Short-baseline neutrino oscillation searches with the ICARUS detector

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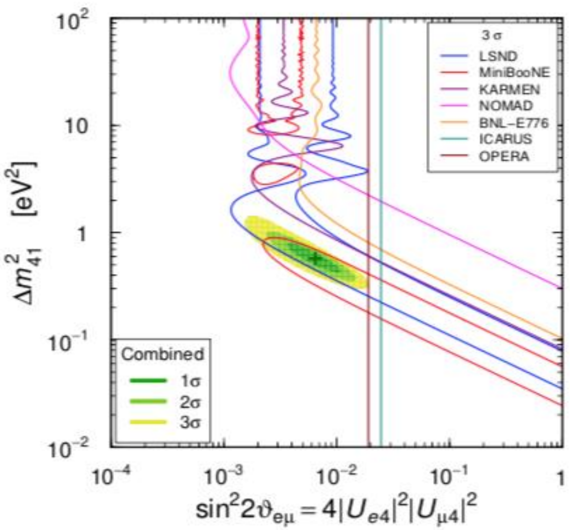
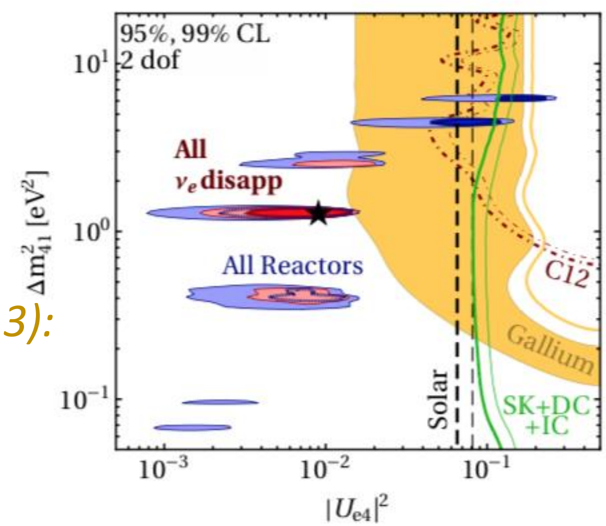
The sterile neutrino puzzle

- While most results in neutrino physics are consistent with the standard 3-neutrino oscillation scenario, some “anomalies” over the last 20 years seem to suggest an **additional sterile state**, with mass in the 1-10 eV range and small mixing angle with standard neutrinos:
  - Appearance of (anti-)ν_e in (anti-)ν_μ beams at accelerators (LSND, MiniBooNE).
  - Disappearance of anti- ν_e at reactors.
  - Disappearance of ν_e from calibration sources for solar experiments.
- However, no model appears able to accommodate all experimental results at once.
- Clear tension between appearance and disappearance results.
- A recent result from Neutrino-4 (*Phys. Atom. Nuclei* **83,** 930–936 (2020)) points to **reactor anti-ν_e disappearance** with large Δm^2 (~ 7 eV^2) and mixing angle ($\sin^2 2\theta$~0.26).

(anti-)νμ appearance (from arXiv:2106.05913):

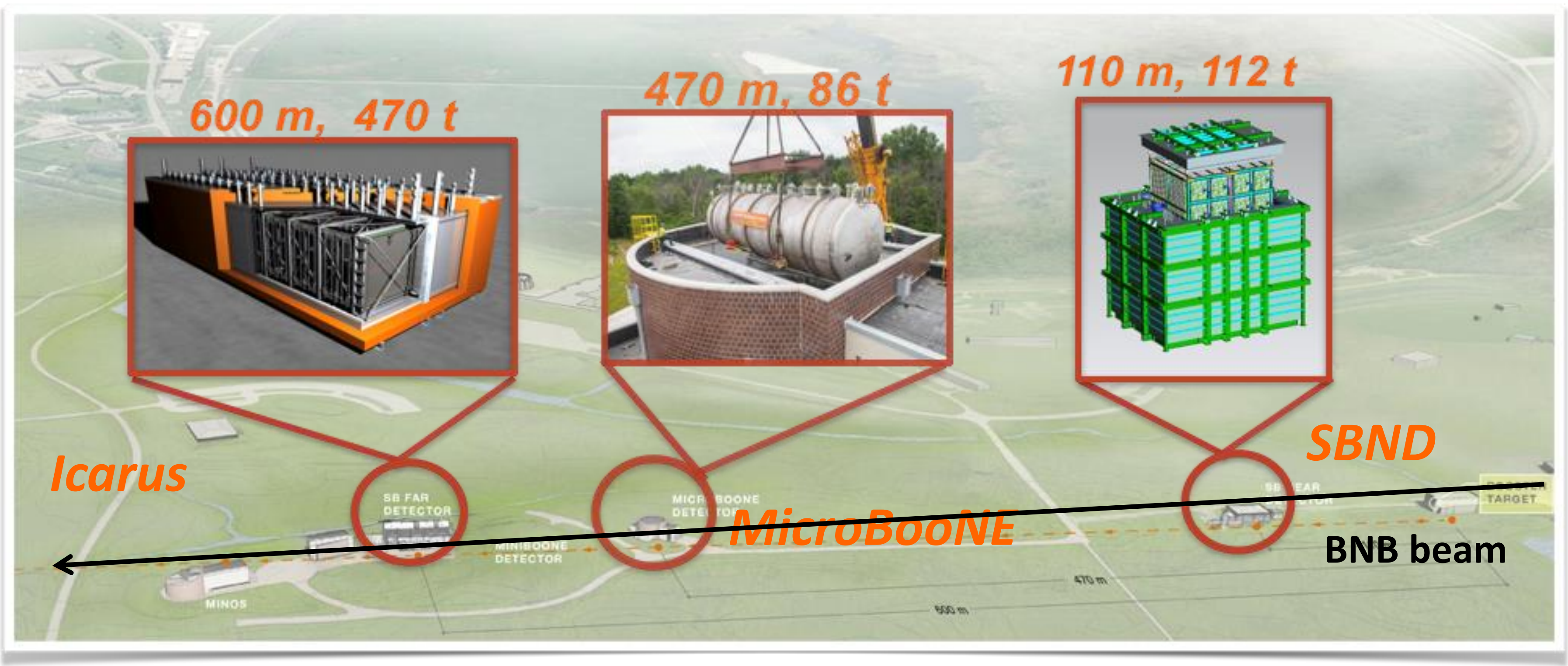


(anti-)νe disappearance (from arXiv:2106.05913):



The *Short Baseline Neutrino* project at FNAL

- SBN will verify the sterile neutrino hypothesis both in the appearance and disappearance channels, exploiting:
  - **Well-characterized beams** at FNAL (**BNB** and **NuMI**).
  - Detectors based on the LAr-TPC technology, ideal for ν_e identification and background rejection.
  - Very **similar near and far detectors**, allowing cancellation of systematics related to beam and cross-sections.

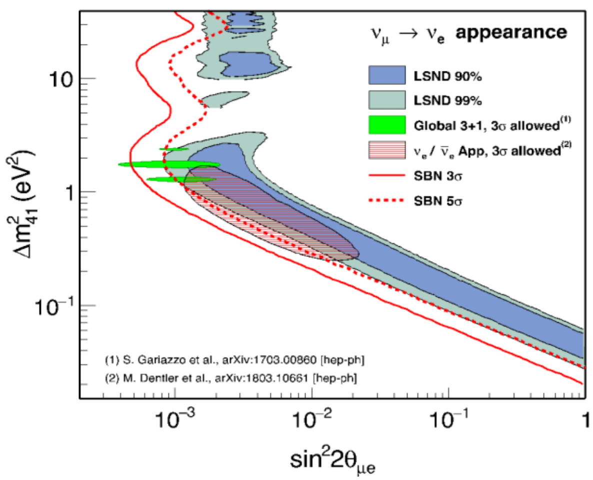


SBN physics program

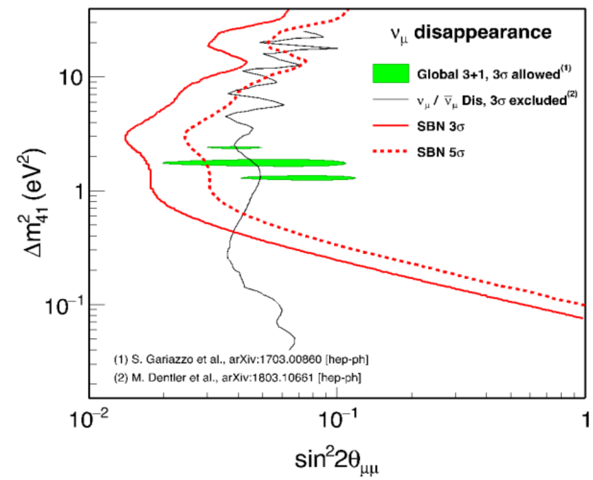
- The main physics motivation of SBN is a conclusive verification of the sterile neutrino hypothesis:
  - The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with **5σ sensitivity** both in **appearance** and **disappearance** channels, in 3 years of data-taking (6.6 10^{20} pot).
  - ICARUS alone (before SBND starts taking data at the end of 2022) can **confirm or refute the Neutrino-4 oscillation signa**l in less than one year.

SBN appearance sensitivity:

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



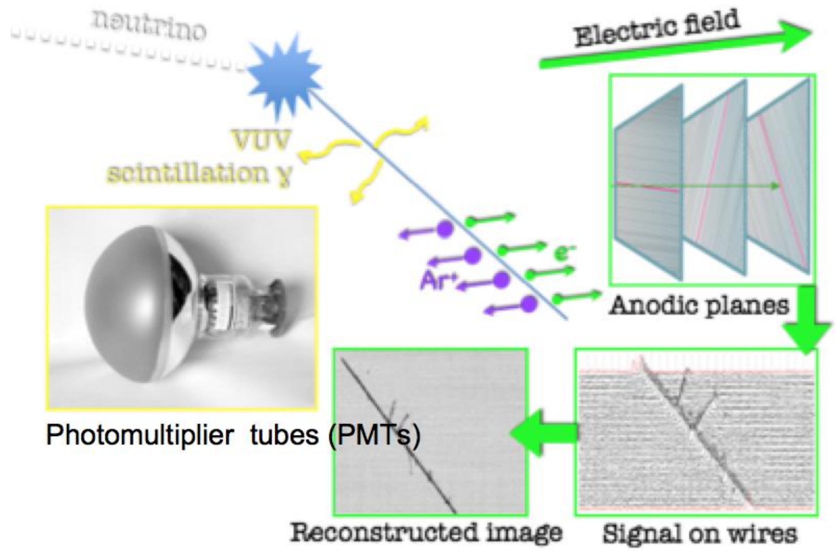
SBN disappearance sensitivity:

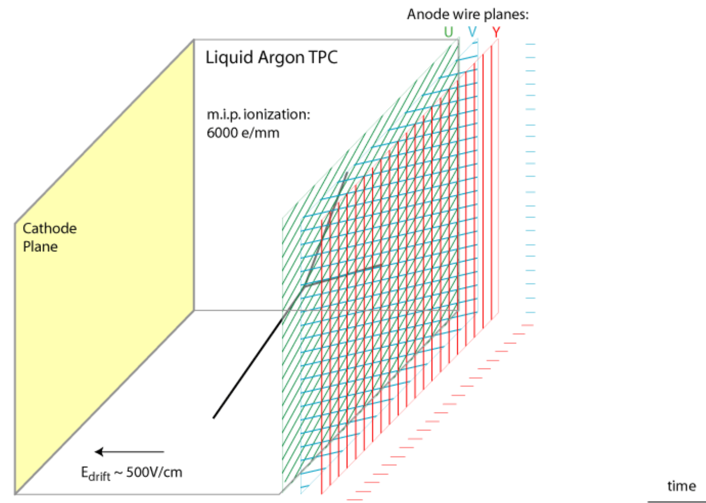


- Moreover, SBN could perform high-statistics measurements of **neutrino-argon cross-sections** which will be important for DUNE:
  - Millions/year events in SBND at low energy (<1 GeV) from BNB beam.
  - Hundred thousands/year events in ICARUS at higher energy (>1 GeV) from NUMI.

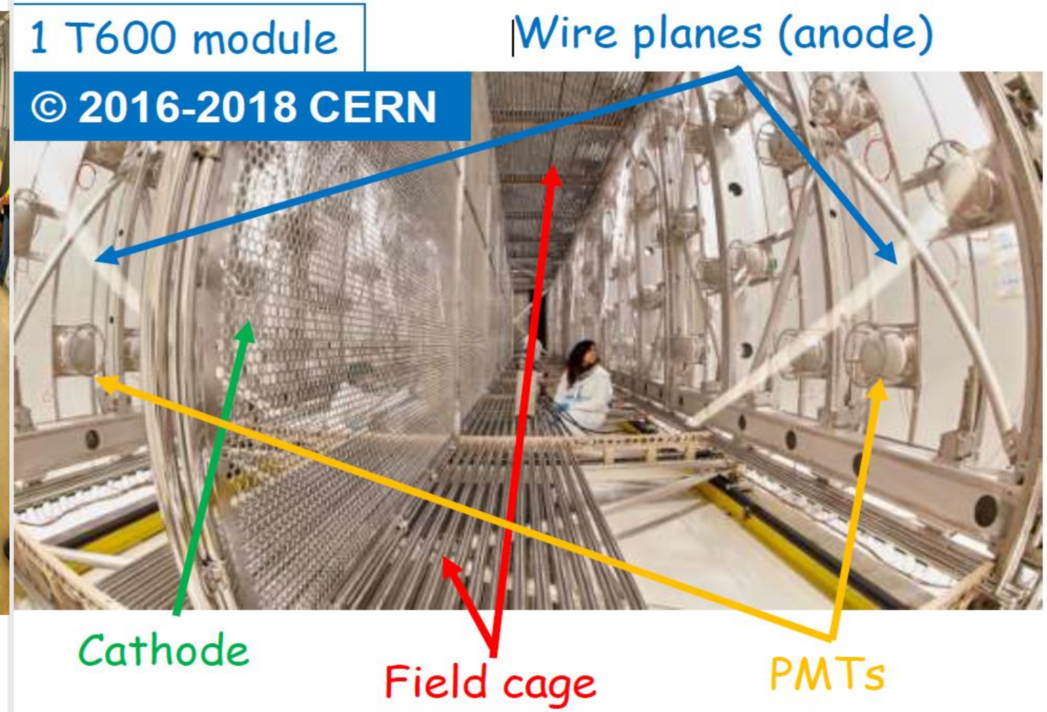
Liquid Argon TPC technology

- Ideal technique for neutrino and rare event physics, first proposed by C. Rubbia in 1977 and pioneered by the ICARUS collaboration.
- Based on **LAr ionization** by charged particles (~5000 e^{-}/mm MIP).
- Ionization electrons are drifted towards an anode made of **several wire planes** (drift time ~ ms).
- **Homogeneous target** that combines large mass with **accurate spatial** and **calorimetric reconstruction**.
- Stereoscopic read-out from multiple wire planes allows **3D reconstruction** with resolution of a few millimeters.
- **Scintillation light** in LAr (~40000 g/mm MIP) provides fast signals (ns-μs), useful for timing and triggering.





The ICARUS-T600 detector



- ICARUS-T600 is the first large LAr TPC detector. Its operation at the underground LNGS laboratory (2010-13) confirmed the maturity of this technique.
- Two identical modules (T300) each 19.6 x 3.6 x 3.9 m^3 . Total **LAr mass 760 t**; **active 476 t**.
- **Drift distance 1.5 m**. Electric field **500 V/cm** (75 kV) -> drift time ~**1 ms**.
- **3 signal wire planes** (2 induction + 1 collection).
- Pitch and inter-plane distances: 3 mm; 400 ns sampling time; ~54,000 channels.
- **8" PMT's**, coated with TPB wls.

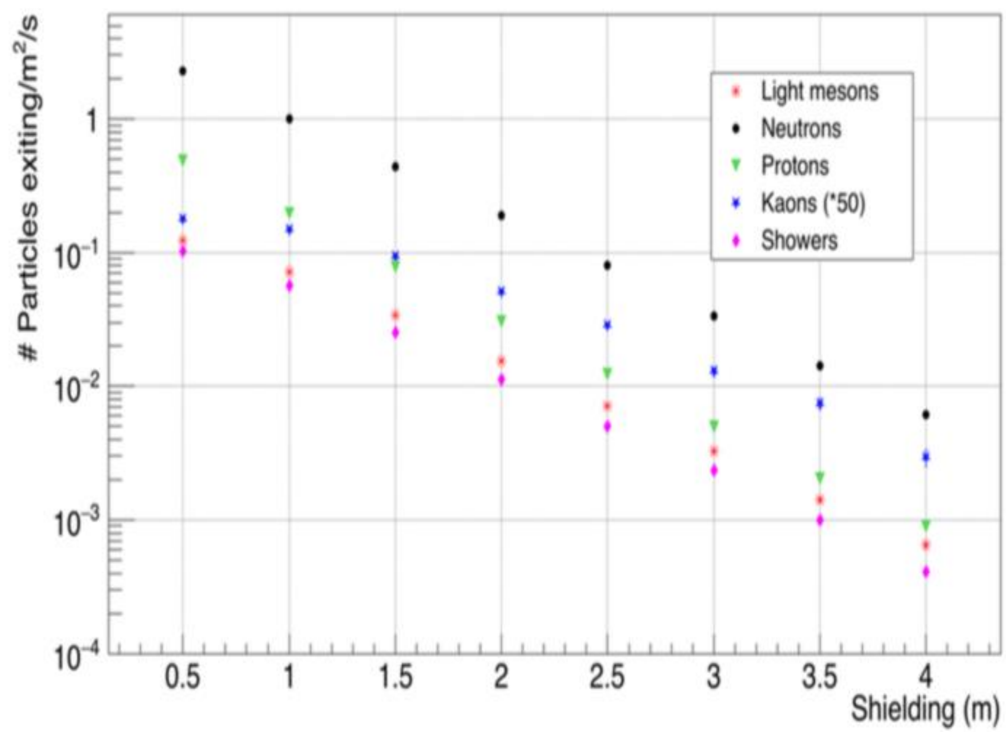
ICARUS Timeline

- 2014: transportation from LNGS to CERN.
- 2015-2017: extensive refurbishing at CERN.
- Summer 2017: Transportation from CERN to FNAL via truck and ship.
- August 2018: TPC installed within warm vessel.
- February 2019: installation of TPC and PMT electronics completed.
- February-April 2020: filling with liquid argon.
- From April 2020 : commissioning phase.
- June 2021 : Run 0.

Cosmic-ray background mitigation

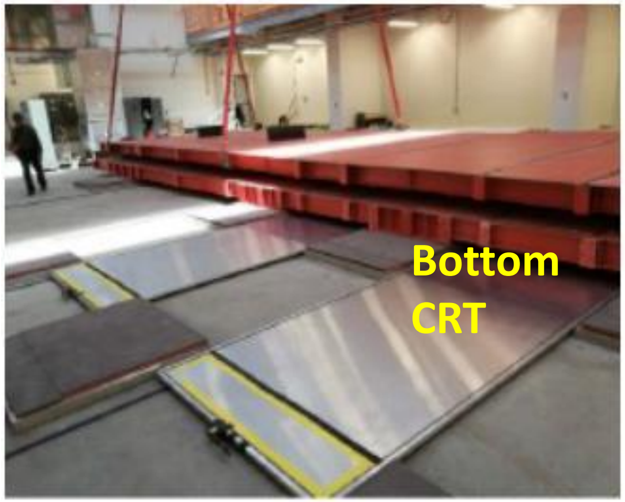
- ICARUS at FNAL is taking data on the Earth surface, in more challenging conditions than at LNGS (where cosmic rays are suppressed by a factor ~10^6).
- Cosmic rays can produce Compton electrons or asymmetric e^+e^- pairs, that can mimic ν_e interactions and produce a significant background to ν_e appearance searches.
- In order to mitigate this problem, an **overburden layer of concrete** (~2.85 m thickness) will be placed above the detector .
- Possible backgrounds are produced by either neutral primaries (n,γ) or muons.
- The overburden will effectively remove all primary photons and reduce neutrons by a factor ~200.
- Primary muons and associated showers will be reduced by ~25%.
- As a consequence, the total number of cosmic-induced backgrounds will be effectively decreased by the overburden.

Particles in LAr from primary hadrons as a function of overburden thickness



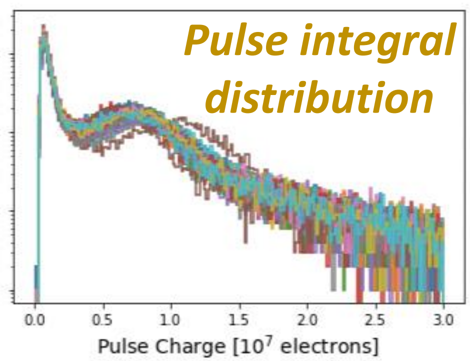
Cosmic Ray Tagger (CRT)

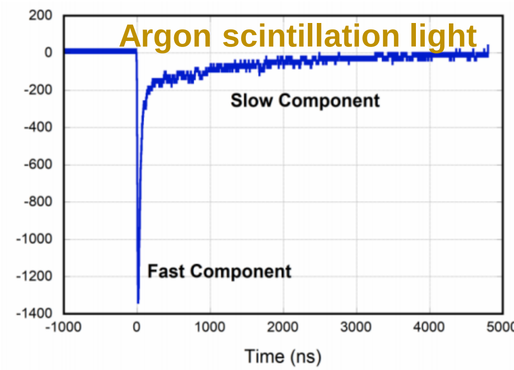
- With the presence of the overburden, primary cosmic muons will be the dominant component of cosmic rays producing background in ICARUS: ~**11 muon tracks** will hit the TPC active volume in the ~1ms drift window.
- To tag charged cosmic rays and determine unambiguously the position and timing of each ionizing events, ICARUS will use:
  - A much improved **light detection system**.
  - A **cosmic ray tagger** (CRT) surrounding the T600 with a double layer of scintillator bars (~1000 m^2) equipped with optical fibers driving light to SiPM for readout.
- CRT is expected to tag **incoming cosmic** and **beam-induced tracks** with ~95% efficiency.
- Its time and position coordinates can be matched to PMT and TPC information.
- Besides muons, CRT will effectively tag charged cosmic hadrons.
- Bottom and side CRT planes are installed and commissioned; installation of top CRT is ongoing.

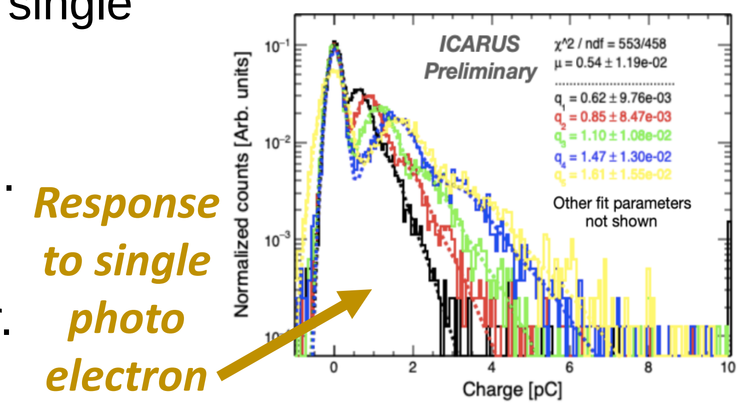


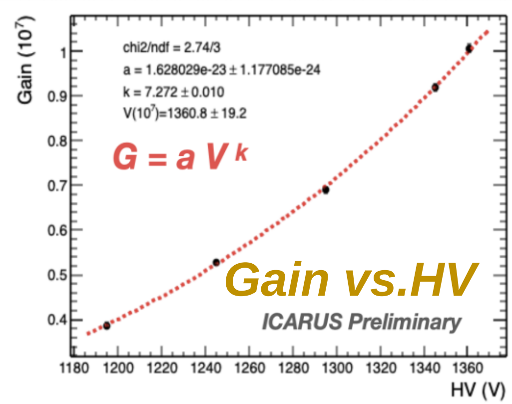
Light detection system

- **Requirements** for light detection system:
  - Generate trigger signals for TPC.
  - Tag the time of occurrence (t_0) of any ionizing event with ~ns resolution.
  - Sensitivity down to ~100 MeV.
  - Localize events with resolution ~50 cm.
  - Determine rough event topology.
- 360 8" PMTs (90 per TPC) -> **5% coverage**.
- PMTs coated with **wavelength-shifter** (TetraPhenylButadiene, 250 mg/cm^2).
- **Transit time resolution ~ns**, dark rate <5kHz QE ~12%.
- **Stable gain** (10^7@87K) to detect single photoelectron.
- All PMTs activated after LAr filling.
- PMT gain calibration in cryogenic environment performed with laser.



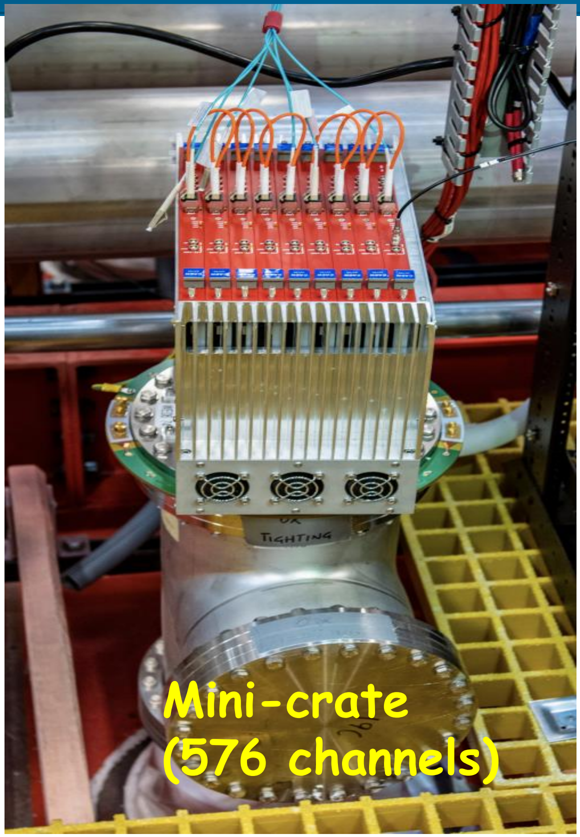




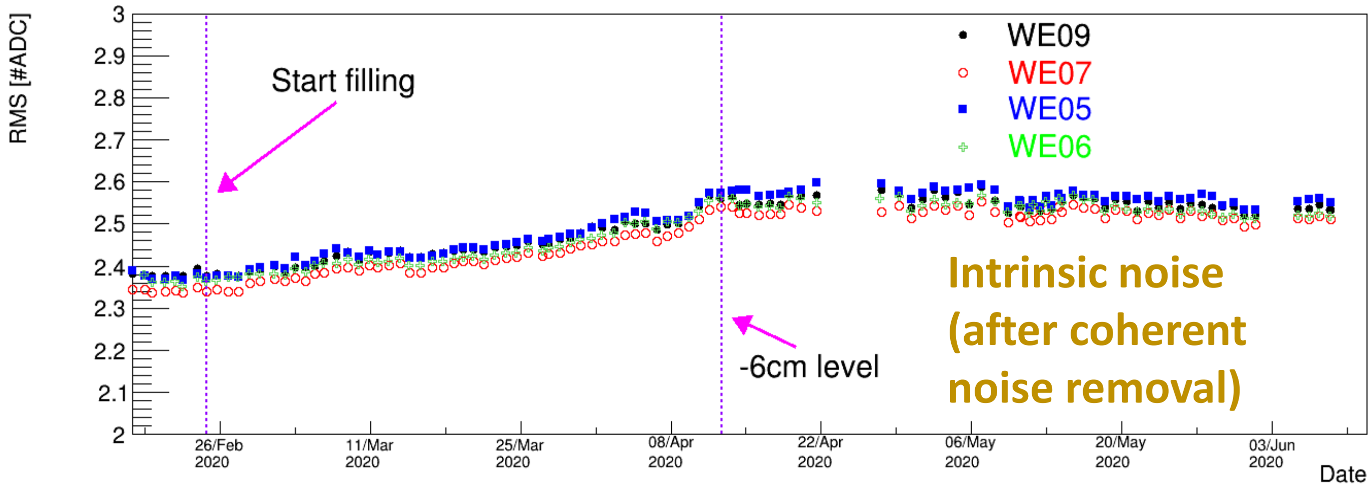


New ICARUS TPC read-out electronics

- New "**warm**" ICARUS electronics developed for SBN:
  - Serial **12-bit ADC**, fully synchronous over the whole detector.
  - More **compact layout**: analog+digital electronics on a single board, mounted directly on the flange.
  - Short ~**1.3 ms shaping time** for all planes allows better reconstruction of dense vertex regions.
  - Full electronic chain tested with cosmic rays at CERN.
- TPC electronics are fully installed and commissioned.
- Steady increase of the noise level measured during LAr filling, agreement with the expected variation of the wire capacitance due to increase of the level of the liquid argon inside the detector.

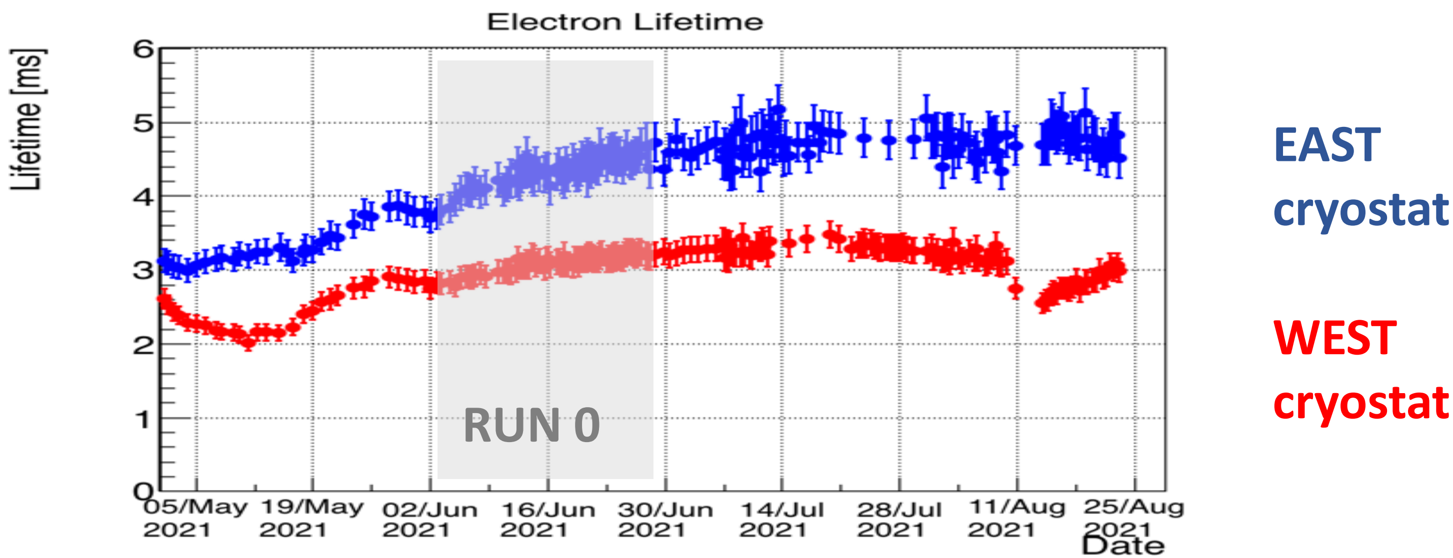


- Interventions to reduce noise level are planned during the shutdown.



Cryogenics and electron lifetime

- Cryogenic system is steady and well performing after filling in spring 2020.
- Electron lifetime is monitored by measuring signal attenuation in cathode-anode crossing cosmic muon tracks.
- Electron lifetime reaches up to ~**4.5 ms** in the West Cryostat and ~**3 ms** in East, allowing efficient signal detection over the full LAr volume.

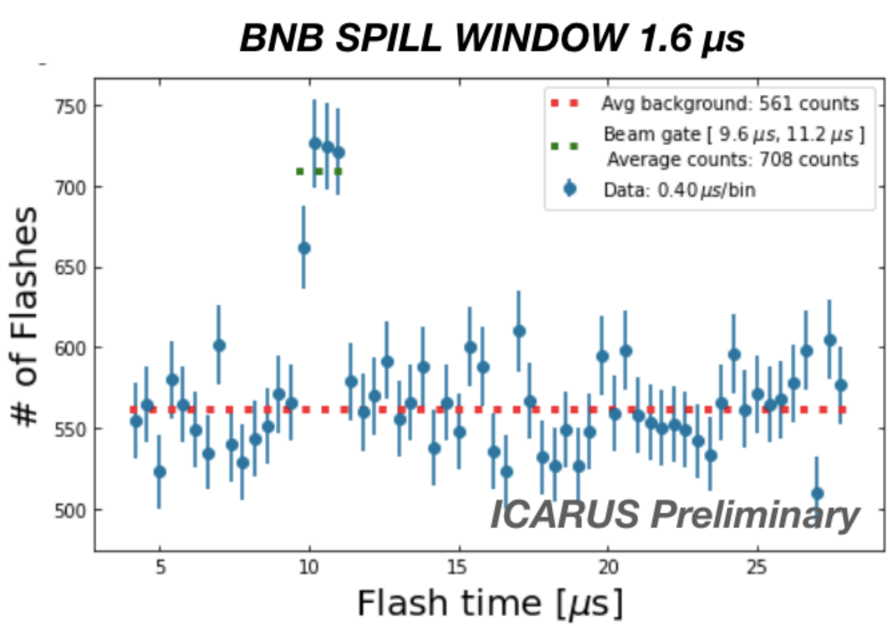


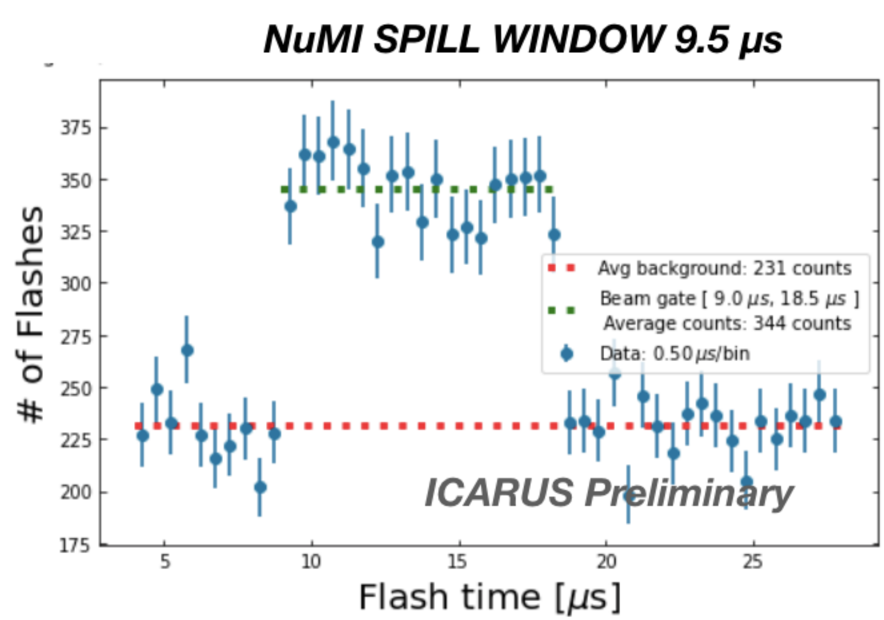
- Lifetime improved in recent months due to improvements on under-performing GAr recirculation units and periodic venting (3 times per day).
- New higher-capacity GAr filters (copper-based with molecular sieves for water adsorption) are under preparation at CERN.
- Their installation is expected to further improve GAr recirculation rate and electron lifetime.

Commissioning of the trigger system

- Commissioning/development of the trigger system performed in **two steps**:
  - Generate "**spill-only**", based on the BNB (NuMI) extraction signal distributed via White Rabbit network.
  - **Scintillation light info** by requesting majority of PMT pairs in each wall of the cryostat inside a BNB (or NuMI) beam gate.
- Time of PMT light flashes (10 fired PMTs within 150 ns window in coincidence in both left and right TPCs) in PMT readout window shows excess over the cosmic background rate at the expected neutrino arrival time.

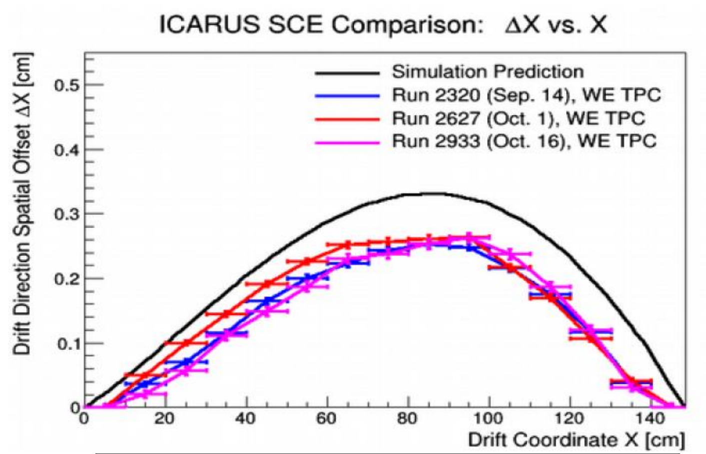
Observations of first neutrino interactions!



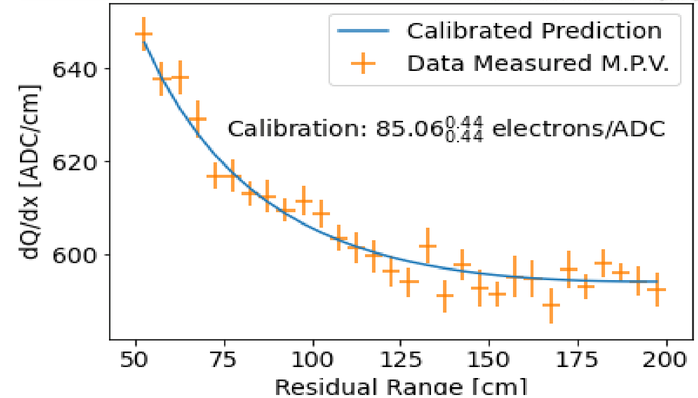


Software and analysis

- Analysis of ICARUS commissioning data currently focused on understanding detector response and systematics.
- As an example, **space charge effects** measured using anode-cathode-crossing cosmic muon tracks. First results show rough agreement with previous ICARUS measurement (JINST 15 (2020) 07, P07001).



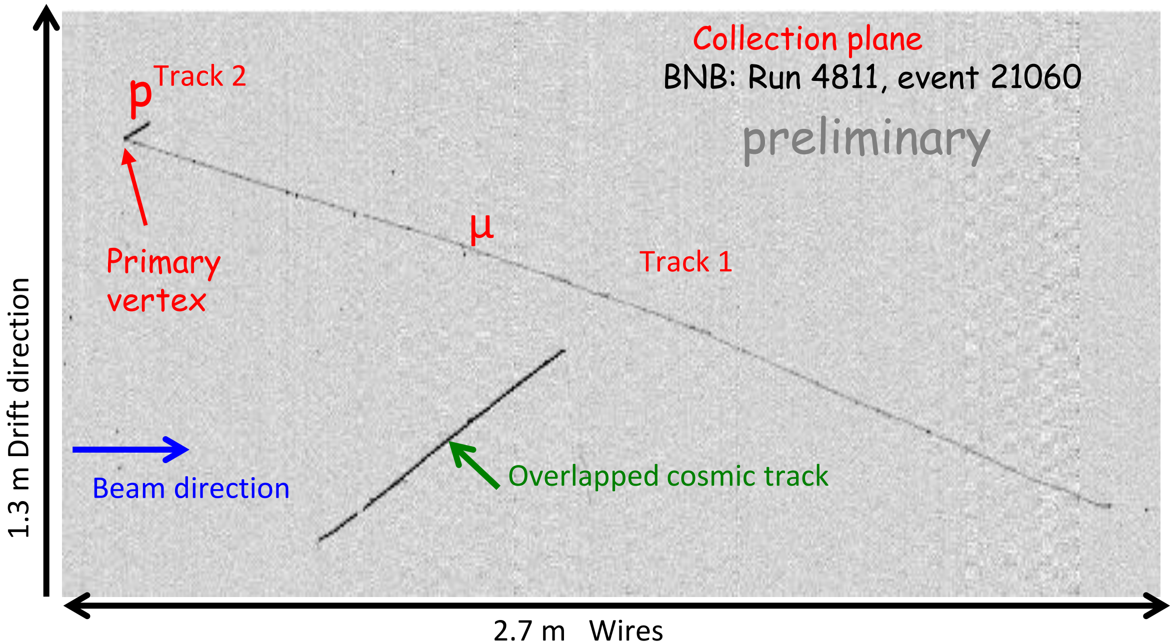
- First absolute calibrations of wire signal response are being performed by looking at the relation between dQ/dx and residual range in stopping muons. Cathode-crossing tracks were selected in order to determine drift coordinate.

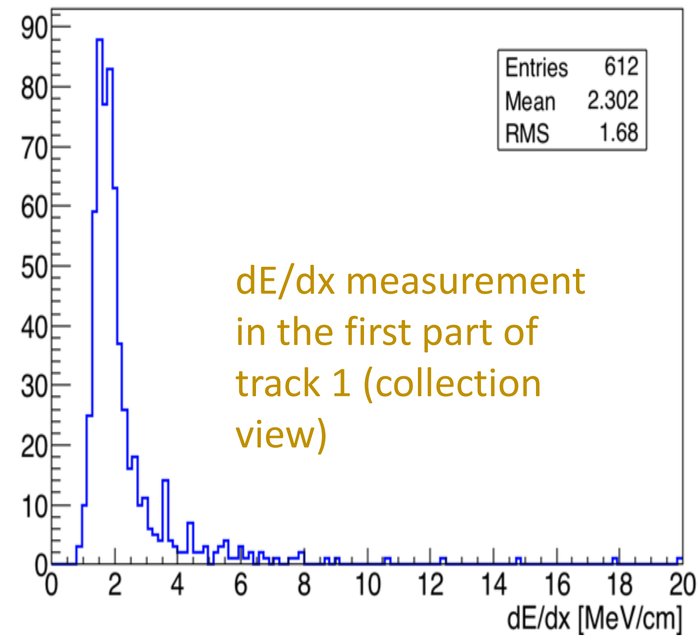


- SBN simulation, reconstruction and analysis will be **common to near and far detector**: common tools have been developed in joint groups since 2016.
- During 2021-22 (ICARUS-only operation) the analysis will focus on **searches for Neutrino-4 signal**, both with BNB and NUMI beams.
- These data will also be useful for **cross-section measurements** of interest for DUNE, dark matter searches, and **validation/fine-tuning** of reconstruction and analysis tools for SBN.

First neutrino candidates (BNB): CCQE

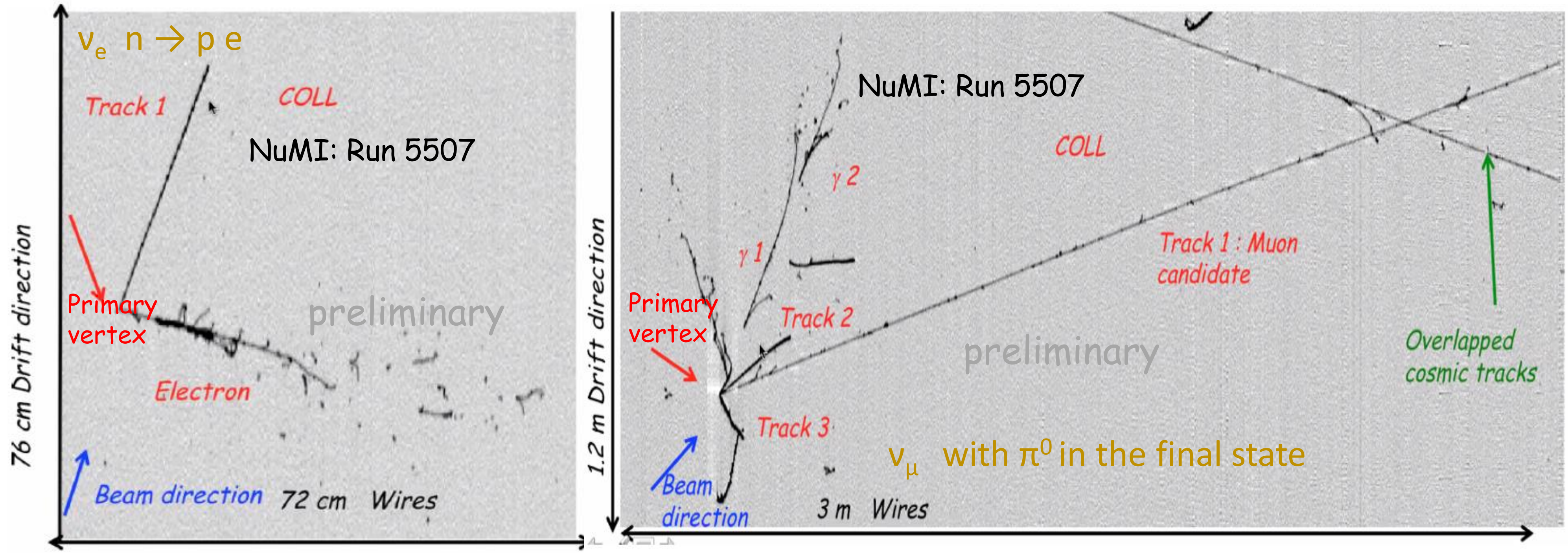
Quasi-Elastic Charged-Current: ν_μ n -> p μ





- Two tracks are both stopping in the picture: Track 1 (muon candidate) is stopping after = 2.8 m and E_{dep} ~ 650 MeV.
- Track 2 (proton candidate) is stopping after 10.9 cm, E_{dep} ~ 100 MeV.
- The graph on the right shows the dE/dx distribution of Track 1 in the first 2 m, in agreement with the expectations of the Landau distribution for a minimum ionizing particle.
- Electron lifetime was ~1.2 ms.

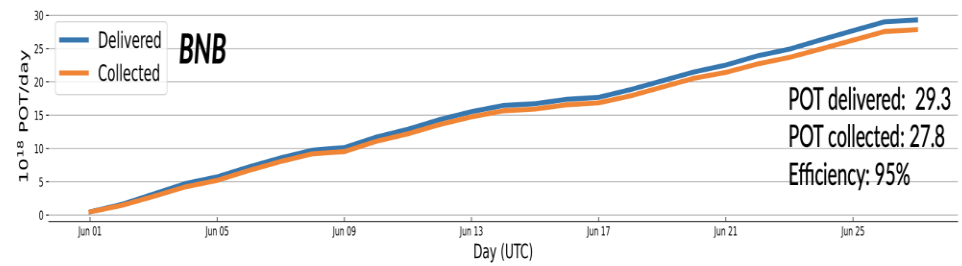
Neutrino Candidates from NuMI beam



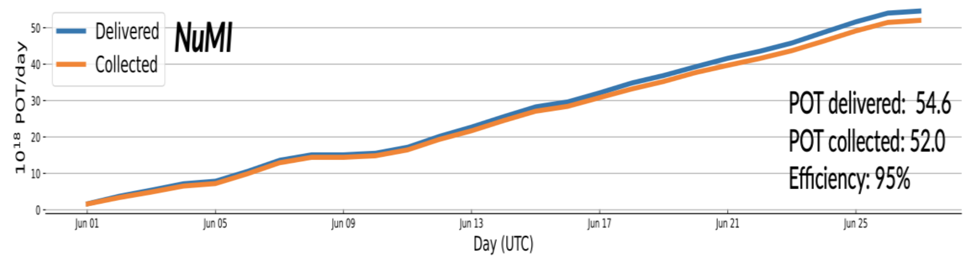
- Electron neutrino candidate shown on the left:
  - Electromagnetic shower with E_{dep} ~ 600 MeV.
  - Upward-going hadron (proton or pion candidate) with length ~ 43 cm.
- Muon neutrino candidate shown on the right:
  - Track 1: crossing the cathode and exiting downstream (L~4.2m, p~1.3 GeV/c from MCS).
  - Track 2: upward-going proton candidate, L~31 cm.
  - γ1,γ2: photons of 200 and 240 MeV respectively, converting at 18 and 58 cm from neutrino interaction vertex. Possible π_0 candidate.

Commissioning and data-taking: status and perspectives

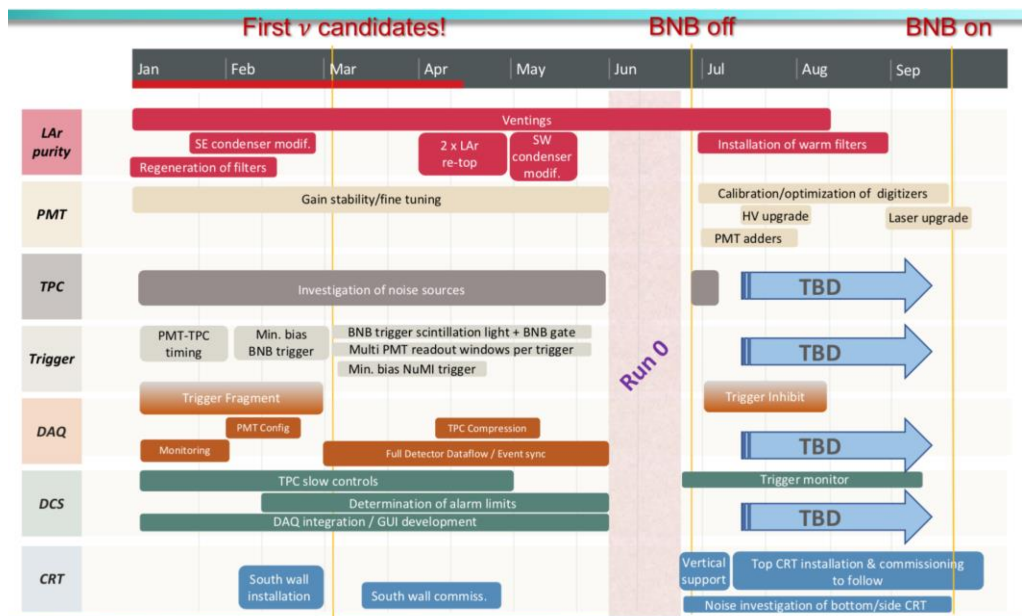
- Neutrinos from BNB and NUMI have been collected since the end of March 2021, in order to setup the data processing workflow and event reconstruction tools.



- Full time ICARUS neutrino beam run as BNB primary user lasted all June 2021, collecting **27.8 10^{18} pot** from BNB and **52.0 10^{18} pot** from NuMI with ~**95% efficiency**.



- During the current summer shutdown:
  - Commissioning activity with cosmic ray data.
  - Upgrade to PMT HV and TPC read-out electronics.
  - Improvements to data processing and data transfer workflow.



- First physics run will start in **October 2021**.

Conclusions

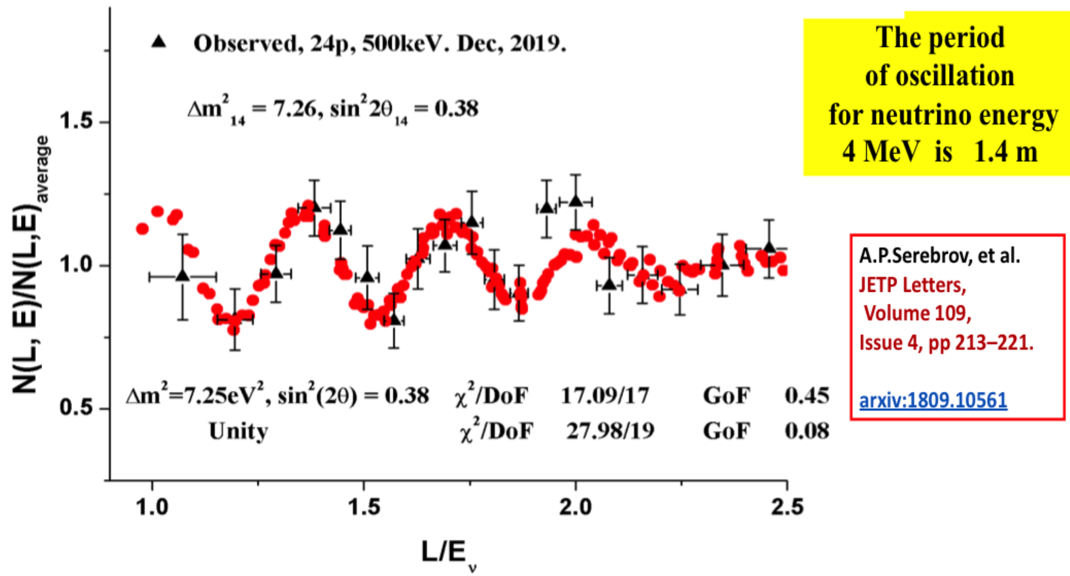
- The commissioning phase of ICARUS-T600 has largely been successful, despite the inconveniences due to the current pandemic.
- Thanks to improvements in cryogenics, the drift electron lifetime reached a level of ~4 ms, adequate for physics data-taking.
- The “run 0” test in June confirmed that ICARUS is able to take physics data continuously with high live-time. The initial deployment of the trigger system allowed to observe the first neutrino events from both BNB and NuMI beams.
- These collected neutrino events are being used to further develop and tune the event filter and the reconstruction software.
- The side CRT completely installed and commissioning in progress.
- The top CRT modules have arrived at Fermilab. Installation is planned to start soon and be completed by end of this year.
- The successive installation of the concrete overburden will allow a significant reduction of the cosmic-ray induced background.
- First physics run is planned by October.

Thanks for the attention

Search for Neutrino-4 oscillation signal

- The Neutrino-4 collaboration claimed a **reactor neutrino disappearance signal** with a clear modulation with L/E ~ 1-3 m/MeV.

NEUTRINO-4 reactor signals



A.P.Serebrov, et al.
JETP Letters,
Volume 109,
Issue 4, pp 213–221.

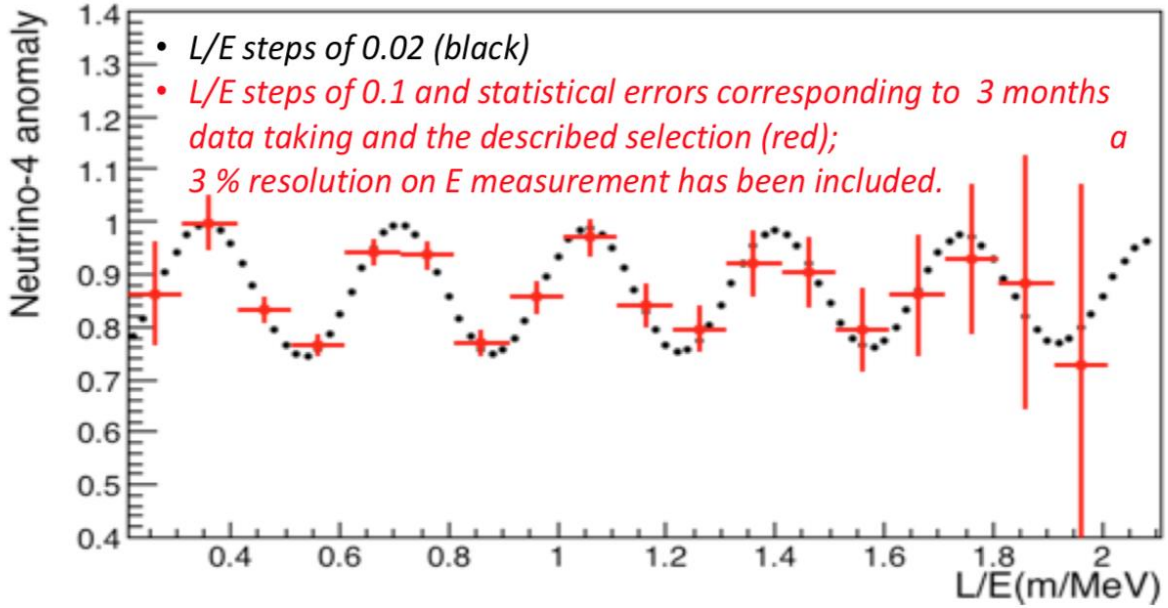
arxiv:1809.10561

- ICARUS will be able to test this oscillation hypothesis in the same L/E range in **two independent channels**, with different beams:
  - **Disappearance of ν_μ from the BNB beam**, focusing the analysis on quasi-elastic ν_μ CC interactions where the muon is contained and at least 50 cm long. ~11500 such events are expected in 3 months data taking.
  - **Disappearance of the ν_e component in the NuMI beam**, selecting quasi-elastic ν_e CC events with contained EM showers. ~5200 events expected per year.

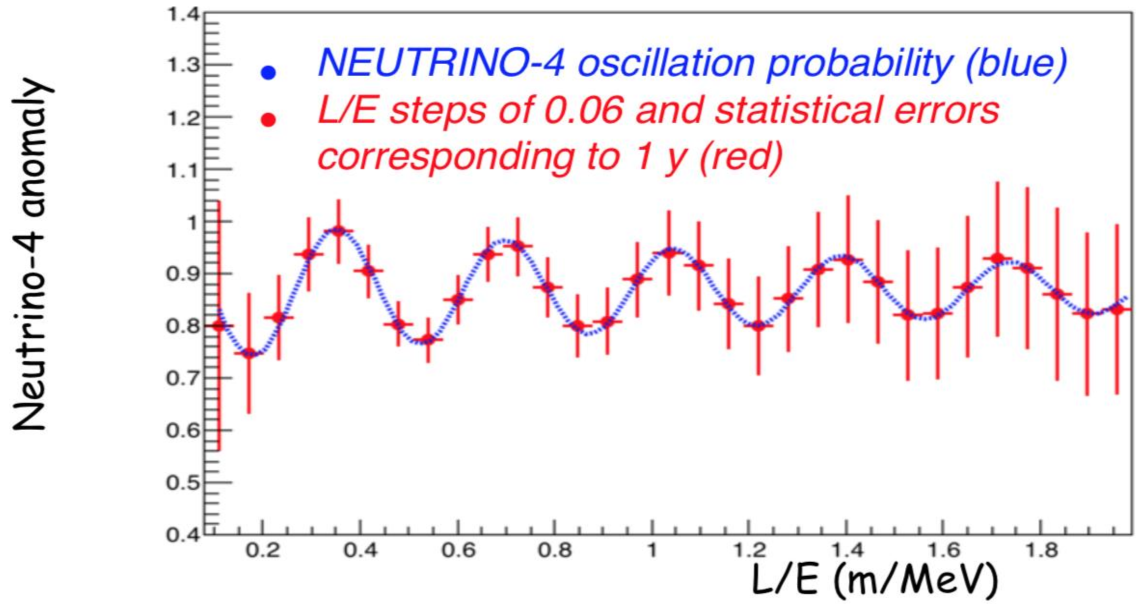
- The study of these channels, complemented with a beam-off sample, would allow to observe or reject a modulation as observed by Neutrino-4.

ICARUS sensitivity to Neutrino-4 signal

- ν_μ **survival probability** assuming the Neutrino-4 best fit oscillation parameters (Δm^2=7.25 eV^2 and sin^2 2θ~0.26) and corresponding ICARUS measurements, assuming 3 months data taking and 3% energy scale resolution.



- ν_e **survival probability** assuming the Neutrino-4 best fit oscillation parameters (Δm^2=7.25 eV^2 and sin^2 2θ~0.26) and corresponding ICARUS measurements, assuming 1 year data taking and statistical-only uncertainties.



ICARUS transportation (from CERN to FNAL)

leaving from CERN, June 12th 2017

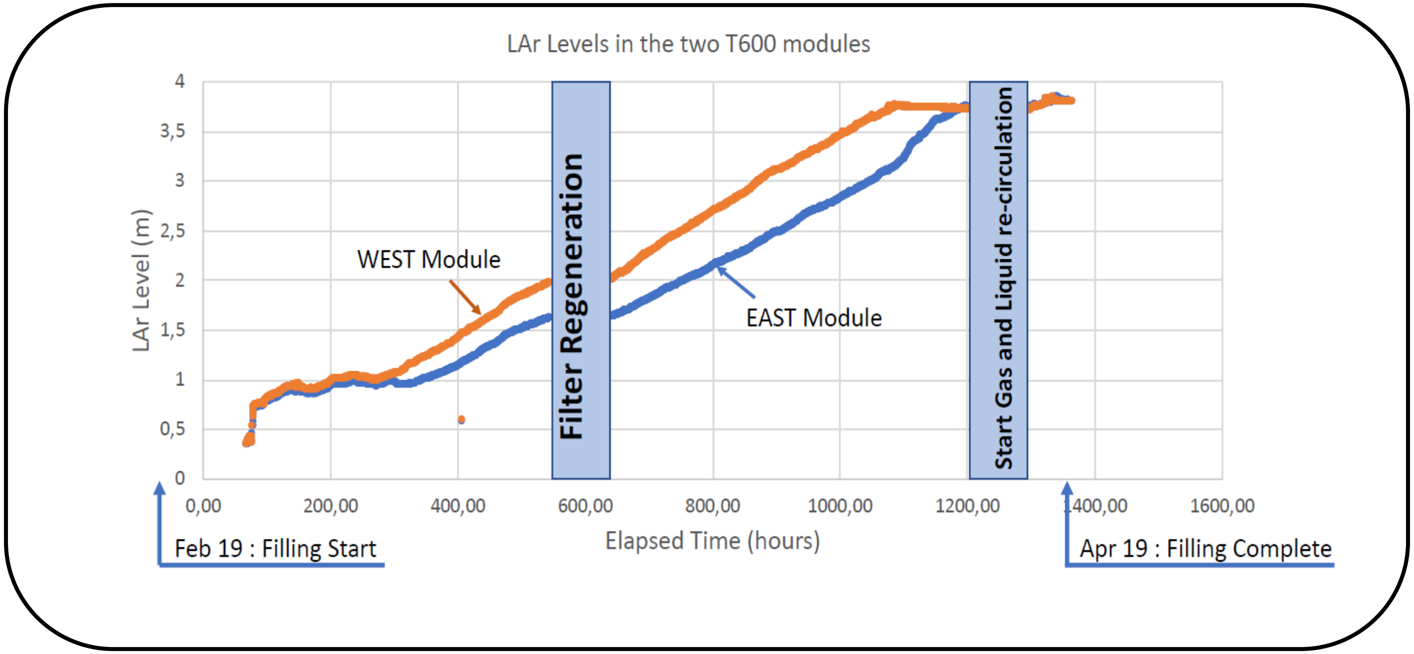
Antwerp: unloading from barge from Basel and loading into ship to Burns Harbor (Indiana)

arriving at SBN Far site building at FermiLab, July 26th 2017

SBN far site building at FermiLab

ICARUS commissioning

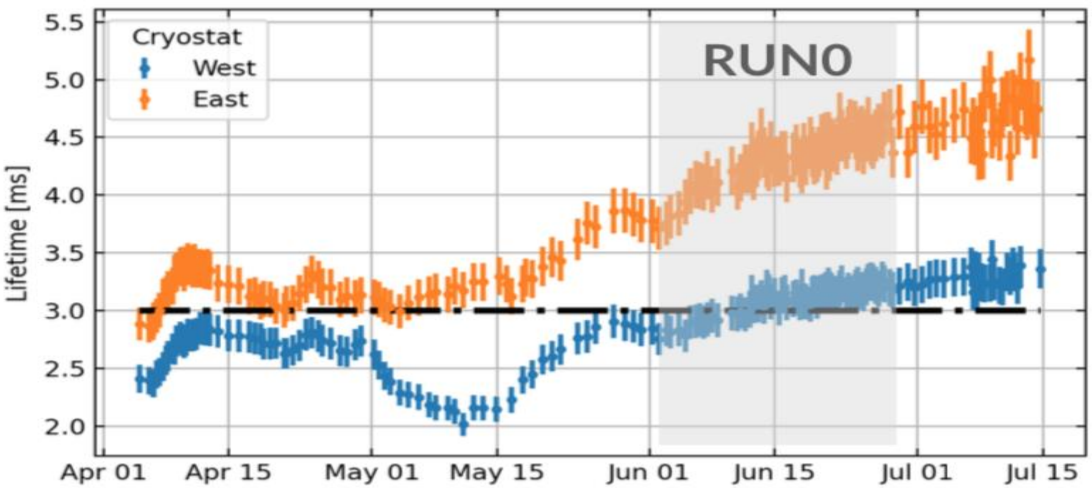
- The cryogenic commissioning of the ICARUS detectors started on February 13th , 2020 by breaking the vacuum in the two main cold vessels with ultra-purified argon gas.
- Cool down started on February 14th by injecting liquid nitrogen in the cold shields.
- The continuous filling with ultra-purified liquid argon started on February 24 and filling completed on April 19th.



- Stable operation with nominal high voltage (drift field 500 V/cm) started on August 27th, 2020.
- Started acquisition of cosmic ray data with random trigger (5 Hz) for measurement of electron lifetime and calibration purposes.

Cryogenics and electron lifetime

- Cryogenic system is steady and well performing after filling in spring 2020.
- Electron lifetime is monitored by measuring signal attenuation in cathode-anode crossing cosmic muon tracks.
- Electron lifetime reaches up to ~**4.5 ms** in the West Cryostat and ~**3 ms** in East, allowing efficient signal detection over the full Lar volume.



EAST cryostat

WEST cryostat

- Lifetime improved in recent months due to improvements on under-performing GAr recirculation units and periodic venting (3 times per day).
- New higher-capacity GAr filters (copper-based with molecular sieves for water adsorption) are under preparation at CERN.
- Their installation is expected to further improve GAr recirculation rate and electron lifetime.