Short-Baseline neutrino oscillation searches with the ICARUS detector

Maria Artero Pons - Università degli Studi di Padova and INFN Padova

On behalf of the ICARUS Collaboration

$108°$ Congresso Nazionale SIF - 15^{th} September 2022

European Commission

Intense

H2020 MSCA ITN

G.A. 858199

ICARUS Collaboration at SBN

P. Abratenko[19], A. Aduszkiewicz[21], F. Akbar[23], M. ArteroPons[15], J. Asaadi[24], M. Babicz[2], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], C. Backhouse[25], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Berkman[5], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13],T. Boone[4], B. Bottino[8], A. Braggiotti[15], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13] , J. Brown[5], H. Budd[23], A. Campani[8], D. Carber[4] , M. Carneiro[1], H. Carranza[24], D. Casazza[8], A. Castro[3], M. Cicerchia[15], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[27], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[26], T. Coan[18], A. Cocco[14], M.R. Convery[17], S. Copello[8], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Donati[26], J. Dyer[4], S. Dytman[22], S. Dolan[2],L. Domine[17], R. Doubnik[5], F. Drielsma[17], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], A. Ferrari[12], F. Ferraro[8], N. Gallice[12], F. Garcia[17], M. Geynisman[5], D. Gibin[15], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], A. Heggestuen[4], B. Howard[5], R. Howell[23], J. Hrivnak[2], C. James[5], W. Jang[24], L. Kashur[4], W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], U. Kose[2],J. Larkin[1], G. Laurenti[6], G. Lukhanin[5], A. Maria[26], C. Marshall[23], S. Martinenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], G.Meng[15], A. Menegolli[16], O.G. Miranda[3], D. Mladenov[2],A. Mogan[4],N. Moggi[6], N. Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], D. Naples[22], M. Nessi[2], T. Nichols[5],S. Palestini[2], M. Pallavicini[8], V. Paolone[22], R. Papaleo[11], L. Pasqualini[6], L. Patrizii[6], G. Petrillo[17], C.Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6],M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], R. Rechenmacher[5], L. Rice[22], E. Richards[22], F. Resnati[2], A. Rigamonti[2], G.L. Raselli[16], M. Rosemberg[19], M.Rossella[16], C. Rubbia[9], P. Sala[12], G. Savage[5], A. Scaramelli[16], A. Scarpelli[1], D.Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], A. Soha[5], L. Stanco[15], J. Stewart[1], N.B. Suarez[22], H.Tanaka[17], M. Tenti[6],K.Terao[17] , F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], F.Tortorici[7], Y.T. Tsai[17], S.Tufanli[2], T. Usher[17], F. Varanini[15], S. Ventura[15], M. Vicenzi[8], C. Vignoli[10], B. Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M..Worcester[1], M. Wospakrik[5],H. Yu[1],J. Yu[24], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

Spokesperson: C. Rubbia, GSSI

12 INFN groups, 11 US institutions, CERN, 1 Institution from Mexico, India and UK

1. *Brookhaven National Lab., USA*
2. *CERN, Switzerland*
3. *CINVESTAV, Mexico,*
4. *Colorado State University, USA*
5. *Fermi National Accelerator Lab., USA*
6. *INFN Bologna and University, Italy*
7. *INFN Catania and University, Italy*
8. *INFN Genova and University, Italy*
9. *INFN GSSI, L'Aquila, Italy*
10. *INFN LNGS, Assergi, Italy*
11. *INFN LNS, Catania, Italy*
12. *INFN Milano, Milano, Italy*
13. *INFN Milano Bic. and University, Italy*
14. *INFN Napoli, Napoli, Italy*
15. *INFN Padova and University, Italy*
16. *INFN Pavia and University, Italy*
17. *SLAC National Accelerator Lab., USA*
18. *Southern Methodist University, USA*
19. *Tufts University, USA*
20. *University of Chicago, USA*
21. *University of Houston, USA*
22. *University of Pittsburgh, USA*
23. *University of Rochester, USA*
24. *University of Texas (Arlington),USA*
25. *University College London, UK*
26. *INFN Pisa and University, Italy*
27. *Ramanujan Faculty Phys. Res. India*

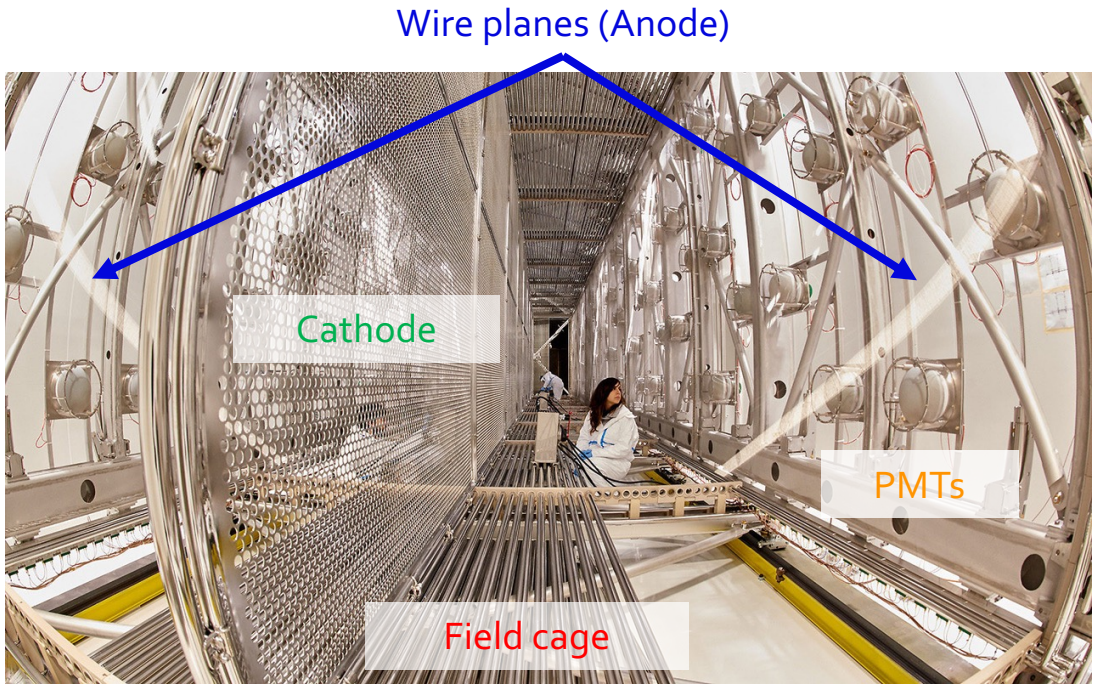
a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

The ICARUS detector

- Uniform Liquid Argon (LAr) time-projection chamber (TPC) detector
- First large LArTPC, still one of the largest in operation
  - 2 Identical modules with $476\ t$ total active mass
- Self-triggering detector, with precise 3 D imaging and calorimetric capabilities
- Its operation at LNGS $(2010-13)$ confirmed the feasibility of this technique
  - sensitive search for LSND-like anomaly with CNGS beam constraining the allowed phase space $(\Delta m^2 < 1\ eV^2, \sin^2\theta \sim 0.005)$
- ICARUS moved to FNAL after overhauling phase at CERN and INFN Labs

ICARUS installation at FNAL FD

The ICARUS detector

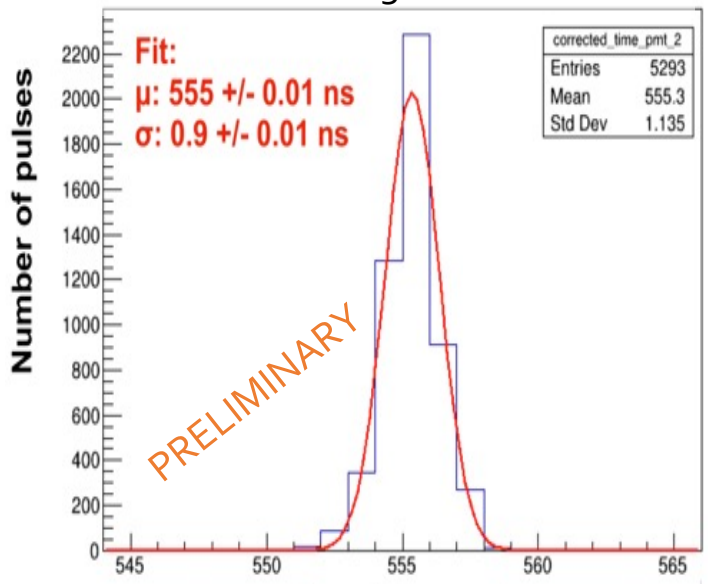


Inside ICARUS: internal view of one cryostat

- 2 TPCs per cryostat, with a common central cathode
  - $1.5\ m$ drift length and $E_{Drift} = 500\ V/cm$
- Ionization charge continuously read ($400\ ns$ sampling time) by 3 readout wire planes per TPC, ≈ 54000 wires at 0°, $\pm 60°$ w.r.t. horizontal and $3\ mm$ pitch

- 360 PMTs ($8''$) located behind the wires for timing and triggering purposes:
  - Precise identification of interaction time, $\sim ns$ time resolution
  - Localization of events with spatial resolution $< 50\ cm$

PMT timing calibration

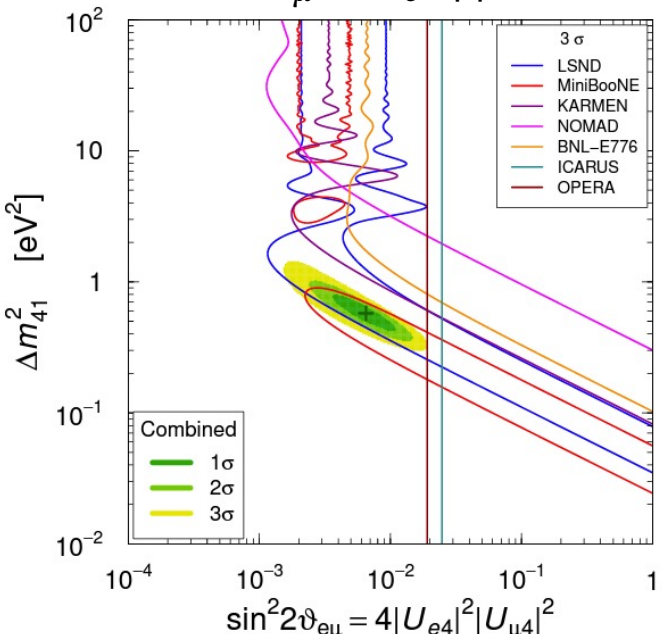


$\Delta t = t_{\mathrm{PMT}} - t_{\mathrm{TRIGGER}}\ (ns)$

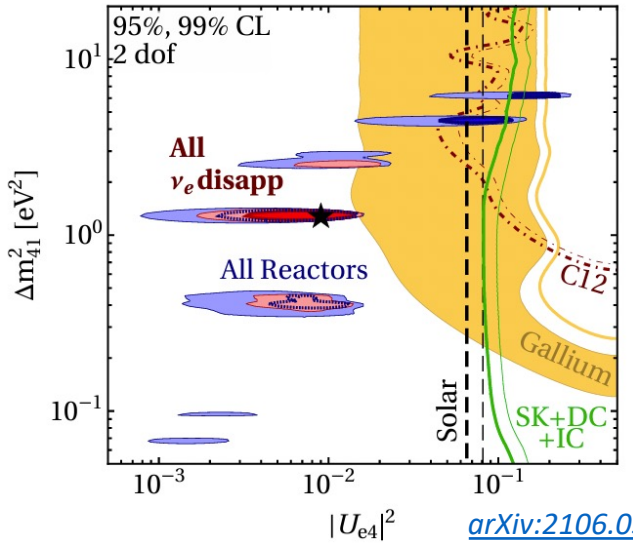
The sterile neutrino puzzle

- Anomalies from accelerator experiments (LSND and MiniBooNE), reactors and radioactive source have been collected in the last 20 years, unable to fit inside the 3-flavor oscillation theory
- 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 has recently reported a hint of oscillation signature at higher mass splitting
  - Reactor $\overline{\nu_e}$ disappearance with $\Delta m^2 \sim 7\ eV^2$ and $sin^2\ 2\theta\ \sim 0.26$
- Clear tension between appearance and disappearance results is observed in global constraint plots. Measuring both channels with the same experiment will help clarify the scenario

(Anti-) $\nu_\mu \rightarrow \nu_e$ appearance

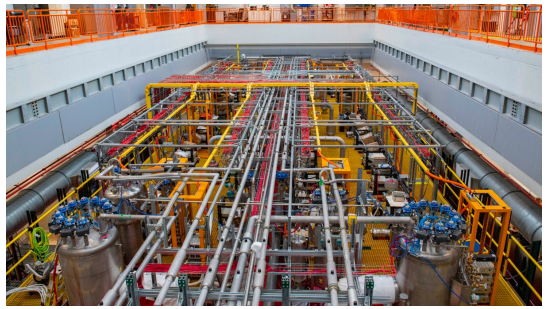


(Anti-) ν_e Disappearance



arXiv:2106.05913

Short Baseline Neutrino Program at FNAL

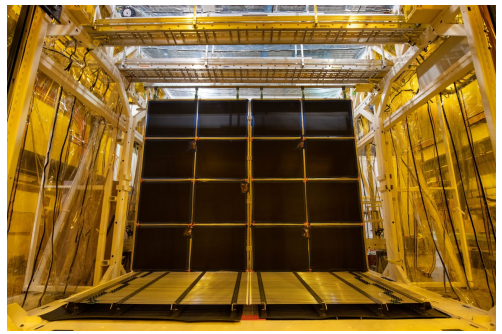


ICARUS

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

SBND

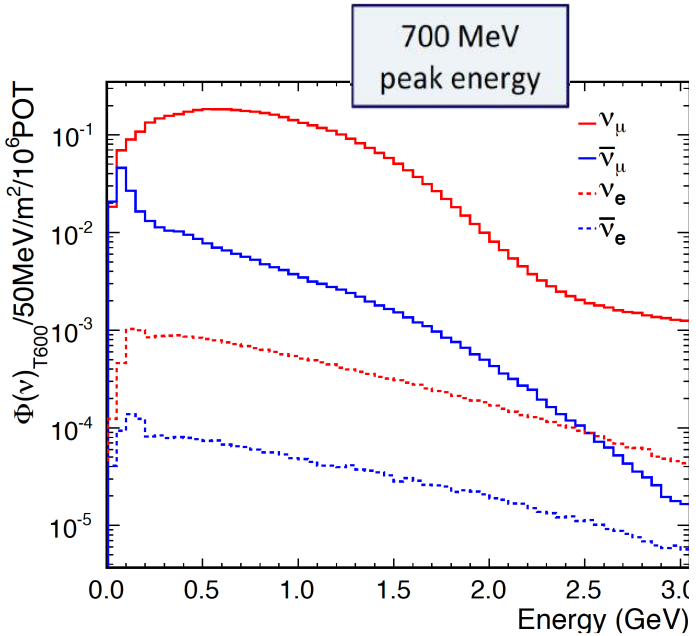
$110\ m$ *baseline*
$112\ t$ *active volume*
Under Construction



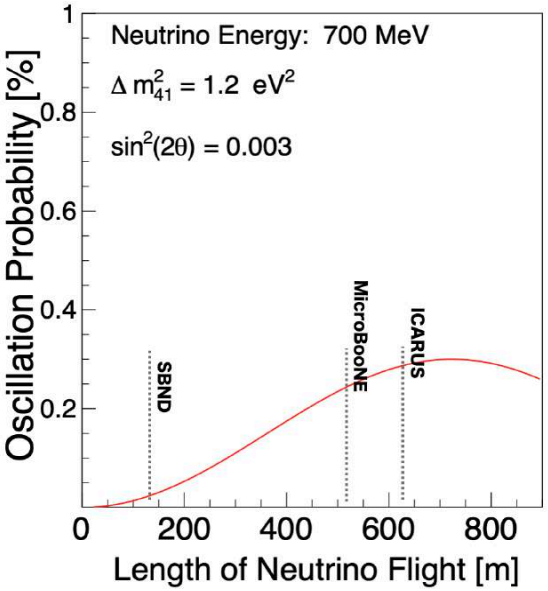
- Short Baseline Neutrino Program (SBN) main goal is to search for sterile neutrino oscillations both in appearance and disapperance channels (at $\sim eV^2$ mass scale)
- Consists of 3 LArTPCs sampling the same neutrino beam (BNB) at different distances
- ICARUS is the Far Detector at $600\ m$ from the Booster target

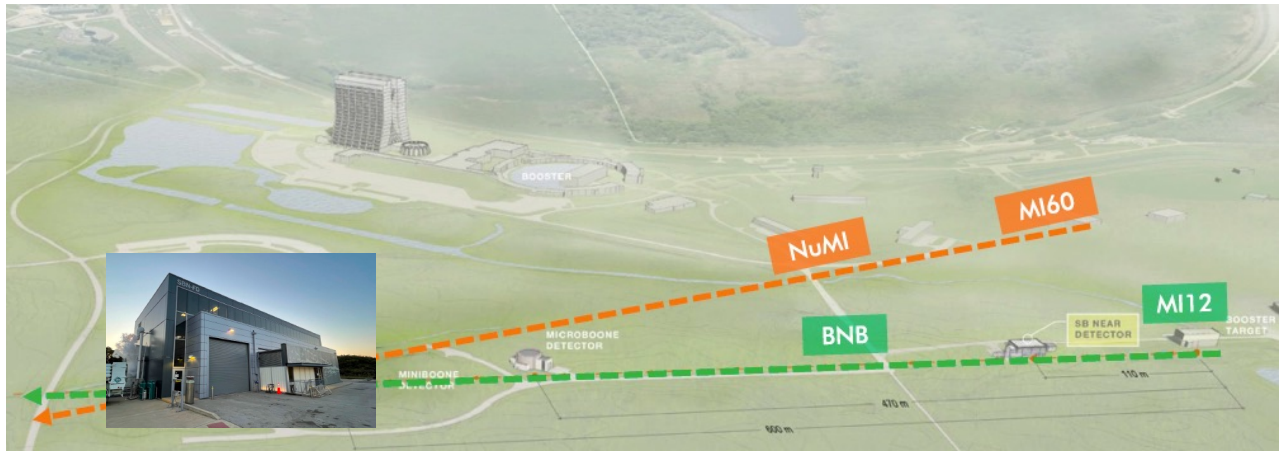
Short Baseline Neutrino Program at FNAL

- 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)
- Measurement of ν-Argon cross-sections and understanding of nuclear effects, final states



arXiv:1503.01520

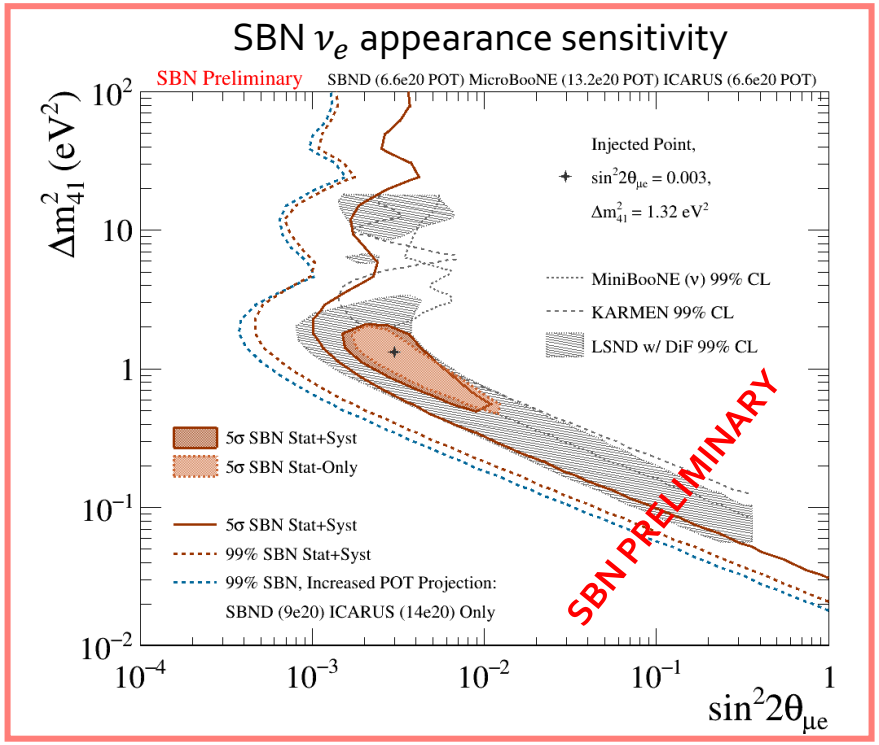


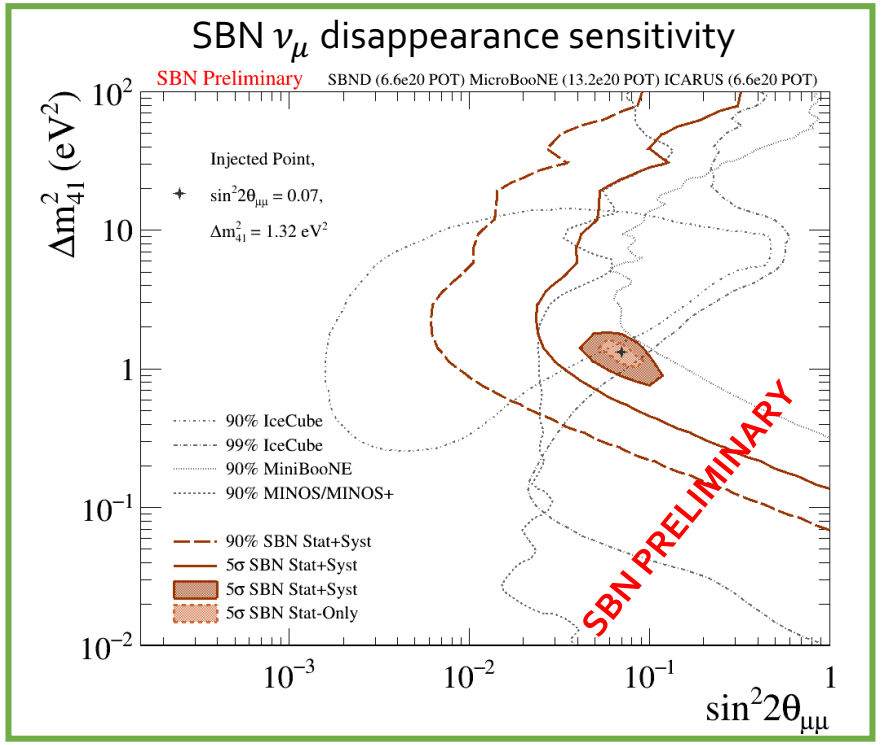


- ICARUS is also exposed off-axis to the NuMI beam and can access the ν_e rich component of the spectrum (up to 3 GeV)

SBN expected sensitivities

- 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 ($6.6 \cdot 10^{20}$ POT)



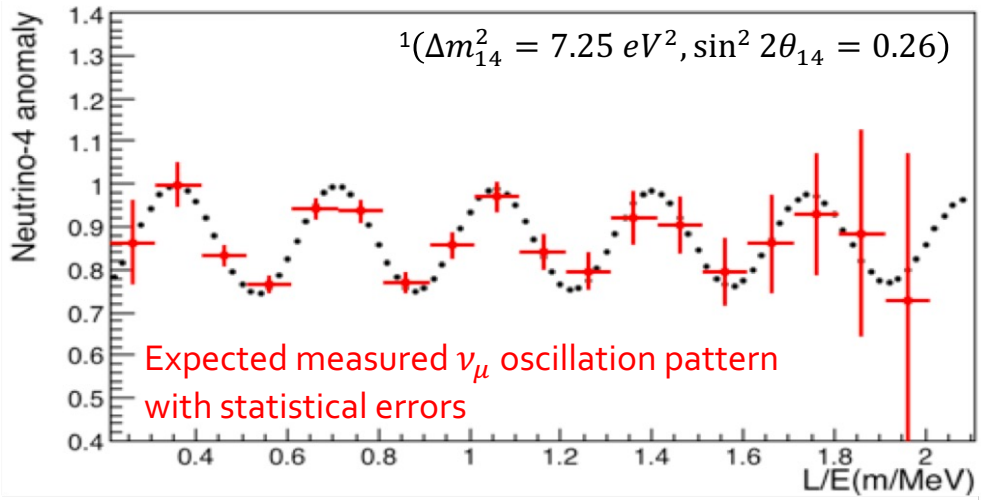


- Using the same detector technology will greatly reduce systematic errors:
  - Near detector helps providing the initial beam composition and spectrum
  - The clear electron neutrino identification capability will help on reducing backgrounds

Neutrino-4 study with ICARUS

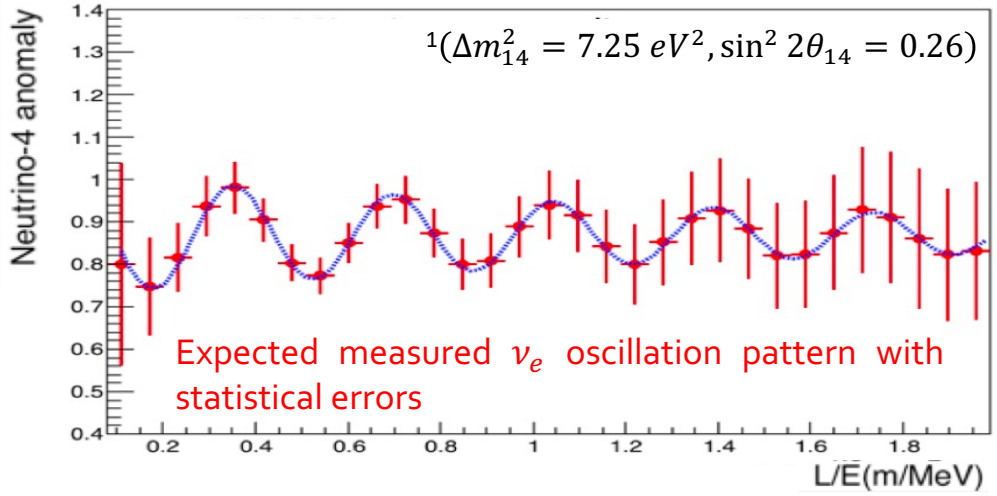
- In the first ICARUS-only phase, it will be able to test this oscillation hypothesis in the same L/E range, collecting ~ 100 times more energetic events
- It will exploit two separate samples and beam-off data, for both available beams
  - ν_μ disappearance channel from BNB: focusing on contained quasi-elastic ν_μ CC interactions
  - ν_e disappearance channel from NuMI: selecting contained EM showers from quasi-elastic ν_e CC interactions

Prediction for Neutrino-4 best fit[1] at BNB



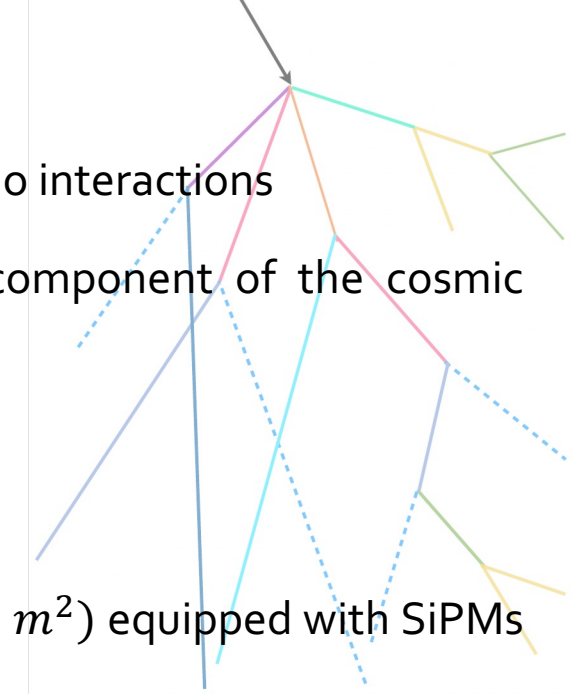
~ 8500 QE events with contained muon track in 3 month of data taking $(L_\mu > 50\ cm)$

Prediction for Neutrino-4 best fit[1] at NuMI



~ 5200 QE events with contained EM shower in 1 year of data taking

Cosmic-ray Background



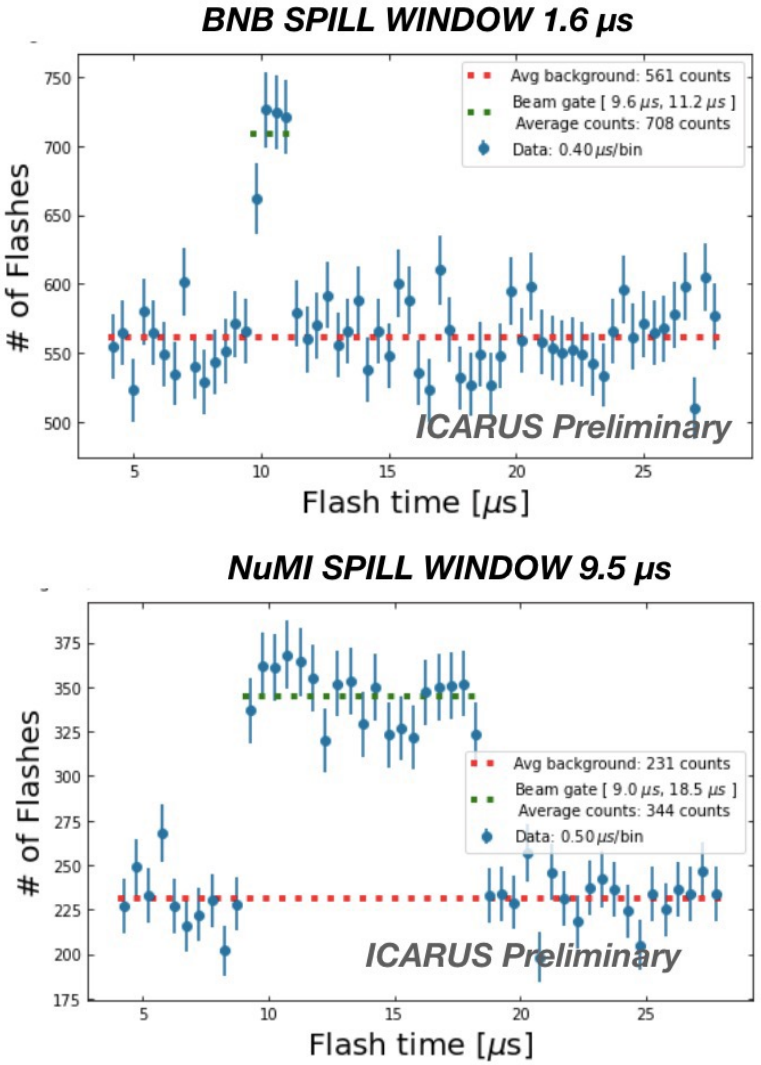
- ICARUS is on the surface and hence exposed to a huge comic activity that can mimic neutrino interactions
- Without shielding, ICARUS would be overwhelmed by the hadronic and soft energy component of the cosmic background
- In order to mitigate as much as possible its contribution, ICARUS is instrumented with
  - $\sim 3\ m$ concrete overburden placed on top of the detector
  - 4π Cosmic Ray Tagger (CRT): 3 subsystems with double layer scintillation bars ($\sim 1000\ m^2$) equipped with SiPMs ($2.4\ ns$ time resolution), tagging incoming cosmics with $\sim 95\%$ efficiency
- Coincidence of CRT signal with the light and charge signals in the TPC

Trigger System

- The ICARUS main trigger signal is generated requiring the presence of light signal from PMTs in coincidence with beam spills
  - $1.6\ \mu s$ for BNB and $9.5\ \mu s$ for NuMI
- PMT light and CRT signals are recorded in $2\ ms$ around the trigger time to help recognizing cosmics crossing the detector during the electron drift time ($\sim 1\ ms$)
- The detector timing has been set by looking for excess of light and hit signals over the cosmic background in agreement with the beam arrival

Excess plateaus correspond to ν from the beam interacting inside the LAr

Light signal excess in PMT system



ICARUS Installation and Commissioning

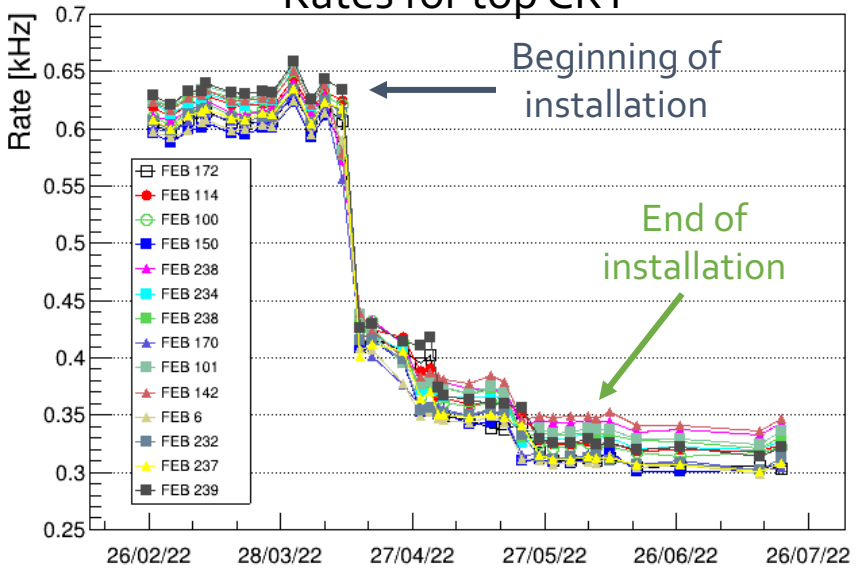
Start of TPC/PMT operation

Completion of CRT installation

Completion of overburden installation

- Steady data taking with BNB and NuMI beams since mid – March 2021, in parallel with commissioning activities
- The overburden installation resulted in a factor ~ 2 reduction of cosmic ray signal on top CRT

Rates for top CRT



ICARUS Installation and Commissioning

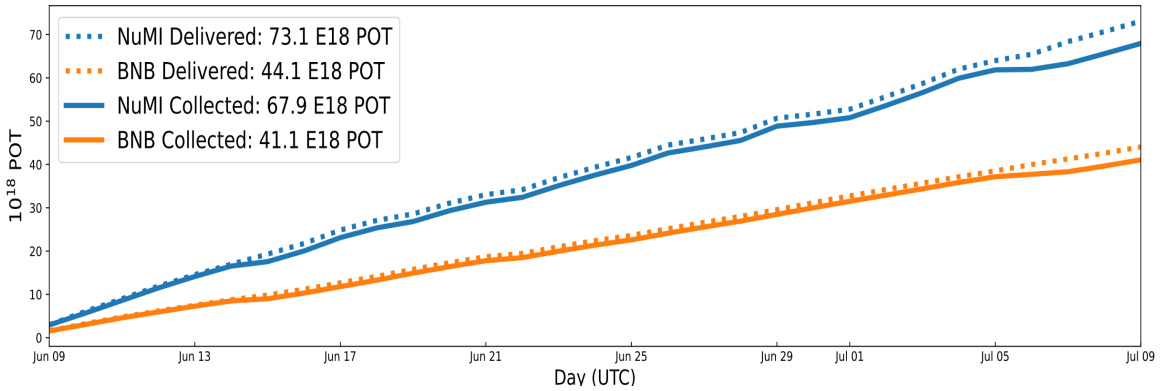
Start of TPC/PMT operation

Completion of CRT installation

Completion of overburden installation

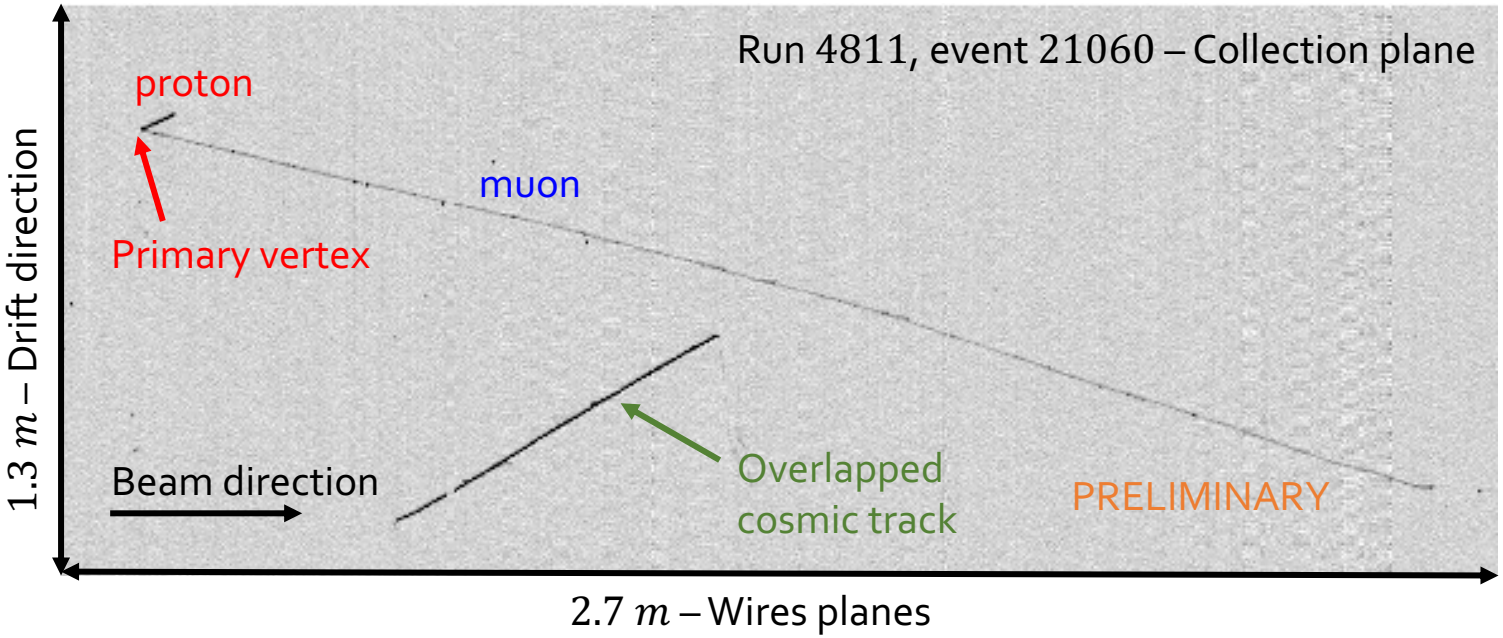
- A new physics data taking started with both beams in June 9^{th} 2022
- Dedicated month of data taking, with overall efficiency of beam data collection $\sim 93\,\%$ and excellent stability on long runs at BNB
- The collected event statistics for a month are:
  - $4.1 \cdot 10^{19}$ POT for BNB and $6.8 \cdot 10^{19}$ POT for NuMI

POT values for "RUN - 1"

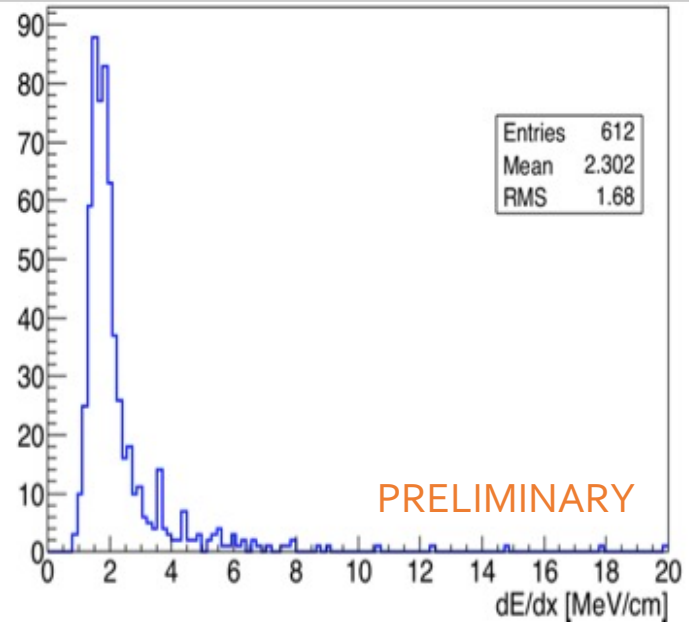


Neutrino candidate from BNB

- Quasi-Elastic Charged Current (QECC) fully contained event: $\nu_\mu + n \rightarrow p + \mu$
- Two tracks are produced at the primary vertex
  - The muon candidate is stopping after $2.8\ m$ with a deposited energy $E_{dep} \sim 650\ MeV$
  - The proton candidate stops after $10.9\ cm$ with $E_{dep} \sim 100\ MeV$
- The dE/dx measurement in the first $2\ m$ for the muon agrees with a Landau distribution expected for a minimum ionizing particle

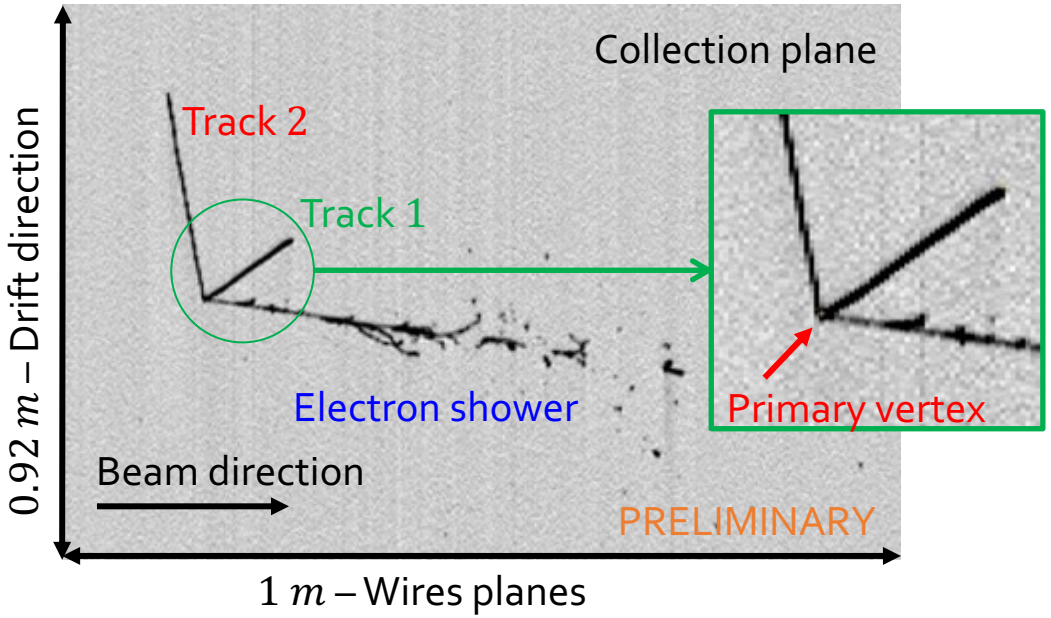


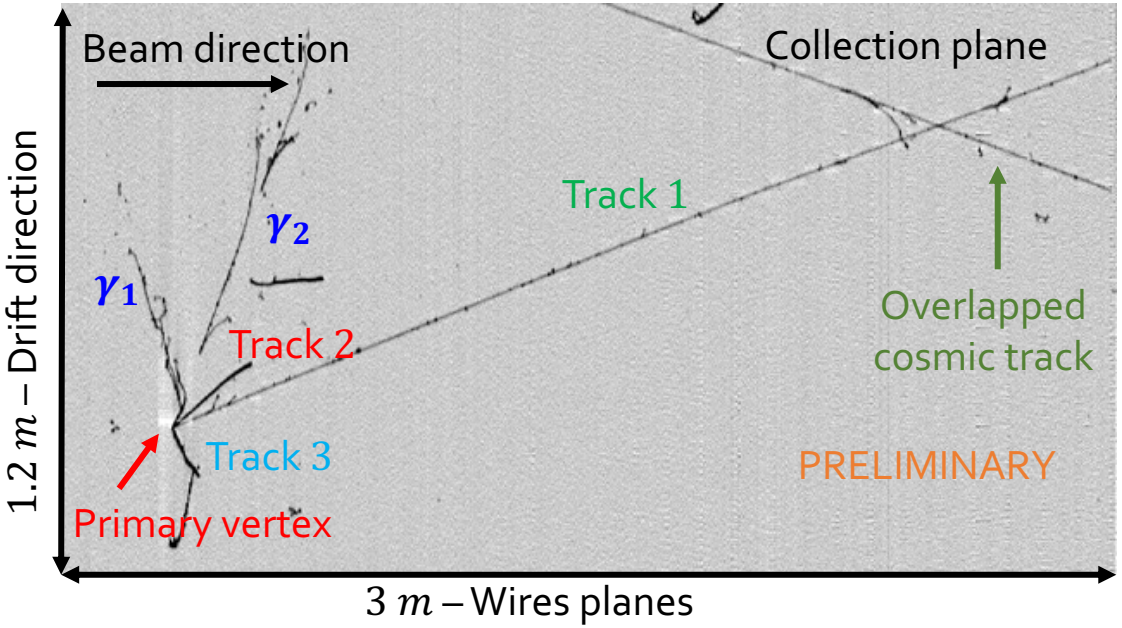
dE/dx distribution for the muon



Neutrino candidate from NuMI

- ν_e Charged Current interaction, fully contained in the active LAr
  - Electron shower depositing $\mathrm{E_{dep}} \sim 570\ MeV$
  - Track 1 : upgoing stopping proton candidate with length $L = 23.7\ cm$
  - Track 2 : possible stopping hadron, $L = 33.4\ cm$

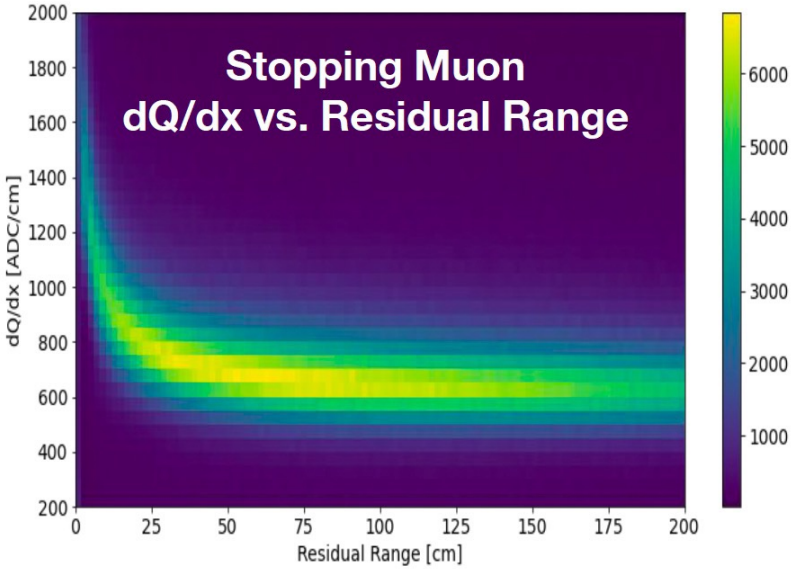


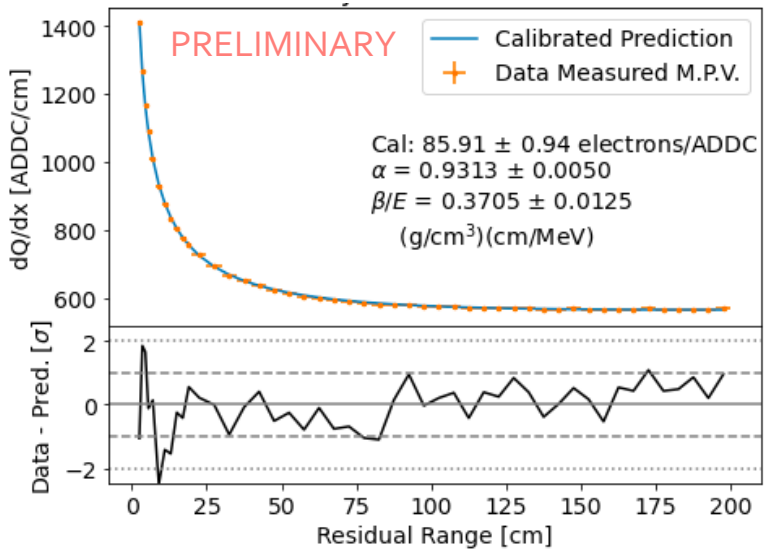


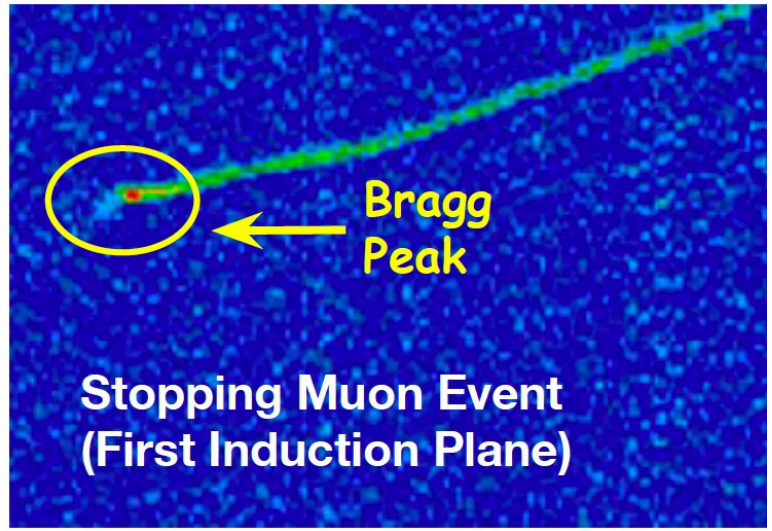
- ν_μ candidate with π_0 in the final state
  - Track 1 : muon candidate crossing the cathode and exiting downstream, $L \sim 4.2\ m$
  - Track 2 : upgoing proton candidate, $L \sim 31\ cm$
  - γ_1 , γ_2: π_0 candidate with two photons $\left(E_{\gamma_1} \sim 200\ MeV\ ,\ E_{\gamma_2} \sim 240\ MeV\right)$ converting at $18\ cm$ and $58\ cm$ respectively from the neutrino interaction vertex

Detector Calibration

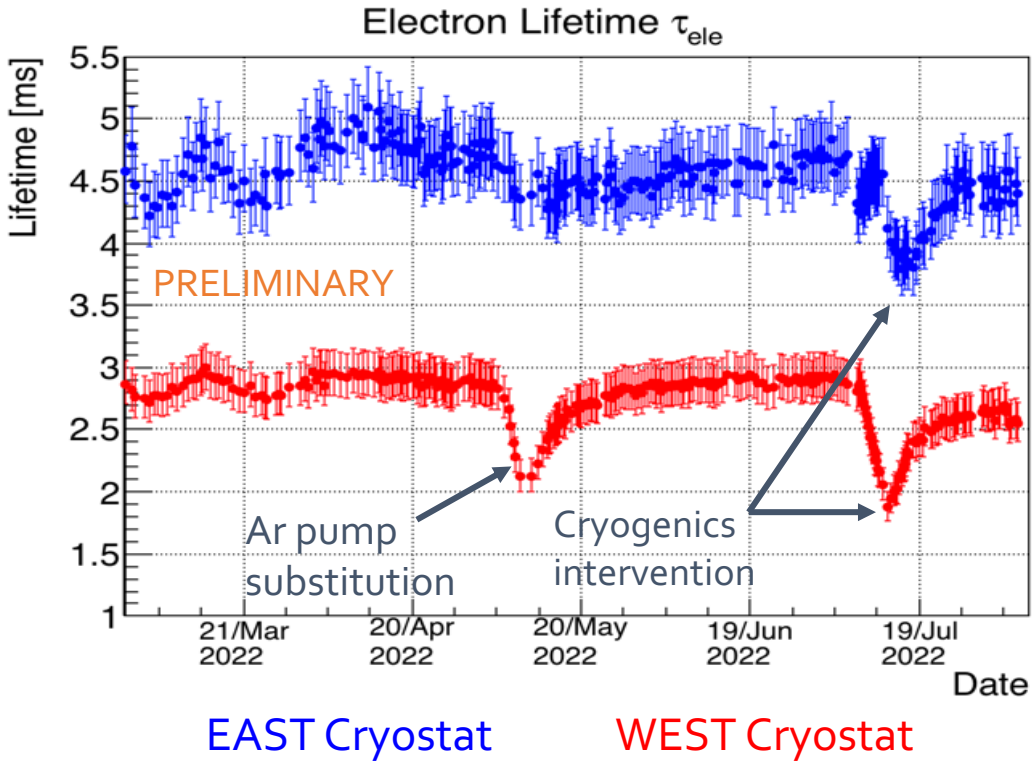
- Ongoing TPC calibration based on the study of ionization vs residual range for cosmic muons crossing the cathode and stopping/decaying in the active LAr
- Goals: calibrate absolute energy scale, equalize individual wire electronic response and improve the modelling of recombination, diffusion and space charge effects
- Possibility to tune and quantify the performance of PID algorithms for stopping particles







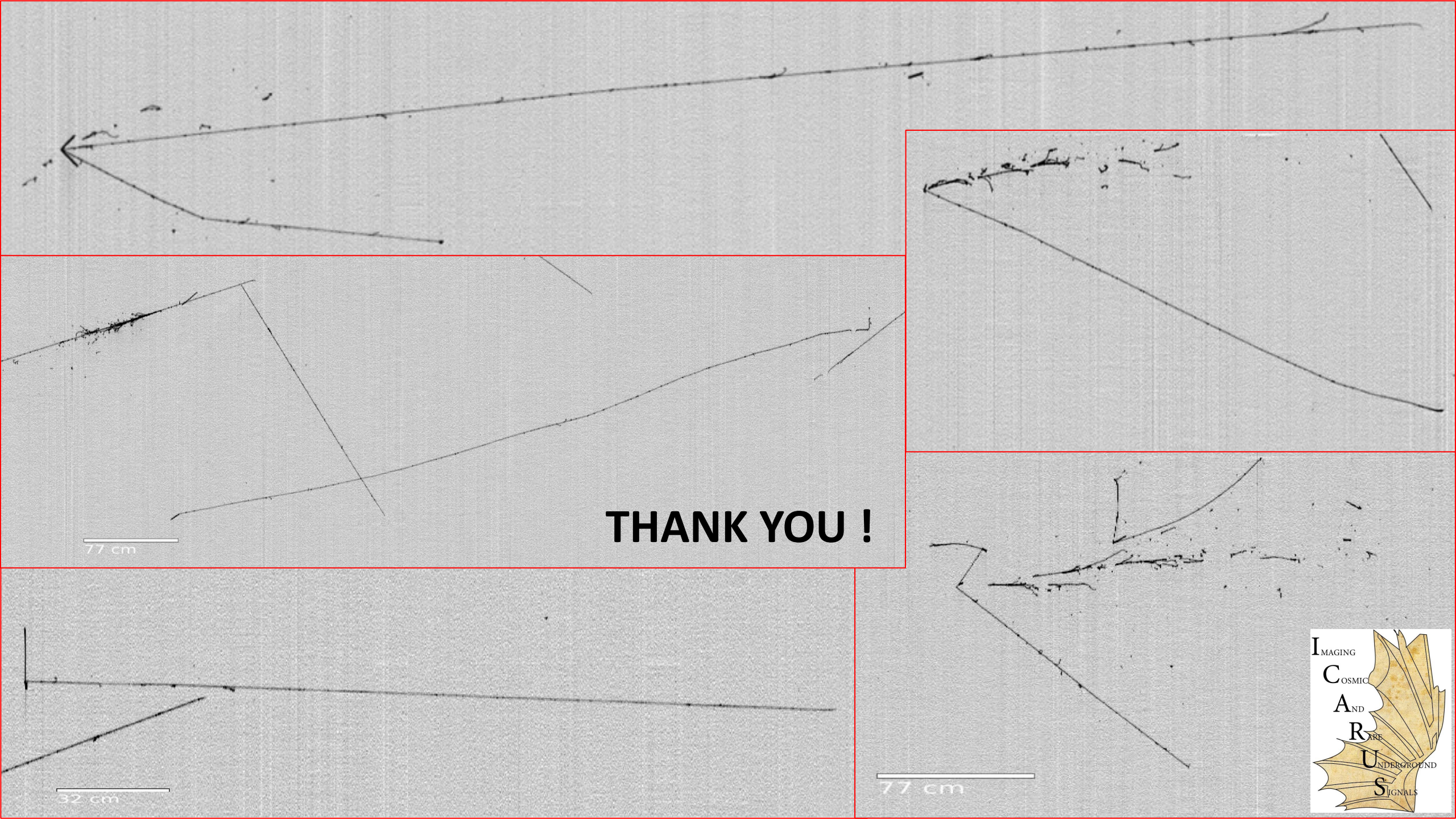
Detector Calibration



- LAr purity level is continuously monitored by measuring the signal attenuation along the drift direction
- Electron lifetime has been stable $\sim 4.5\,ms$ in the East Cryostat and $\sim 3\,ms$ in the West Cryostat
- Allows an efficient signal detection over the full LAr volume

Conclusions

- The ICARUS detector has continued to operate with excellent stability since its activation in August 2020, taking data with BNB and NuMI beams part-time as the installation and commissioning phases progressed
- Installation and commissioning can be considered completed. Improvements will continue, trying to maximize the beam data collection
- The events collected so far are being used to further develop and tune the event simulation and reconstruction tools to obtain a precise calibration of the detector
- The full-time neutrino beam run started on June 9^{th} 2022 exploiting both BNB and NuMI beam, with optimal efficiency
- ICARUS early phase primary focus: study of the Neutrino-4 claims searching for ν_μ disappearance with BNB and ν_e disappearance in the NuMI off-axis beam
- After the ICARUS-only phase, the SBND detector will be added soon at shorter distance from the BNB target to perform a definitive 5σ analysis of sterile neutrinos



THANK YOU !

IMAGING COSMIC AND RARE UNDERGROUND SIGNALS