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

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The Short Baseline Neutrino program at Fermilab will address one of the most urgent question in the neutrino physics scenario, namely the possible existence of a sterile neutrino at 1 eV mass scale, as suggested by past experimental anomalies. The experiment will search both ν_e appearance and ν_μ disappearance with the Booster Neutrino Beam. After a significant overhaul at CERN, the Short Baseline Neutrino Far Detector, ICARUS T600, was installed at Fermilab. The detector has started operations in summer 2020 and its commissioning was completed in May 2022, collecting the first neutrino events from the Booster Neutrino Beam and the Neutrinos at the Main Injector off-axis beam. In this paper the ICARUS status and plans for data analysis are addressed as well as the ongoing developments of the analysis tools needed to fulfill its physics program.

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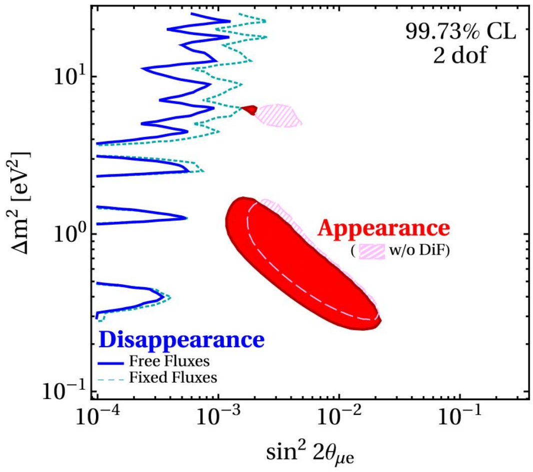


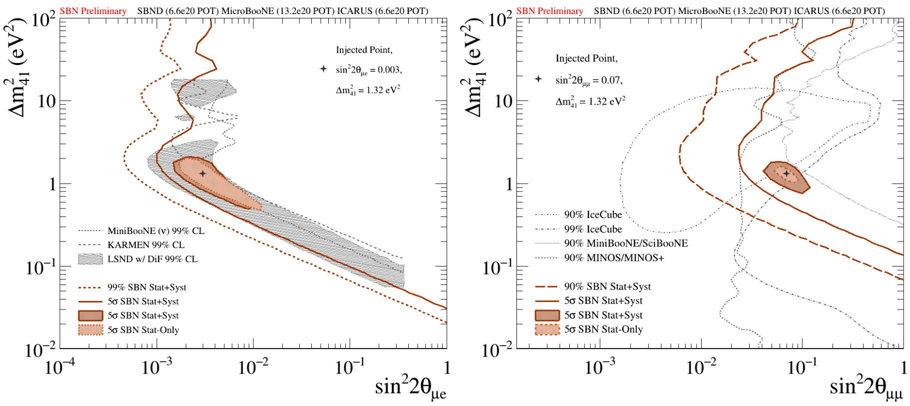
Figure 1: Allowed regions in the $\sin^2 2\theta_{e\mu} - \Delta m^2_{41}$ plane obtained from fits of appearance and disappearance data. The blue curves show limits from the disappearance data that strongly excludes the parameter region favoured by appearance data.

1. The sterile neutrino puzzle

The paradigm of three standard neutrinos oscillations has been confirmed by several experiments. However, existing experimental anomalies may indicate the existence of at least one additional neutrino, the so called sterile neutrino, at eV mass scale. The LSND experiment [1] observed an excess of $\overline{\nu}_e$ events at a distance $L \sim 30$ m in a beam of $\overline{\nu}_\mu$ with a significance of 3.8 σ. The radiochemical experiments GALLEX and SAGE [2, 3] found an observed over predicted ratio of ν_e flux produced from calibration sources R = 0.84 ± 0.05 which indicates a ν_e disappearance signal, recently confirmed at 4 σ by the BEST experiment [4]. Another indications consists in the reactor antineutrino anomaly [5] with ~ 3 σ sensitivity, which is a deficit of the rate of $\overline{\nu}_e$ observed in several short-baseline reactor neutrino experiments in comparison with that expected from the calculation of the reactor neutrino fluxes. These anomalies can be explained by neutrino oscillations generated by a squared-mass difference of $\Delta m^2_{41} \sim 1$ eV^2. Further tests have been performed at short-baseline accelerator experiments: the MiniBooNE collaboration observed an electron-like excess both in ν and $\overline{\nu}$ mode with a significance of 4.7 σ [6] while the MicroBooNE experiment found no evidence of oscillations into light sterile neutrinos [7]. Fig. 1 shows the allowed regions in the plane $\sin^2 2\theta_{e\mu} - \Delta m^2_{41}$ obtained in the hypothesis of oscillations into one light sterile neutrino. The combined disappearance constraint in that plane excludes the region allowed by ν_e appearance data, leading to the appearance-disappearance tension. Furthermore, in 2019 the Neutrino-4 short baseline reactor experiment claimed a signal from the disappearance of $\overline{\nu}_e$ at $\Delta m^2 \sim 7$ eV^2 and $\sin^2 2\theta \sim 0.36$ [8].

2. The Short Baseline Neutrino program

The Short Baseline Neutrino (SBN) program at Fermilab was designed in order to definitively confirm or rule out the light sterile neutrino hypothesis. The main goal is to measure both ν_e



(a) **(b)**

Figure 2: (a) Constraints on the ν_e appearance and (b) on the ν_μ disappearance set by SBN at 99 % (dashed line) and at 5 σ sensitivity (solid line) after 3 years of data taking.

appearance and ν_μ disappearance exploiting three Liquid Argon Time projection Chambers (LArTPCs) located at different positions along the ~ 0.8 GeV ν_μ Booster Neutrino Beam (BNB): the Near Detector (ND) SBND at 110 m, the already existing MicroBooNE detector at 470 m and the Far Detector (FD) ICARUS located at 600 m from the neutrino source, respectively. By combining data from the three detectors, SBN will reach a 5 σ sensitivity to a light sterile neutrino in 3 years of data taking, corresponding to $6.6 \times 10^{2}0$ POT (Proton On Target) exposure, as shown in Fig. 2 (a) and (b). In addition, being located 6° off-axis along the Neutrinos at the Main Injector (NuMI) beam, ICARUS will collect a large event sample from the ν_e component in the 0-3 GeV energy range, allowing to perform high precision measurement of ν Argon cross sections and test interaction models in the few hundred MeV to few GeV energy range extremely useful for SBN oscillation analysis and for the upcoming DUNE experiment [9] as well as search for Physics Beyond the Standard Model (Higgs portal scalar, neutrino tridents, light dark matter, heavy neutral leptons, etc...).

The first analysis that will be performed using ICARUS-only data is the study of the Neutrino-4 anomaly by measuring the disappearance of ν_μ from BNB, focusing on contained quasi-elastic (QE) ν_μ charged current (CC) interactions and the disappearance of ν_e from NuMI beam, selecting contained QE ν_e CC candidates. For the former analysis the statistics is already available. The latter analysis will allow a more direct comparison with Neutrino-4 results.

3. The ICARUS detector and its performances

ICARUS is a self-triggering detector that successfully ran at Laboratori Nazionali del Gran Sasso from 2010 to 2013 as the first and largest LArPTC ever operated collecting a statistics of 8.6 $\times 10^{19}$ POT from the Cern Neutrino to Gras Sasso beam. ICARUS underwent an overhauling at CERN in the years 2015 - 2017 and in 2018 was transported to FNAL where it was installed in the Far detector hall. In 2020 began the filling with LAr and the commissioning. ICARUS then started its operations collecting the first neutrino events from BNB and NuMI beams [10].

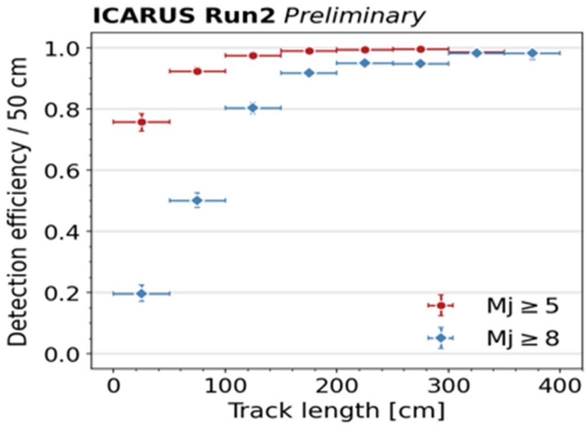


Figure 3: The trigger efficiency measured exploiting almost vertical cosmic muons independently selected by TPC tracks matched with CRT signals.

LArTPCs are ideal detectors for neutrino physics with excellent imaging and calorimetric capabilities allowing to reconstruct events with complex topologies. Charged particles in LAr emit scintillation light (40000 γ/MeV at λ = 128 nm and E_D = 0 V/cm) detected by PhotoMultipliers Tubes to provide the event time and the trigger to start events' acquisition. Charged particles also ionize the LAr producing electrons (42000 e^-/MeV) that drift towards readout sense wires: by combining the wire coordinates at the same drift time a 3 D track reconstruction with ~ 1 mm spatial resolution is achieved. ICARUS is composed of two identical modules 19.6 (L) × 3.6 (W) × 3.9 (H) m^3 each with a total (active) LAr mass of 760 (476) tons. Each module is placed inside a cryostat (East and West) and is divided in two TPCs with a common central cathode producing an electric field of 500 V/cm along 1.5 m drift length. Each TPC has three parallel anode wires planes at different orientation (0°, ± 60°) w.r.t. the horizontal to readout continuously the ionization charge. The ionization charge is collected by the outermost plane (collection plane), while the innermost planes (induction planes) provide a non destructive charge measurement. The detector is fully instrumented with 360 Hamamatsu PMTs installed behind the wire planes and coated with tetra-phenyl butadiene to convert the VUV photons into visible light. Laser sources (λ ~ 405 nm) and cosmic rays data were used to calibrate and equalize the PMT gain and the timing [11].

Since at Fermilab ICARUS operates at ground level, the cosmic rays induced background must be mitigated. To this end 3 m of concrete overburden was installed reducing the rate of cosmic neutrons and γ by a factor 200 and of muons by 25%. The residual cosmic ray induced activity is identified by a Cosmic Ray Tagger (CRT) system ensuring 4π coverage of the detector with 95% tagging efficiency, few ns time resolution and ~ cm spatial resolution. The CRT system is made by modules of plastic scintillator bars with embedded Wavelength Shifter (WLS) fibers coupled to Silicon Photomultipliers (SiPM). Coincidence of CRT signals with the light signal in PMTs and the matching with TPC tracks ensures a cosmic background rejection which is crucial for rejecting γs produced by muon interactions in the surrounding materials that can generate an electromagnetic shower miming a ν_e signal.

The ICARUS main trigger signal is generated by a majority of discriminated pairs of PMT signals in coincidence with BNB (1.6 μs) and NuMI (9.5 μs) beams spill gates distributed via White

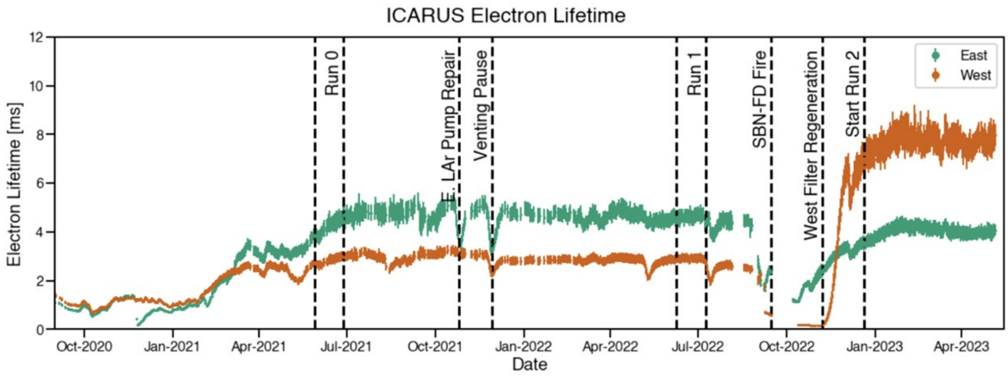


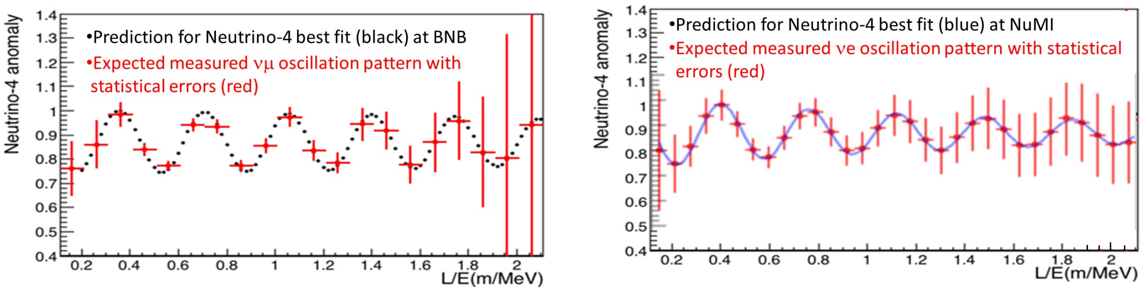
Figure 4: The electron lifetime monitored during the detector operations.

Rabbit network. Beam events are collected requiring at least 5 fired PMT pairs inside a limited TPC region. In presence of a global trigger signal, 1.5 ms and 30 μs acquisition windows are activated for the TPC and PMT signal recording, respectively. In addition, PMT waveforms and CRT signals are collected inside 2 ms and 6 ms time windows around the beam spill, respectively, to record all cosmic muons crossing the TPCs during the electron drift time. In Fig. 3 is shown the ICARUS trigger efficiency that has been measured exploiting almost vertical cosmic muons independently selected by TPC tracks matched with CRT signals. The efficiency is almost 1 for in-spill events with one track above 1 m length (deposited energy $\sim$ 200 MeV).

The LAr purity, namely the free electron lifetime in LAr, is a fundamental parameter to be continuosly monitored in order to ensure an accurate measurement of the energy deposition from the ionization charge signal in the collected events. The electron lifetime is evaluated by measuring the charge attenuation along the drift path of the electron ionization signals generated by cosmic ray tracks crossing both the anode and the cathode. In Fig. 4 is shown the electron lifetime monitored since the commissioning and during the physics runs for both the east and west cryostats: except for variations above the error bars due to maintenance of argon pumps, the purity has a steady behaviour with a value > 3 ms which ensure a precise reconstruction of ionizing events. Improvements in increasing the electron lifetime are achieved by regeneration of LAr purity filters performed during summer shutdowns.

4. Data analysis

Since June 2022 ICARUS started to take physics quality data during *Run1* (June - July 2022) and *Run2* (December 2022 - July 2023) collecting a total statistics of 2.46$\times 10^{20}$ POT for BNB and 3.42$\times 10^{20}$ POT for NuMI beams. Reconstruction and analysis tools have been developed and calibrated with real data. These tools are based on pattern recognition algorithms specifically



(a) **(b)**

Figure 5: Survival oscillation probabilities as a function of L/E for ν_μ at BNB (a) and for ν_e at NuMI (b) expected to be osbserved by ICARUS in presence of Neutrino-4 anomaly after collecting 8.4×10^{19} pot for BNB and 9×10^{20} pot for NuMI.

developed for LArTPC detectors [12] in order to perform a 3D reconstruction of the full image recorded of the collected event, including the identification of interaction vertices and of tracks and showers inside the TPC. A parallel method based on machine learning technique is also under study.

Significant overlap of L/E coverage between ICARUS and the Neutrino-4 experiment will allow one to settle the the sterile-ν claims with initial ICARUS-only data. An oscillation should produce a disappearance pattern of ν_μ in BNB and of ν_e in NuMI in the same L/E ratio ~ 1-3 m/MeV range but with events collected with ~ 100 times the energy. In Fig. 5 are shown the survival oscillation probabilities as a function of L/E for ν_μ at BNB (a) and for ν_e at NuMI (b), respectively, expected in the presence of Neutrino-4 anomaly after collecting 8.4×10^{19} pot for BNB and 9×10^{20} pot for NuMI. The former is obtained selecting 8500 QE ν_μ CC contained events from a BNB sample with a muon track > 50 cm while the latter selecting 5200 QE ν_e CC events from a NuMI sample with a contained electromagnetic shower. For this analysis a preliminary automatic procedure for selecting ν_μ CC QE interactions with one muon and one proton fully contained in the LAr active volume is being prepared starting from Monte Carlo (MC) events. In order to select QE ν_μ CC candidates with high purity the following criteria must be satisfied:

- the ν interaction vertex must be inside the fiducial volume, i.e. 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls, respectively;
- the interaction must be fully contained in the active volume;
- the presence of a stopping muon of $L_\mu > 50$ cm.

To further simplify, the presence of only one proton produced at the primary vertex with $L_p >$ 1 cm is required. The distribution of the reconstructed neutrino energy for the selected QE ν_μ CC candidate is shown in Fig. 6 for MC events. Improvements of the selection criteria are under study such as exploiting CRT-PMT matching for cosmic background rejection, upgrade of calibration, tuning of event reconstruction and include events with multiple proton in the selection.

Events selected manually by a visual scanning procedure are used to validate the automatic event selection. In Fig. 7 is shown a BNB QE ν_μ CC candidate with one muon and one proton

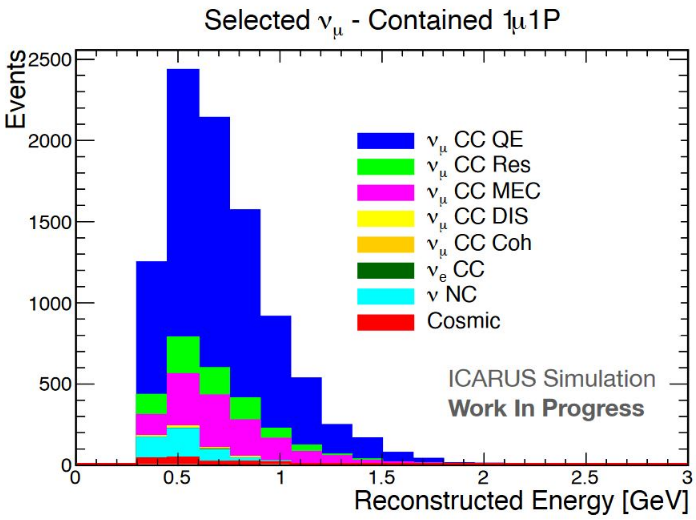


Figure 6: Distribution of the reconstructed neutrino energy for the selected QE ν_μ CC candidate for MC events.

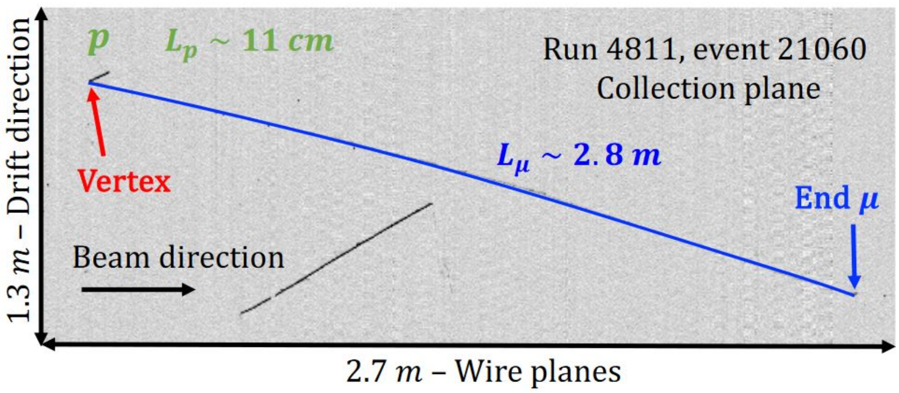


Figure 7: A BNB QE ν_μ CC candidate with 1 muon and 1 proton at the primary vertex found by the visual scanning procedure.

at the primary vertex found by the visual scanning procedure. For each visually scanned event the measured 3D position of the vertex, the end muon and the end proton positions are compared with the quantities reconstructed by the automatic software tool. For example, in Fig. 8 is shown the difference between automatic and manual measured longitudinal coordinate of the neutrino interaction vertex for a sample of BNB ν_μ CC candidate: in 90 % of these events the differences between the two estimates is within 3 cm. The particle identification is performed exploiting the dE/dx versus range measurement and comparing the measured values with the theoretical profiles from different particles.

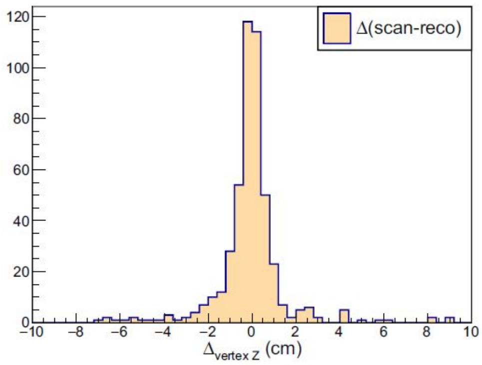


Figure 8: Difference Δz between automatic and manual measured longitudinal coordinate of the neutrino interaction vertex for a sample of BNB ν_μ CC candidate.

5. Conclusions and perspectives

ICARUS has been taken physics data in stable conditions since June 2022 with both BNB and NuMI beams. The neutrino candidates have been successfully collected and are being used to further develop and tune the automatic selection and reconstruction software tools. First ICARUS will study the Neutrino-4 claims by measuring the ν_μ disappearance from BNB and the ν_e disappearance from NuMI. After the ICARUS-only phase, the SBND detector will join the SBN program as the near detector from the BNB target. A joint analysis between the two detectors will allow to confirm or exclude definitively the light sterile neutrinos hypothesis in 3 years of data taking with 5 σ sensitivity.

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