Short base-line neutrino oscillation searches with the ICARUS detector

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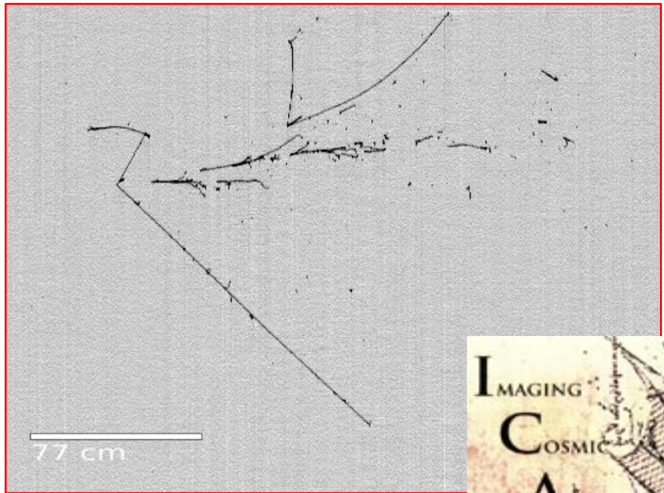

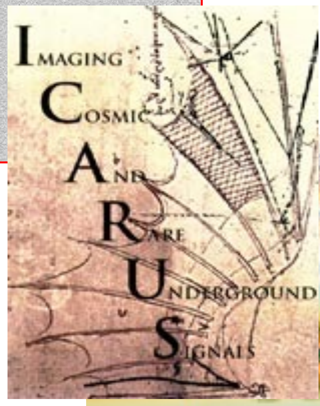

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ICARUS Collaboration at SBN

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Spokesperson: C. Rubbia, GSSI

Neutrino related anomalies ?

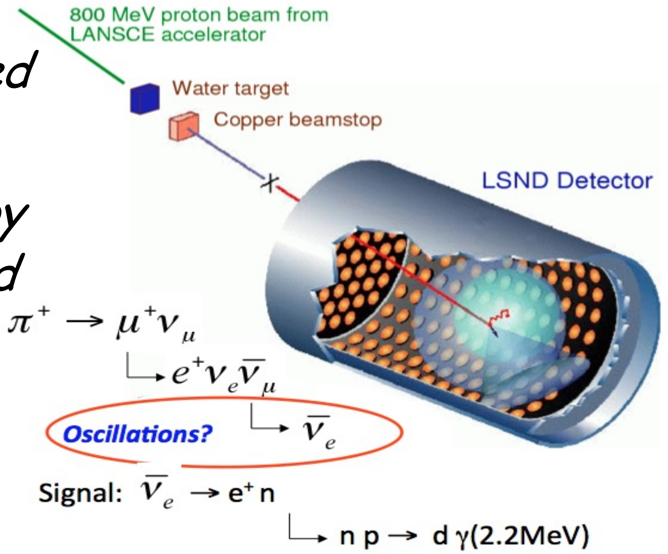
- For several decades, many anomalies beyond an ordinary 3-flavour mixing picture have been collected in the neutrino sector, suggesting some additional new related physics:

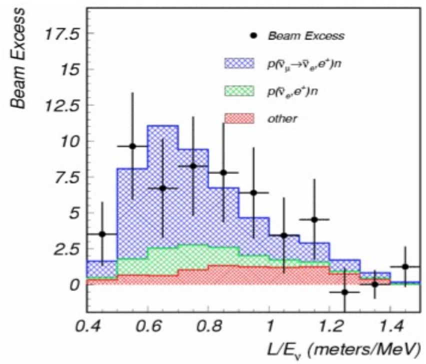
  - *anti–νe appearance: anti-$\nu\mu$ accelerator LSND experiment where anti-νe -> e+ + n with neutron captured by a proton, n + p into d + γ.*

  - *νe disappearance: SAGE, GALLEX experiments with Mega-Curie sources with observed/predicted rate R = 0.84$\pm$0.05;*

  - *anti-νe disappearance of near-by nuclear reactor experiments and rate R = 0.934$\pm$0.024.*

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)%.

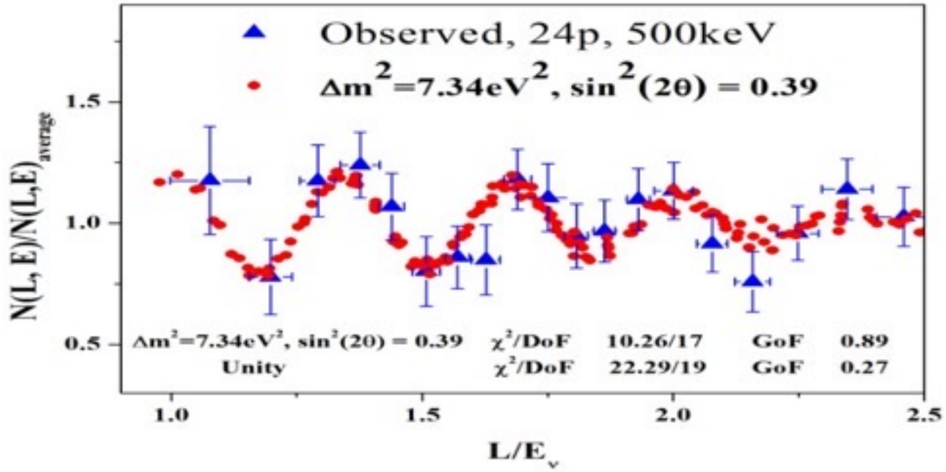
3.8 σ evidence for oscillation.

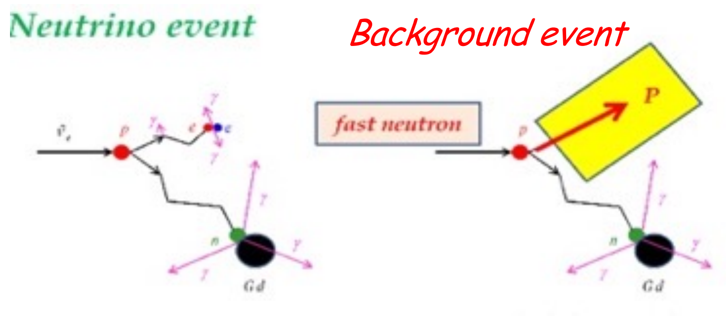
In addition: the recent observation of sterile neutrino oscillations by NEUTRINO-4 experiment.

Evidence for oscillations of sterile neutrinos at reactor

- In '18 Neutrino-4 experiment *(A.P. Serebrov et al.)* at Dimitrovgrad SM-3 reactor gave evidence of ν oscillations into sterile-νs showing a disappearance signal with a clear L/Eν ~ 1-3 m/MeV modulation:

Reactor-on data (blue) compared as function of L/Eν with expectation for Δm^2, $\sin^2 2\theta$ values (red).





- Neutrino event signature: anti-νe + p -> e^++n followed by delayed n capture by gadolinium in liquid scintillator.
- Background: fast n emitted in interaction of high E cosmic μs with matter around the detector, n + p -> p + n

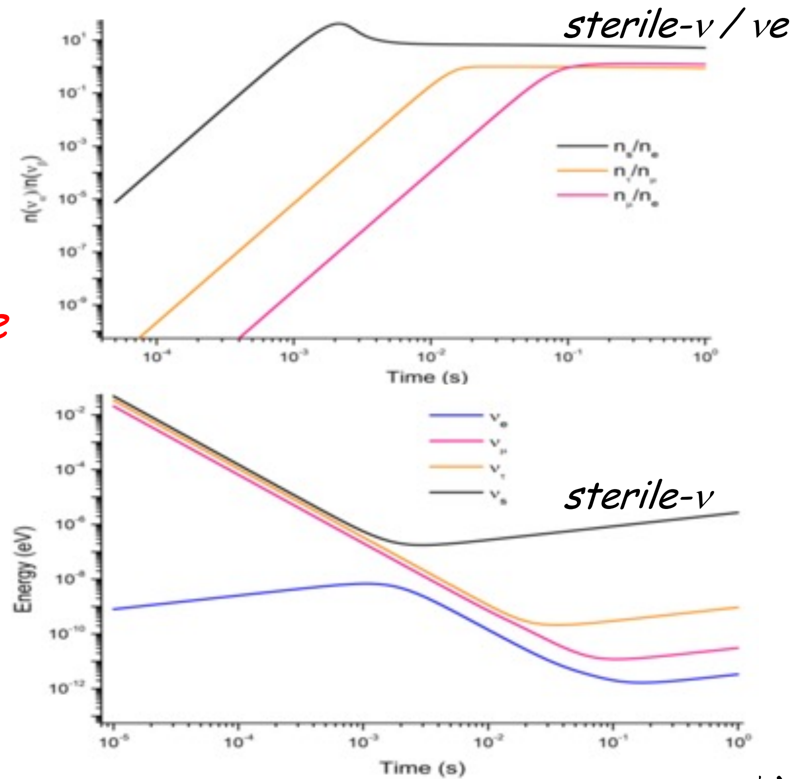
- 3 years data taking until June '19, moving the segmented liquid scintillator detector from 6.4 to 11.9 m distance from the reactor core in 24 steps: 720 (417) days reactor-On (-Off) -> *On-Off: 223 events/day with S/B ~0.54.*
  - The square difference between the masses of electron and sterile neutrinos is *$\Delta m_{14}^2 = 7.25 \pm 1.09\ eV^2$ with $\sin^2(2\theta_{14}) = 0.26 \pm 0.08$ stat $\pm$ 0.05.*

Sterile neutrinos as the origin of Dark Matter ?

- Neutrino-4 additional evidence in '22 suggesting sterile neutrinos as the candidate for Dark Matter (DM) with a quite obvious dominant contribution due to the high density of relic sterile-νs with $m\nu_4$ = 2.7 eV:

  - 24% (+5,-3)% sterile-ν contribution to the total energy density of Universe Ω_0 compared with the 26.4 % known estimate of so far unknown DM *-> an obvious reason for considering the existence of this sterile neutrino as a possible DM source!*

  - Ordinary νs contribute to Ω_0 as $m(\nu_1\nu_2\nu_3)$ /1 eV · 0.01 h^{-2}, h: Hubble constant. By the time all νs freeze out, sterile ν density is 5.1 times ν–e density => *expected contribution* $\Omega(\nu_4) \approx (2.7\ eV / 1\ eV) \cdot 0.01\ h^{-2} \cdot 5.1 = 0.24.$



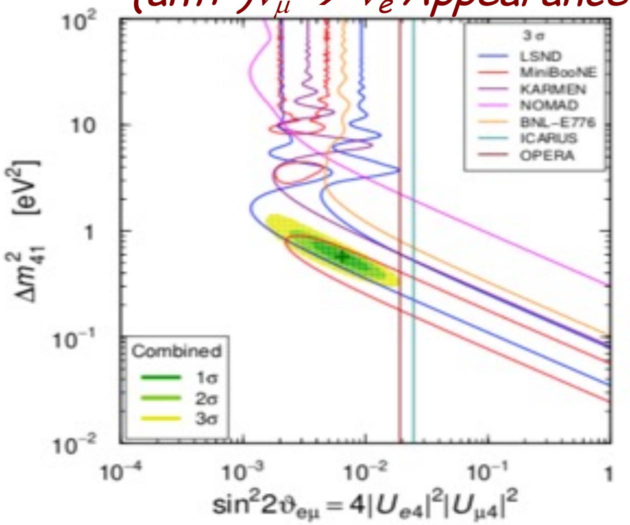
number and energy of sterile νs (black) versus ordinary νs as a function of time.

- Another obvious reason for considering sterile-ν as DM candidate is the absence of interaction between sterile-ν and matter: the scattering of strongly/weakly interacting particles on clusters of sterile-νs occurs only due to gravitational interaction.

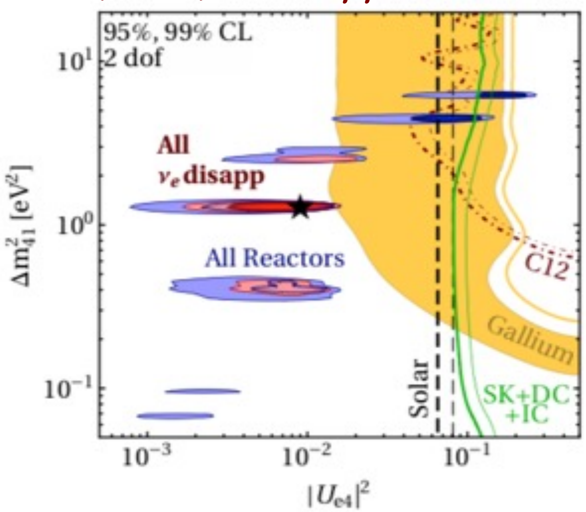
The sterile neutrino puzzle

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

(anti-)ν_μ → ν_e Appearance



(anti-)ν_e Disappearance

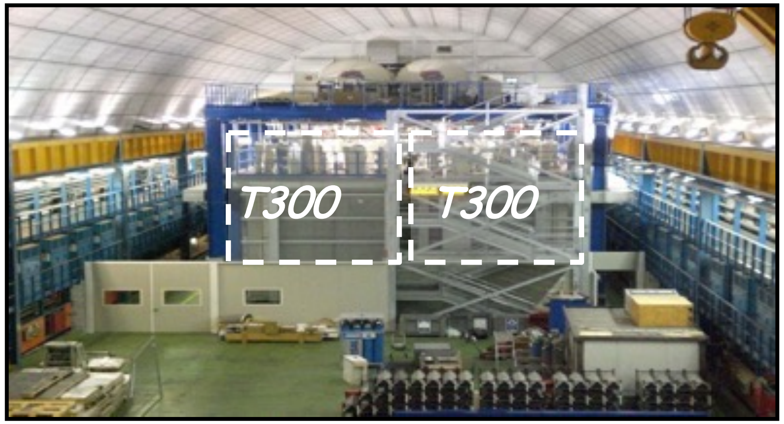


(arXiv:2106.05913)

- ✓ *Measuring both appearance/disappearance channels in the same experiment using a detection technique with an excellent neutrino identification/strong reduction of possible background sources is mandatory to disentangle the physics scenario;*
- ✓ *Far to near detector neutrino spectra comparison is crucial for any accelerator experiment for the control of backgrounds and beam/detector systematics.*

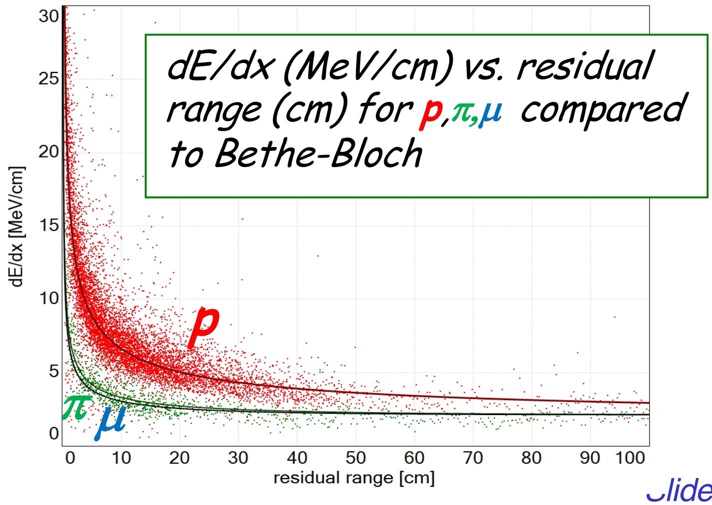
The remarkable evolution of ν- experiments: the LAr-TPC

- 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:



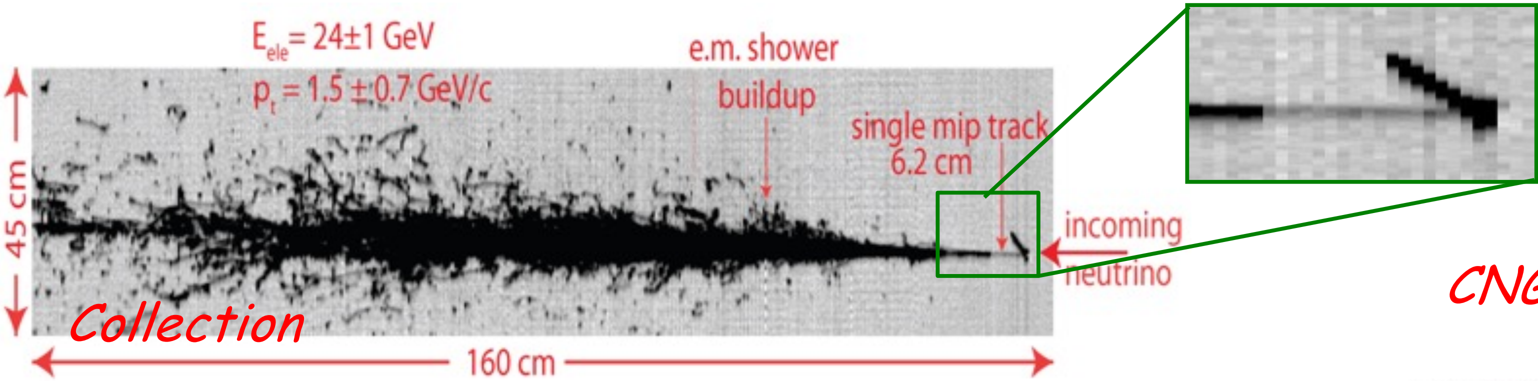
- 2 TPCs per module with central cathode, 1.5 m drift E_D= 0.5 kV/cm, Δt_{DRIFT}~1 ms;
- 3 readout wire planes per TPC, ~54000 wires at 0, ± 60⁰, 3 mm pitch, 0.4 μs sampling time;
- PMTs +TPB wavelength-shifter coating for detecting the scintillation light.

- Tracking device: 3D event topology with Δx ~ mm^3
- Full sampling homogeneous calorimeter: E measurement by charge integration; escaping μ measured by MCS with Δp/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

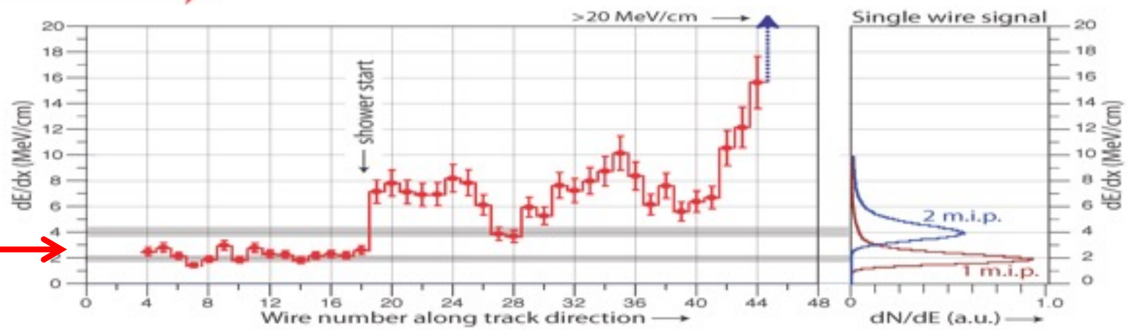
- ICARUS concluded in 2013 a successful 3 years long run exposed to CNGS beam and cosmic rays with several physics/technical achievements:
  - Demonstrating the unique LAr-TPC performance in νe interaction identification and π^o background rejection to unprecedented level;
  - Performing a sensitive 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

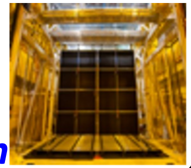
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos*

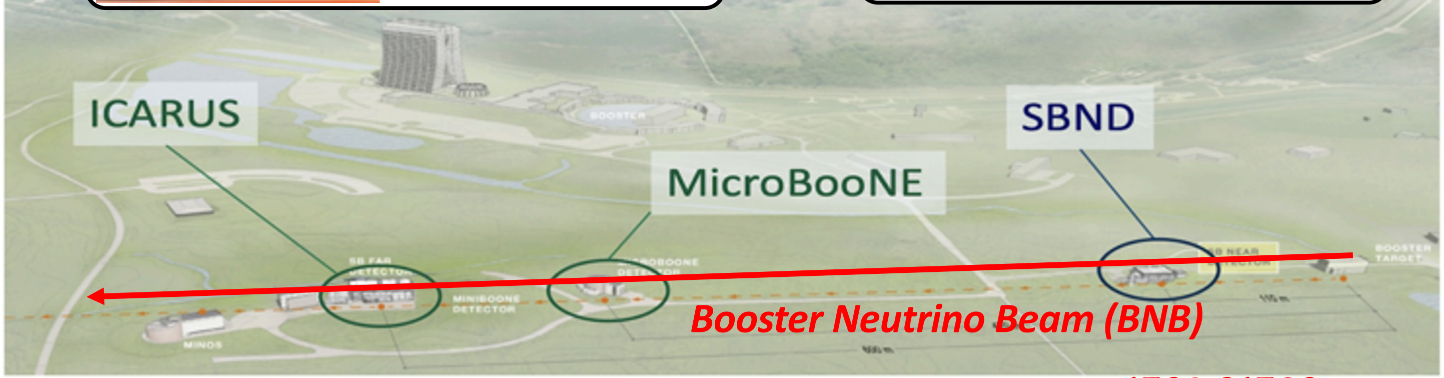
ICARUS

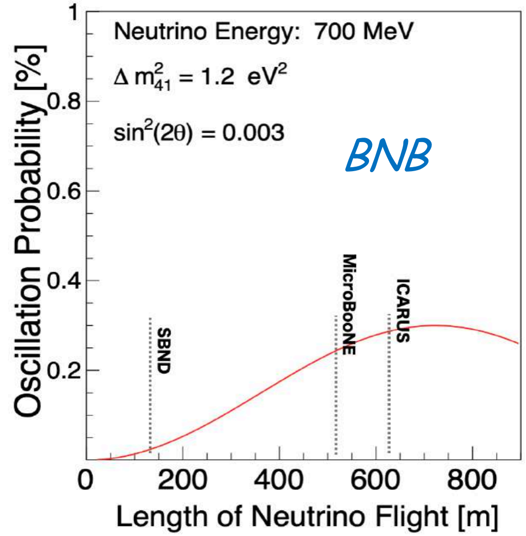
600m baseline
470t active volume
Data Taking

SBND

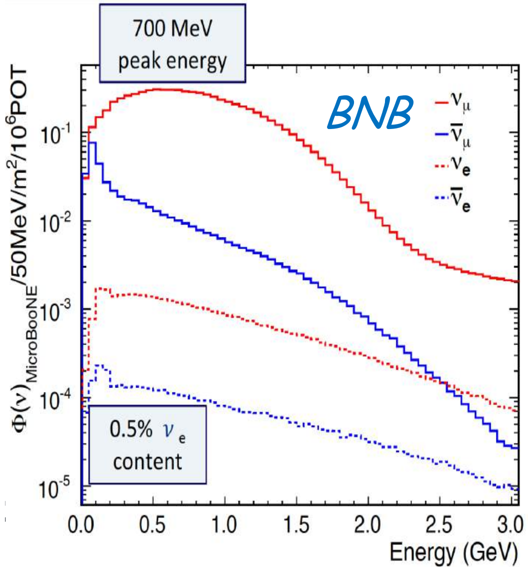
110m baseline
112t active volume
Under Construction







arxiv:1503.01520

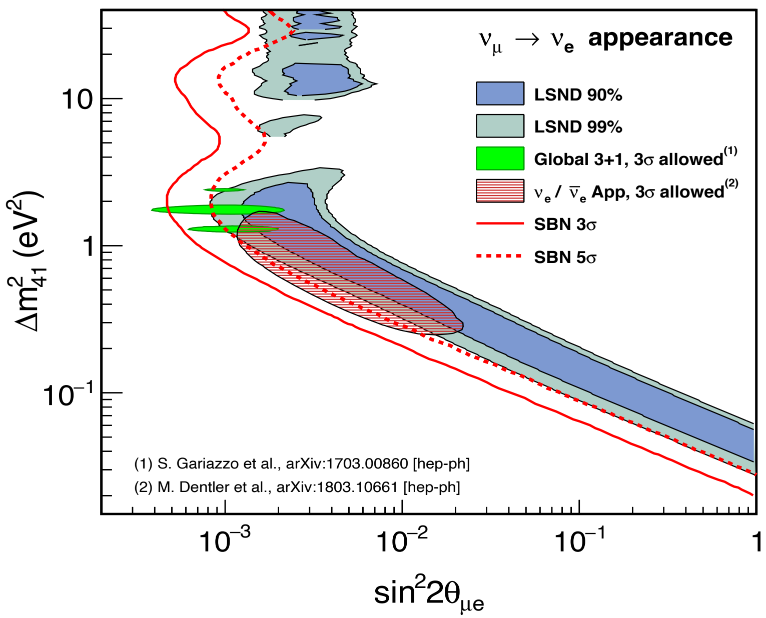


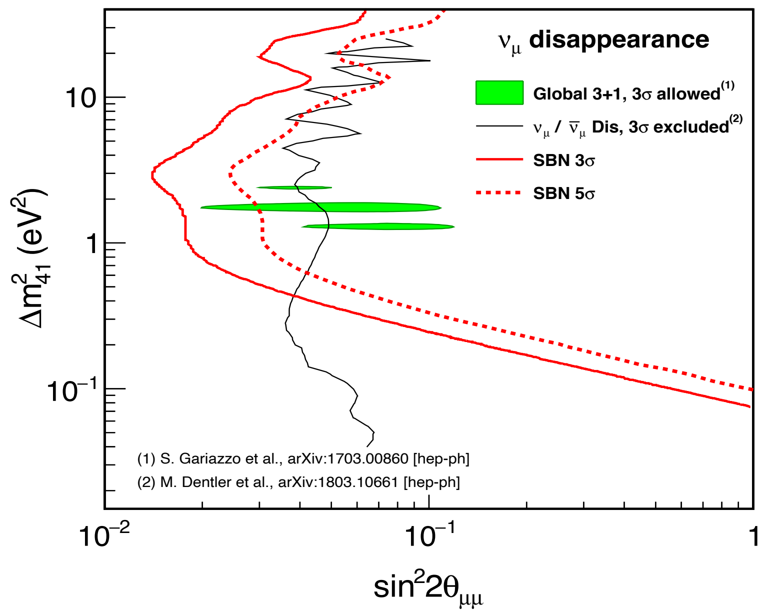
- ICARUS and SBND LAr-TPC's installed at 600 m and 110 m from the Booster target are searching for sterile-ν oscillations both in appearance and disappearance channels.
- Furthermore, high-statistics ν-Ar cross-sections measurements and event identification/reconstruction studies in view of DUNE:
  - Millions events/y in SBND <1 GeV from Booster
  - Hundred thousands events/y in ICARUS >1 GeV from NUMI at 700 m, 6^0 off-axis from target.

SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- Combined analysis of events collected far from ICARUS and near by SBND using the same LAr-TPC event imaging technology greatly reduces the expected systematics:
  - High νe identification capability of LAr-TPC's rejecting NC event background;
  - "Initial" BNB beam composition and spectrum provided by SBND detector.

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





5σ coverage of the parameter area relevant to LSND anomaly

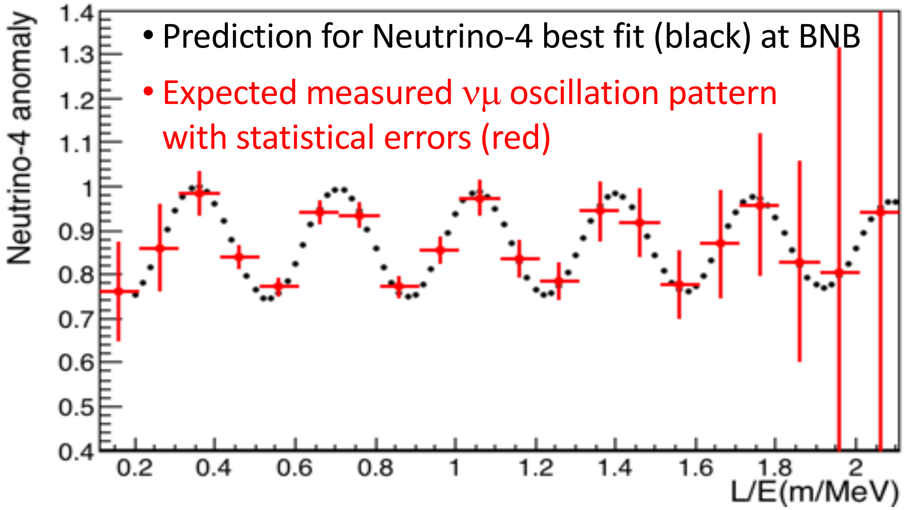
Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study appearance and disappearance channels simultaneously

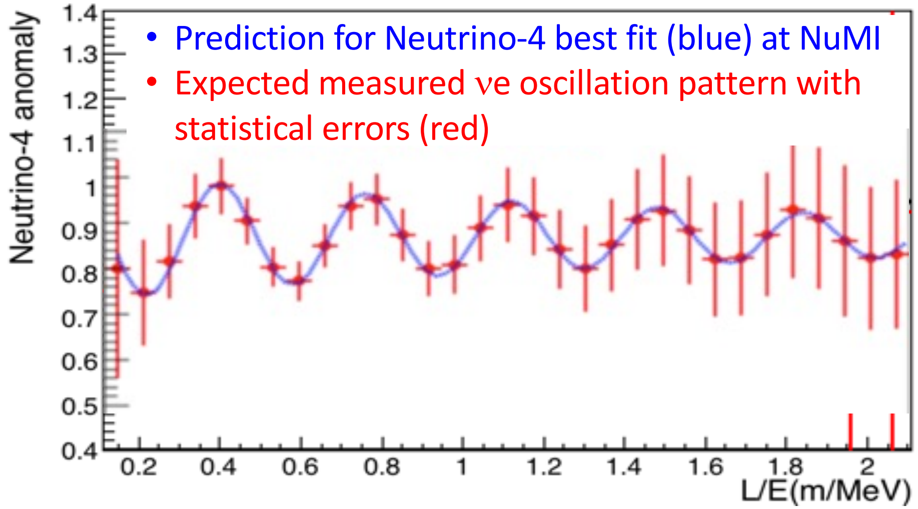
ICARUS search for Neutrino-4 claims at FNAL

- ICARUS at FNAL presents remarkable similarities to NEUTRINO-4 which should allow to settle the NEUTRINO-4 sterile-ν claims in the initial ICARUS-only run:
  - Oscillations produce disappearance pattern of νμ in BNB and of νe in NuMI in the same L/E ~ 1-3 m/MeV but with events collected with ~100 times the energy;
  - L/Eν effect is mostly related to variation of Eν with L ~constant and large for both BNB and NuMI, where νe are mostly produced by kaons decaying close to target.
  - ICARUS focus on the well defined QE CC νμ, νe interactions fully contained in the LAr:

Δm^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 %.

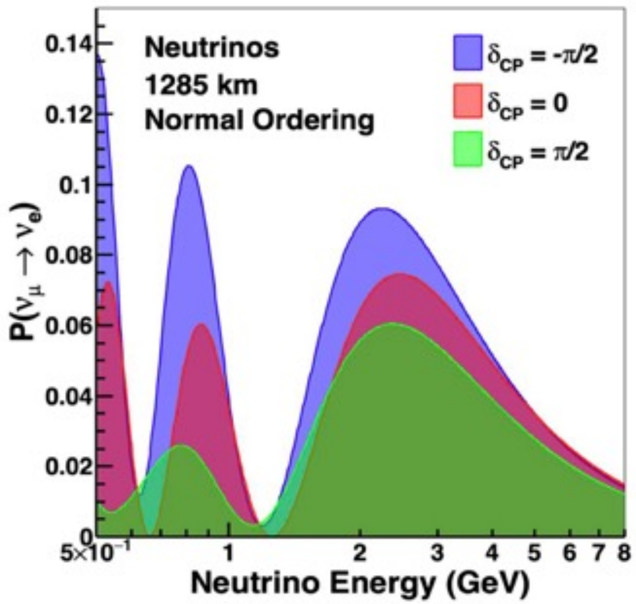


νe survival oscillation probability at NuMI:
~ 5200 QE events with contained E.M. shower,
1 year data taking, ~6 x 10[20] pot.

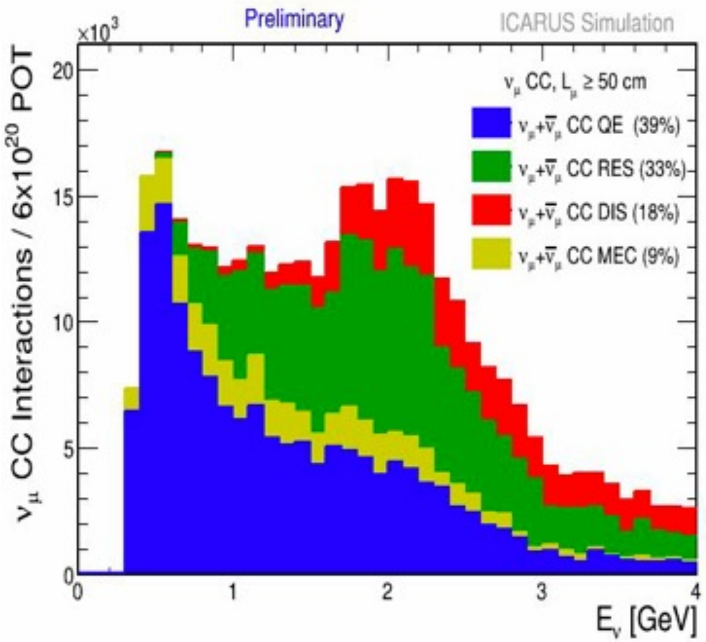
ICARUS physics searches with NuMI beam

- Further exploitation of the NuMI Off-Axis beam (6^0 from ICARUS):
  - High statistics precision measurements of ν-Ar cross sections (~10^5 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, ν tridents, light dark matter, heavy neutral leptons …

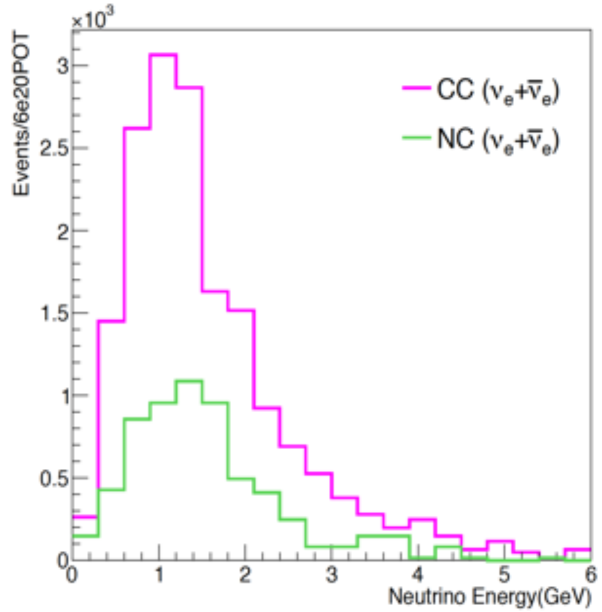
Oscillation probability at DUNE



ν_μ from NuMI at ICARUS

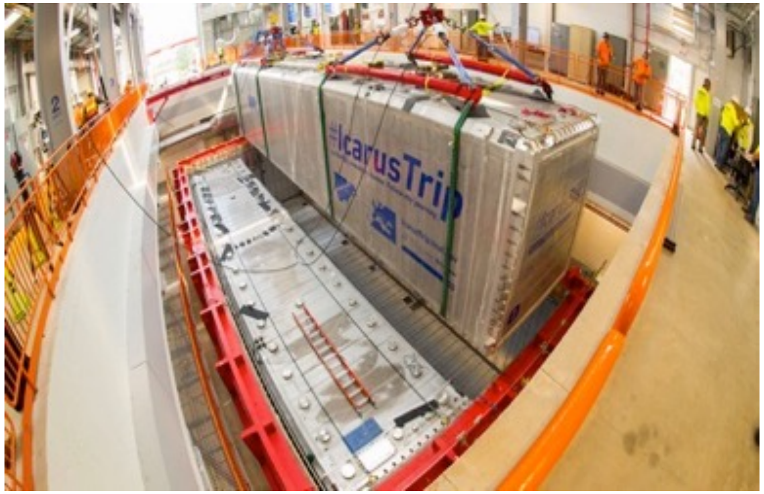


ν_e from NuMI at ICARUS

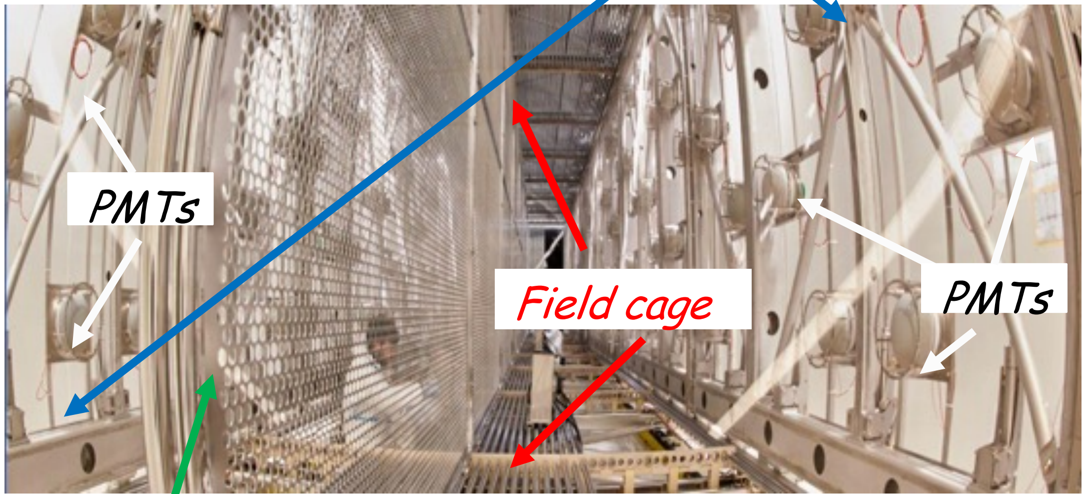


ICARUS T600 detector: from Gran Sasso to Fermilab

2 identical modules: 476 t total active mass



2 TPCs per modules



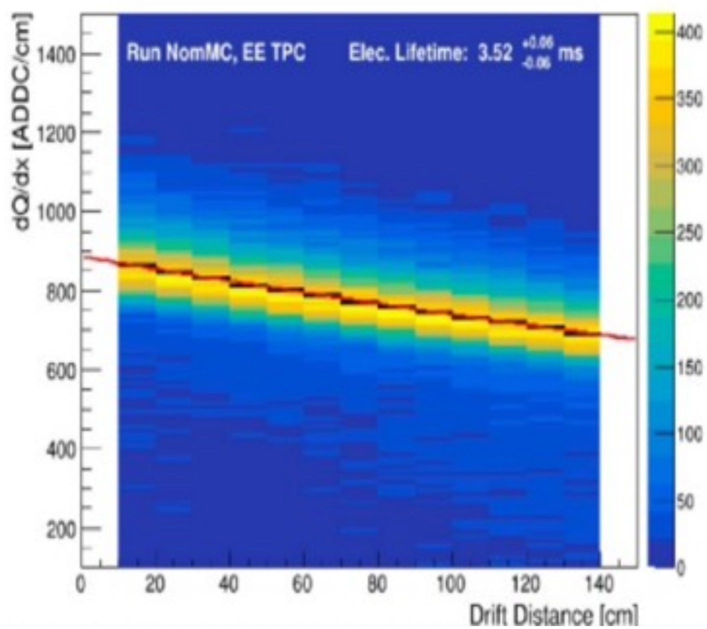
ICARUS was moved to FNAL after an overhauling phase at CERN and INFN Labs:

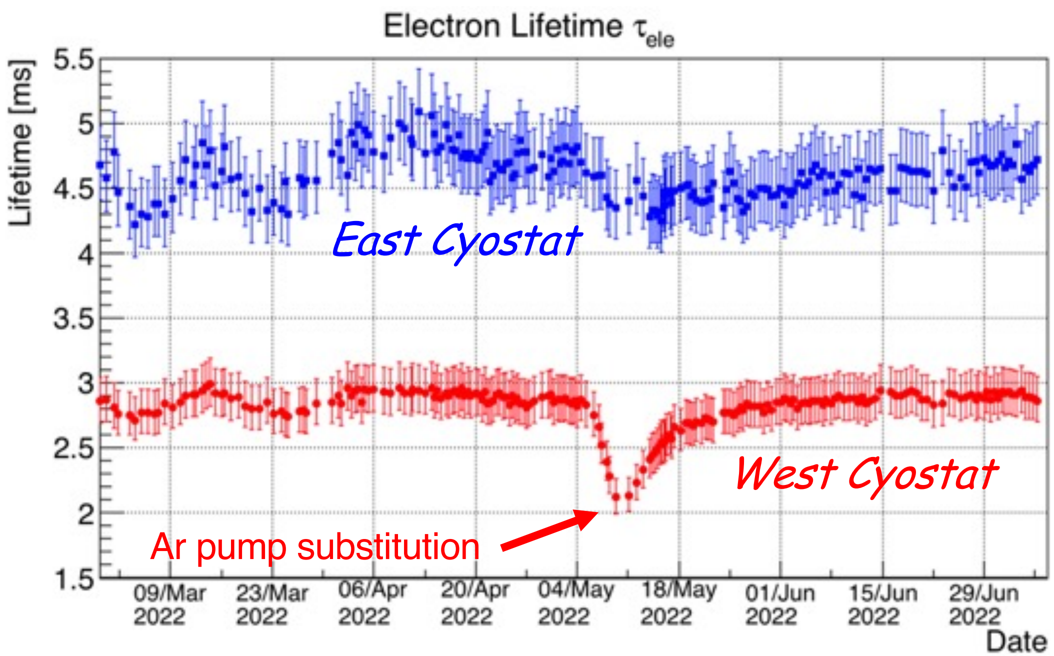
- 2 TPCs/module, common central cathode: E_{Drift}=500 V/cm,v_{Drift}~1.6 mm/μs;
- Ionization charge on 3 wire planes per TPC, ≈ 54000 wires at 0°, ±60° w.r.t. horizontal, 3 mm pitch (Induction-1, Induction-2 and Collection), is continuously read with a new electronics, 0.4 μs sampling time;
- 360 8" 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.

- The LAr purity is monitored by measuring the dE/dx signal attenuation along the drift direction for anode to cathode crossing cosmic μ tracks:
  - Free-electron lifetime: τ ~ 4.5 ms in East Cyostat, ~3 ms in West, allowing a good track detection, even if τ lower than at G. Sasso ICARUS operation.

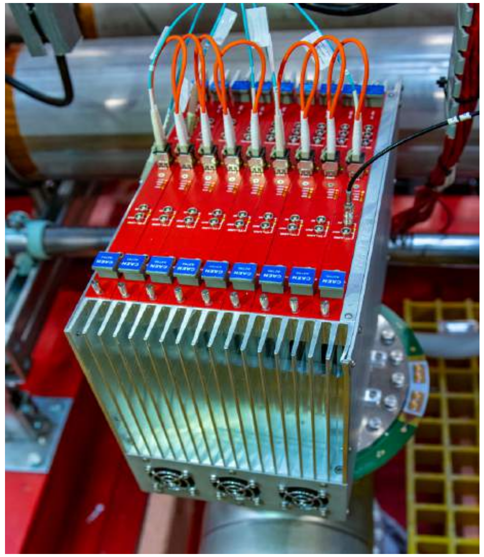




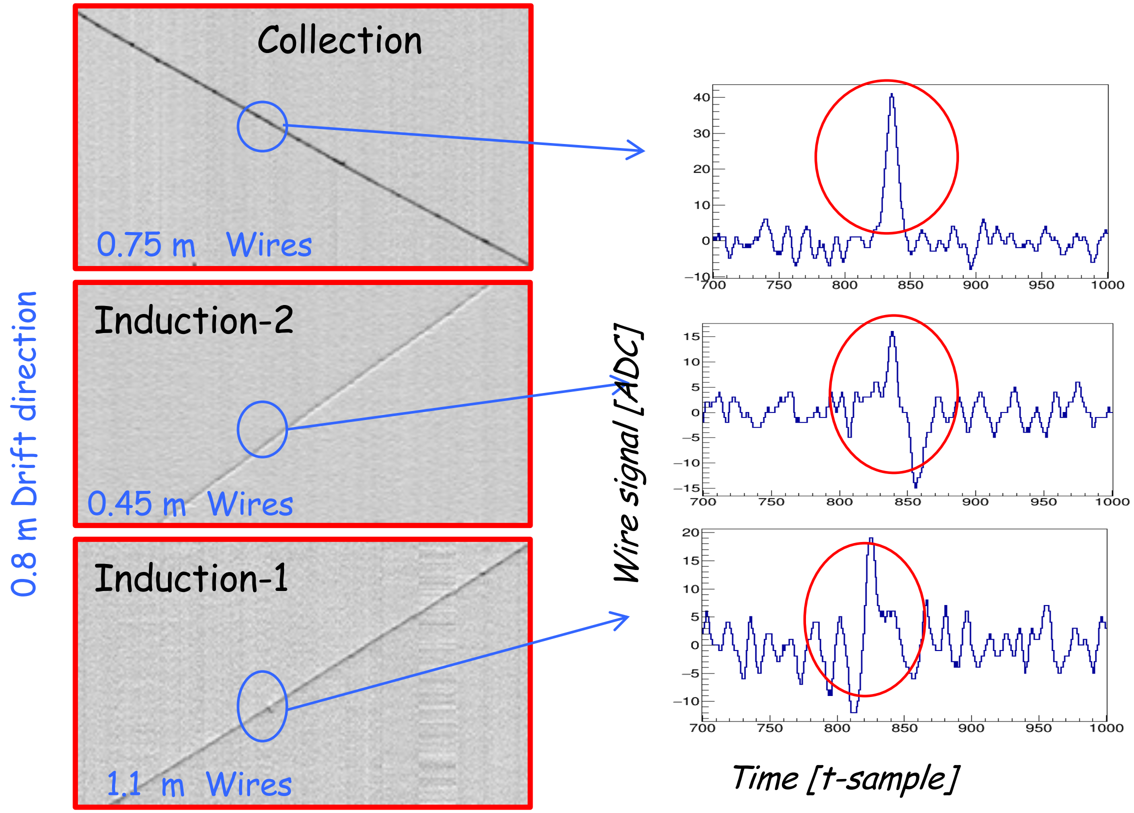
- *Planned regeneration of liquid filters in West module, possibly resulting in an improvement and equalization of the LAr purity*

Upgrade of TPC read-out electronics

- Front-end based on analogue low noise, charge sensitive pre-Amp;
- Shorter signal shaping time ~1.3 μs matching e- transit time between Induction-1, 2 and Collection wire planes (3 mm apart) 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.



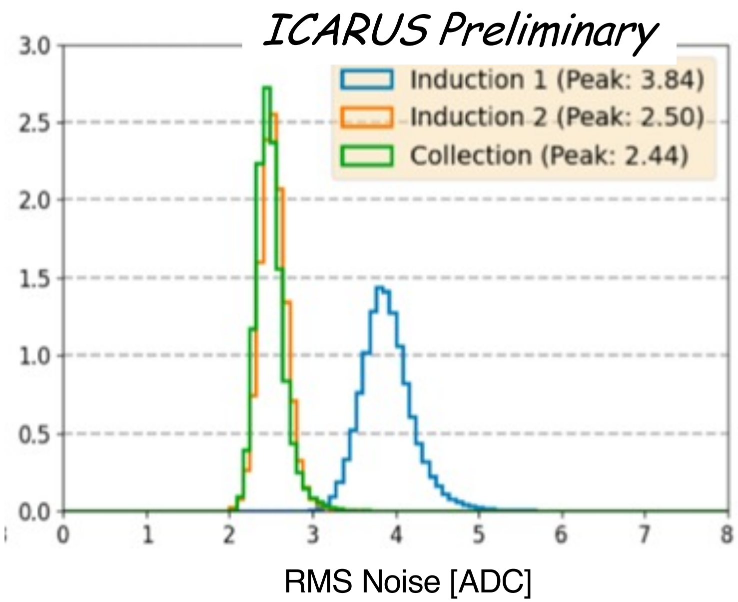
10 liter mini-crate on a feed-through hosting 9 boards (576 wires)



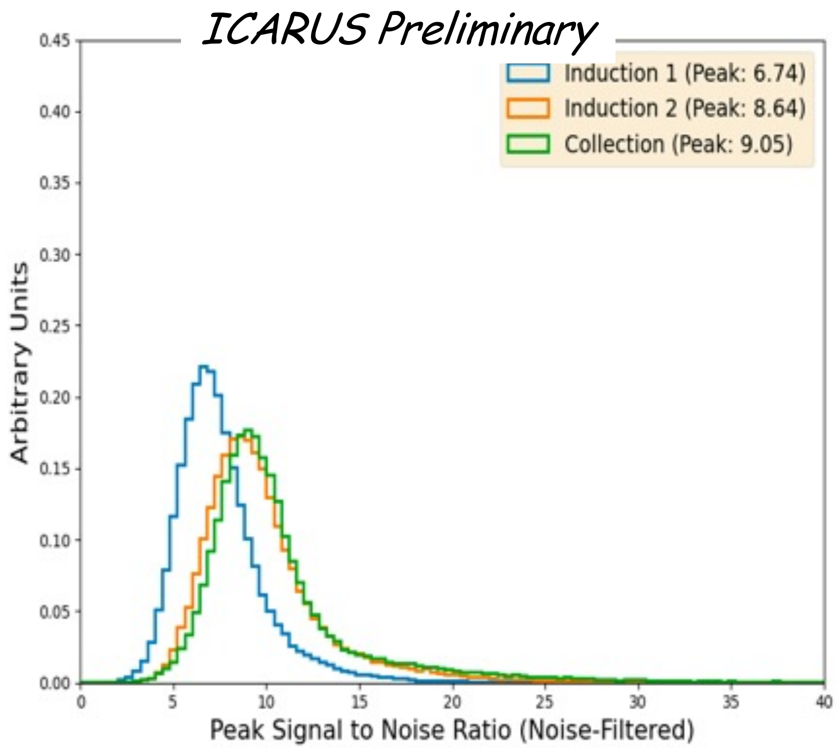
Recorded cosmic muon track:
the characteristic bipolar shape of e-signals traversing the wire plane is recognized in Induct.-1, 2 views.

Upgrade of the TPC read-out electronics

- Some anomalous coherent noise present in the TPCs upon activation mainly injected by ancillary cryogenic instrumentation has been addressed and mitigated:
  - 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.

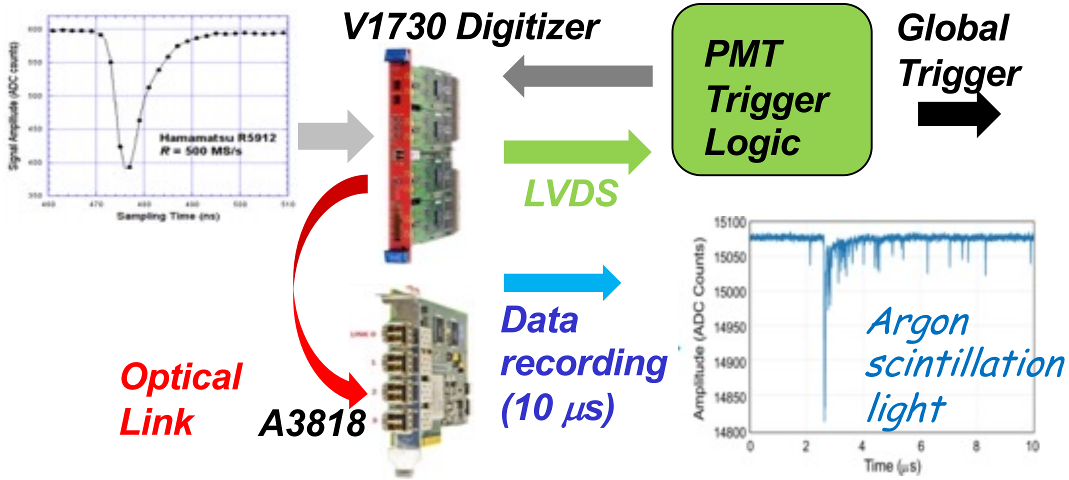


Studies are on-going to further mitigate the coherent noise.

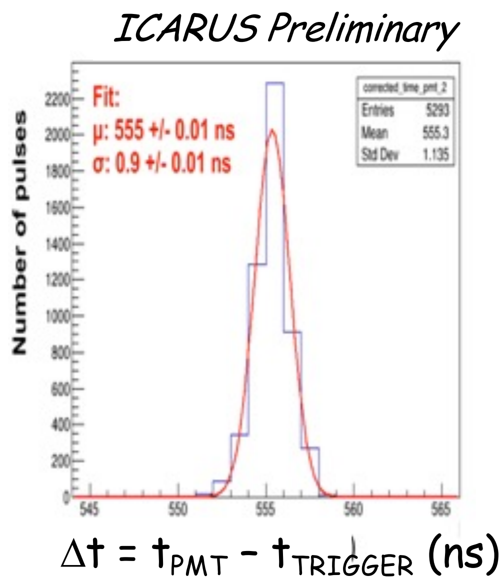


Upgrade of the light collection system

- 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.



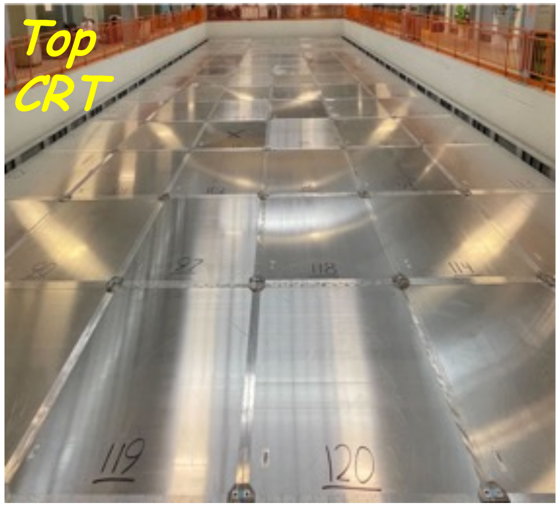
- PMT gain equalized at ~ 0.5 $10^7 \pm 1\%$ with λ ~ 405 nm laser and measuring the 4 mV PMT response to single phe backgr.
- ~3 kHz PMT counting rate at 50 mV ~13 phe threshold.
- PMT time response equalized by Laser to Trigger signal with 1 ns resolution allowing to perfectly determine the time of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



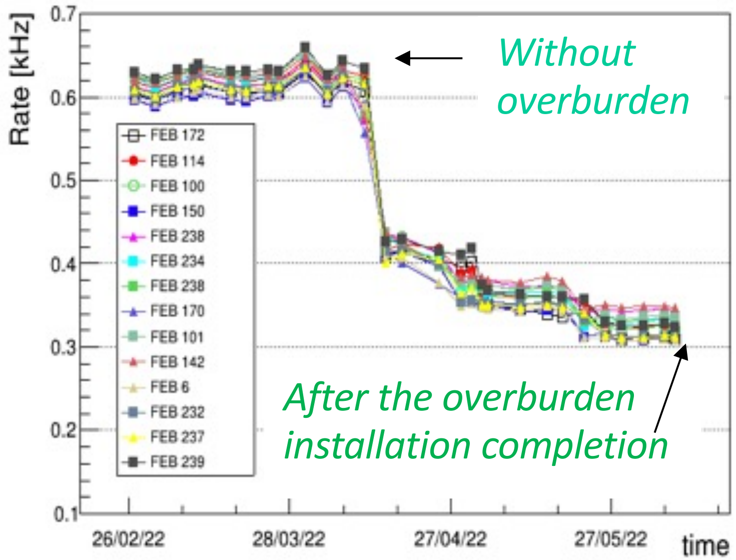
Cosmic-ray background mitigation in ICARUS

- ICARUS LAr-TPC is installed in a pit exposed to cosmic rays where electrons produced by γ's via Compton Scatt./Pair Prod. can mimic a genuine ν_e CC interaction:
  - Primary γ's and mostly of cosmic neutrons are suppressed by 2.85 m concrete overburden installed above ICARUS;
  - Residual cosmic rays entering ICARUS, ~ 11 μ in 1 ms TPC drift time, are identified in time/position by the 4π Cosmic Ray Tagger (CRT) detector surrounding the LAr-TPCs as matched to TPC and PMT systems.

CRT: a double layer scintillation bars (~1000 m²) with SiPMs, tagging incoming cosmics with ~95% efficiency



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

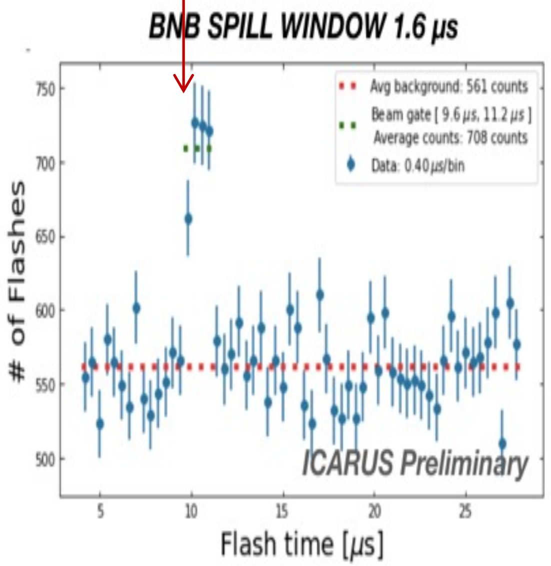


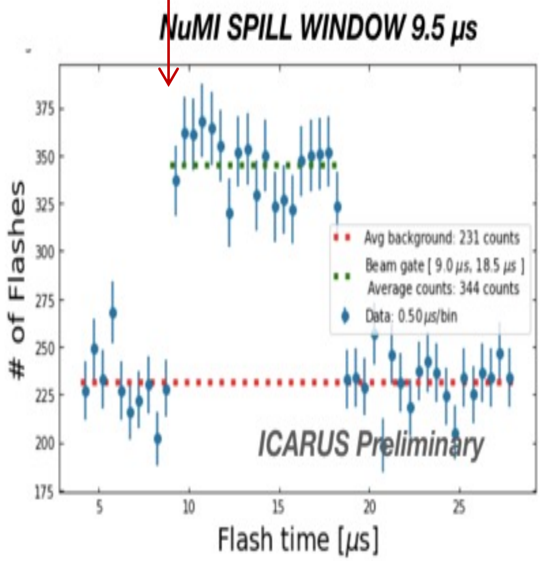
Trigger deployment

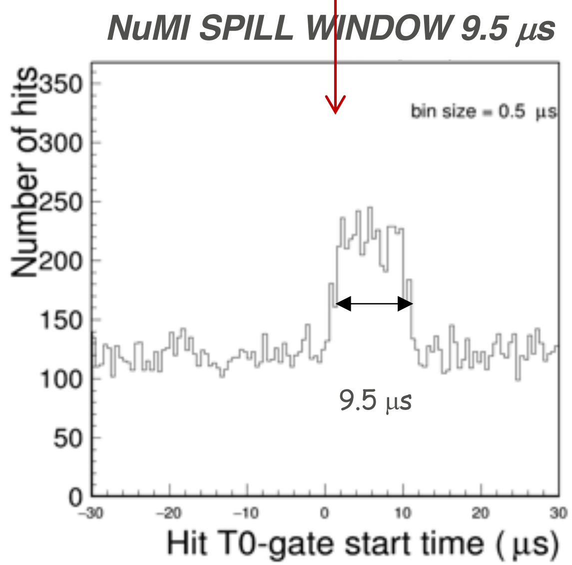
- The ICARUS trigger system relies on the light signals from PMTs in coincidence with the beam spills, 1.6 μs and 9.5 μs of BNB and NuMI:
  - All ICARUS subsystems are synchronized at ~ns level with beams radiofrequency by a White Rabbit Network distributing proton extraction signals;
  - Early warning signal of beam extraction is used to open spill gates at proper 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.

ν arrival time *ν arrival time* *ν arrival time*







Light signals excess in PMT system

Hit signals excess in Side CRT

Trigger commissioning status

- Data are collected using mainly two types of trigger:
  - *"PMT Majority":* coincidence of beam gate with al least Mj = 5 fired PMT pairs inside a 6 m longitudinal slice of a cryostat (30 left + 30 right PMTs), 13 phe PMT threshold;
  - *"Spill-only" or Min-Bias trigger*, collecting every beam spill without any PMTs signal requirement for control of the detector.

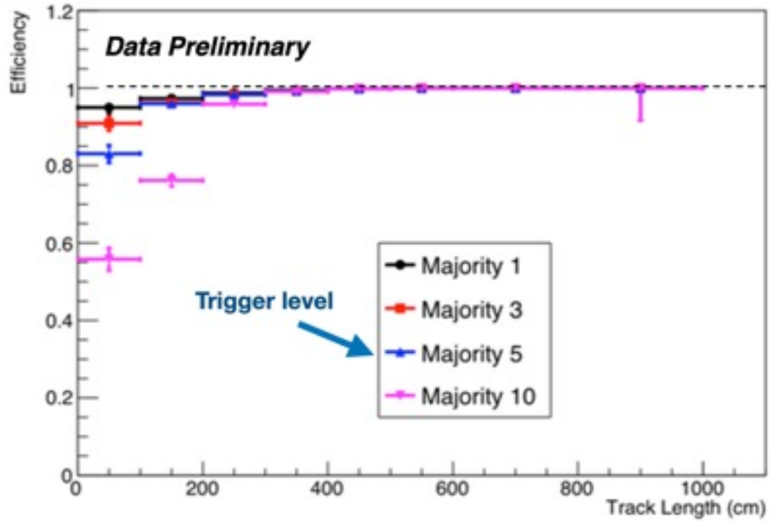
  PMT and CRT signals are recorded 2 ms around the trigger to recognize/tag cosmics crossing the LAr-TPCs during the 1 ms e- drift time.

- Out-of-spill cosmic events are also collected in parallel with the same trigger logics to evaluate the cosmic event background for neutrino oscillation searches.

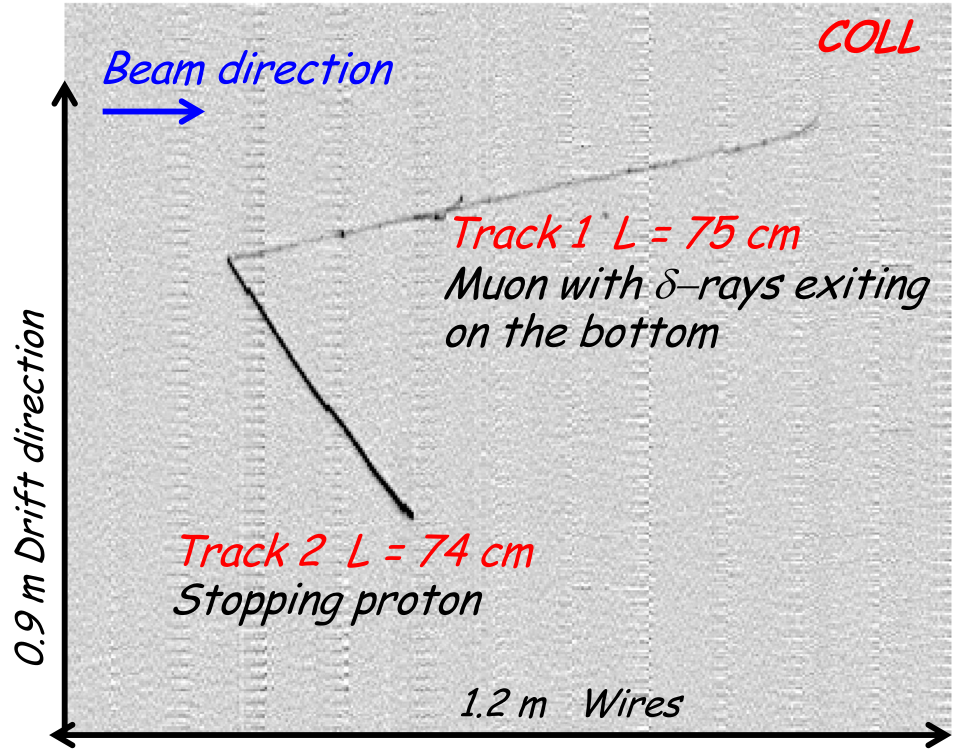
- At current Mj=5 setting MonteCarlo predicts >97% efficiency in detecting $\nu\mu$, νe CC, E_{DEP} >250 MeV.

- Trigger efficiency initially evaluated on cosmic μ:
  - Response of PMT Majority trigger determined by PMT light associated to the selected tracks;
  - A ~ 97 % efficiency has been determined for muon track with L > 130 cm, i.e. E_{DEP} > 250 MeV.

Trigger efficiency measured on crossing cosmic μ

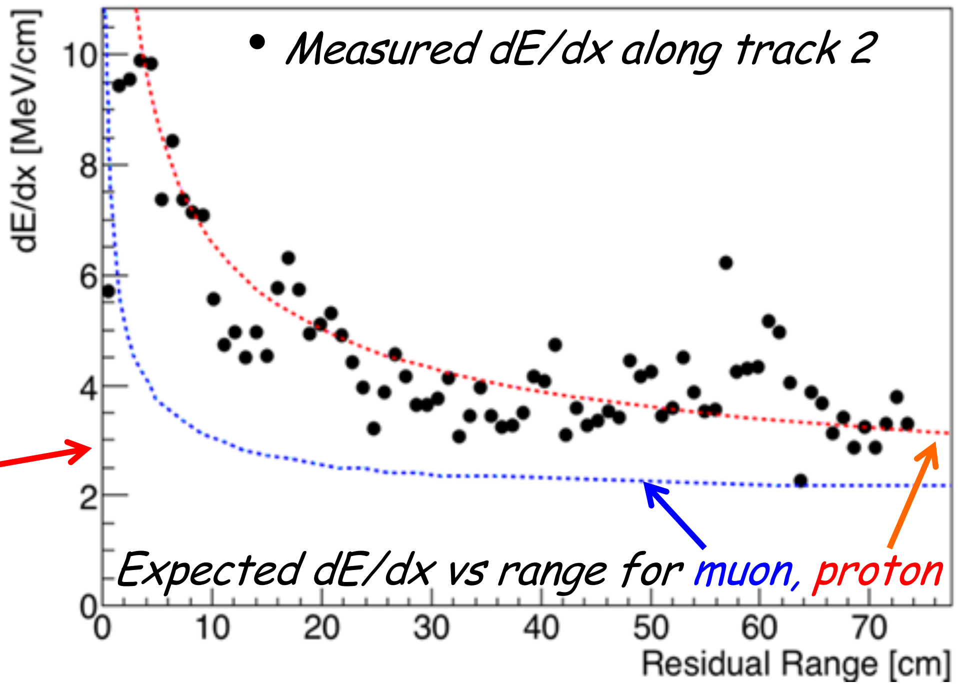


First collected neutrino events: a BNB QE ν_μ CC candidate

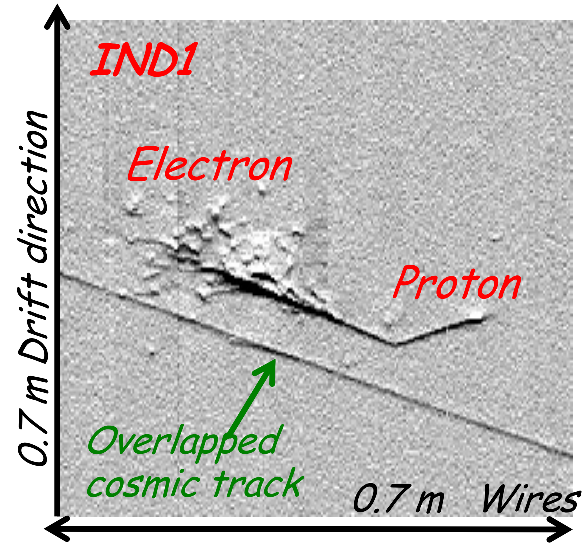


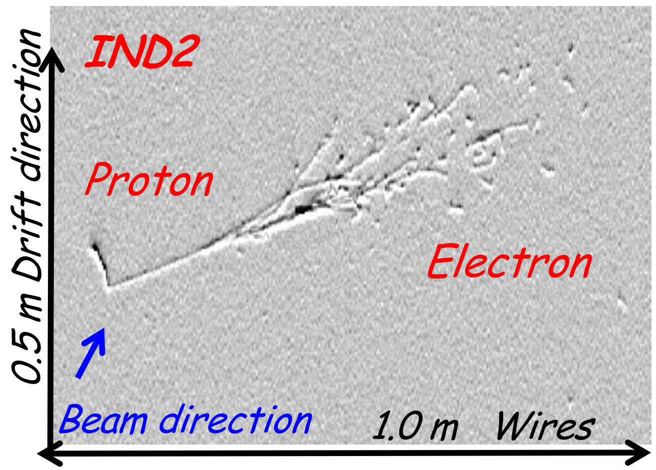
- Neutrino interaction vertex well inside the active LAr volume. Two tracks are produced:
  - ✓ Track 1: downward going μ candidate, exiting on bottom (confirmed by δ rays)
  - ✓ Track 2: upward going stopping proton,.

- From the study of dE/dx vs range, track 2 is compatible with a proton: E_{DEP}~ 340 MeV, E_K=370 MeV (if evaluated from range).

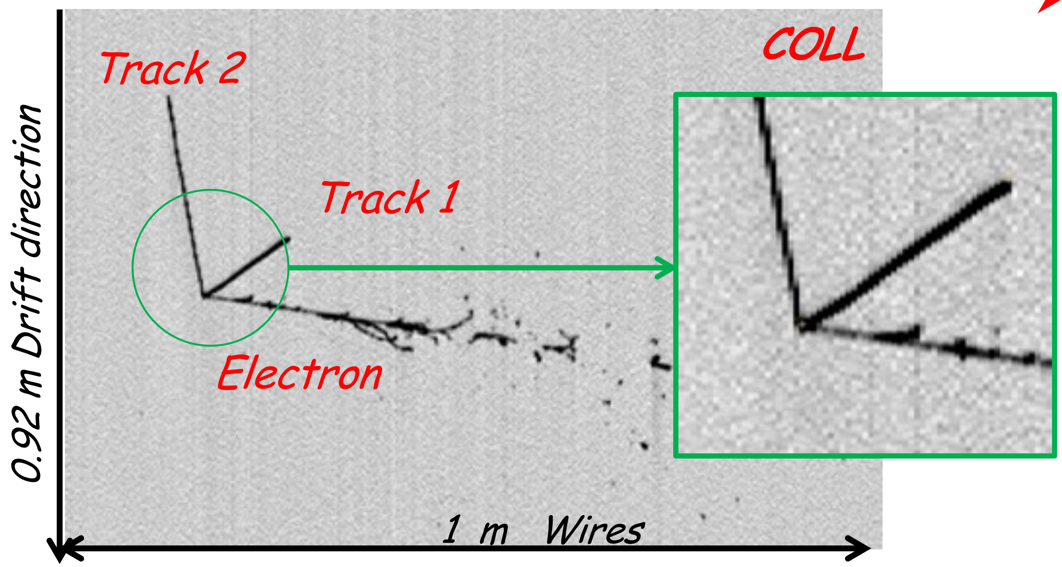


NuMI νe CC candidates





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



- νe CC event candidate fully contained in active LAr, E_{dep}~830 MeV:
  - ✓ The electron shower, E_{DEP}~570 MeV is downward going;
  - ✓ Track 1: upward going, stopping proton candidate, L = 23.7 cm;
    Track 2: stopping hadron, L = 33.4 cm.

ICARUS Installation, Commissioning and Data taking

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

Dec. 2021: completion of CRT installation

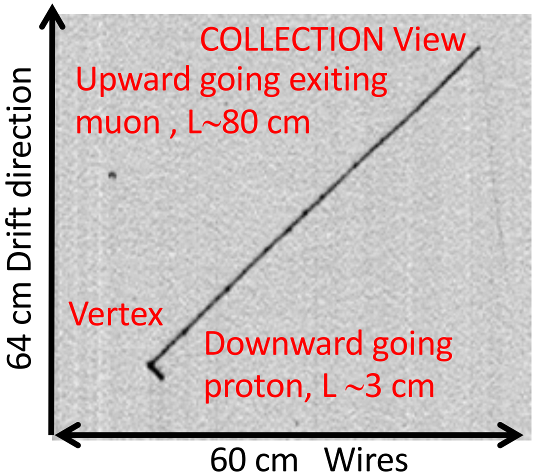
June 7th 2022: completion of overburden installation

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

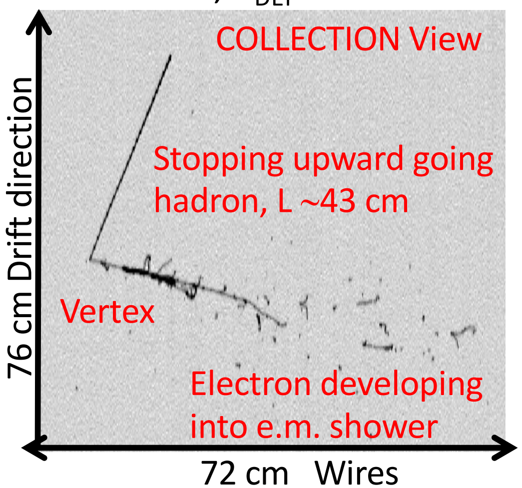
Cosmics, ν_μ, and ν_e samples collected for trigger/calibration/event reconstruction studies.

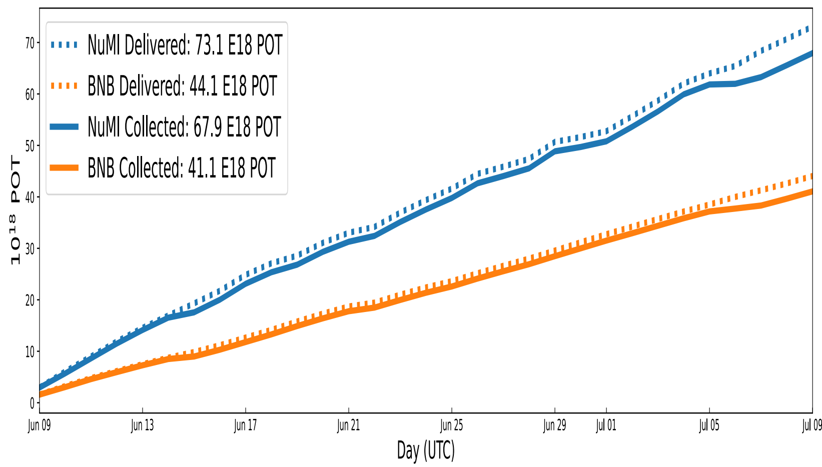
Started data taking for physics with BNB, NuMI: June 9th 2022

BNB CC QE $\nu\mu$ candidate, E_{DEP}~ 200 MeV



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

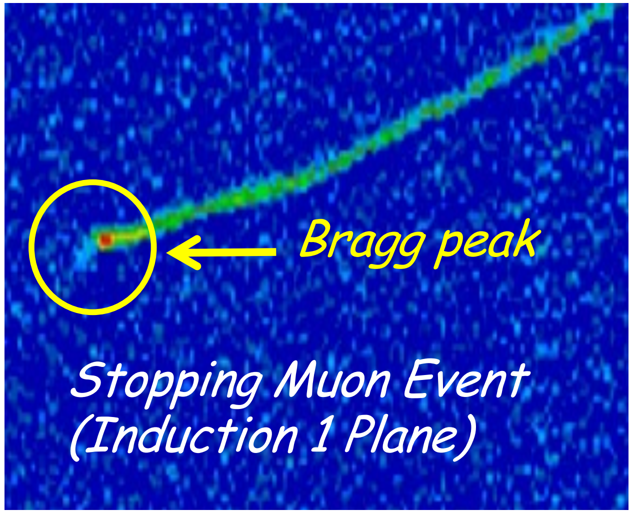


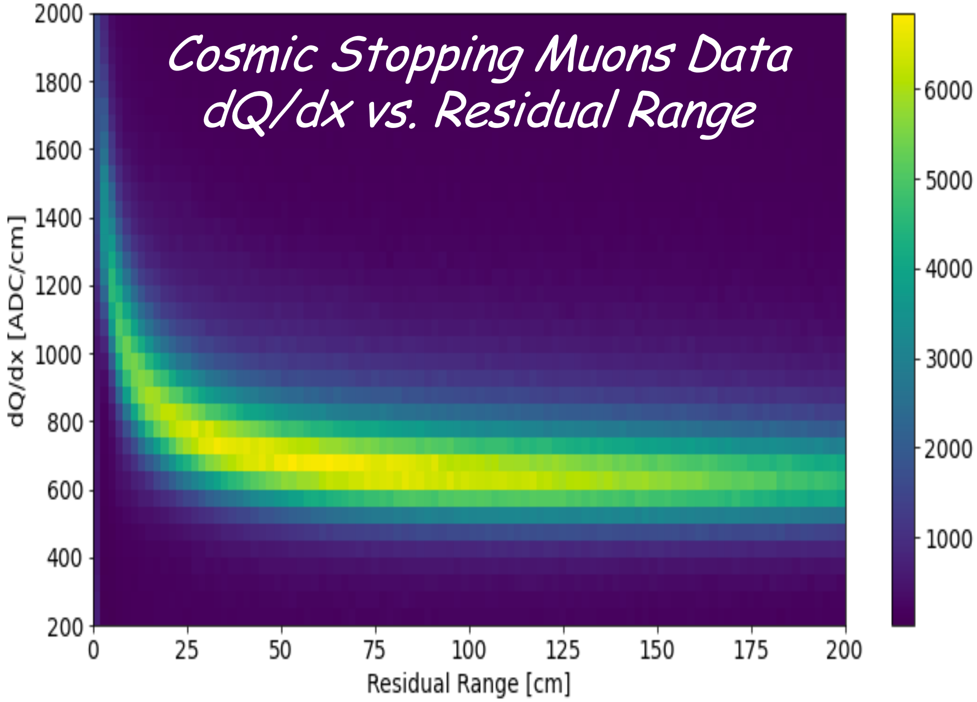


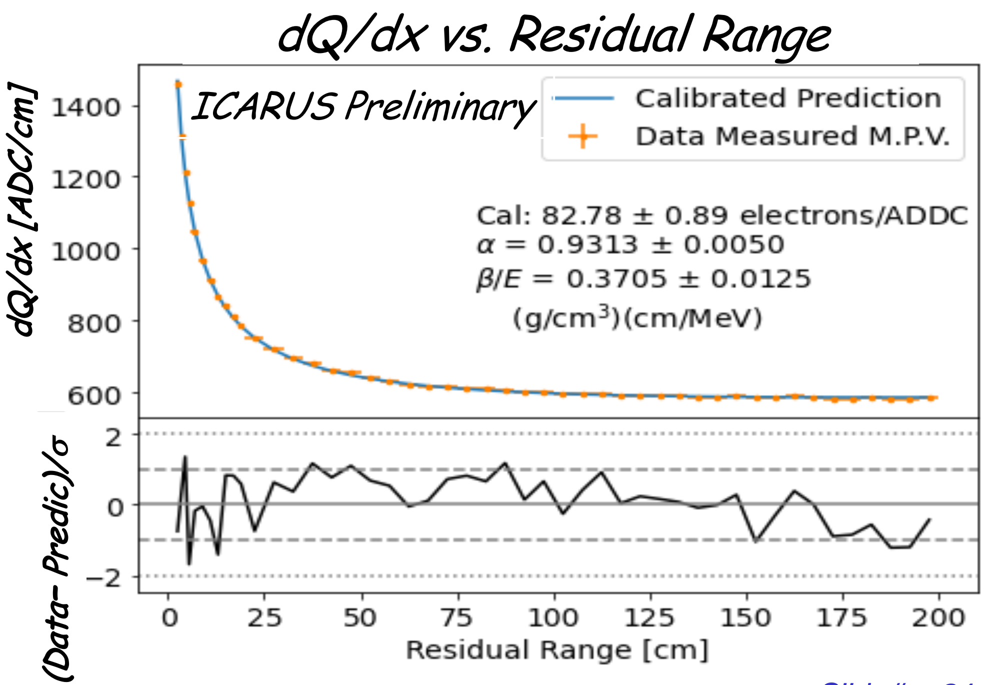
Collected event statistics (93% efficiency): 4.1×10^{19} pot (BNB), 6.7×10^{19} pot (NuMI)

On-going TPC wire signal reconstruction/calibration

- TPC Calibration procedure is based on the measurement of dE/dx ionization density versus residual range of cosmic μs stopping/decaying in active LAr:
  - ✓ Calibrate the absolute energy scale;
  - ✓ Equalize the individual wire electronic response;
  - ✓ Improve the modeling of e- recombination/diffusion, and space charge effects;
  - ✓ Measure e-drift velocity and detail the wire response.

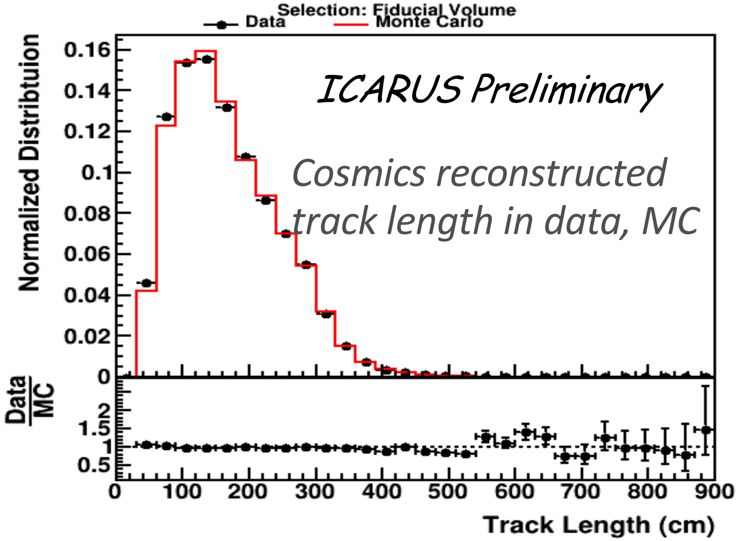






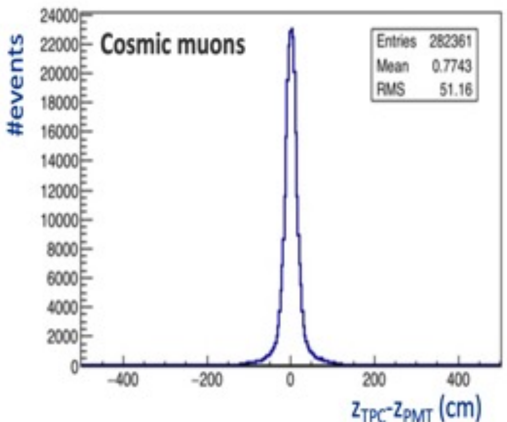
On-going event reconstruction

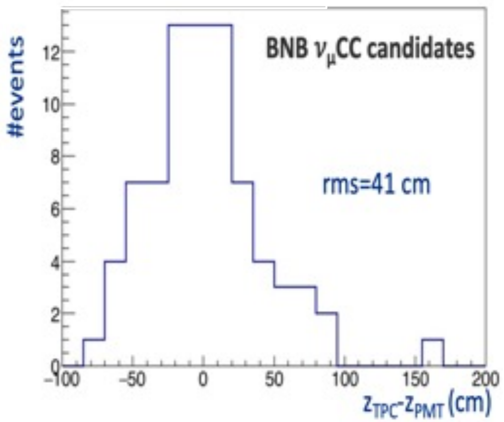
- TPC event reconstruction uses Pandora pattern-recognition software within LArSoft framework:
  - ➢ Reconstruct particle trajectories in 3D starting from the hits in the TPC wire planes;
  - ➢ Reconstruct interaction vertices and particle production chain;
  - ➢ Classify particles as track-like or shower-like and perform P.Id by dE/dx and range measurements.

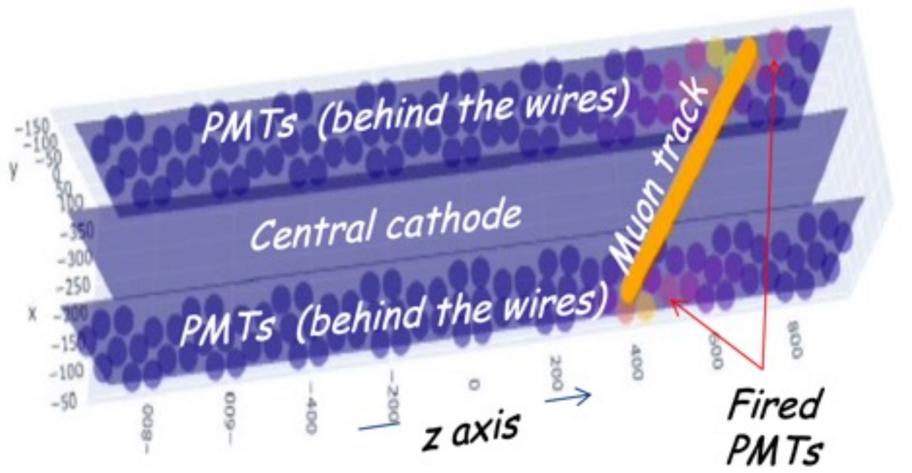


- Comparing track and light signal barycenter along the detector longitudinal axis allows to recognize/disentangle $\nu\mu$ CC with $L\mu$ > 50 cm from crossing cosmic μ within Δz~1m.

ICARUS Preliminary







Neutrino events found from visual scanning of collected data are used to investigate/test automated software tools and compare MC/data performance.

Conclusions

- Despite the present pandemic, 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 installation/commissioning progressed.
- Data collected so far have been instrumental for calibrating the detector, tuning simulation and event reconstructions tools.
- Installation and commissioning has been completed: full time neutrino beam run started on June 9th 2022 exploiting regularly both the Booster and NuMI beams
- Early phase of ICARUS data taking is started, primarily dedicated to the study of Neutrino-4 claims looking for the $\nu\mu$ *disappearance* in the Booster beam and νe *disappearance* in the NUMI off-axis beam.
- After the first year ICARUS-only operations, SBND LAr-TPC detector will be operative at shorter distance from Booster to perform with ICARUS a definitive 5 σ analysis of sterile neutrinos.

The INTENSE EU Madame CURIE program has played and is still 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!