagger system for cosmic ray rejection



Panels made of scintillator strips

TPC Cold electronics

Two Time Projection Chambers
Total dimension: 4m x 4m x 5m



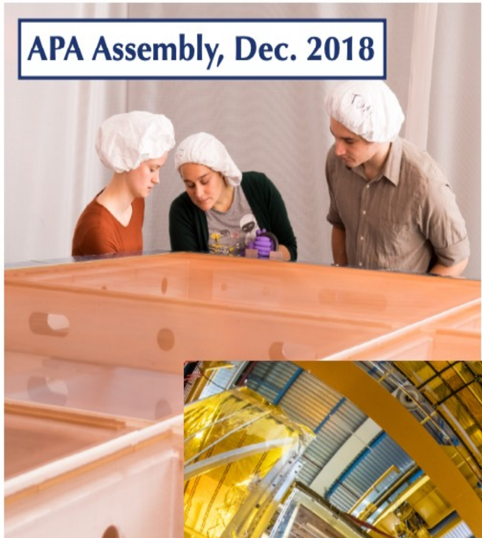
APA-Wire Planes- 3 planes, ~11000 wires

CPA-Cathode covered with TPB coated reflectors

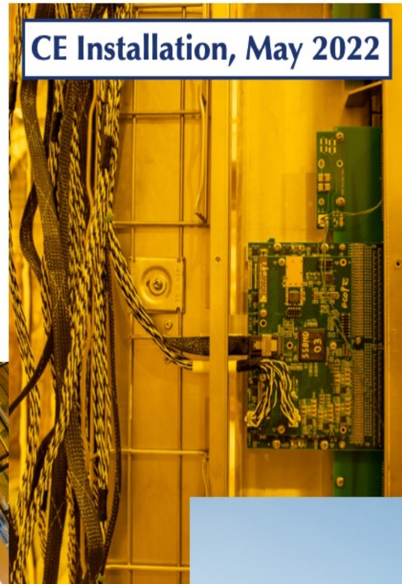
Field Cage

Photon Detection Systems: 120 PMTs, 192 X-Arapucas

SBND Assembly and installation

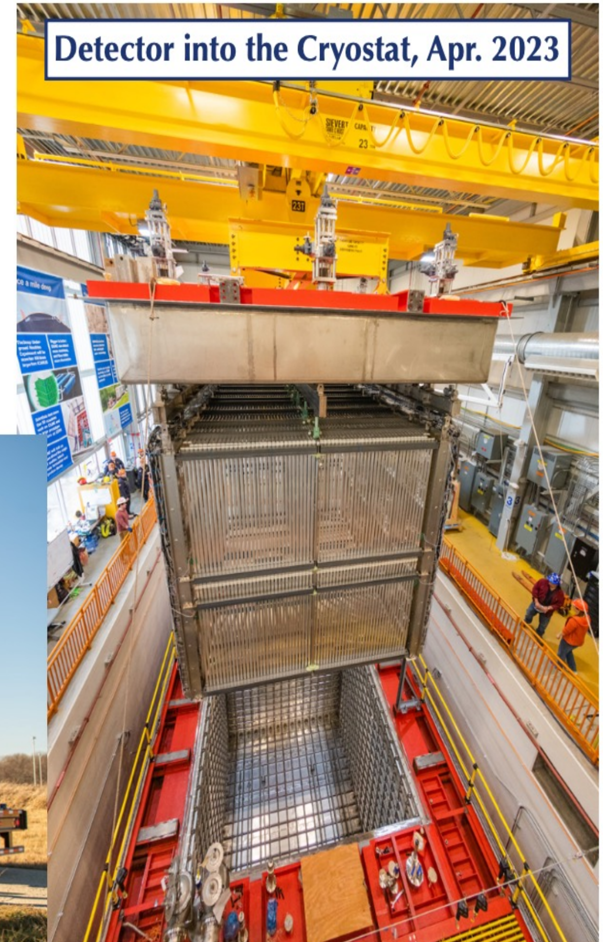


APA Assembly, Dec. 2018

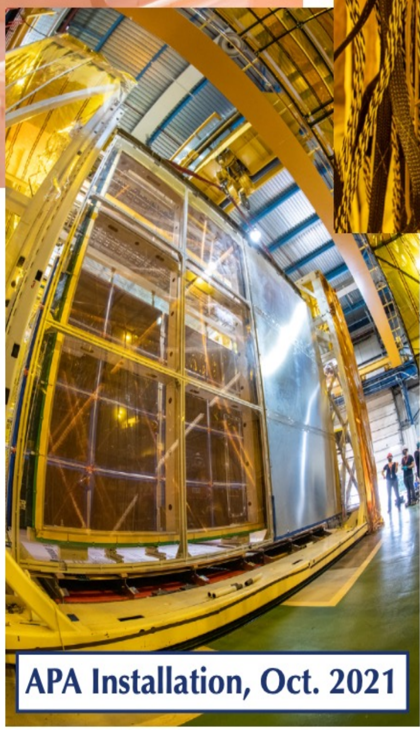


CE Installation, May 2022

PDS Box Installation, Sep. 2022



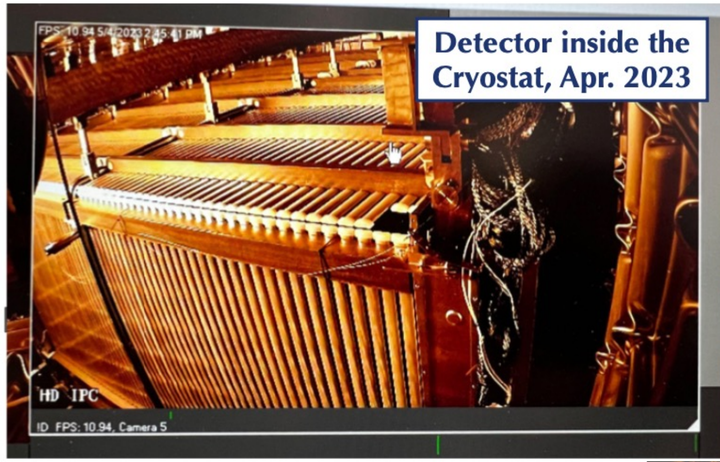
Detector into the Cryostat, Apr. 2023



APA Installation, Oct. 2021

Detector to SBND, Dec. 2022

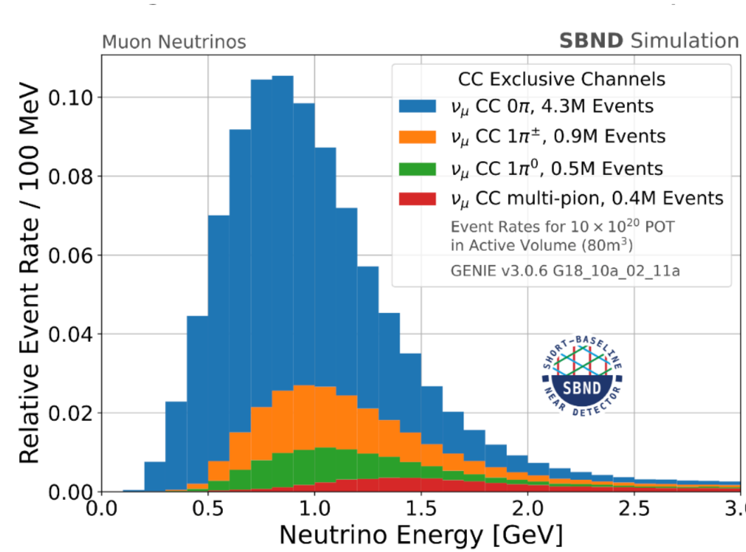
SBND Assembly and installation

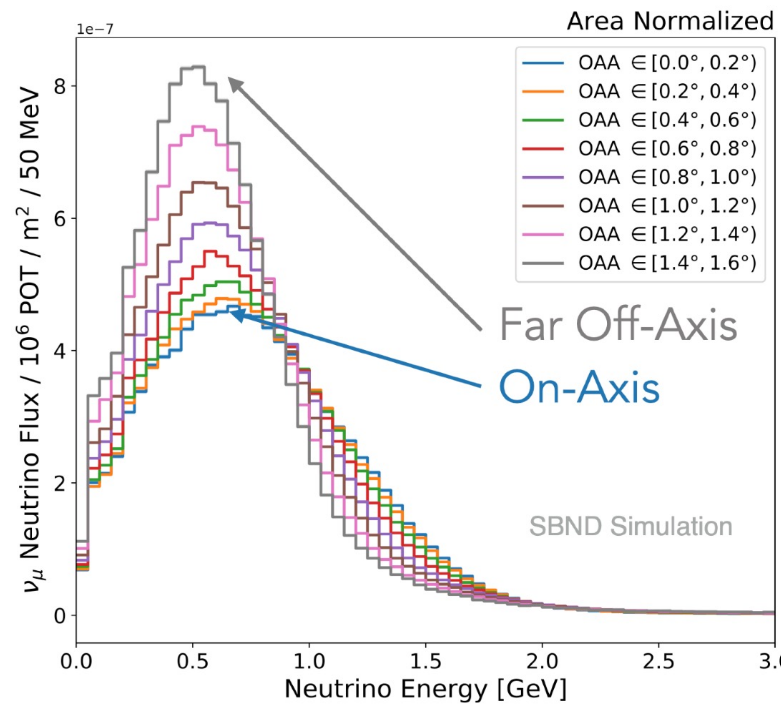


- Detector assembly and installation of all components inside the cryostat is complete, cryostat is closed
- Cryogenics installation is being finalized, to be completed by next month
- TPC calibration lasers currently being installed
- Cabling completed, cables undergoing quality control
- Bottom and North CRTs installed. Other walls will be installed after stable cryogenics operations are established
- Expect to fill SBND with liquid Argon at the beginning of 2024

SBND cross-section physics program

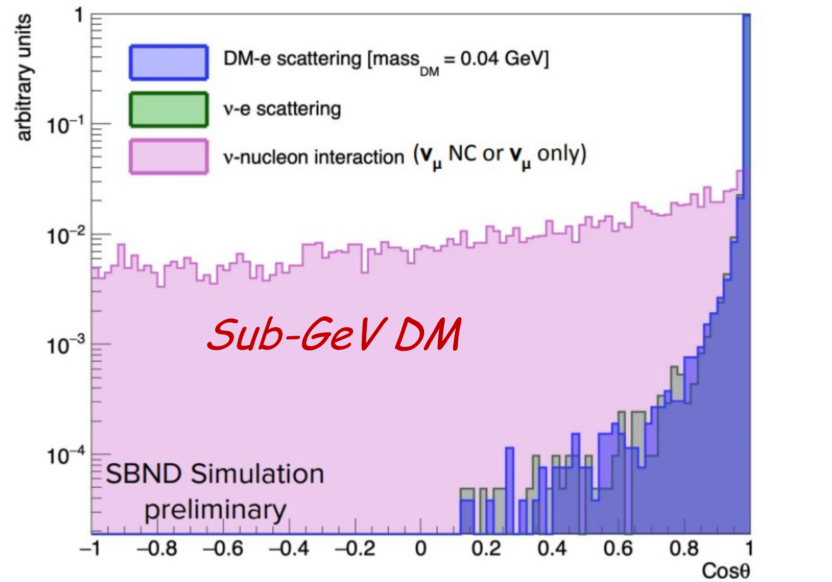
- SBND expects ~2 10^6 $\nu\mu CC$ and ~15000 $\nu e CC$ events/yr: will collect an order of magnitude more neutrino interactions than currently available
- Besides its crucial role in SBN measurement, it will have an unprecedented stand-alone program of neutrino interaction measurements: both precision measurements of common channels and searches for rare ones
- Excellent S/N ratio expected in SBND will allow study of low energy deposition, such as neutron scatters
- The short distance from target allows to exploit the PRISM concept: looking at different positions wrt beam center allows to scan a wide range of off-axis angles



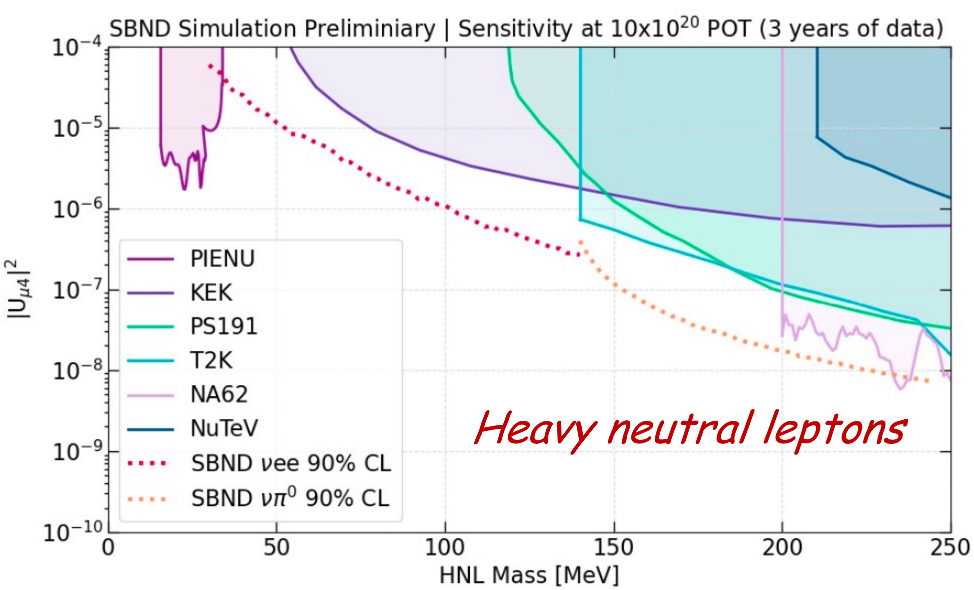


SBND BSM physics program

- Any new physics signal from BNB will show up with the highest statistics at SBND, due to the short distance from target
- The ns-level time resolution of the photon detection system will allow to resolve the BNB bunch structure, allowing to detect massive long-lived particles
- Planned studies include:
  - Sub-GeV dark matter
  - Dark neutrinos (possibly explaining the MiniBoone excess)
  - Heavy neutral leptons (produced by $U_{\mu 4}$ mixing). Best sensitivity under 250 MeV

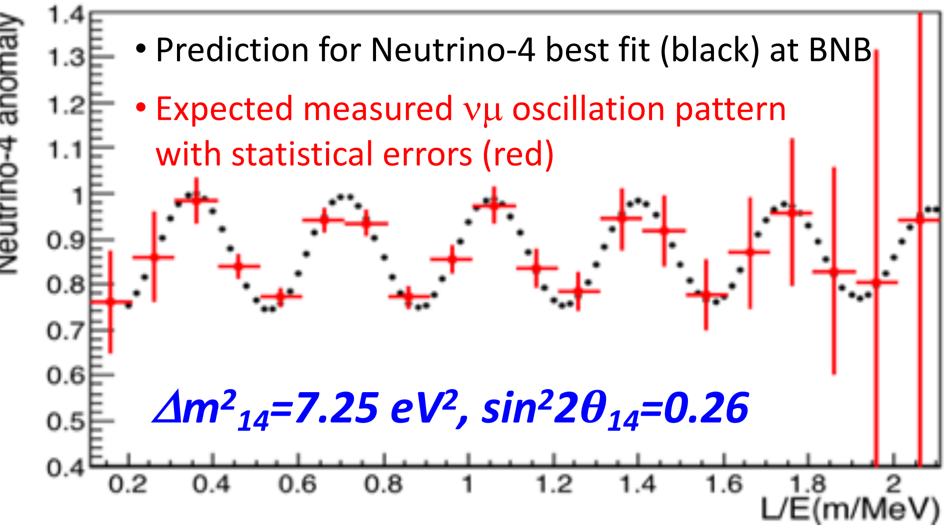


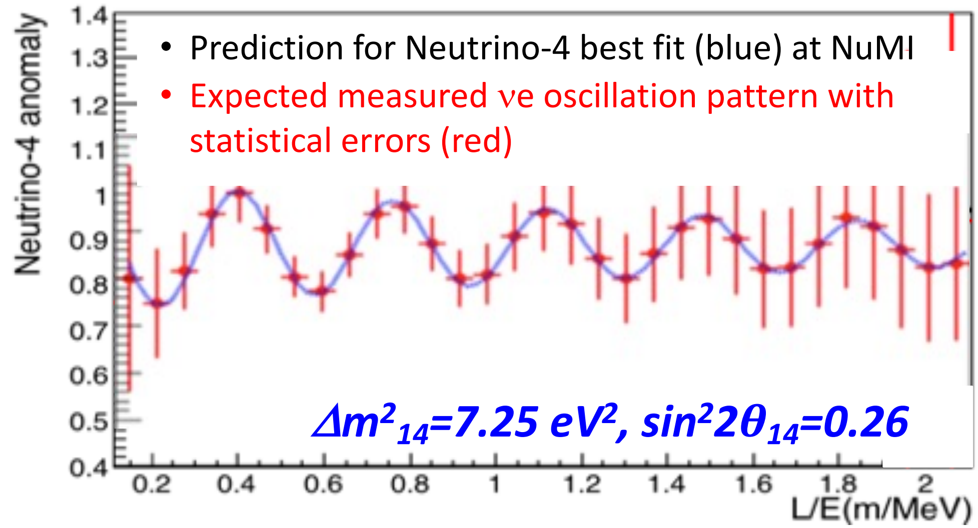
Distribution of events with respect to the beam direction



ICARUS stand-alone oscillation searches at FNAL

- The new result from Neutrino-4 experiment requires a prompt investigation by ICARUS, before the start of SBND physics data-taking, with both Booster and NuMI beams
- Both BNB and NuMI neutrinos in ICARUS are characterized by an L/E ~ 1-3 m/MeV, to similar Neutrino-4 but in a different energy range
- A νe disappearance search at NuMI would provide a more direct comparison with Neutrino-4
- ICARUS will initially focus on a νμ disappearance search at BNB (high statistics already available), selecting a subsample of νμCCQE interactions





νμ survival probability at BNB: *~8500 QE events with >50 cm contained μ track,*
~8.4 x 10^{19} pot (Run1+Run2~2.4 10^{20} pot)

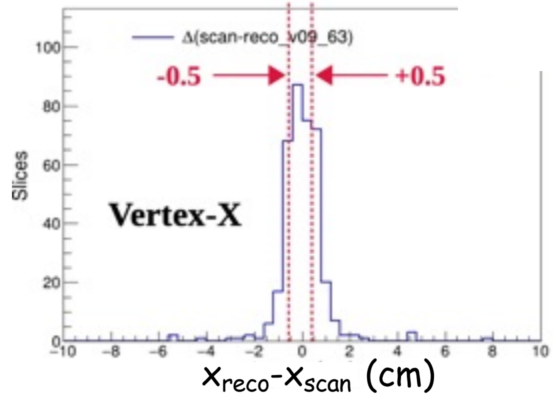
νe survival oscillation probability at NuMI: *~ 5200 QE events with contained E.M. shower,*
~9 x 10^{20} pot (Run1+Run2~ 3.3 10^{20} pot) .

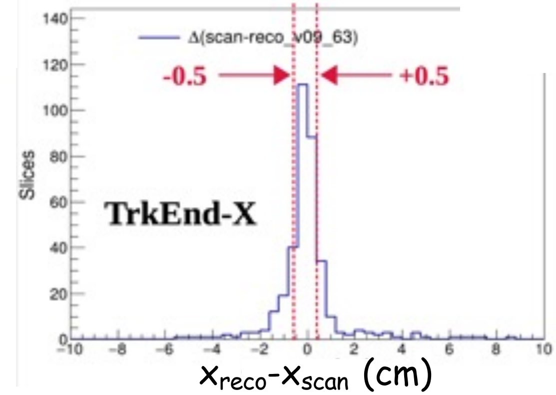
Comparison with a beam-off event sample will allow to observe the Neutrino-4 modulation!

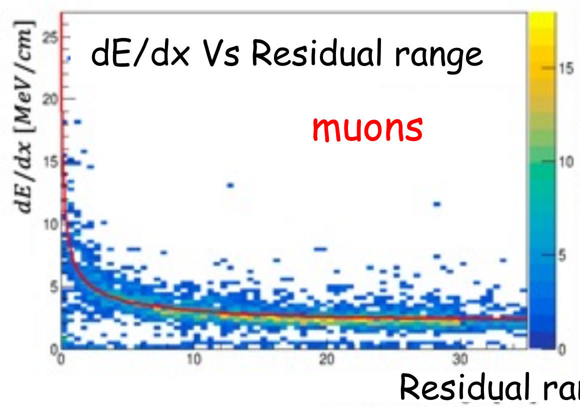
Check of event reconstruction with visually selected ν_μCC events

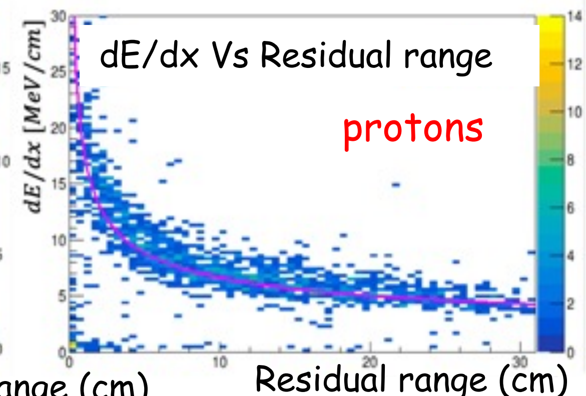
- Automatic procedures for selecting 1μ 1p ν_μCCQE interactions fully contained in LAr active volume are under tuning/validation:
  - Reconstructed ν interaction vertex and μ end-point (x_{reco}) within ~2 cm from the measured one (x_{scan}) ;
  - 1μ 1p fully contained ν candidates: demonstrating particle identification and kinematic reconstruction capabilities in the transverse plane

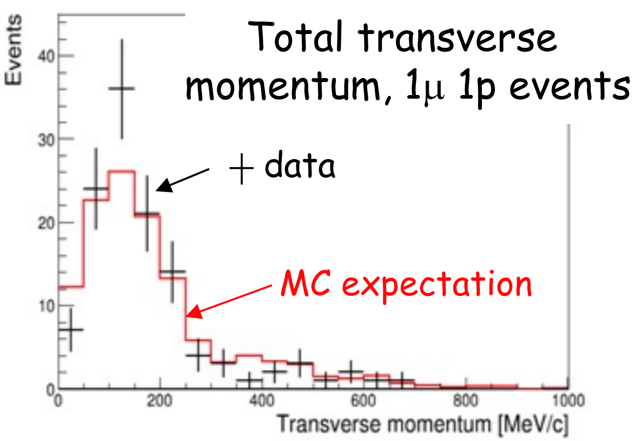
Pandora-based reconstruction shown here
arXiv:1506.05348
Complementary ML-based reconstruction also being developed

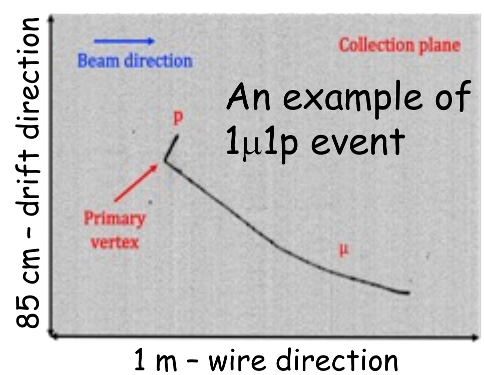


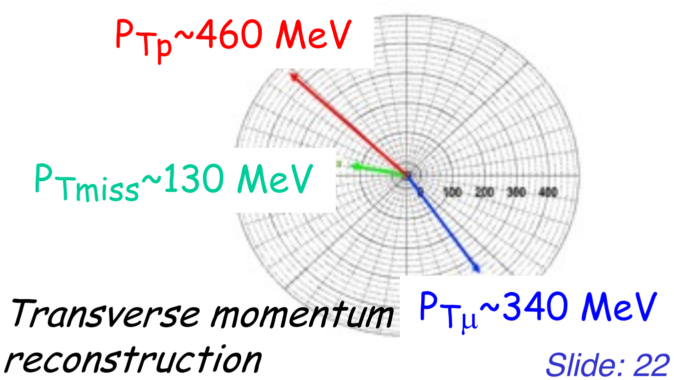










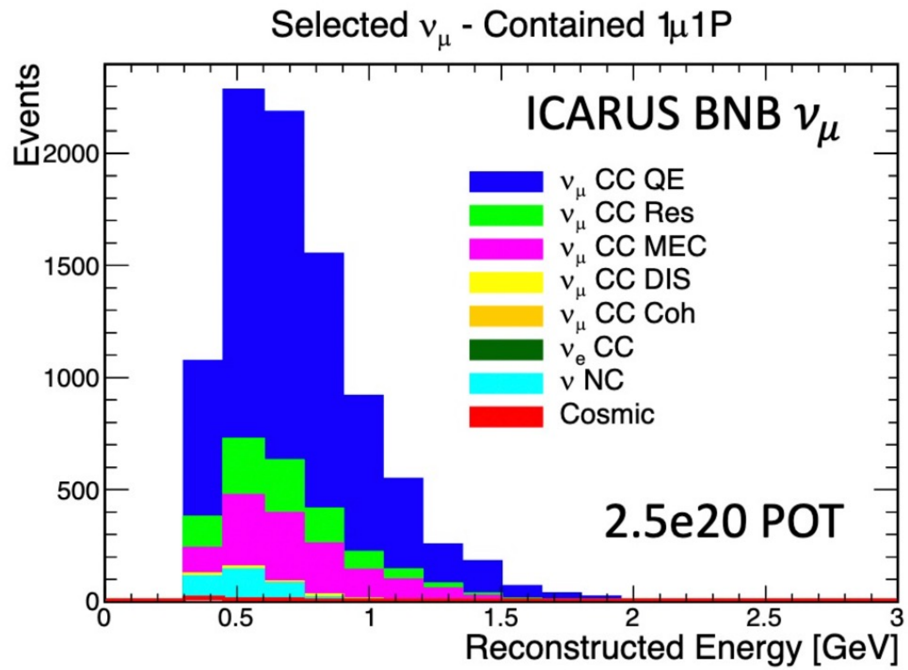


Automatic selection of a clean νμCCQE MC sample

- A first automatic procedure for selecting 1μ 1p νμCCQE interactions fully contained in the active volume is being prepared starting from MC events to be then applied to data:
  - TPC tracks matched with PMT light signals recorded in beam-spill;
  - Rejection of cosmics based on their vertical direction;
  - Interaction vertex in the fiducial volume;
  - Fully contained μ candidate >50 cm and a single contained proton; no other particles or showers in the event.

- According to MC, this selection procedure is characterized by ~27% efficiency and ~62% purity for true νμCCQE fully contained, also largely rejecting cosmic rays;

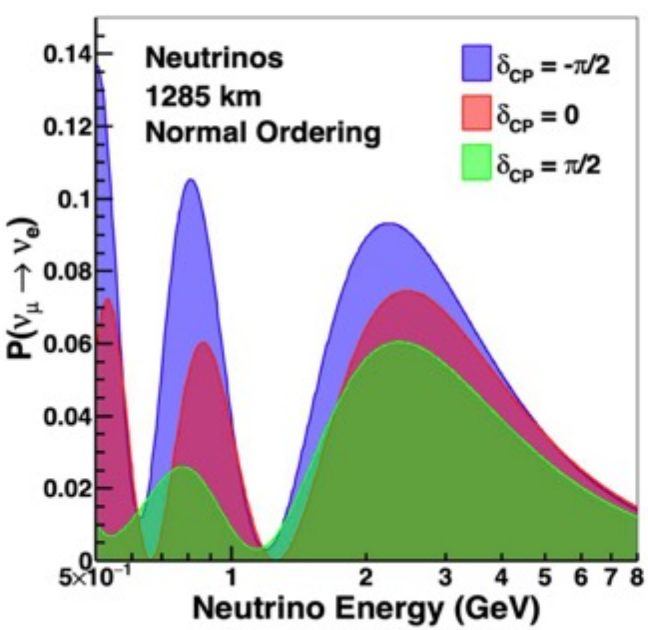
- Progress expected from ongoing activities:
  - Cosmics rejection exploiting CRT/PMT;
  - Upgraded calibration and PID;
  - Improved event reconstruction;
  - Include events with multiple protons in the selection.



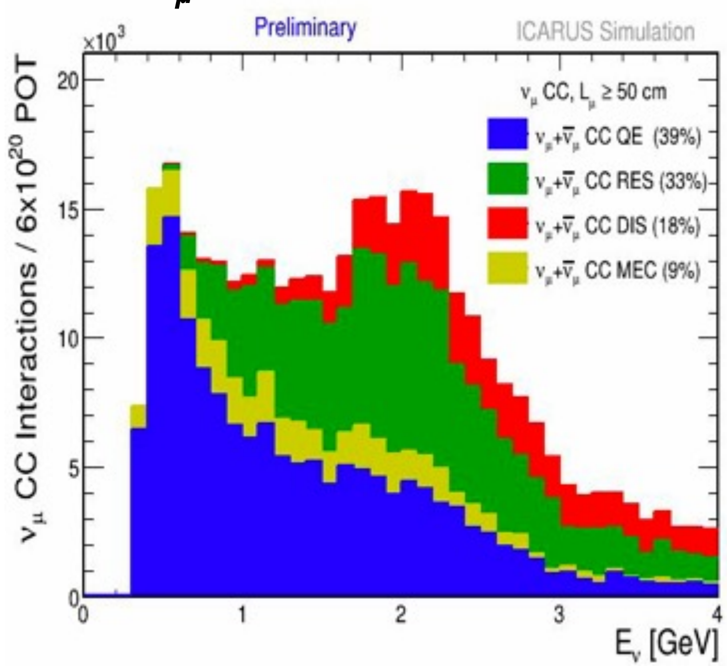
ICARUS physics searches with NuMI beam

- Further exploitation of the NuMI Off-Axis beam (6 degrees from ICARUS):
  - High statistics precision measurements of ν-Ar cross sections (~10^4 νe events/year) and tests of interaction models in the few hundred MeV to few GeV energy range, of use to SBN oscillation studies and DUNE.
  - Develop a rich Beyond Standard Model search program: Higgs portal scalar through di-muon final states (advanced analysis), ν tridents, light dark matter, heavy neutral leptons …

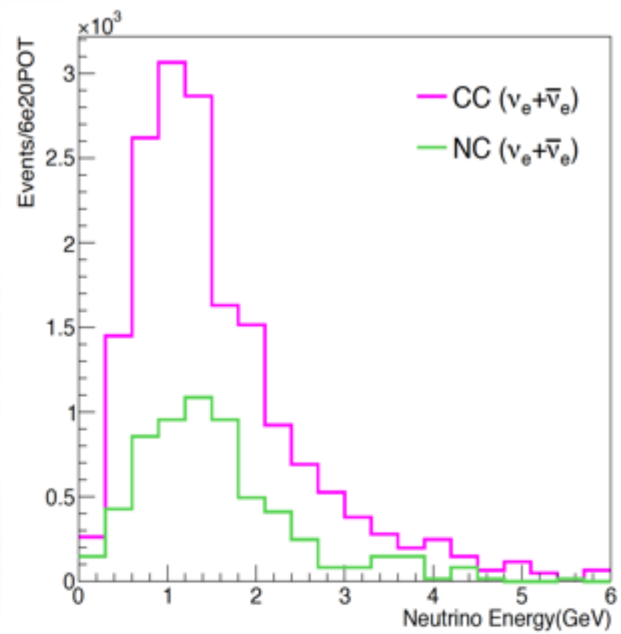
Oscillation probability at DUNE



ν_μ from NuMI at ICARUS

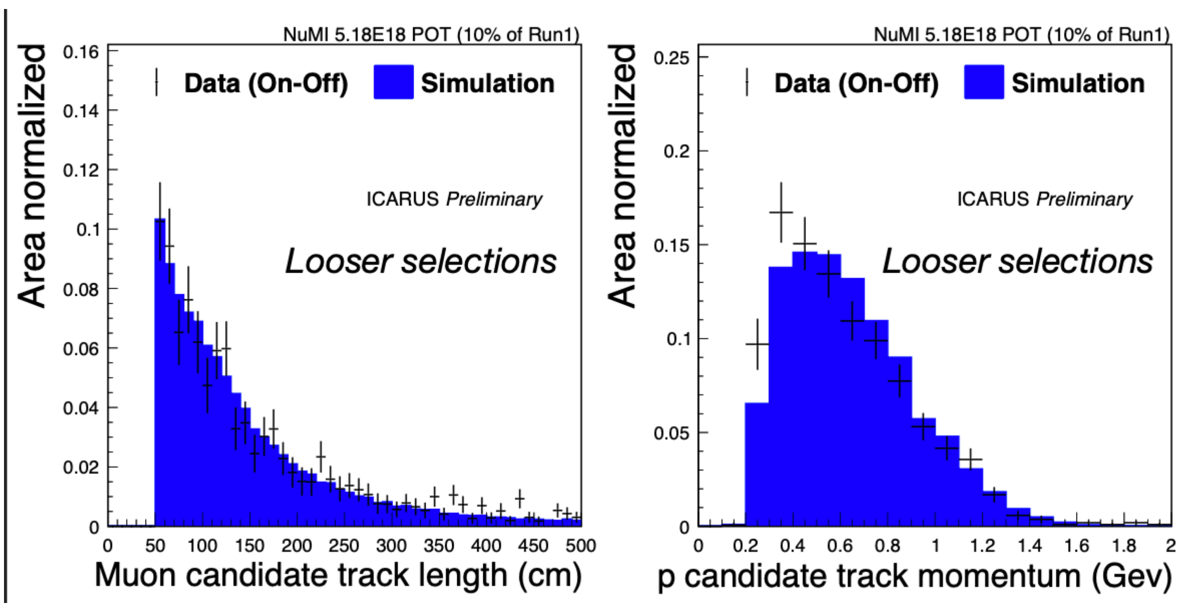


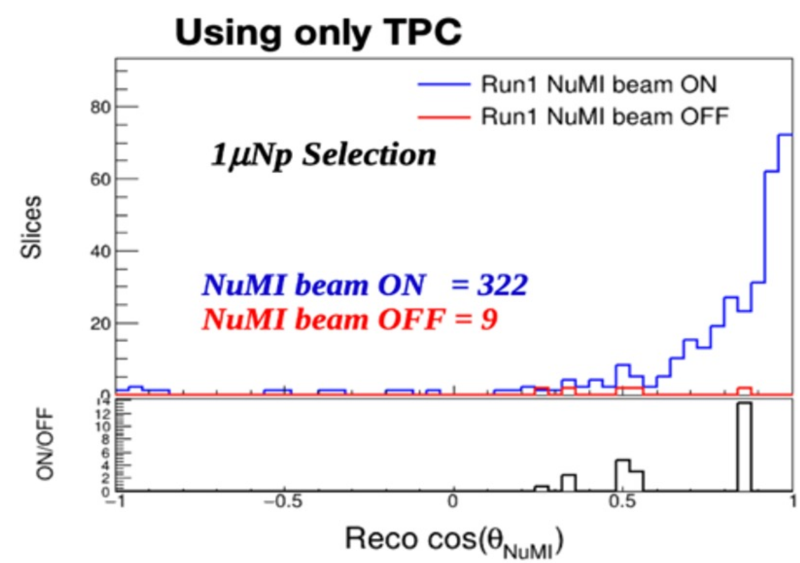
ν_e from NuMI at ICARUS

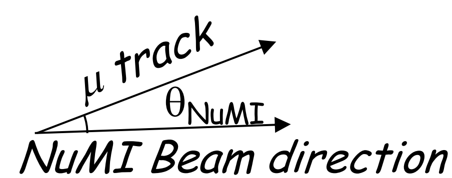


Ongoing analyses with NuMI beam

- Selection of charged current $\nu\mu$ interactions from NuMI beam inside fiducial volume:
  - Reject events tagged as clear cosmic by Pandora and close to vertical;
  - Muon candidate: contained track L >50 cm identified by PID or exiting with L>100 cm;
  - At least a contained proton identified by PID (for the 1μNp selection).
  - Event excess in beam direction is clearly recognized in data
  - Fair data/MC agreement in both muon and proton reco (for looser selection)







Conclusions

- ICARUS has been taking high-quality physics data in stable conditions, with both Booster and NuMI beams, since June 2022:
  total collected event statistics: ~2.5 10^{20} BNB, ~3.4 10^{20} NuMI.

- SBND is in the final stages of installation. Filling with LAr is expected in early 2024

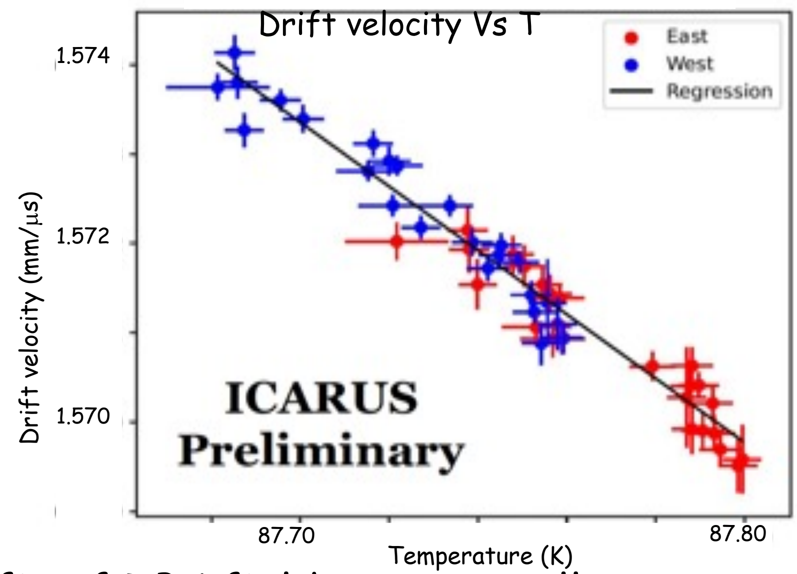
- The comparison between near and far detector data will allow to exploit the full capabilities of the SBN program, verifying the currently allowed region in sterile neutrino parameter space with 5σ sensitivity

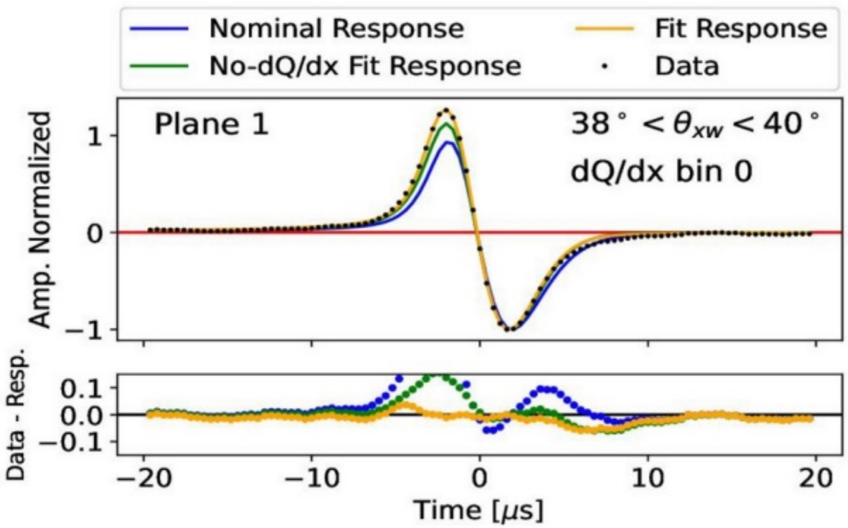
- Both detectors will have a rich physics program besides the joint SBN measurement:
  - Measurement of ν-Ar interaction cross-sections in a range of interest for DUNE (SBND will have unprecedented $\nu\mu$ and νe statistics from BNB, while ICARUS will be able to also detect a high statistics sample of $\nu\mu/\nu e$ from off-axis NuMI beam);
  - Search for sub-Gev Dark Matter signals and other BSM physics;
  - ICARUS stand-alone verification of the Neutrino-4 claim

ICARUS and SBND are well on their way for intriguing physics searches with SBN and beyond!

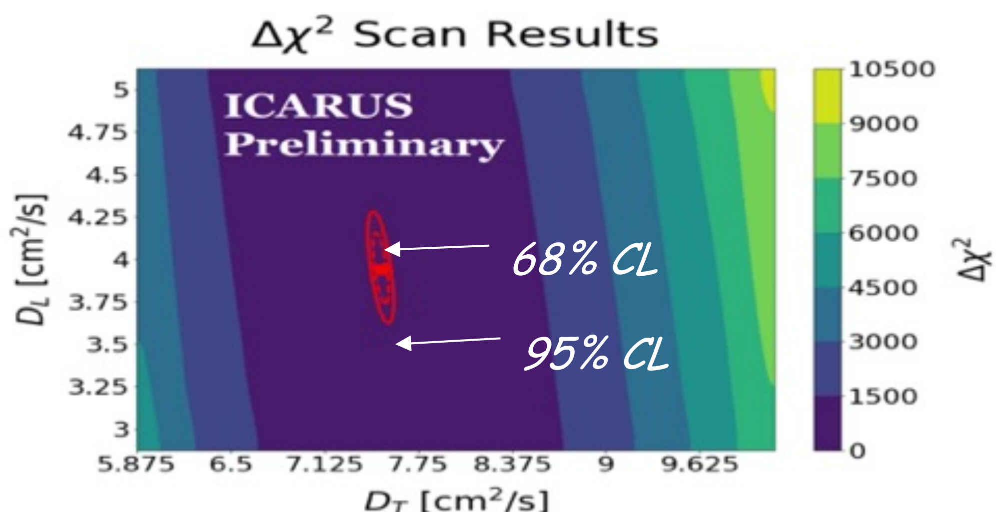
Detector Physics measurements

- Accurate measurements of main detector parameters with cosmic rays are improving the global understanding of LAr-TPC detectors:
  - electron drift velocity as a function of LAr temperature (measured from cryogenic parameters). Confirms the expected linear relation





- Data-driven fit of TPC field response allows better description of signal shapes in all planes, including for possible non-transparency effects

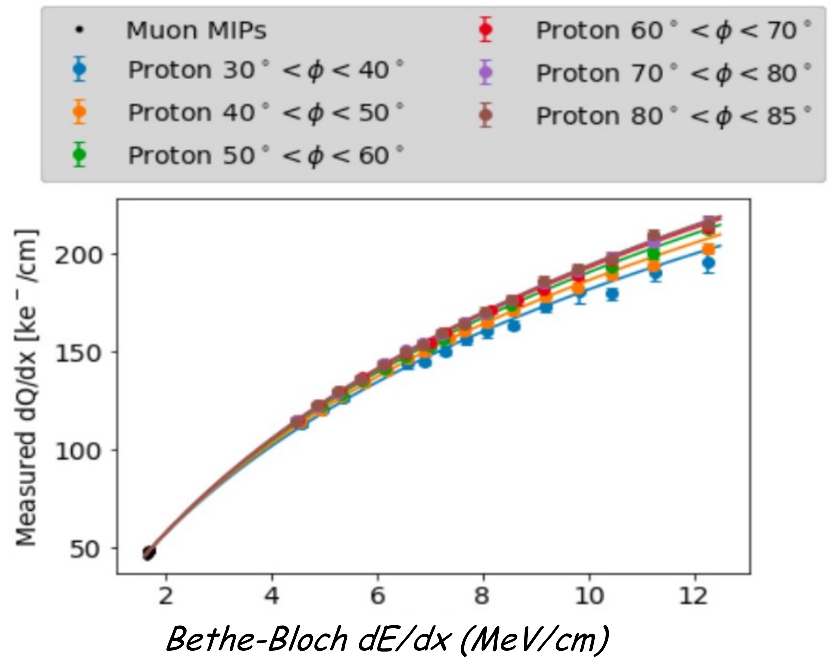


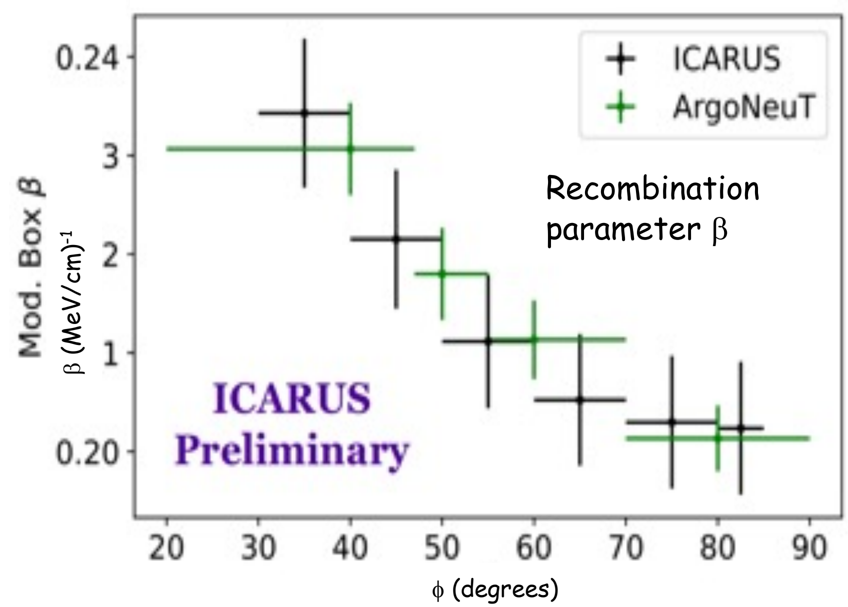
- Longitudinal (D_L) and transverse (D_T) electron diffusion coefficients in LAr by measuring the dependence of average signal width as a function of drift coordinate.

first D_T measurement in this E-field range!

Angular dependence of recombination

- The recombination of drift electron has been accurately studied for both MIP (muons) and high-dE/dx (proton) tracks as a function of the track angle ϕ with the drift direction
- The measured ionization density, compared with expected Bethe-Bloch dE/dx, shows a clear angular dependence for protons
- This dependence is fitted to several possible recombination models, extracting parameters
- The results are compatible with previous ArgoNeut ones, and favour an ellipsoid modified box model, with a parameter B depending on the track angle ϕ:

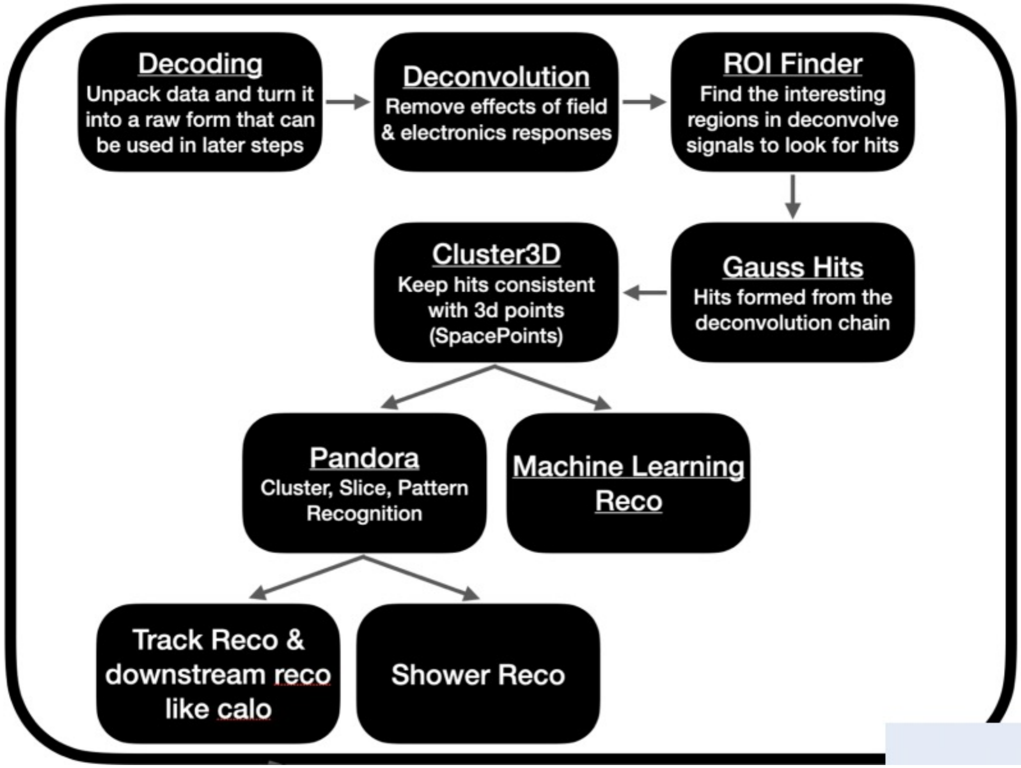




- Correcting for this dependence allows significant improvement in particle ID performances

TPC reconstruction

- Two parallel approaches to track and vertex finding and event classification: Pandora *https://github.com/PandoraPFA* and Machine Learning-based *https://github.com/DeepLearnPhysics/lartpc_mlreco3d*
- Both algorithms are developed on MC and validated on a sample of hand-scanned events



Set of MC events with a muon and proton that pass some cuts on reconstruction. ICARUS Simulation