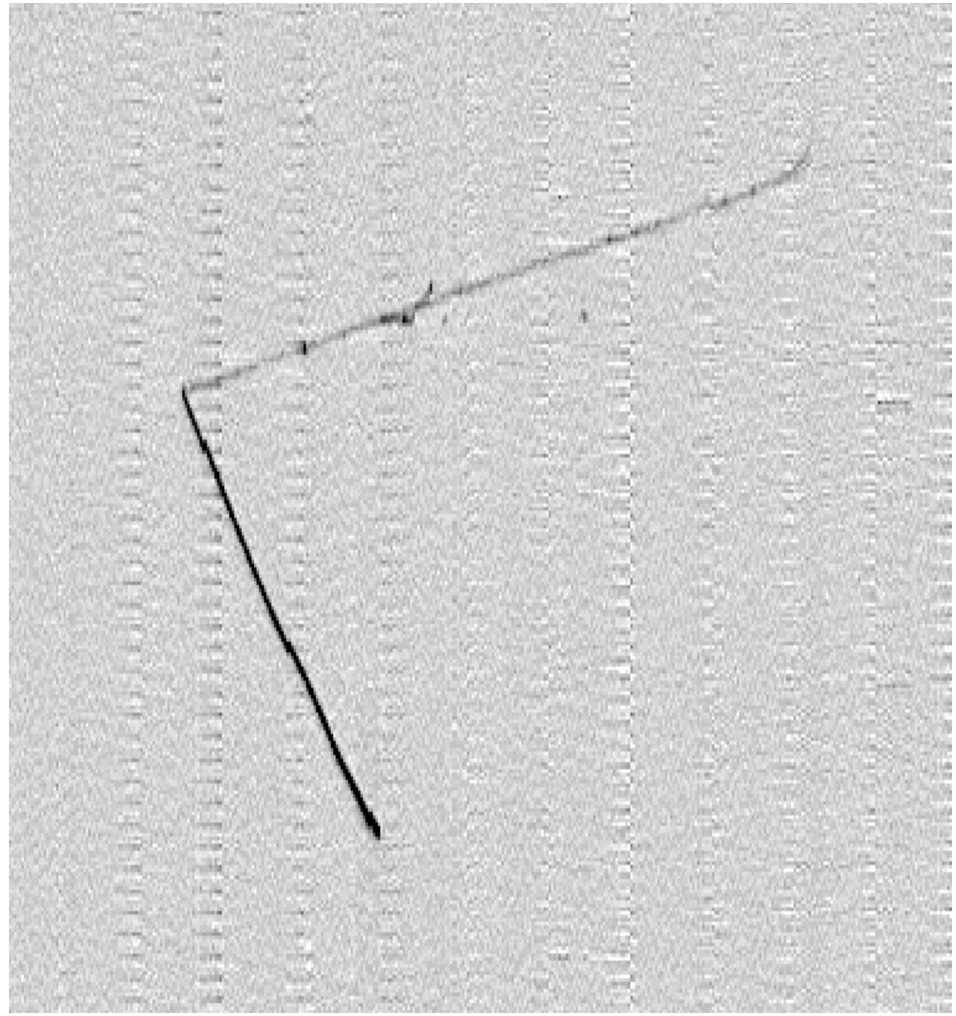
Short-baseline neutrino oscillation searches with the ICARUS detector



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on behalf of the ICARUS Collaboration

EPS-HEP 2021, July 27th, 2021

The ICARUS Collaboration

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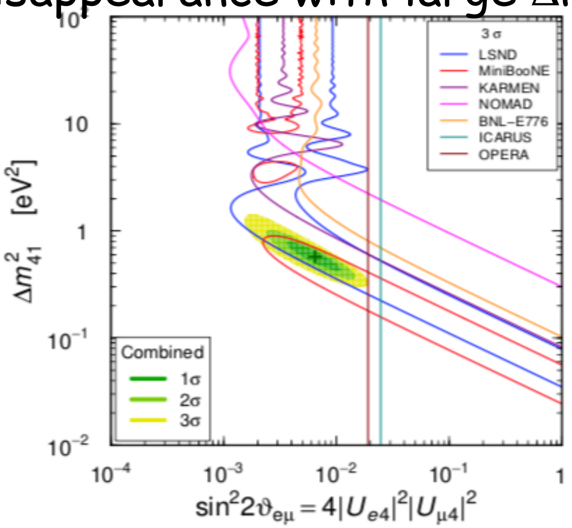
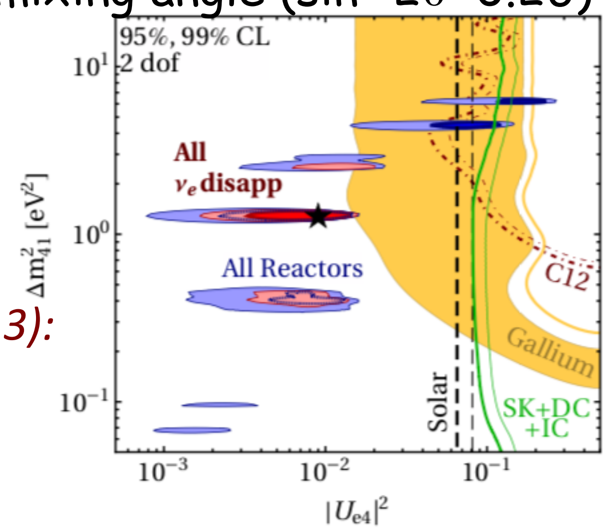
The sterile neutrino puzzle

- 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 νe 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-νe disappearance with large Δm^2 (~ 7 eV^2) and mixing angle ($\sin^2 2\theta$~0.26)

(anti-)$\nu\mu$ appearance (from arXiv:2106.05913):



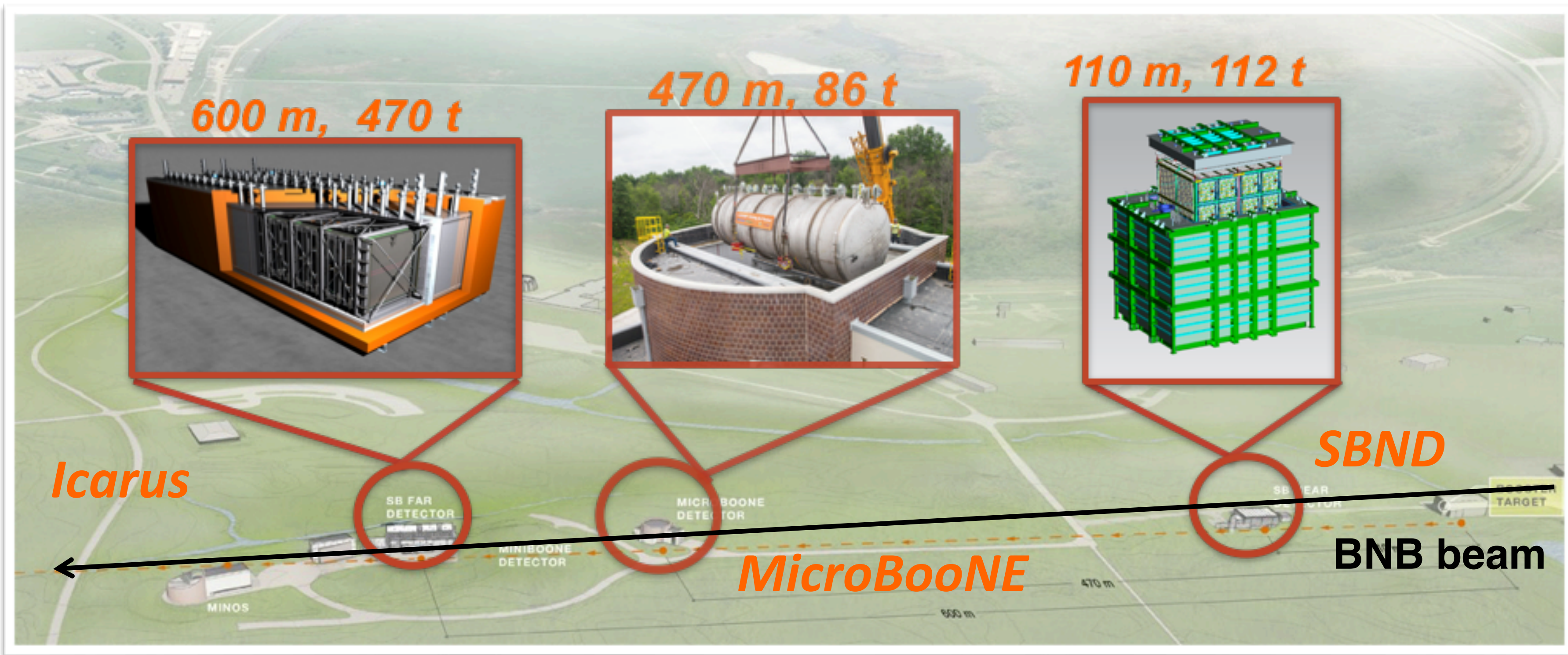
(anti-)νe disappearance (from arXiv:2106.05913):



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

(see Diana Mendez's SBND talk!)

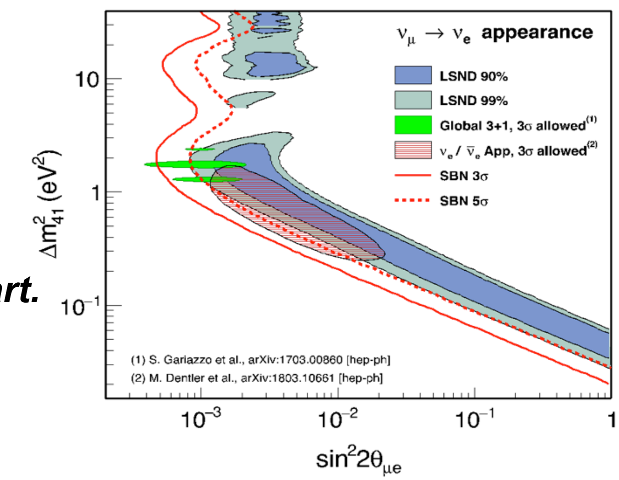


SBN physics program

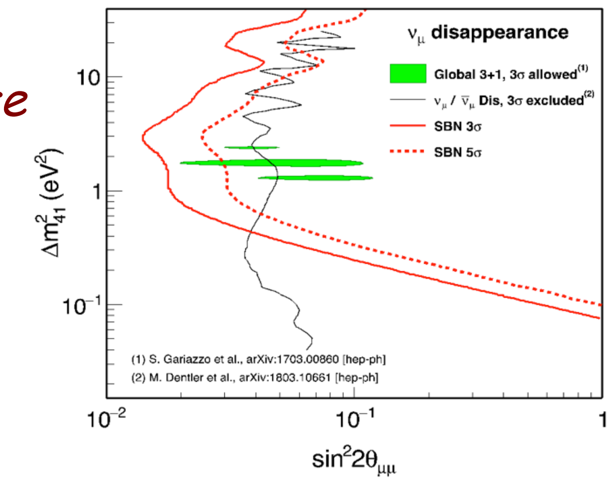
- The main physics motivation of SBN is a conclusive verification of the sterile neutrino hypothesis
  - The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels, in 3 years of data-taking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

SBN appearance sensitivity:

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



SBN disappearance sensitivity:

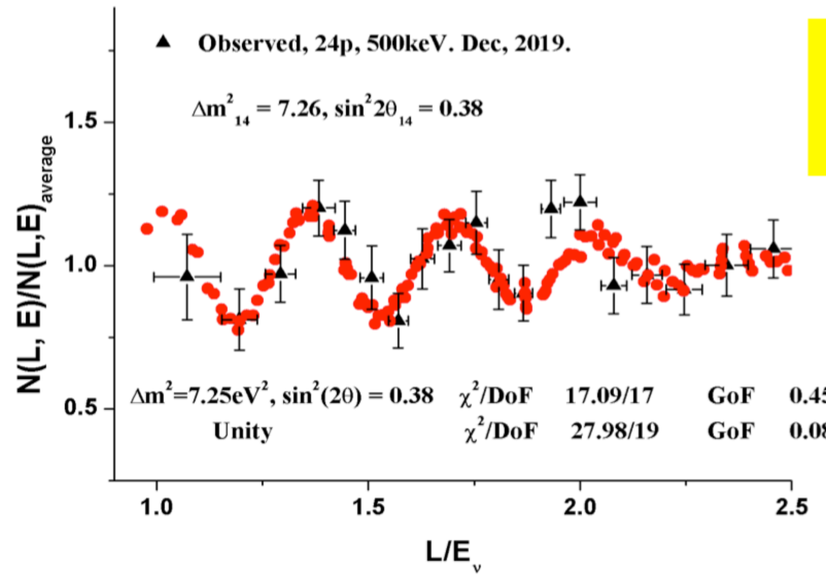


- Moreover, SBN could perform high-statistics measurements of neutrino-Argon cross-sections which will be important for DUNE:
  - Millions/year events in SBND at low energy (<1 GeV) from BNB beam
  - Hundred thousands/year events in ICARUS at higher energy (>1 GeV) from NUMI

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



The period of oscillation for neutrino energy 4 MeV is 1.4 m

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

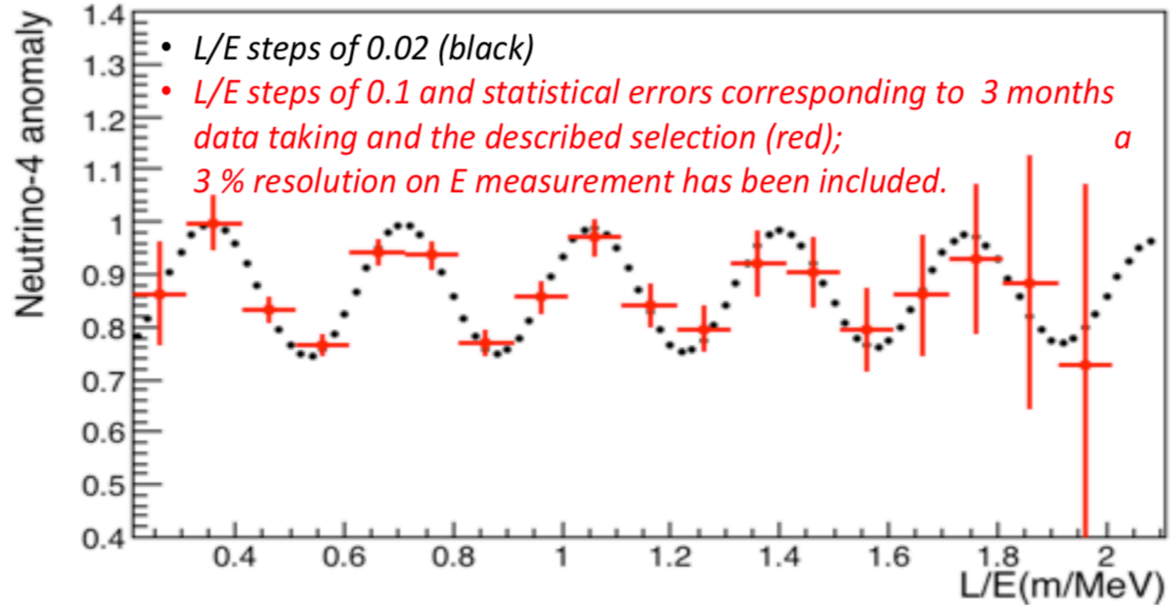
arxiv:1809.10561

- 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_μCC 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 νe component in the NuMI beam, selecting quasi-elastic ν_eCC events with contained EM showers. ~5200 events expected per year

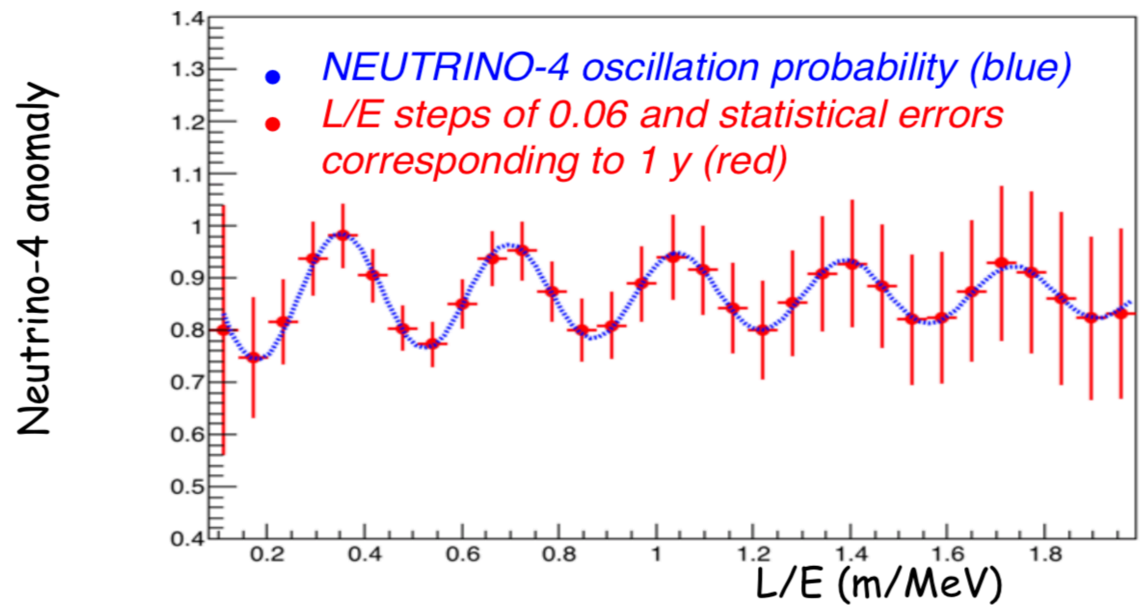
- The study of these channels, complemented with a beam-off sample, would allow to observe or reject a modulation as observed by Neutrino-4

ICARUS sensitivity to Neutrino-4 signal

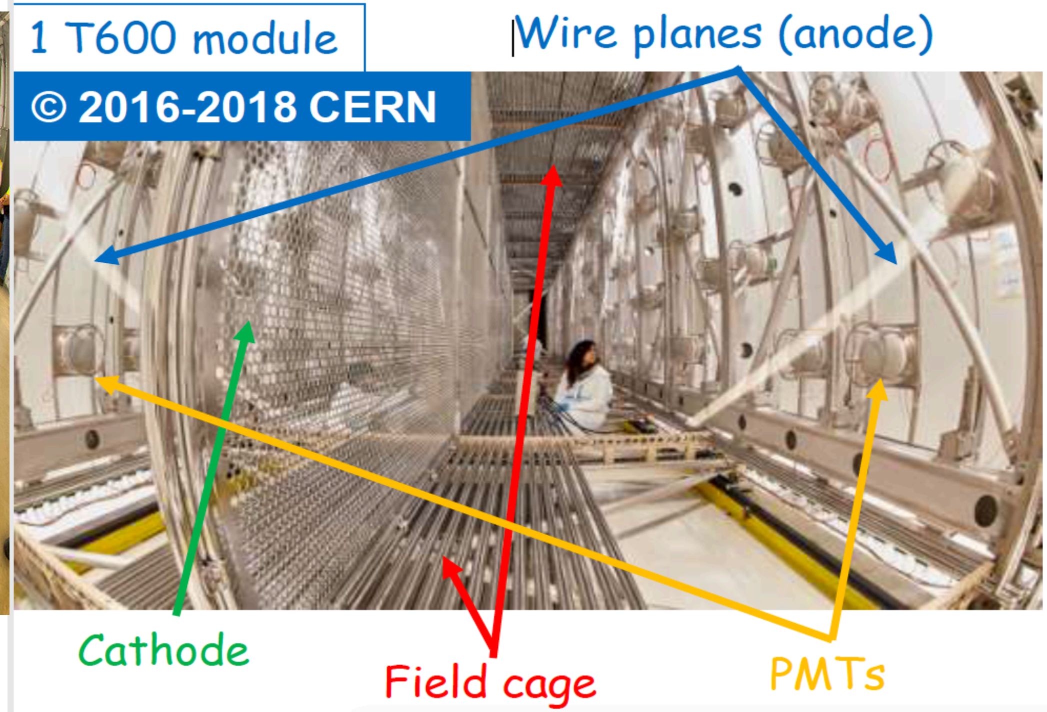
- $\nu\mu$ survival probability assuming the Neutrino-4 best fit oscillation parameters (Δm^2=7.25 eV^2 and $\sin^2 2\theta$~0.26) and corresponding ICARUS measurements, assuming 3 months data taking and 3% energy scale resolution



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



The ICARUS-T600 detector



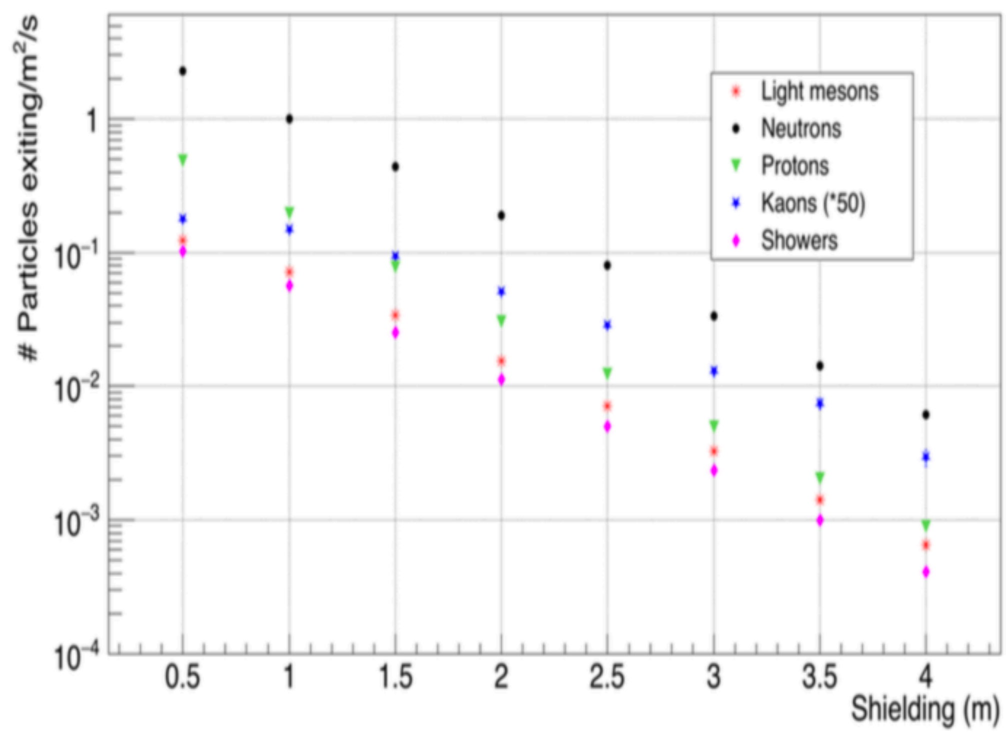
- ICARUS-T600 is the first large LArTPC detector. Its operation at the underground LNGS laboratory (2010-13) confirmed the maturity of this technique
- Two identical modules (T300) each 19.6 x 3.6 x 3.9 m^3 . Total LAr mass 760 t; active 476 t
- **Drift distance 1.5 m. Electric field 500 V/cm (75 kV) -> drift time ~1 ms**
- 3 signal wire planes (2 induction + 1 collection). Signals allow calorimetric measurement of contained particles
- Pitch and inter-plane distances: 3 mm; 400 ns sampling time. ~54,000 channels

Cosmic-ray background mitigation

- ICARUS at FNAL is taking data on the Earth's 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 νe apperance searches
- In order to mitigate this problem, an overburden layer of concrete (~2.85 m thickness) will be placed above the detector

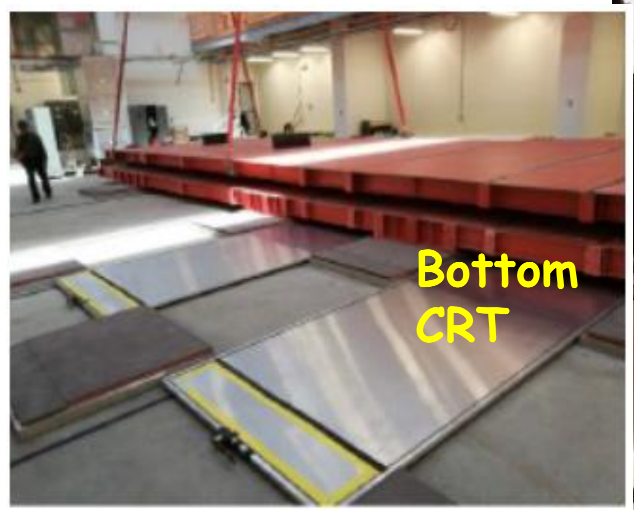
- Possible backgrounds are produced by either neutral primaries (n,γ) or muons.
- The overburden will effectively remove all primary photons and reduce neutrons by a factor ~200
- Primary muons and associated showers will be reduced by ~25%
- As a consequence, the total number of cosmic-induced backgrounds will be effectively decreased by the overburden

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



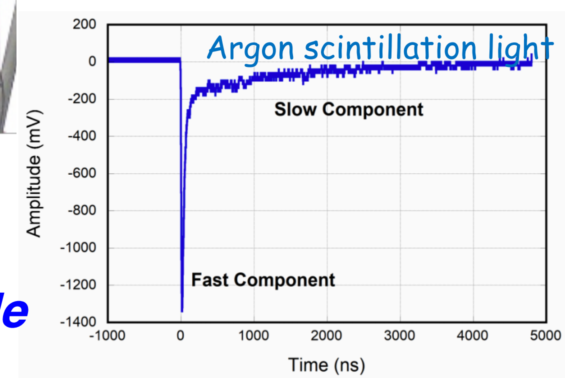
Cosmic Ray Tagger (CRT)

- 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 (see next slide)
  - 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 measurements of time (~ns resolution) and position (~tens of cm) 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 planned during this summer

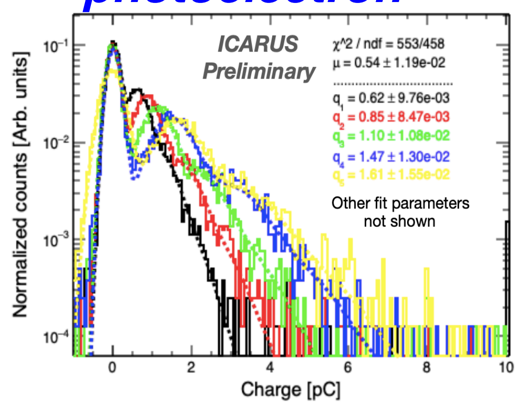


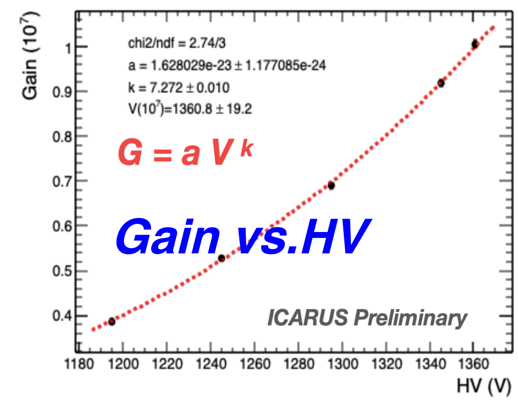
ICARUS light detection system

- Requirements for light detection system:
  - Generate trigger signals for TPC
  - Tag the time of occurrence (t0) 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 are coated with wavelength-shifter (TetraPhenylButadiene, 250 μg/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



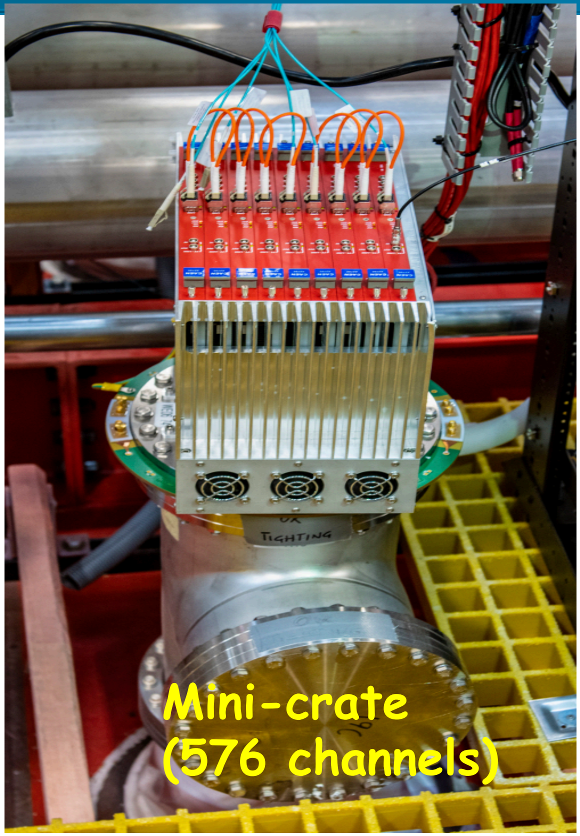
Response to single photoelectron





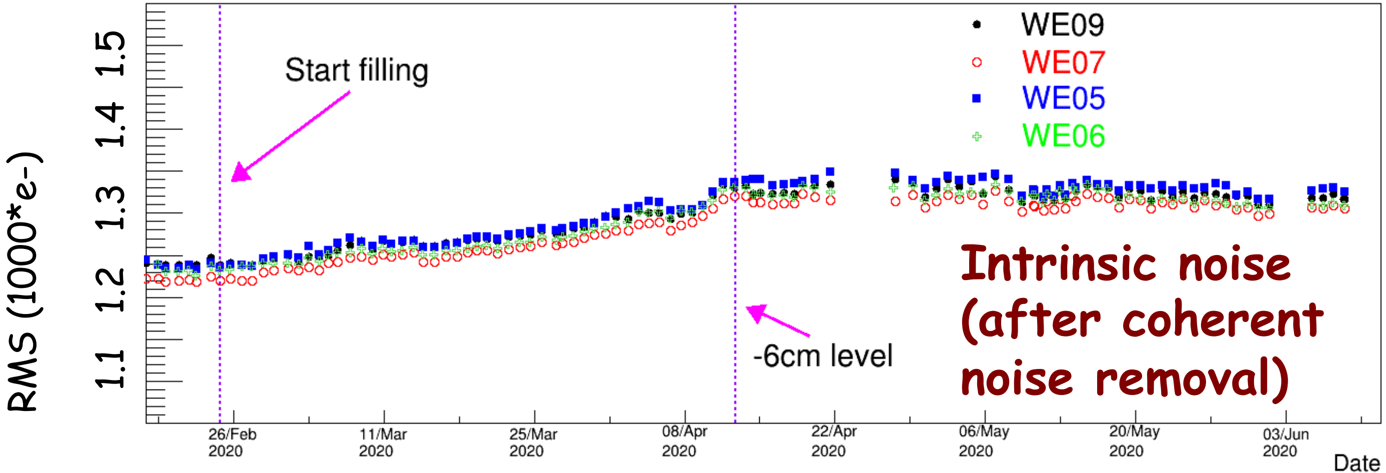
New ICARUS TPC read-out electronics

- 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 μs shaping time for all planes allows better reconstruction of dense vertex regions
  - Full electronic chain tested with cosmic rays at CERN



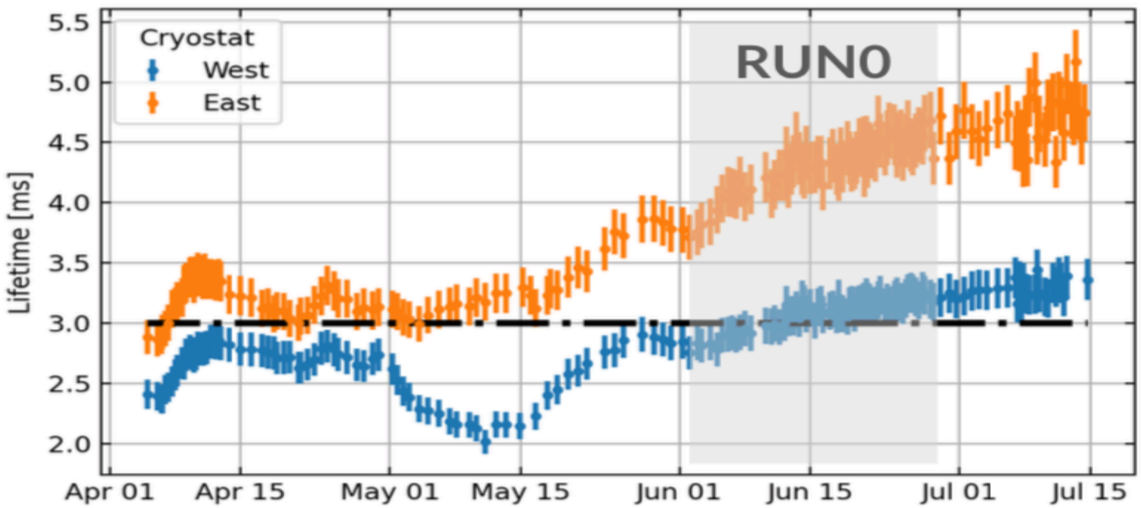
- TPC electronics are fully installed and commissioned
- Steady increase of the noise level measured during LAr filling, as expected

- Interventions to reduce noise level are planned during the summer beam 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



EAST cryostat

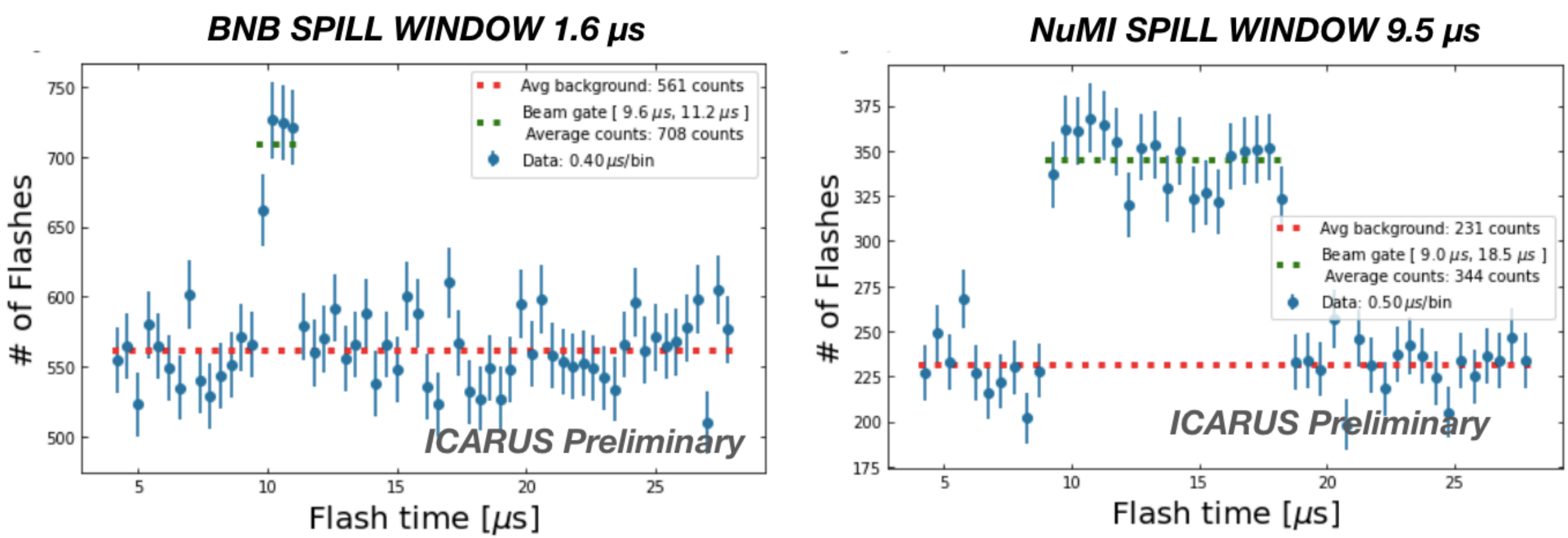
WEST cryostat

- 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, planned during summer beam shutdown, is expected to further improve GAr recirculation rate and electron lifetime

Commissioning of the trigger system

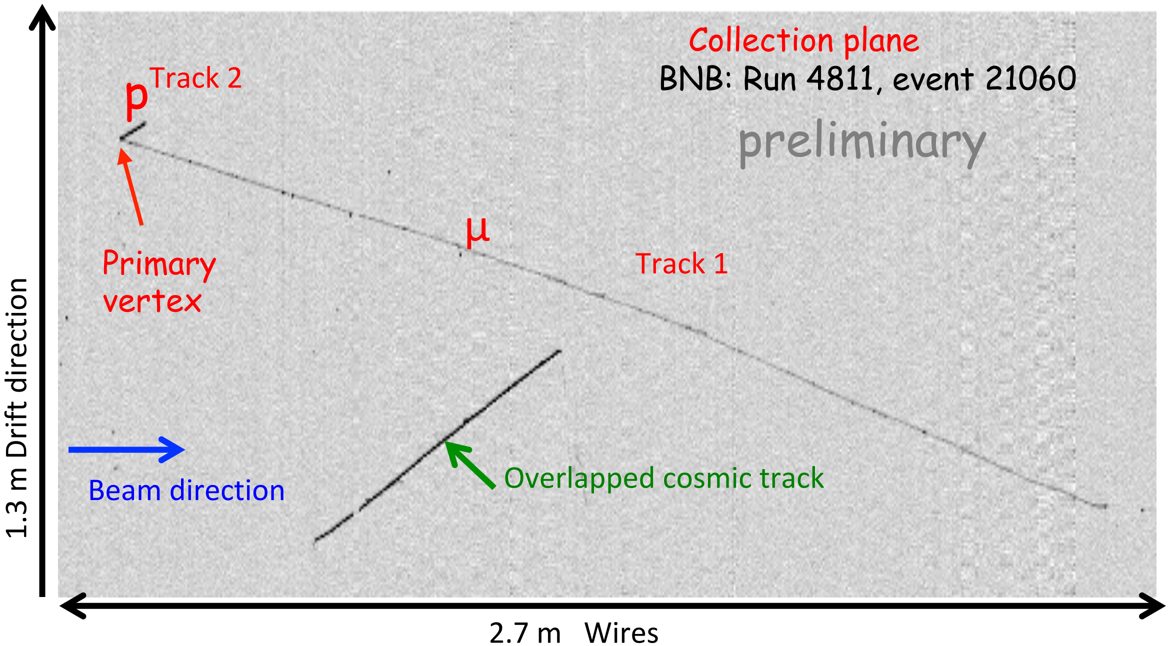
- Commissioning/development of the trigger system performed in two steps:
  - Generate "spill-only", based on the BNB (NuMI) extraction signal distributed via White Rabbit network
  - Scintillation light info by requesting majority of PMT pairs in each wall of the cryostat inside a BNB (or NuMI) beam 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

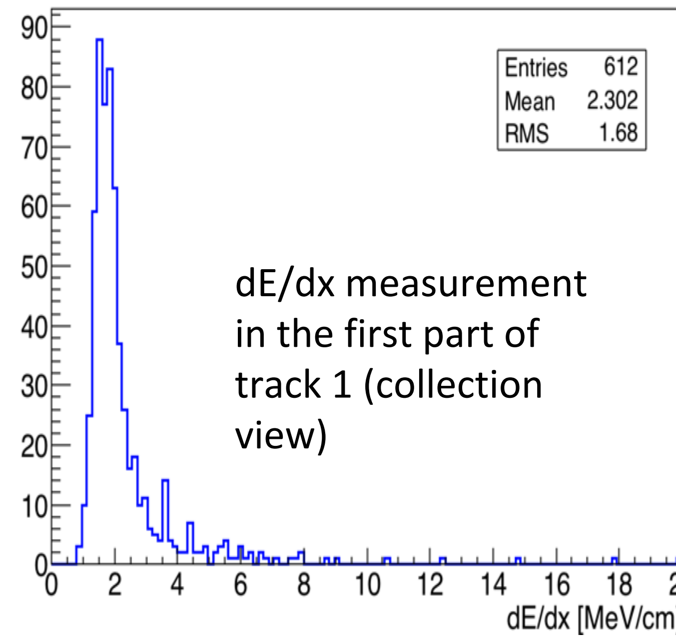
Observations of first neutrino interactions!



First neutrino candidates (BNB): CCQE

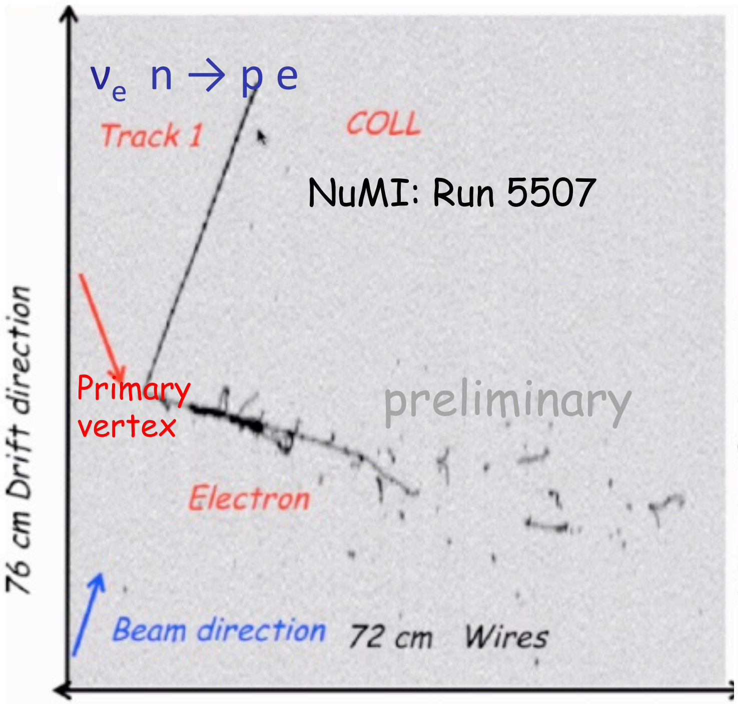
Quasi-Elastic Charged-Current: $\nu_\mu\ n \to p\ \mu$

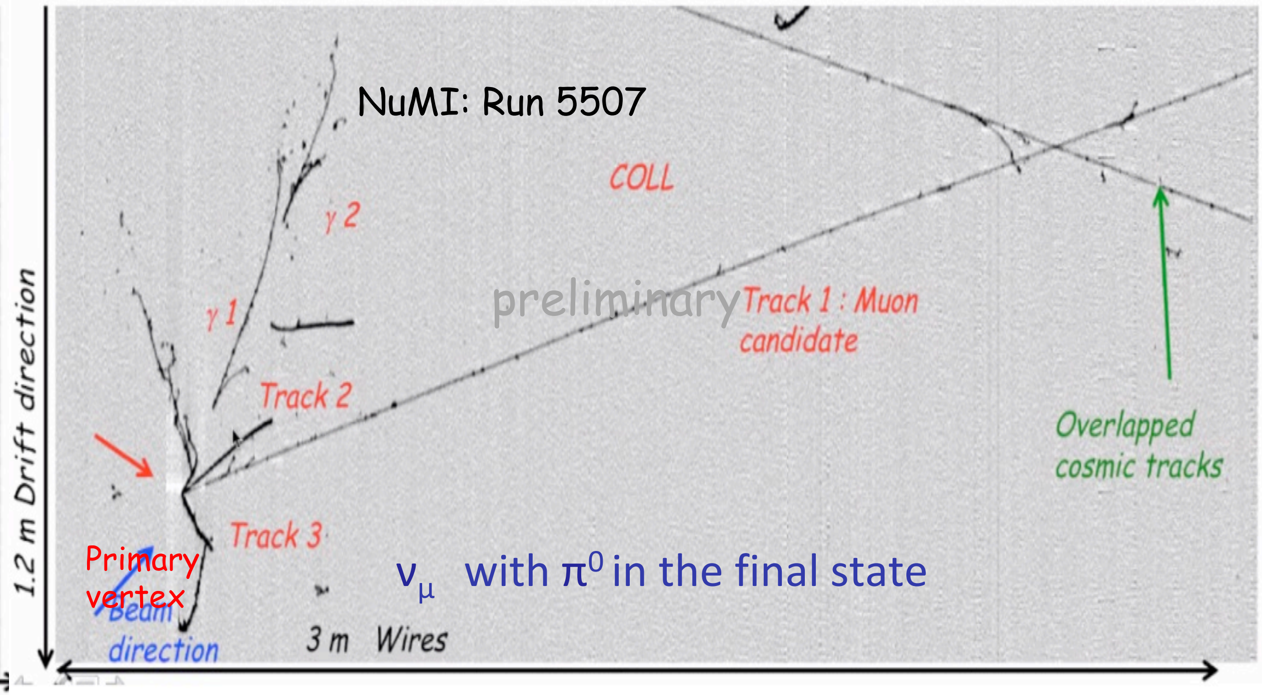




- Two tracks are both stopping in the picture: Track 1 (muon candidate) is stopping after = 2.8 m and E_{dep} ~ 650 MeV
- Track 2 (proton candidate) is stopping after 10.9 cm, E_{dep} ~ 100 MeV
- The graph on the right shows the dE/dx distribution of Track 1 in the first 2 m, in agreement with the expectations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

Neutrino Candidates from NuMI beam

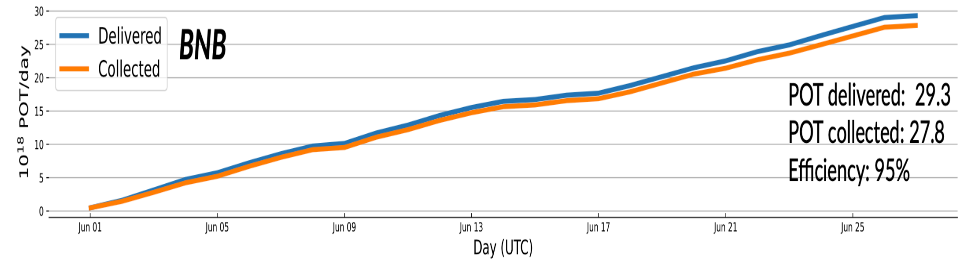


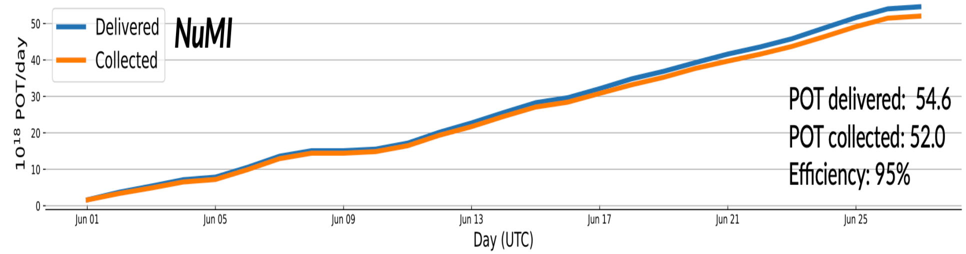


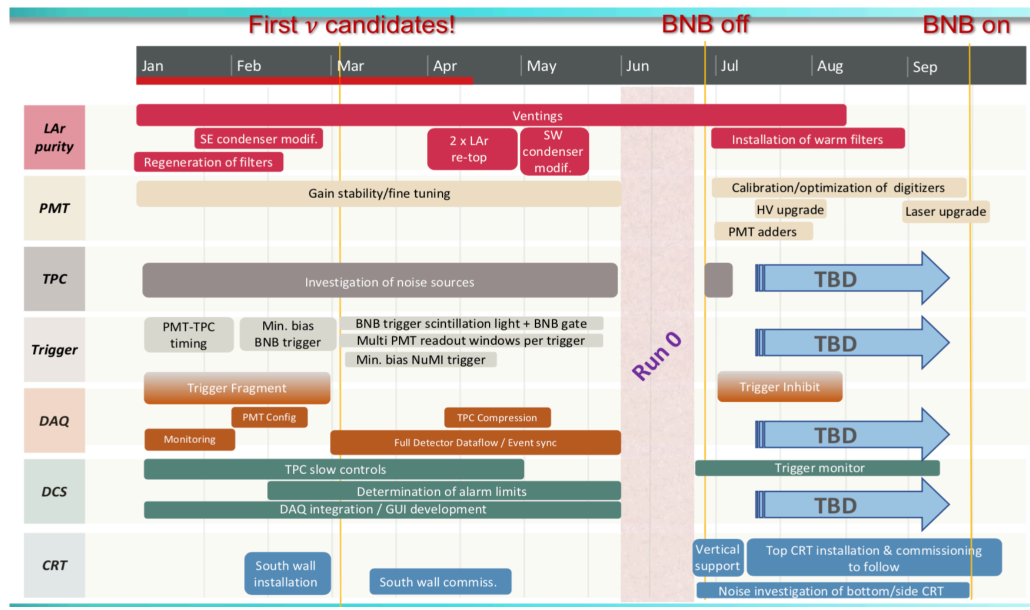
- Electron neutrino candidate shown on the left:
  - Electromagnetic shower with E_{dep} ~ 600 MeV
  - Upward-going hadron (proton or pion candidate) with length ~ 43 cm
- Muon neutrino candidate shown on the right:
  - Track 1: crossing the cathode and exiting downstream (L~4.2m, p~1.3 GeV/c from MCS)
  - 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
  - Installation of top CRT
  - Upgrade to PMT HV and TPC read-out electronics
  - Improvements to data processing and data transfer workflow





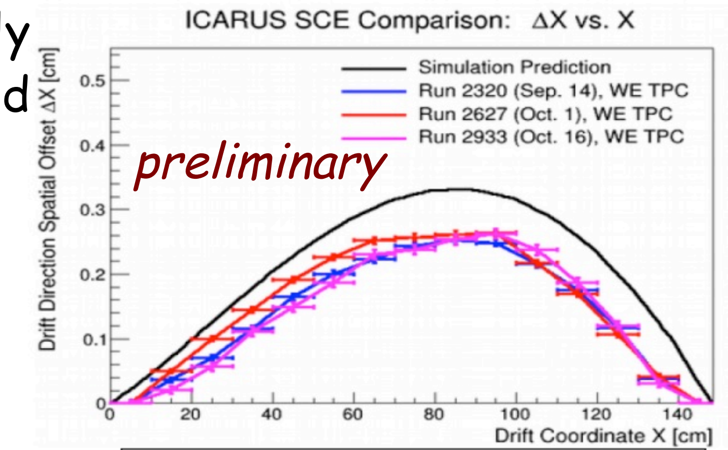


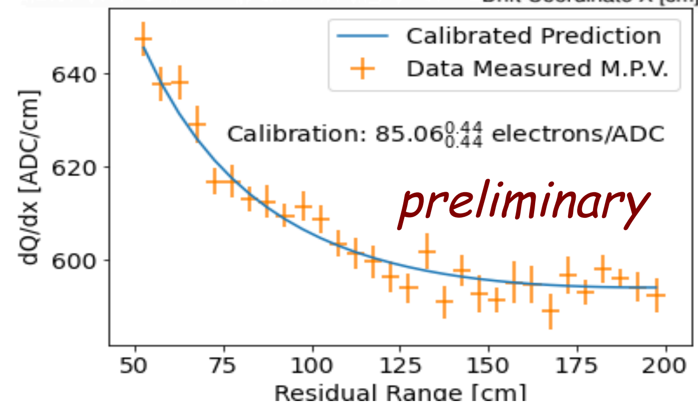
- First physics data will start in October 2021

Software and analysis

- Analysis of ICARUS commissioning data currently focused on understanding detector response and systematics

- As an example, space charge effects (SCE) 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

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 September.
- 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.

STAY TUNED !