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Status and perspectives of the ICARUS experiment at the Fermilab Short Baseline Neutrino program

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ABSTRACT: The ICARUS collaboration has employed the 760 t T600 detector in a successful three-year physics run at the underground LNGS laboratory, performing a sensitive search for LSND-like anomalous ν_e appearance in the CERN Neutrino to Gran Sasso beam, which contributed to the constraints on the allowed neutrino oscillation parameters to a narrow region around $\Delta m^2 \sim 1\ eV^2$. After a significant overhaul at CERN, the T600 detector has been installed at Fermilab. In 2020 the cryogenic commissioning began with detector cool down, liquid Argon filling and recirculation. ICARUS then started its operation collecting the first neutrino events from the Booster Neutrino Beam (BNB) and the Neutrinos at the Main Injector (NuMI) beam off-axis, which were used to test the ICARUS event selection, reconstruction and analysis algorithms. ICARUS successfully completed its commissioning phase in June 2022, moving then to data taking for neutrino oscillation physics, aiming at first to either confirm or refute the claim by Neutrino-4 short-baseline reactor. ICARUS will also jointly search for evidence of sterile neutrinos together with the Short-Baseline Near Detector, within the Fermilab Short-Baseline Neutrino program experiment, and will perform measurements of neutrino cross sections with both beams and several Beyond Standard Model searches with the NuMI beam. In this paper, the main technical achievements of the ICARUS detector subsystems (Time Projection Chambers, Light Detection System, Cosmic Ray Tagger, Trigger and Data Acquisition) obtained with both BNB and NuMI neutrino beams during the commissioning phase, will be presented in terms of the overall detector performance and capability to select and reconstruct neutrino events.

KEYWORDS: Noble liquid detectors (scintillation, ionization, double-phase); Neutrino detectors; Time projection Chambers (TPC)

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1 The sterile neutrino puzzle

Neutrino oscillations represent today the major experimental evidence of physics beyond the Standard Model of the fundamental interactions. Despite the well-established description of three neutrino flavors mixing, several anomalies have been collected so far by the pioneering LSND experiment and in the measurements of the (anti) neutrino flux from nuclear reactors and from intense radioactive sources, hinting to the existence of additional sterile neutrino states [1]. Furthermore, an electron-like events excess has been observed at the Neutrino Booster Beam accelerator (BNB) by MiniBooNE at Fermilab [2]. A large part of the oscillation parameters has been already investigated by the ICARUS and OPERA experiments at LNGS with the CNGS neutrino beam constraining the allowed oscillation parameters to$\Delta m^2 \sim 1\,\mathrm{eV}^2$ [3].

More recently, the Neutrino-4 experiment at Dimitrovgrad SM-3 reactor reported evidence of neutrino disappearance with a liquid scintillator detector moved from 6.4 to 11.9 m distance from the reactor core, observing a characteristic L/E modulation in the 1÷3 m/MeV range [4]. The combined Neutrino-4 data with the flux measurements of GALLEX, Sage and BEST radioactive sources would result in 5.8 σ C.L. oscillation signal with $\Delta m^2 \sim 7.3\,\mathrm{eV}^2$ and $\sin(2\theta) \sim 0.36$. A $2.7\,\mathrm{eV}^2$ squared mass neutrinos could be also a quite obvious Dark Matter candidate if the high density of relic neutrinos is considered.

A clear tension between appearance and disappearance experiments characterized by different neutrino energy range and detection technique is evident, as shown in figure 1. In order to untangle the actual physics scenario, it is crucial to conduct an experiment that measures simultaneously both ν_e appearance and disappearance, employing a detection technique with superior neutrino identification capabilities and effective background rejection.

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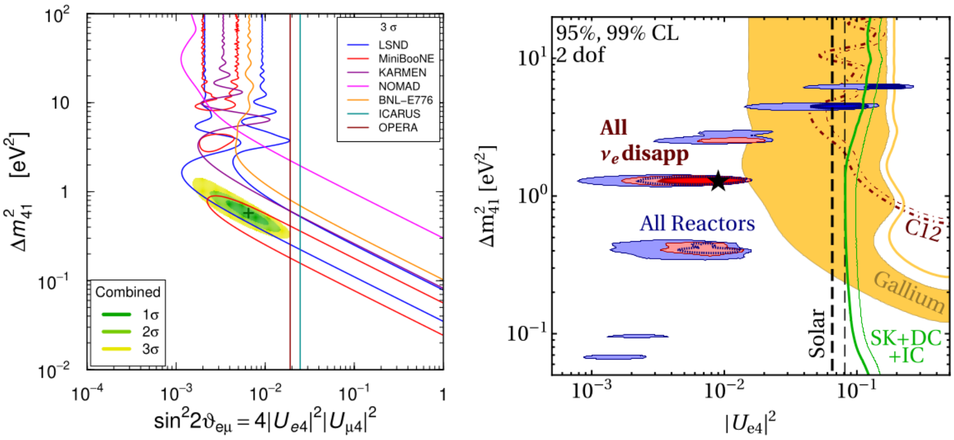

Figure 1. Global constraints on short-baseline $\nu_\mu \to \nu_e$ oscillations for ν_e appearance (left) and ν_e disappearance (right) [5].

2 The Short Baseline Neutrino (SBN) program

2.1 The SBN program

The Short Baseline Neutrino (SBN) program at Fermilab, is intended to carry out a sensitive search for new physics beyond the Standard Model, recording millions of charged (CC) and neutral current (NC) neutrino interactions and hopefully give some definite answers to many of the open questions in the neutrino puzzle.

Three large Liquid Argon Time Projection Chambers (LAr-TPC) detectors are installed at shallow depth and exposed to the ~ 0.8 GeV BNB neutrinos at different distances from the target, as shown in figure 2: ICARUS-T600 (467 t active mass), MicroBooNE[1] (89 t active mass) and SBND (82 t active mass) at 600 m, 470 m and 110 m respectively [6]. This multiple LAr-TPC configuration should provide a world-leading sterile neutrino search experiment with high sensitivity for $\nu_\mu \to \nu_e$ appearance signals by comparing the neutrino interactions at different distances from the target.

The initial BNB neutrino beam will be characterized by the SBND near detector, greatly reducing the systematic uncertainties in the search for oscillation signals at the far site. The significant cancellation of neutrino flux and cross sections uncertainties in the near to far detectors flux comparison, combined with the huge event statistics, will allow for a sensitive oscillation search in the ν_μ disappearance channel. Furthermore, the simultaneous analysis of ν_e and ν_μ CC events will allow to untangle the effects of ν_μ disappearance and ν_e appearance at $\Delta m^2 \sim 1\,\mathrm{eV}^2$ mass-splitting.

Both SBNB and ICARUS detectors will look for sterile neutrino oscillation in both disappearance and appearance channels. In addition they will produce high statistics ν-Ar cross sections measurements and develop and tune event identification and reconstruction studies useful for future LAr-TPCs.

The ICARUS physics will also include the study of neutrino cross sections and interaction topologies at energies of interest to the long baseline research program with the multi-kt DUNE LAr-TPC detector. In addition to the BNB beam, ICARUS is also receiving, at 6° off-axis, the higher energy neutrinos from the Main Injector (NuMI) collecting a significant event statistics in the 0÷3 GeV energy range with a ~5% ν_e-enriched component from the dominant three body-decay of K produced

[1] MicroBooNE is now decommissioned, leaving only SBND and ICARUS as running detector in the program.

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at the target. The not negligeable ν_e components of the NuMI beam spectrum will grant ICARUS access to a rich BSM (Beyond Standard Model) search program, including Higgs portal scalar search, neutrino trident, heavy neutral leptons and light Dark Matter search.

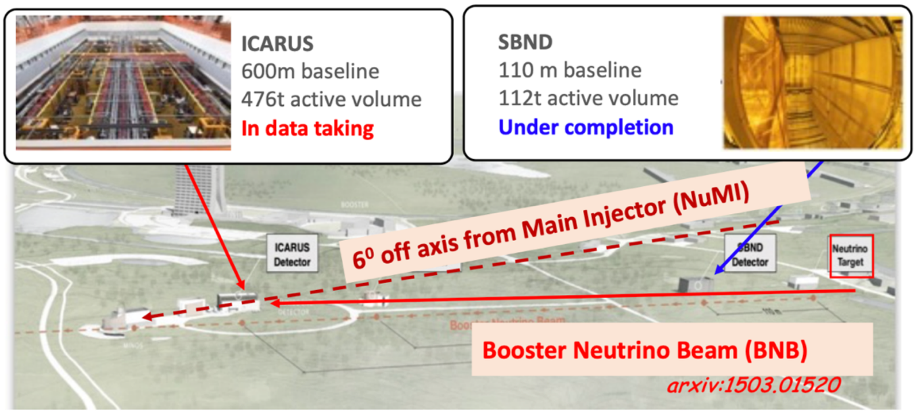

Figure 2. SBND and ICARUS location in the SBN program.

2.2 ICARUS esclusive analysis: testing Neutrino-4 claim

While SBND is preparing to join the SBN program, ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation claim in the same baseline over energy range (1÷3 m/MeV) but collecting 100 times more energetic events. The Neutrino-4 oscillation-like signal can be initially addressed by ICARUS at the BNB studying the ν_μ disappearance channel as a function of the neutrino energy, to be followed by an analogous search exploiting the NuMI beam enriched ν_e-signal.

3 The ICARUS detector

ICARUS-T600 is presently the largest liquid Argon detector operating in a neutrino beam and consists of two identical, but separated modules, filled overall with 760 t of LAr, with an active volume of 476 t. Each module, as shown in figure 3, houses two LAr-TPCs separated by a common cathode with a maximum drift distance of 1.5 m, equivalent to ~1 ms drift time for the nominal 500 V/cm electric drift field.

ICARU is a self-triggering detector with precise 3D imaging and calorimetric precision [7]. It operated underground for three years in the Gran Sasso laboratory (Italy) and then moved to Fermilab in 2017 after an extensive overhauling phase at CERN, needed for its new operating condition at shallow depth, which involved several subsystems: the cryogenics, the LAr purification system, the TPC readout electronics and the light detection system [8]. We are going to cover some of these here.

3.1 The TPC readout electronics

The TPC readout electronics was updated to be compliant with higher data rates at shallow depths using a front end electronics based on analogue low noise, charge sensitive preamplifiers [9]. This allowed a more compact layout with both analogue and digital electronics on the same board, as shown in figure 4. A signal shaping of ~1.3 µs, to match the electrons drift time between the wires' planes, improved the hits position resolution.

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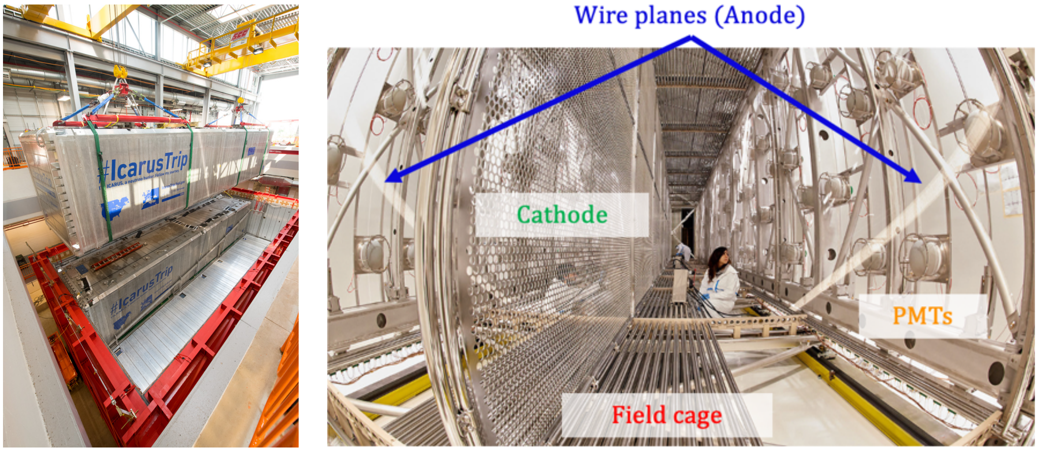

Figure 3. ICARUS cryostats being installed into the warm vessel (left). Internal view of one of the two cryostats during the CERN upgrade (right).

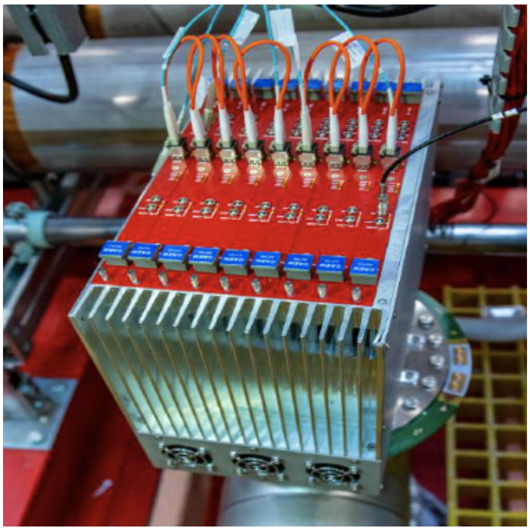

Figure 4. TPC minicrate hosting 9 readout boards (576 wires each) installed on top of one of the 96 feed-thought flanges.

3.2 The light detection system

The light detection system consists of 360 8" Hamamatsu PMTs (5% coverage, 15 phe/MeV) installed behind the wire planes, 90 PMTs per TPC chamber. The system allows a continuous readout, digitization and discrimination and waveforms recording of the PMT signals. The readout is performed by CAEN V1730 digitizer boards (24 in total) with a 500 MHz sampling rate, allowing signals sampling every 2 ns in a recording window of 10 µs [10].

The PMT gain was equalized at 0.45×10^7 ±1% with a photoelectron signal of 4 mV and a timing resolution of 1 ns, monitored by means of laser pulses (λ = 405 nm, FWHM = 60 ps).

The PMT signals are digitized by CAEN V1730 boards (see figure 5). These modules produce also LVDS logical outputs (8 LVDS per board), in terms of OR signals of adjacent PMTs above a set threshold. These signals are processed by an FPGA according to a majority logic to produce a

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Global Trigger (GT) if the majority logic is satisfied within the beam gate. This GT activates the acquisition of the TPC wires and PMTs waveforms. The recorded data is sent to the DAQ together with the information of the GT (such as time stamp, beam gate type, and more). The Cosmic Ray Tagger (CRT) data timing information is also recorded and is used offline during the event reconstruction to reject the cosmic background.

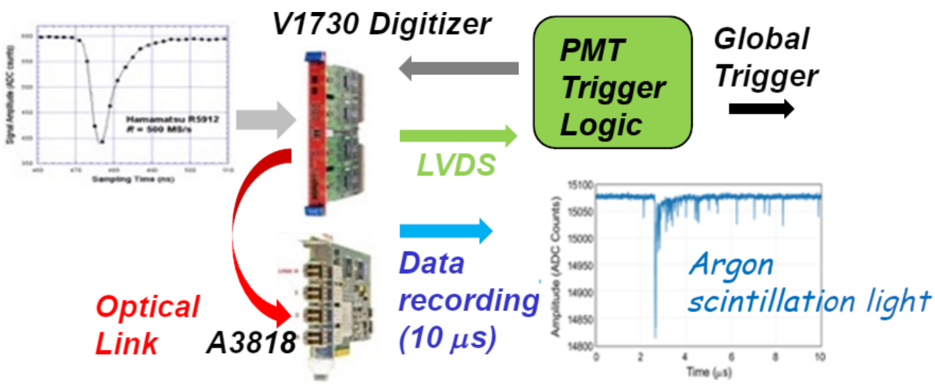

Figure 5. Conceptual design of the light detection system readout.

3.3 The Cosmic Ray Tagger system

Being on the surface, ICARUS is now exposed to a huge cosmic activity that can mimic neutrinos interaction and mask the real signal. To mitigate this background as much as possible, ICARUS was shielded with a ~3 m concrete overburden, placed on top of the detector. A $\sim 4\pi$ CRT system (see figure 6), was installed around the detector, consisting of 4 subsystem of scintillator bars equipped with Silicon Photo Multipliers (SiPMs) to tag cosmic incoming particle with a 95% efficiency. The coincidence of the CRT signals with the PMT light and charge from the TPC will be used for background rejection.

Figure 6. From the left: the sides CRT modules, the Top and the installation of the overburden's concrete blocks (eventually a 3 m thick layer).

3.4 The trigger system

The ICARUS trigger system exploits the coincidence of the BNB and NuMI beam spills, of 1.6 and 9.5 µs respectively, with the prompt scintillation light detected by the PMTs. The proton extraction is signaled to the experiment via beams' Early Warning signals distributed by a fully deployed White Rabbit network [11].

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The base trigger requires at least 5 fired PMT pairs during the beam spill window inside a 6 m longitudinal section of the detector, along the beam direction, with 30 + 30 facing PMTs, as shown in figure 7. The PMT and CRT signals are recorded within 2 ms window around the trigger timestamp to recognize the cosmic rays crossing the detector during the 1.3 ms drift time.

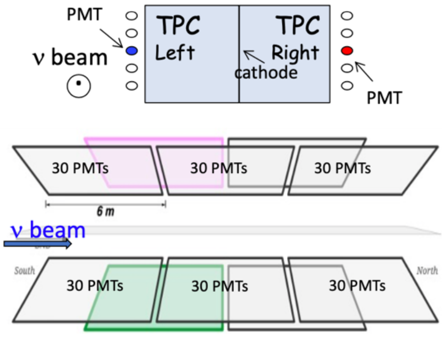

Figure 7. Picture showing the principle behind the majority trigger requirement of N pairs of PMTs above threshold in 5 longitudinal windows along the beam direction.

Figure 8 shows the trigger efficiency measured selecting vertical muon tracks reconstructed in the TPC and matched to CRT hits without any requirement on the PMT light signal, ie Minimum Bias events. A full efficiency is found for tracks length above 1 m (corresponding to a deposited energy E_{dep} of about 200 MeV) for in-spill triggers and a majority of 5 PMT pairs. Out-of-spill cosmic muons are recognized with an efficiency of only about 90% for tracks lengths >1.5 m and a majority trigger requirement of 8 PMT pairs.

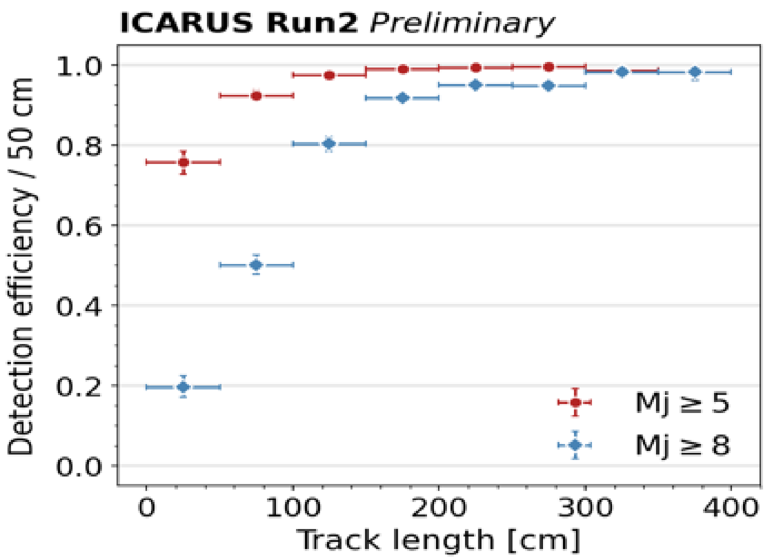

Figure 8. Preliminary trigger recognition efficiency as measured with almost vertical crossing cosmic muons as a function of the track length (1 m muon track corresponds to approximately $E_{dep}$of 100 MeV).

To improve the trigger efficiency on low energy events at $E_{dep} < 150$ MeV, an additional and independent trigger system is being implemented, based on the scintillation light signal amplitude instead of the multiplicity of fired PMTs. The system consists of 24 analog-adder boards, which sum

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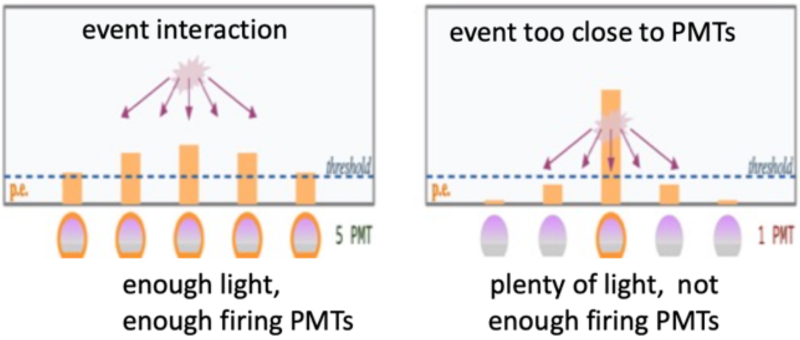

Figure 9. Majority trigger satisfied (left); analog-adders trigger satisfied (right).

up 5% of the light's signal of each group of PMTs in a 3 m detector slice. This way, we'll be looking at signals over a set threshold to identify PMTs that saw a lot of light. This system will recover events too close to PMTs in which the requested majority is not satisfied, as shown in figure 9. Preliminary studies of trigger efficiency show a 20% recovering of events missed by the majority trigger.

3.5 The data taking and overall detector performance

The commissioning phase started on March 2021 and physics quality data taking in June 2022 with two physics run period. The overburden installation resulted in a factor 2 reduction of the cosmic rays signal on the Top CRTs, as shown in figure 10. The data taking was steady with an uptime of ~93% and remarkably stable with the BNB beam at a nominal 4 Hz repetition rate, as shown in figure 11.

The free electron lifetime has been monitored by measuring the charge signal attenuation along cosmic muon tracks. A stable value of $\tau \sim 4.5$ ms was measured in the East cryostat during the whole commissioning phase and physics runs, whereas τ increased from 3 ms to 8.5 ms in the West one by regenerating the LAr cryogenic filters, as shown in figure 12. The filter regeneration in the East cryostat is planned for fall 2023 before the start of Run3.

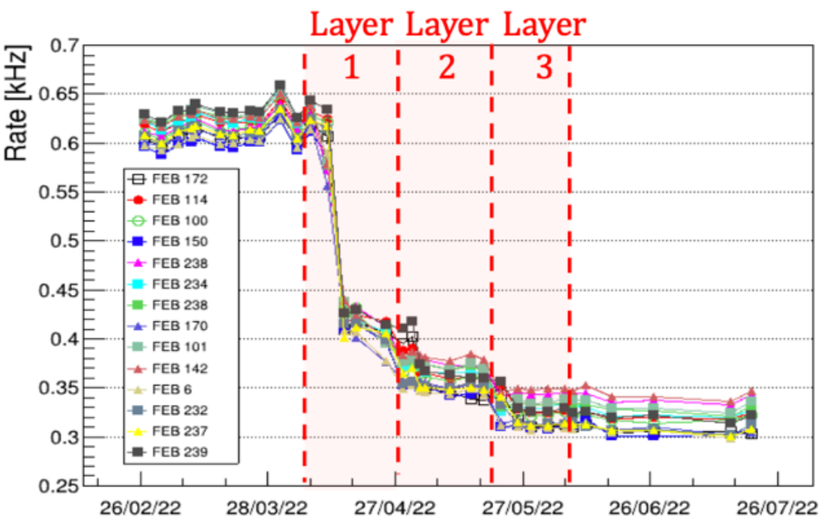

Figure 10. Reduction of cosmic background after the installation of 3 m concrete overburden.

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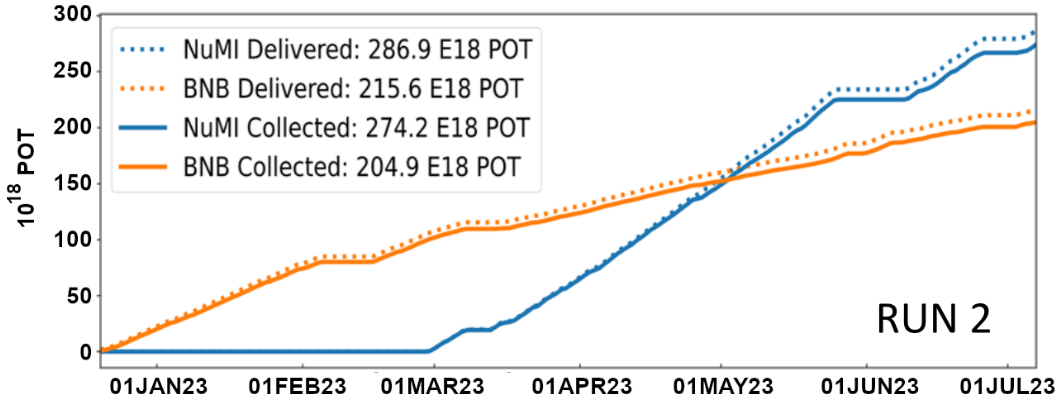

Figure 11. Delivered and acquired POTs (Proton on Target) during Run 2 data taking.

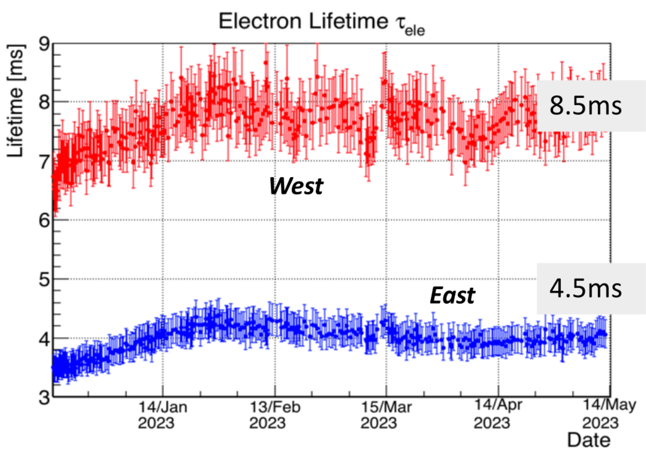

Figure 12. Electron lifetime monitoring plot.

4 Ongoing and future ICARUS research program

The Neutrino-4 search is the main focus of the ICARUS with Booster and NuMI data: a total of about 1500 ν_μ CC candidates visually selected/measured are being exploited to improve the automatic event selection and address the major event reconstruction issues. In the meantime, validation of the whole dataset is being pursued and a production of a million of MC events is planned to take place in fall 2023.

In parallel, study of ν_e and ν_μ events from NuMI will allow ICARUS to measure ν-Ar cross section and optimize ν reconstruction/identification in an energy range of interest for DUNE. The NuMI beam data will allow to search for sub-GeV Dark Matter signals.

The tuning of events reconstruction tools is underway using visually selected ν_μ CC events.

Automatic procedures for selecting events fully contained in the LAr active volume are underway. Among them: the reconstruction of the ν vertex endpoint within 2 cm; the study of particle identification for muons and protons; the demonstration of capability of particle identification and kinematic variable reconstruction in the transverse plane.

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5 Conclusions and perspectives

Since the completion of the commissioning phase in 2021, the ICARUS detector has been running smoothly collecting data with both BNB and NuMI beams accumulating a total sample of $2.5{\times}10^{20}$BNB and $3.4{\times}10^{20}$ NuMI POT. Neutrino candidates have been successfully collected and are being used to further develop and tune automatic selection and reconstruction software tools. The ICARUS experiment will focus first on the study of Neutrino-4 claim, searching for ν_μ disappearance in the BNB sample and ν_e appearance in the NuMI off-axis data. The collaboration is working towards producing a first analysis by the end of 2023. After this ICARUS- standalone phase and after the near detector comes alive in taking data, a definite 5σ CL analysis of sterile neutrino will become a reality. Overall, ICARUS is well on its way to report exciting physics results soon.

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