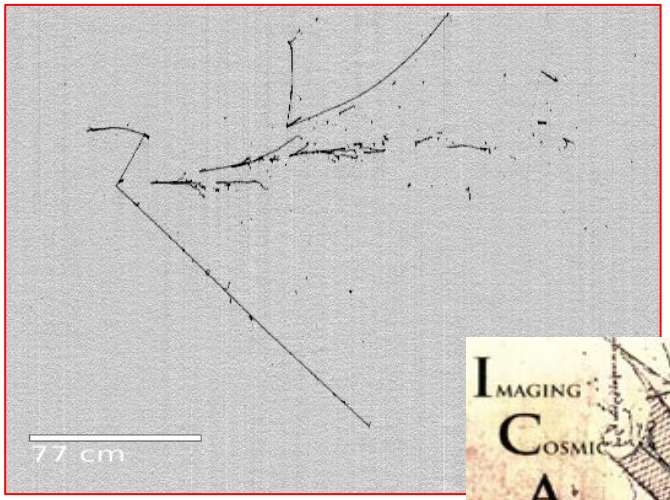
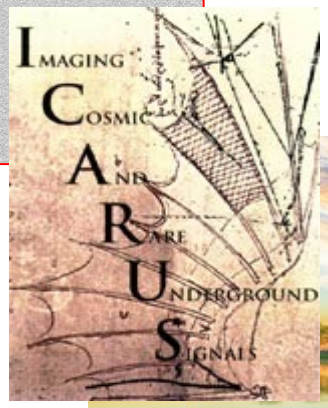
ICARUS commissioning and operation



Alberto Guglielmi
INFN Padova



European Commission

H2020, M. Sklodowska-Curie
R&I No. 822185

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], 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[26], D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], 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[25], 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], A. Gioiosa[25], 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.M. Ricci[25], 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], 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]

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

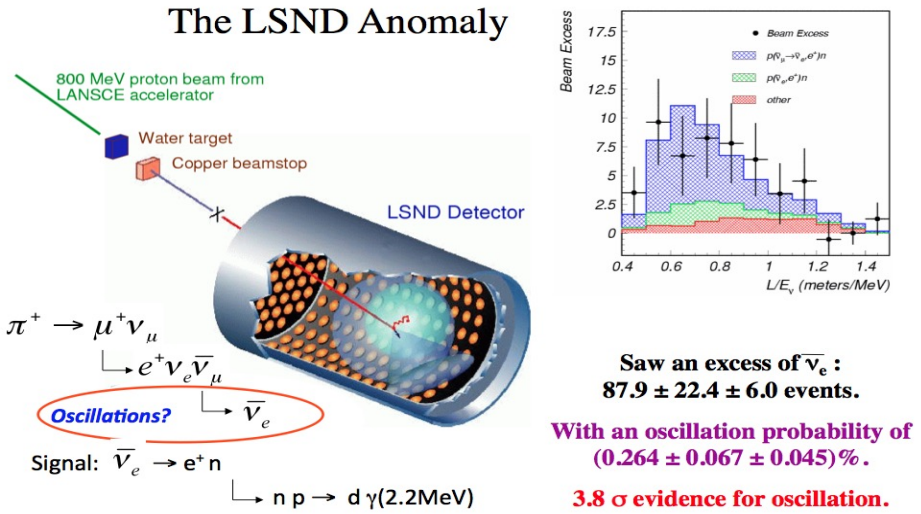
1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico,
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN 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. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India

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

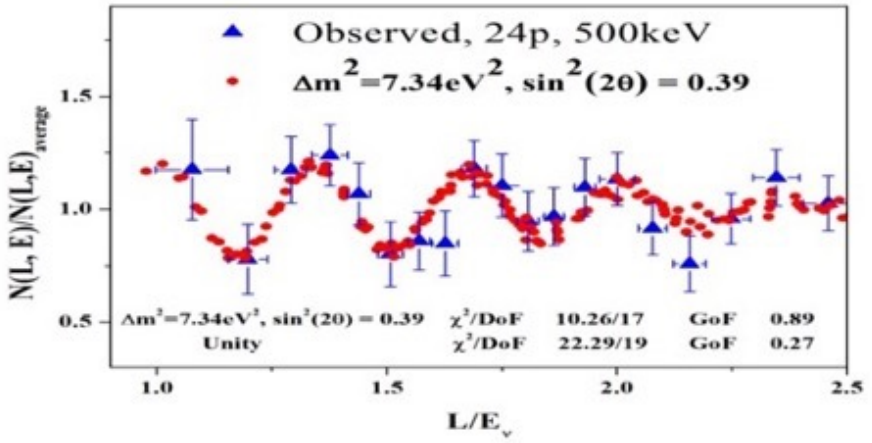
Spokesperson: C. Rubbia, GSSI

Neutrino related anomalies ?

- For several decades, many anomalies beyond an ordinary 3-flavour mixing picture have been collected in the neutrino sector, suggesting some additional new related physics:
  - *anti–νe appearance: anti-νμ accelerator LSND experiment where anti-νe -> e+ + n with neutron captured by a proton, n + p into d + γ.*
  - *νe disappearance: SAGE, GALLEX experiments with Mega-Curie sources with observed/predicted rate R = 0.84±0.05;*
  - *anti-νe disappearance of near-by nuclear reactor experiments and rate R = 0.934±0.024.*



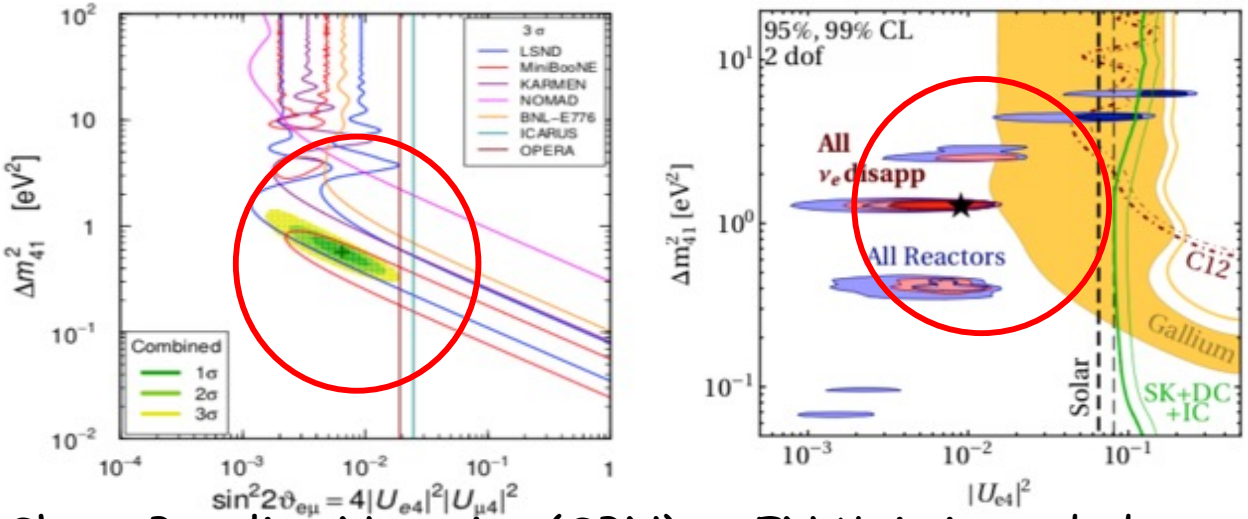
- *In addition: recent observation of sterile neutrino oscillation by NEUTRINO-4 exp.* at Dimitrovgrad SM-3 reactor *showing a disappearance signal with a clear L/Eν ~ 1-3 m/MeV modulation:*



The sterile neutrino puzzle: the SBN LAr-TPC program

- Several studies/experiments at reactors, accelerators have been performed to verify these "ν anomalies" both in appearance and disappearance but without conclusive result:
  - A clear tension between appearance and disappearance experiments characterized by different neutrino energy range and detection technique is evident.

(anti-)$\nu_\mu \rightarrow \nu_e$ Appearance *(anti-)ν_e Disappearance*



(arXiv:2106.05913)

Neutrino-4:
$\sin^2 2\theta = 0.39$ $\Delta m^2 = 7.3$ eV2

- The Short Baseline Neutrino (SBN) at FNAL is intended to solve all these "ν anomalies" with liquid argon TPC (LAr-TPC) exposed at different distances from beam target
  - ✓ *Far to near detector neutrino spectra comparison is crucial for the control of backgrounds and beam/detector systematics.*
  - ✓ *Measuring both appearance/disappearance in the same experiment using LAr_TPC technique with an excellent ν identification/strong reduction of possible NC bckg is mandatory to disentangle the physics scenario;*

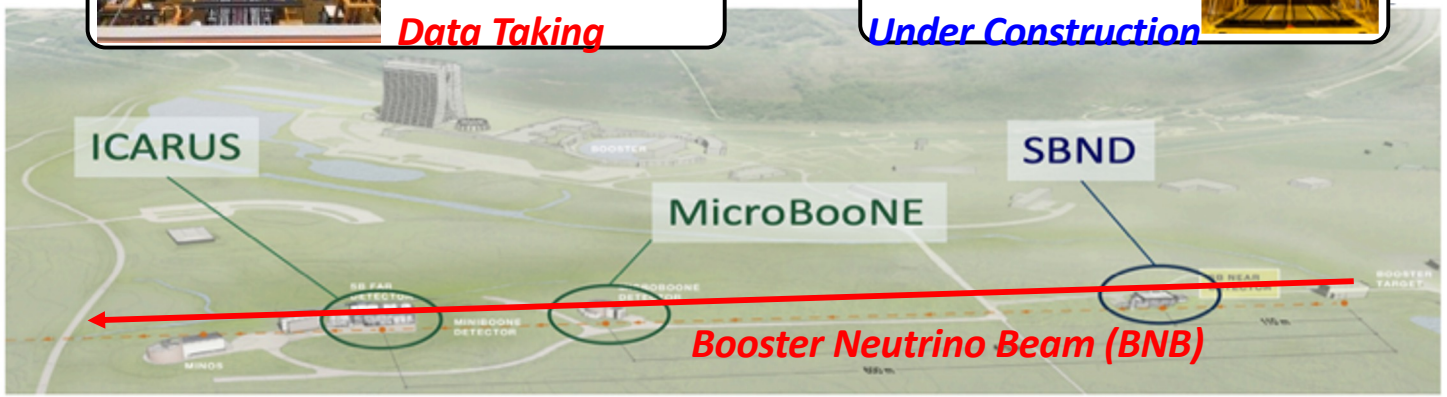
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos*

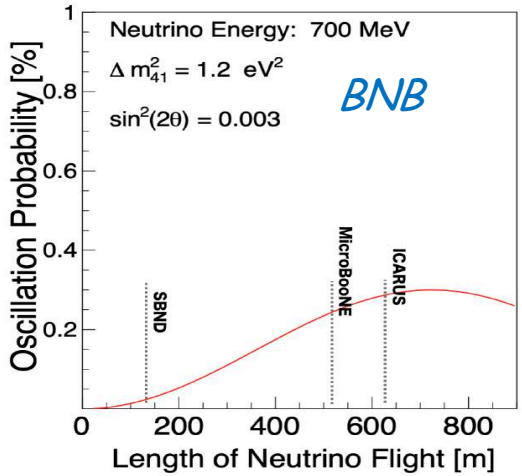
ICARUS

600m baseline
470t active volume
Data Taking

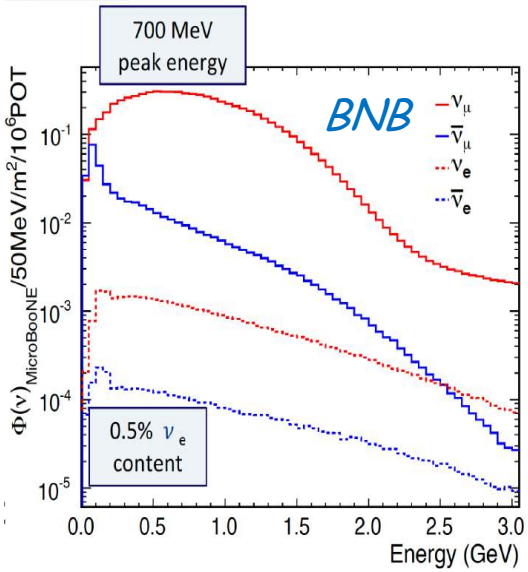
SBND

110m baseline
112t active volume
Under Construction



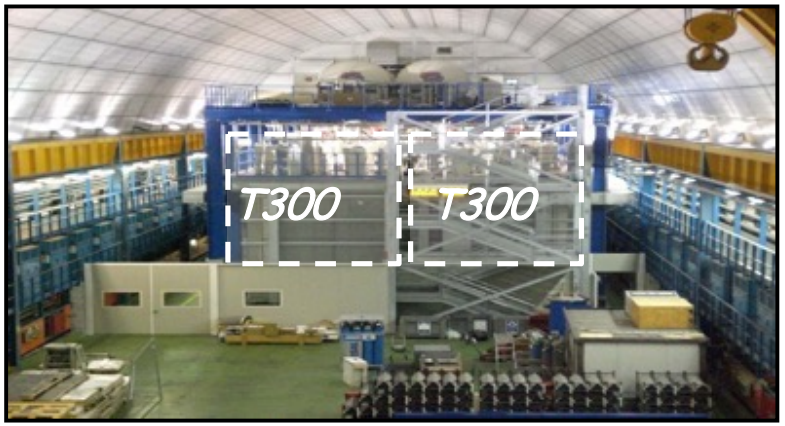


- ICARUS, SBND LAr-TPC's installed at 600 m and 110 m from the Booster target are searching for sterile-ν oscillations both in appearance and disappearance channels.
- Furthermore, high-statistics ν-Ar cross-sections measurements and event identification/reconstruction studies in view of DUNE:
  - Millions events/y in SBND <1 GeV from Booster
  - ICARUS: ~ 5 10^5 events/y E > 1 GeV from NUMI at 700 m, 6^0 off-axis from target.
- Beyond Standard Model searches: Higgs portal scalar, ν tridents, light dark matter, heavy neutral leptons …



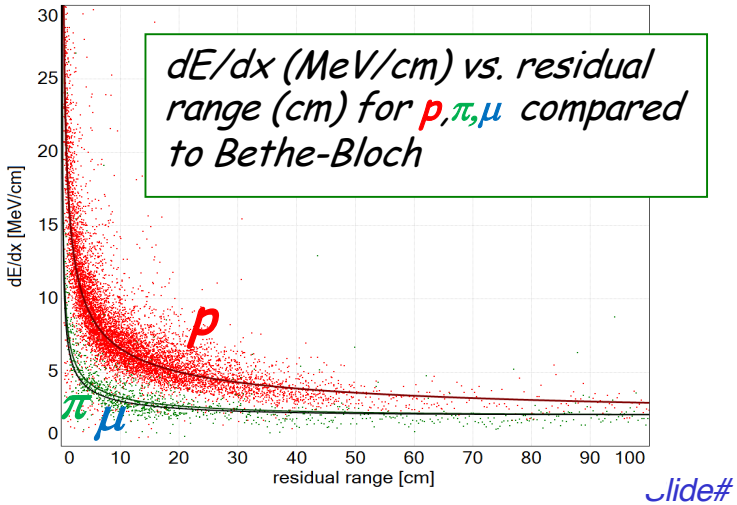
The remarkable evolution of ν- experiments: the LAr-TPC

- Liquid Argon Imaging technology LAr-TPC, an "electronic bubble chamber" which allow to identify unambiguously each ionizing track in complex ν events, was proposed by C. Rubbia [CERN-EP/77-08] as an alternative to Cherenkov detector.
- Many years long R&D at INFN/CERN culminated in first large-scale experiment ICARUS-T600, 0.76 kt ultra-pure LAr at Gran Sasso INFN underground labs:



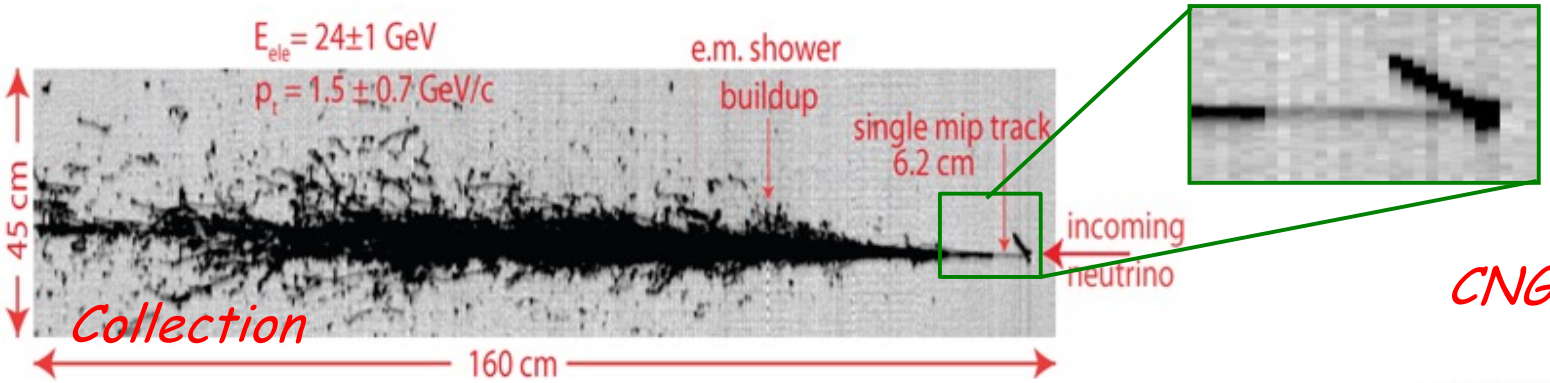
- 2 modules, 2 TPCs per module, central cathode
- 3 readout wire planes per TPC, ~54000 wires, 3 mm pitch, 3 mm plane separation
- PMTs +TPB wavelength-shifter coating for detecting the scintillation light.

- Tracking device: 3D event topology with $\Delta x \sim mm^3$
- Full sampling homogeneous calorimeter:
  E measurement by charge integration; escaping μ measured by MCS with $\Delta p/p$ ~15% below 2.5 GeV;
- 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.



ICARUS T600: a powerful detector for neutrino experiments

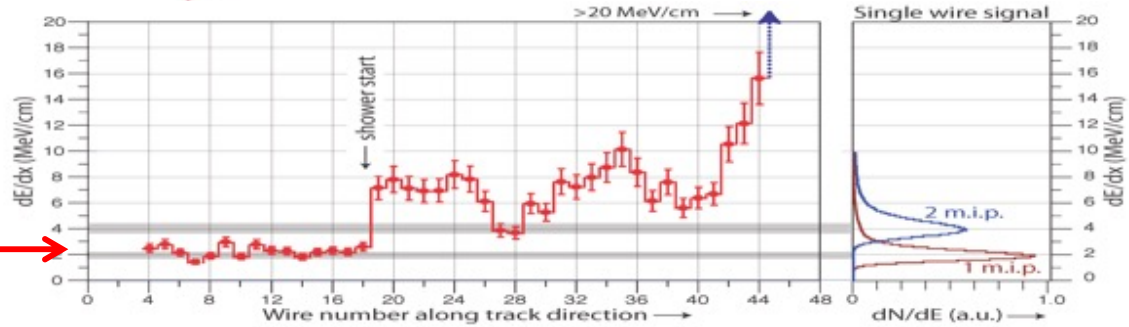
- ICARUS concluded in 2013 a successful 3 years long run exposed to CNGS beam and cosmic rays with several physics/technical achievements:
  - Demonstrating the unique LAr-TPC performance in νe interaction identification and π^0 background rejection to unprecedented level;
  - Performing a sensitive search for LSND-like anomaly through νe appearance in the CNGS beam *constraining LSND result to a narrow region* *EPJ C (2013) 73:2599*



CNGS νe CC

Evolution from single e-mip to EM shower is evident from dE/dx on individual wires.

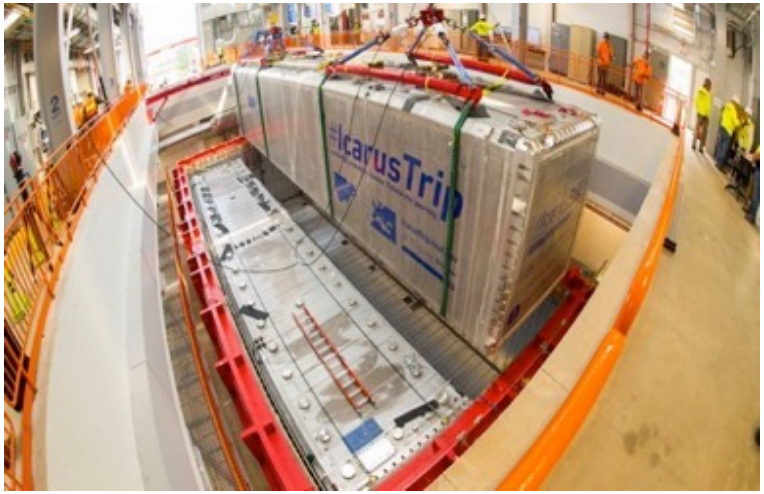
Single mip



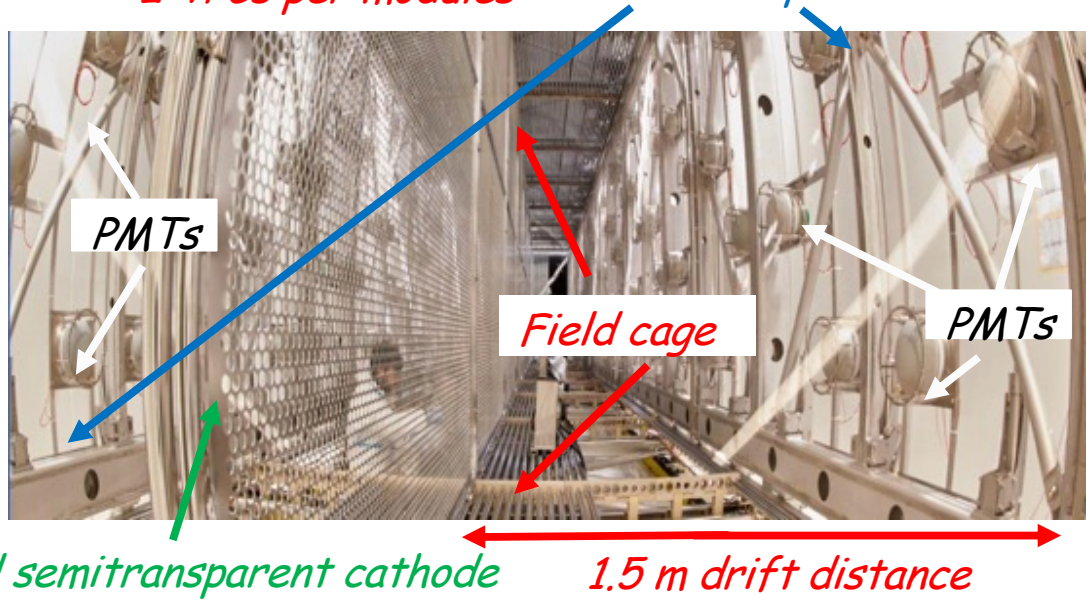
… paving the way for huge LAr-TPCs, eg DUNE

ICARUS T600 detector: from Gran Sasso to Fermilab

2 identical modules: 476 t total active mass



2 TPCs per modules



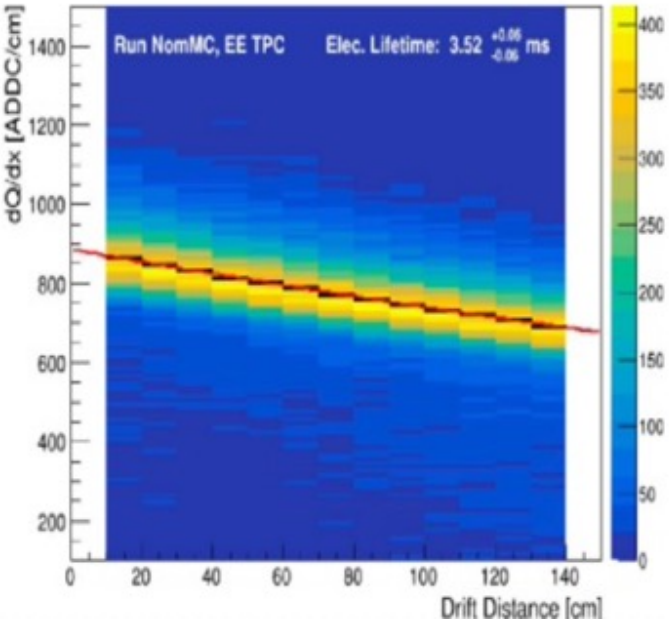
ICARUS was moved to FNAL after an overhauling phase at CERN and INFN Labs:

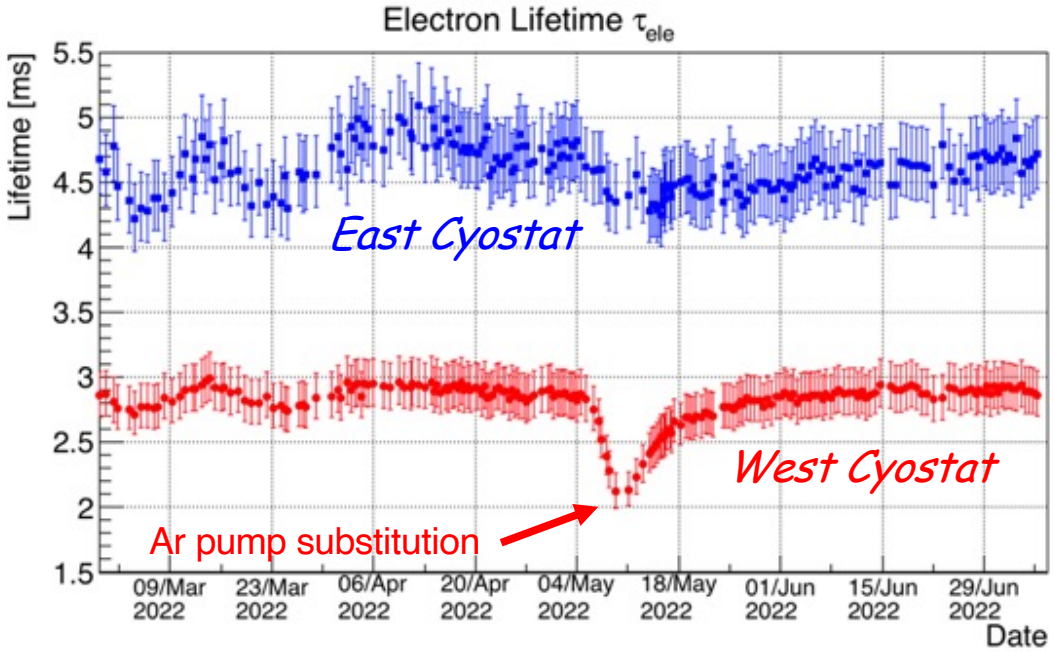
- 2 TPCs/module, common central cathode: E_{Drift}=500 V/cm,v_{Drift}~1.6 mm/μs;
- Ionization charge detected on 3 wire planes per TPC, ≈ 54000 wires at 0°, ±60° w.r.t. horizontal, 3 mm pitch (Induction-1, Induction-2 and Collection), is continuously read with a new electronics, 0.4 μs sampling time;
- 360 8" PMT's, coated with TPB wavelength shifter are installed behind the wire planes to detect the UV scintillation light in LAr for t_0, event timing and triggering purposes;
- The detector is protected from cosmics by scintillators counters and passive overburden.

Cryogenics and free-electron lifetime

- Argon is continuously recirculated and purified by a new cryogenic system in both liquid/gas phases by copper-based filters with molecular sieves for water absorption.

- LAr purity measured by dE/dx signal attenuation along drift direction for cosmic μ:
  - Free-electron lifetime: τ ~ 4.5 ms in East Cyostat, ~3 ms in West, allowing a good track detection (max e-drift time: 1 ms).

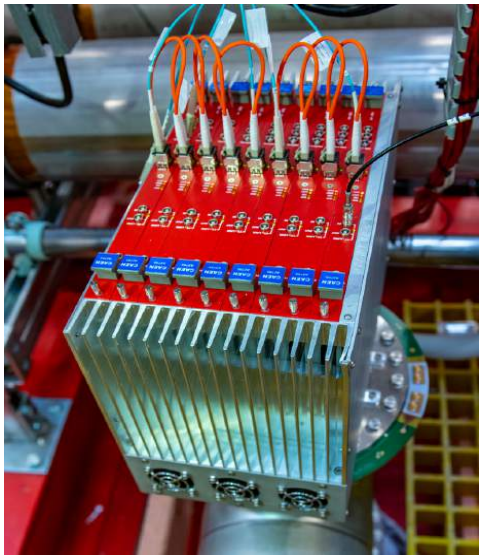




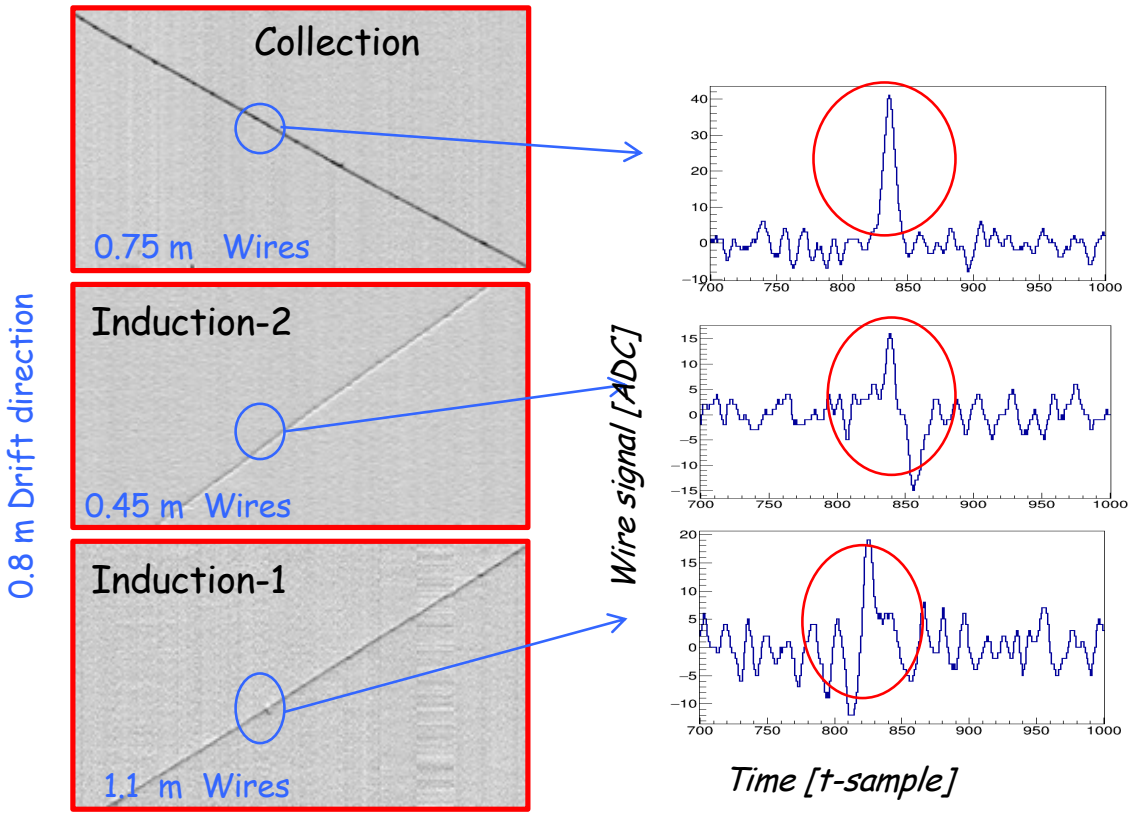
- *The filters in West module has been recently regenerated. Recirculation of liquid argon just started… waiting for improvement and equalization of the LAr purity*

Upgrade of TPC read-out electronics

- Front-end based on analogue low noise, charge sensitive pre-Amp;
- Shorter signal shaping time ~1.3 μs for a better separation of the hit position;
- Compact layout with both analog/digital electronics in a single board: 96 mini-crates installed on the signal feed-through flanges.



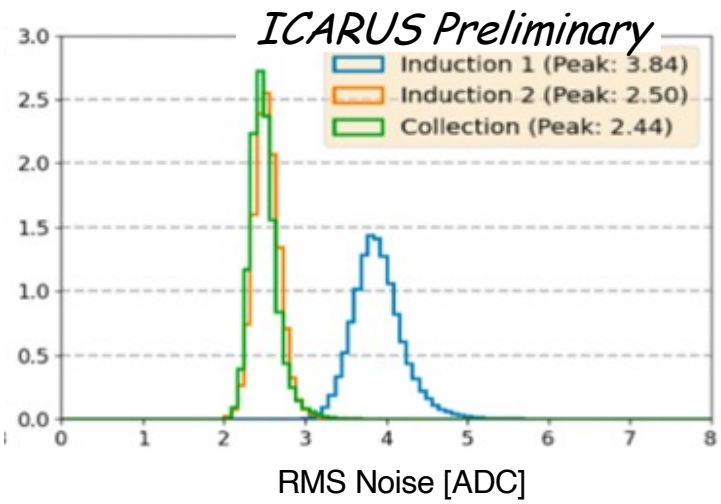
10 liter mini-crate on a feed-through hosting 9 boards (576 wires)



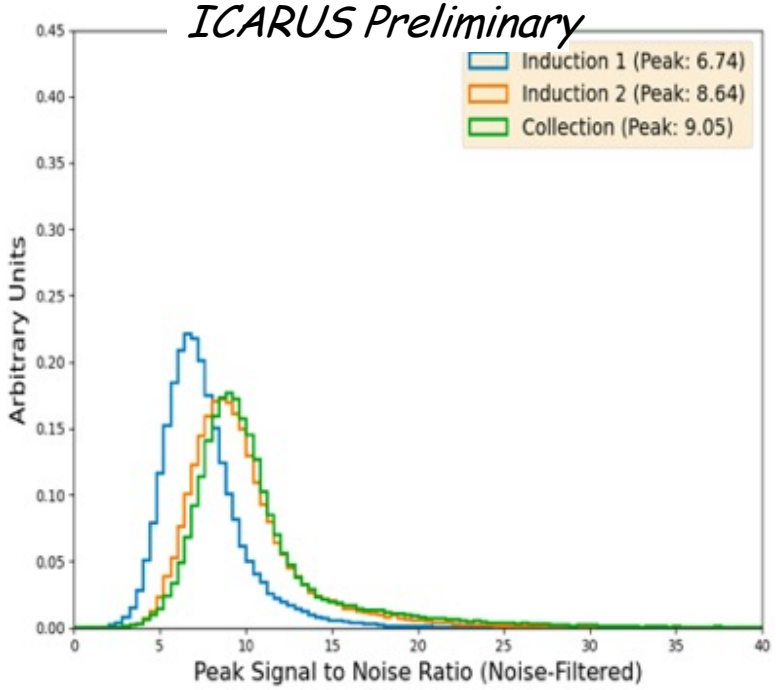
Recorded cosmic muon track: the characteristic bipolar shape of e-signals traversing the wire plane is recognized in Induct.-1, 2 views.

Upgrade of the TPC read-out electronics

- Extended tests performed within INTESE framework at FNAL allowed to mitigate anomalous coherent noise present in the TPCs upon activation mainly injected by ancillary cryogenic instrumentation:
  - Presently uniform intrinsic RMS noise in all TPCs, (1 ADC: 550 e-):
    ~ 2.5 ADC in Collect./Ind-2 views, 3.9 m wires; ~ 3.8 ADC in Ind-1, 9 m wires
  - Average Signal to Noise ratio S/N > 10 in Collect./Ind-2 views for mip signals from almost vertical muon tracks.

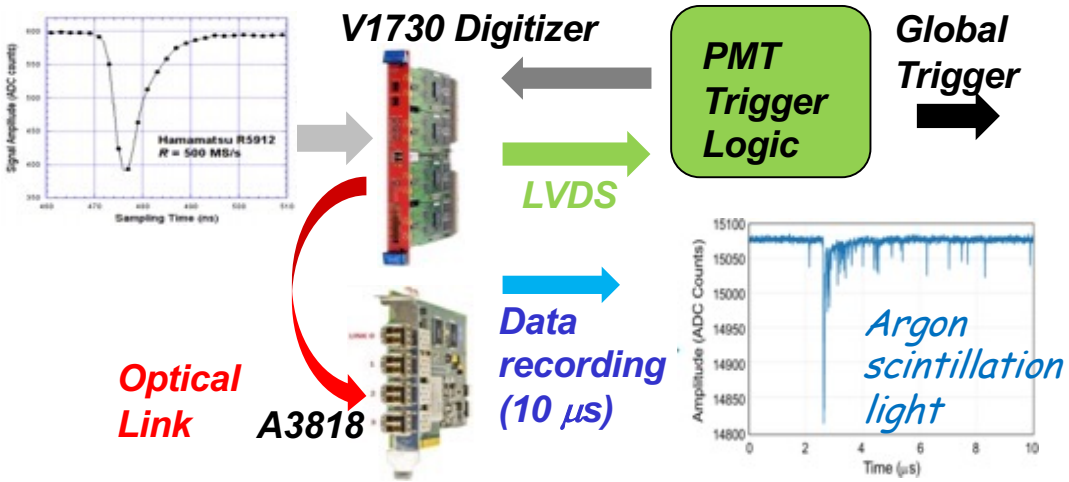


Studies are on-going to further mitigate the coherent noise.

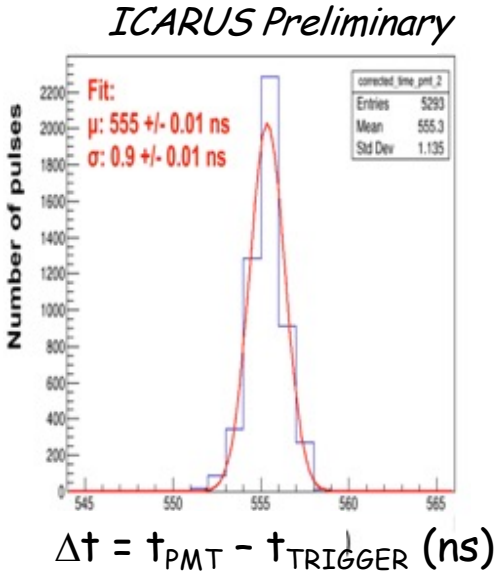


Upgrade of the light collection system

- 360 Hamamatsu 8" PMT (5% coverage, 15 phe/MeV) installed behind the wire planes, 90 PMTs per TPC:
  - Continuous read-out, digitization, discrimination and waveform recording of PMTs signals (V1730 digitizers).
  - PMT signals sampled every 2 ns and recorded in 10 μs windows.



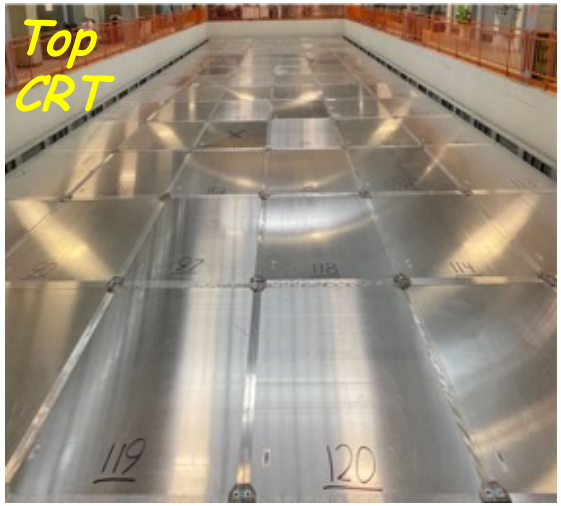
- PMT gain equalized at ~ 0.5 10^7 ± 1% with λ ~ 405 nm laser and measuring the 4 mV PMT response to single phe backgr.
- ~3 kHz PMT counting rate at 50 mV ~13 phe threshold.
- PMT time response equalized by Laser to Trigger signal with 1 ns resolution allowing to perfectly measure the time of collected events.



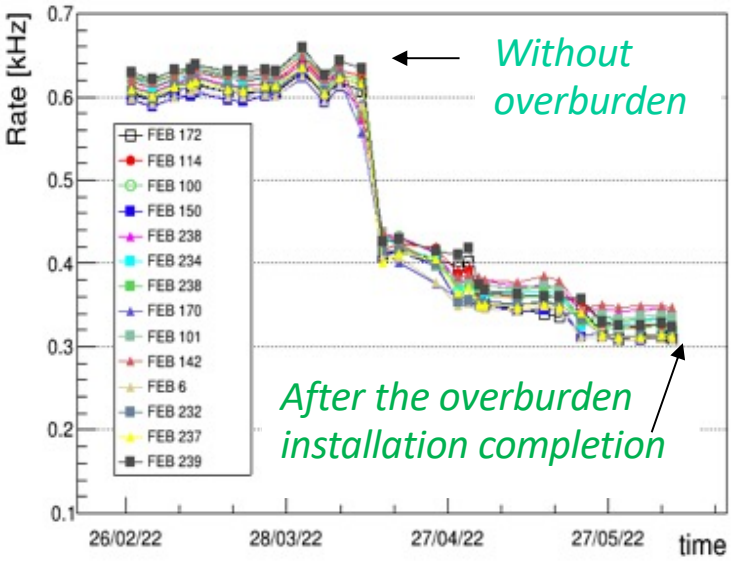
Cosmic-ray background mitigation in ICARUS

- ICARUS LAr-TPC is installed in a pit exposed to cosmic rays where produced electrons can mimic a genuine ν_e CC interaction:
  - Primary γ's and mostly of cosmic neutrons suppressed by ~ 3 m concrete overburden above ICARUS;
  - Residual cosmic rays entering ICARUS, ~ 11 μ in 1 ms TPC drift time, are identified in time/position by 4π Cosmic Ray Tagger (CRT) detector surrounding LAr-TPCs

CRT: a double layer scintillation bars (~1000 m^2) with SiPMs, tagging incoming cosmics with ~95% efficiency

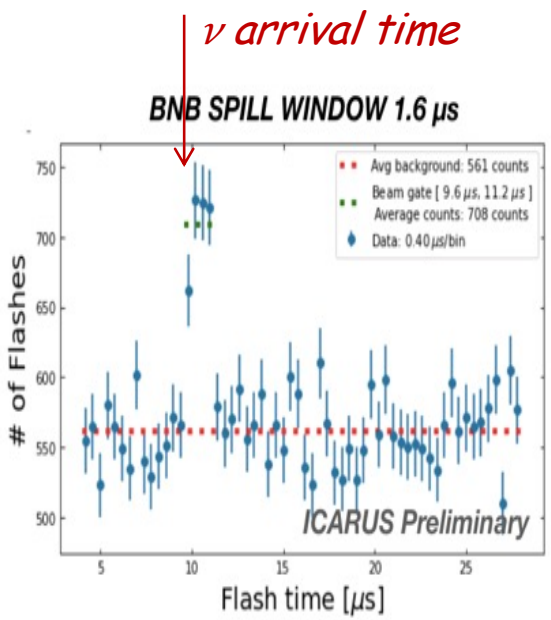


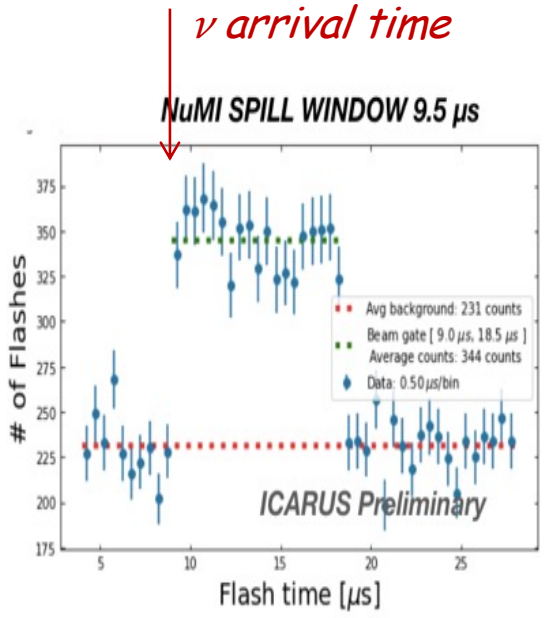
Overburden reduced by a factor 2 the cosmics signals on Top CRT



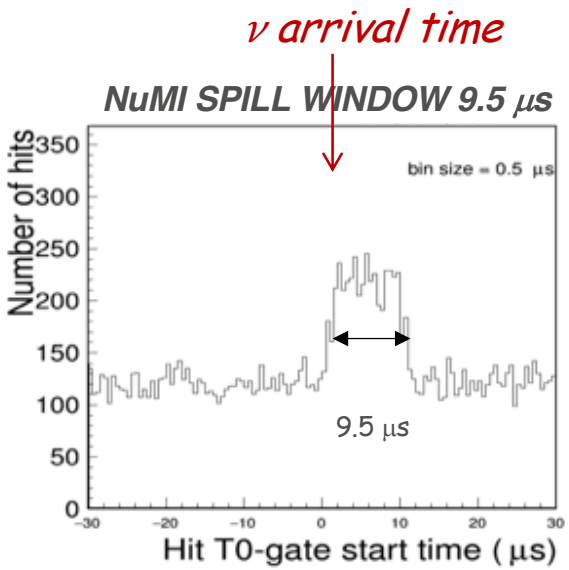
ICARUS Trigger system

- Trigger signal: scint. light from >5 fired PMT pairs in a 6 m longitudinal detector slice (30 left + 30 right PMTs per cryostat) in coincidence with the beam spill identified by an Early Warning signal of proton beam extraction.
- PMT and CRT signals are recorded 2 ms around the trigger to recognize/tag cosmics crossing the LAr-TPCs during the 1 ms e- drift time.
- The detector timing has been set by looking for excess of PMT light signals and of side CRT hit signals over the cosmic background in correspondence of the beam arrival.





Light signals excess in PMT system



Hit signals excess in Side CRT

- Trigger efficiency initially evaluated on cosmic muons: > 97 % for E_{DEP} >250 MeV

ICARUS Installation, Commissioning and Data taking

Aug. 28th 2020: start of TPC/PMT operation

Dec. 2021: completion of CRT installation

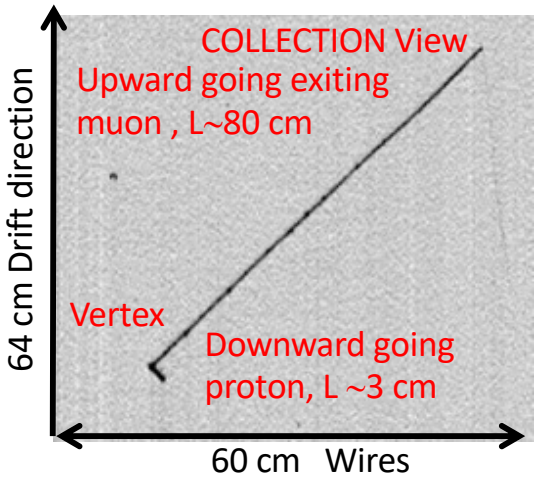
June 7th 2022: completion of overburden installation

Steady data taking with BNB, NuMI beams since March 2021, in parallel with commissioning activities.

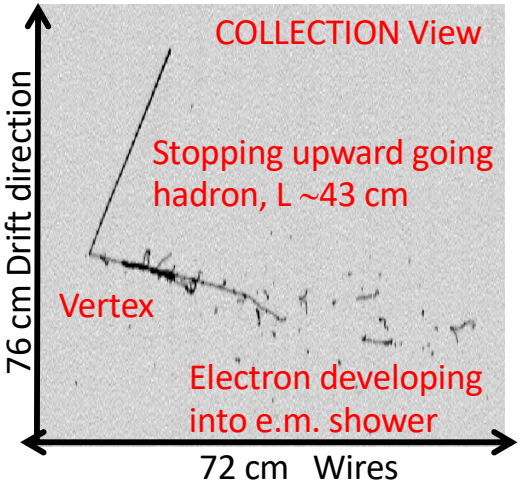
Cosmics, ν_μ, and ν_e samples collected for trigger/calibration/event reconstruction studies.

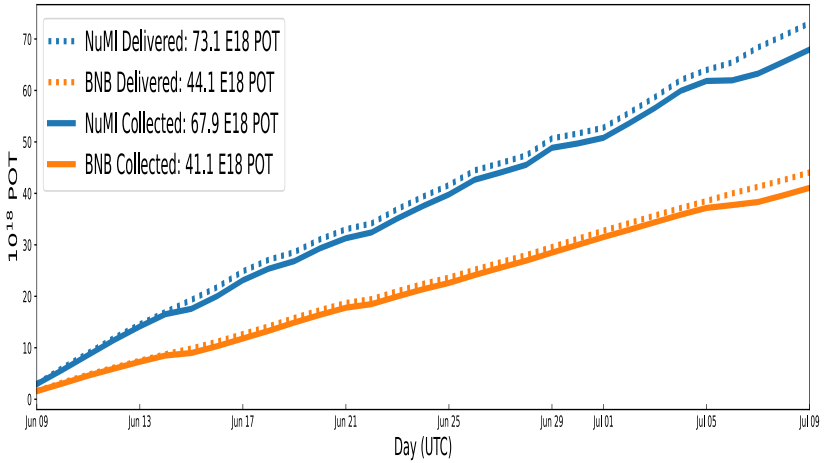
Started data taking for physics with BNB, NuMI: June 9th 2022

BNB CC QE νμ candidate, E_{DEP}~ 200 MeV



Contained NuMI CC QE νe candidate, E_{DEP} ~ 800 MeV





Collected event statistics (93% efficiency): 4.1x10^{19} pot (BNB), 6.7x10^{19} pot (NuMI)

Conclusions

- ICARUS detector installation started in 2019 with the secondments at FNAL of electronic technicians/physicists from INFN and activated in 2020 continuing to operate with excellent stability and taking data with BNB/NuMI beams part-time as installation/commissioning progressed.
- Data collected so far have been instrumental for calibrating the detector, tuning simulation and event reconstructions tools.
- Commissioning has been completed with the fundamental support of INTENSE EU: full time neutrino beam Run-1 started on June 9th 2022 exploiting regularly both BNB and NuMI beams. Run-2 is expected to start next week.
- Early phase of ICARUS data taking is started, primarily dedicated to the study of Neutrino-4 claims looking for $\nu\mu$ *disappearance* in the BNB beam and νe *disappearance* in the NUMI off-axis beam.
- After first year ICARUS-only operations, ICARUS will perform with SBND detector at shorter distance from Booster a definitive 5 σ search for sterile neutrinos

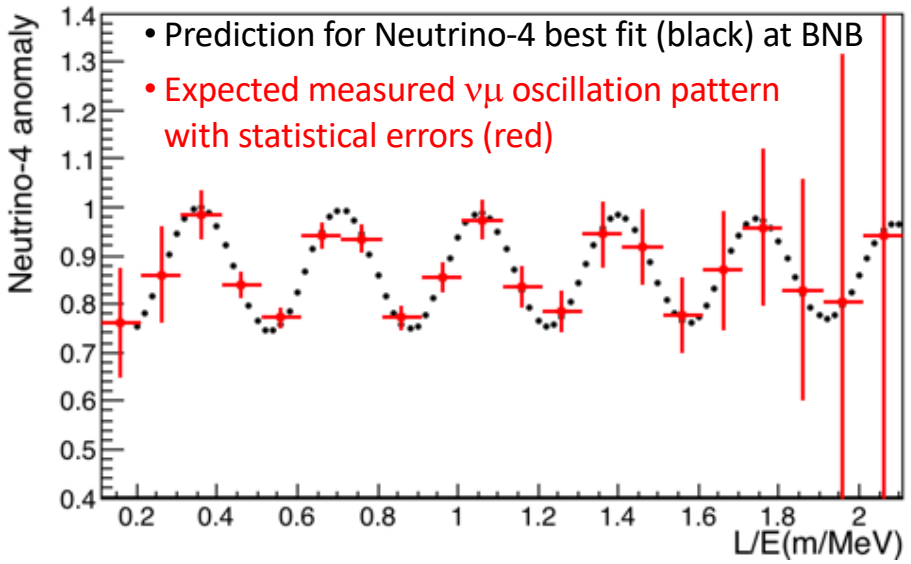
The INTENSE EU Marie Sklodowska-Curie Action has played and is playing a fundamental role in the success of ICARUS investigation on sterile neutrino anomalies at FERMILAB allowing the networking of a large community of Researchers, in particular of Youngers!

BACK-UP

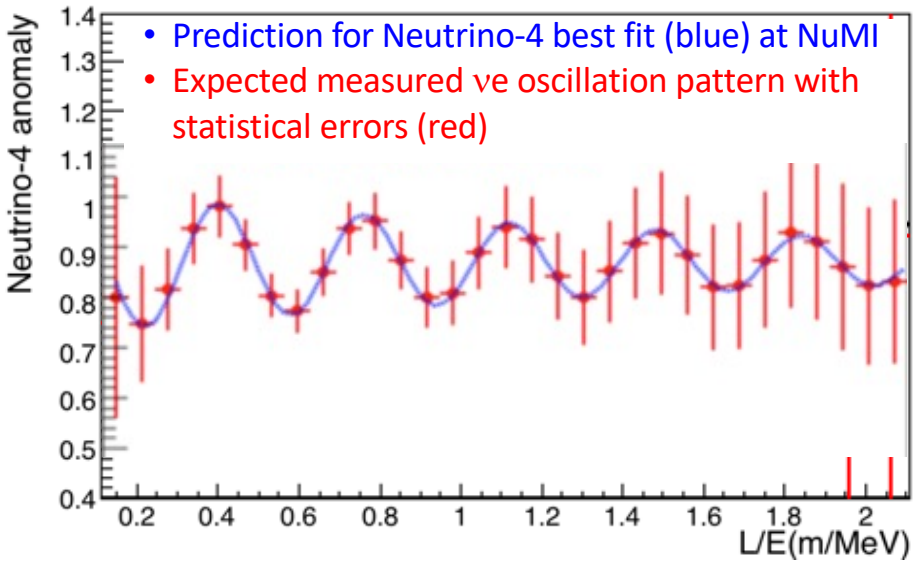
ICARUS search for Neutrino-4 claims at FNAL

- Initial run with ICARUS-only operational detector:
  - settling NEUTRINO-4 sterile-ν claim by disappearance pattern of νμ in BNB and of νe in NuMI, same L/E ~ 1-3 m/MeV but with ~100 time event energy

$\Delta m^2_{14}=7.25\ eV^2$, $\sin^2 2\theta_{14}=0.26$



νμ survival oscillation probability at Booster:
~8500 QE events with >50 cm contained μ track, ~ 3 months data taking, ~7 x 10^{19} pot, ΔE/E ~ 3 %.



νe survival oscillation probability at NuMI:
~ 5200 QE events with contained E.M. shower, 1 year data taking, ~6 x 10^{20} pot.