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Short Baseline neutrino oscillation searches with the ICARUS detector at Fermilab

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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, by searching both ν_e appearance and ν_μ disappearance with the Booster Neutrino Beam. The Short Baseline Neutrino Far Detector, ICARUS T600, successfully operated at Laboratori Nazionali del Gran Sasso from 2010 to 2013 studying neutrino oscillations with the CERN Neutrinos to Gran Sasso beam. ICARUS performed a sensitive search for Liquid Scintillator Neutrino Detector-like anomalous ν_e appearance in the CERN Neutrinos to Gran Sasso beam, constraining the allowed parameters to a narrow region around 1 eV^2. After a significant overhaul at CERN, ICARUS 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 ICARUS achievements are addressed as well as its status and plans for the new run at Fermilab and the ongoing developments of the analysis tools needed to fulfill its physics program.

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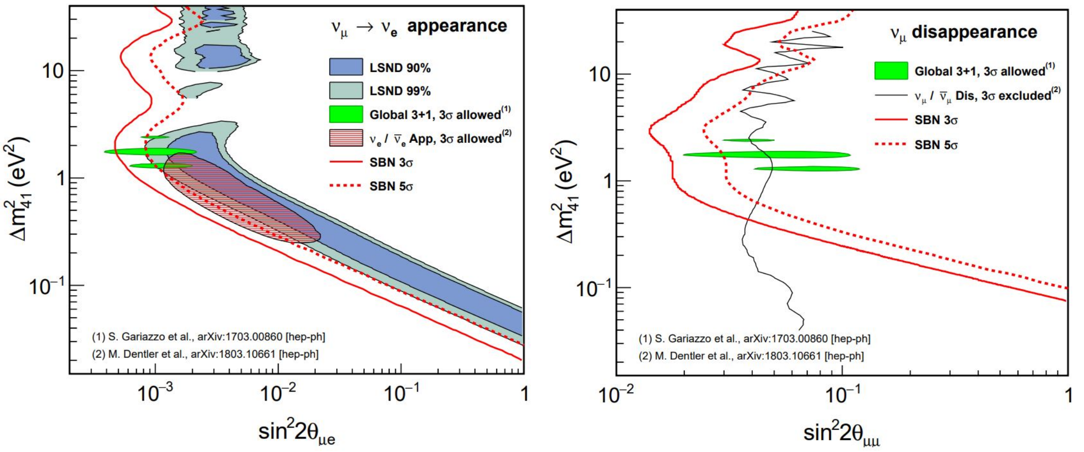

Figure 1: Expected SBN 3σ (solid red line) and 5σ (dotted red line) sensitivities to a light sterile neutrino in the $\nu_\mu \rightarrow \nu_e$ appearance channel (left) and in the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel (right) in 3 years of data taking.

1. The Short Baseline Neutrino and ICARUS Physics program

The Short Baseline Neutrino (SBN) program aims to confirm or definitively rule out the existence of a light sterile neutrino as hinted by experimental anomalies [1–3], namely a fourth neutrino that doesn't interact weakly but participates to the oscillations with the three standard neutrinos. The main goal is to measure the $\nu_\mu \longrightarrow \nu_e$ neutrino oscillations at ~ 1 km/1 GeV exploiting three Liquid Argon Time Projection Chambers (LArTPCs) located at different positions along the ν_μ Booster Neutrino Beam (BNB) (E_ν ~ 0.8 GeV) at Fermilab: the Short Baseline Near Detector (SBND) at 110 m, the already existing MicroBooNE detector at 470 m and the Far Detector (FD) ICARUS T600 at 600 m from the neutrino source, respectively. By combining ND and FD data, SBN will reach a 5σ sensitivity to a light sterile neutrino in 3 years of data taking (6.6×10^{20} pot) as shown in Fig. 1. Additionally, being located 6° off-axis along the Neutrinos at the Main Injector (NuMI) beam, ICARUS T600 will collect a large event sample from the ν_e NuMI component in the 0-3 GeV energy range, that will allow to perform precision measurements of ν Argon cross section, test interaction models in the few hundred MeV to few GeV energy range extremely useful both for SBN oscillation analysis and for the upcoming DUNE experiment [4] as well as search for Physics Beyond the Standard Model (Higgs portal scalar, neutrino tridents, light dark matter, heavy neutral leptons, etc...). The Neutrino-4 short baseline reactor experiment recently claimed a signal from the disappearance of reactor $\overline{\nu_e}$ at Δm^2 ~ 7 eV^2 and mixing angle $\sin^2 2\theta$ ~ 0.36 [5]. ICARUS can confirm or exclude the Neutrino-4 oscillation signal by measuring disappearance of ν_μ from BNB, focusing on contained quasi-elastic (QE) ν_μ charged current (CC) interactions (~ 11500 events in 3 months) and disappearance of ν_e from NuMI beam, selecting contained QE ν_e CC candidates (~ 5200 events per year). The ν_μ survival oscillation probability expected in the presence of Neutrino-4 anomaly is shown in Fig. 2.

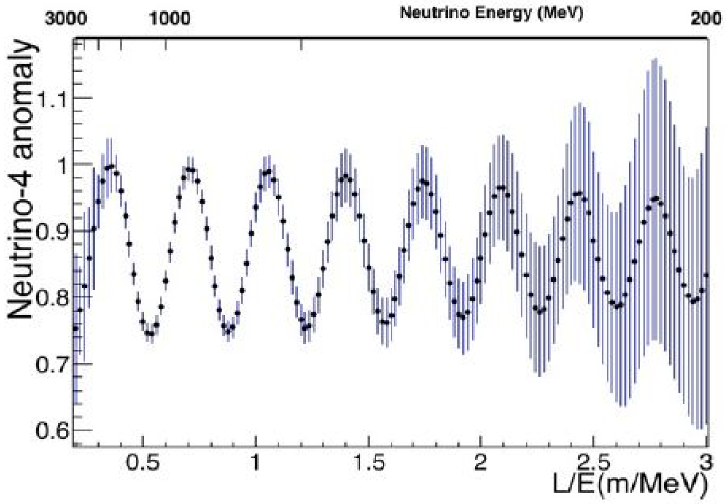

Figure 2: Survival oscillation probability as a function of L/E for ν_μ expected to be observed by ICARUS in 3 years of data taking in presence of the Neutrino-4 anomaly. Bars are statistical errors.

2. The ICARUS T600 detector

The ICARUS T600 detector is composed of two identical modules 19.6 (L) x 3.6 (W) x 3.9 (H) m^3 each with a total (active) LAr mass of 760 (476) tons. Each module is divided in 2 Time Projection Chambers (TPCs) with a common central cathode at 75 kV producing an electric field of 500 V/cm along 1.5 m drift length. The anode in each TPC is made of three parallel wire planes oriented at different angle (0°, ±60°) with respect to horizontal direction. The ionization charge is collected by the outermost plane (collection plane), while the innermost planes (induction planes) provide a non destructive charge measurement. By combining wire coordinates at the same drift time a 3D track reconstruction with a $O(1\text{ mm})$ resolution is achieved. Given their excellent imaging and calorimetric capabilities, LArTPCs are ideal detectors for neutrino physics. For example, the combination of the event topology reconstructed in different views with the dE/dx measurement allows distinguishing between electromagnetic showers generated by γ or by electrons, resulting in a high ν_e identification efficiency [6]. Additionally, the TPC is instrumented with 360 PhotoMultiplier Tubes (PMTs) to detect the scintillation light and to provide the event time and the trigger.

At Fermilab ICARUS is operated at ground level. The cosmic rays induce a background which has to be mitigated, as, in particular γ produced by cosmic muons interacting in the surrounding materials and mimicking a ν_e signal. 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, estimated as $\sim$ 11 muon tracks in 1 ms TPC readout, is identified by a Cosmic Ray Tagger (CRT) system ensuring 4π coverage of the detector with 95% tagging efficiency and few ns time resolution. The CRT system is made by modules of plastic scintillator bars with embedded Wavelength Shifter (WLS) fibers coupled to Silicon Photomultipliers (SiPM).

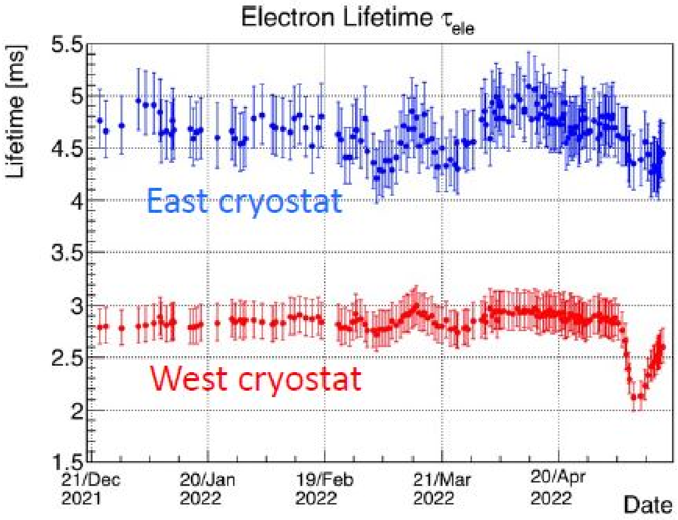

Figure 3: Electron lifetime for east and west cryostats monitored during the detector commissioning phase. Bars indicate statistical and systematic errors. Fluctuations above the error bars are due to maintenance operations of argon pumps.

3. ICARUS T600 calibration and event reconstruction

After a significant detector overhauling at CERN, ICARUS T600 was moved at Fermilab and installed at SBN FD location. In 2020 the detector commissioning began with detector cool down, liquid Argon filling and recirculation. The first neutrino events from BNB and NuMI beams were detected in March 2021 and the detector ended its commissioning phase in May 2022 with the installation of overburden. In June 2021 and 2022 ICARUS took data continuously as primary BNB user during *Run 0* and *Run 1* collecting 2.7 $\times 10^{18}$ and 41.1 $\times$ 10^{18} pot, respectively.

The main trigger signal is generated by a majority of discriminated PMT pairs with a light signal $>$ 13 p.e. in coincidence with BNB or NuMI spill gates (1.6 μs and 9.6 μs width, respectively), distributed via White Rabbit network. PMT light and CRT signals are recorded around the trigger time to recognize and tag cosmics crossing the detector during 1 ms drift time. Additional trigger signals are generated for calibration purposes outside beam spills to detect cosmic rays interactions.

The LAr purity which determines the free electron lifetime in LAr is a fundamental parameter to be monitored to ensure an accurate measurement of the energy deposition from the ionization charge signals. The e 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. The electron lifetime measured in East and West cryostats during the commissioning period is plotted in Fig. 3: 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.

Reconstruction and analysis tools have been developed and calibrated with real data. For example, cosmic muons tracks that crossed both the anode and the cathode are used to measure the drift velocity, to provide an absolute calibration of the wire signal response and to quantify the

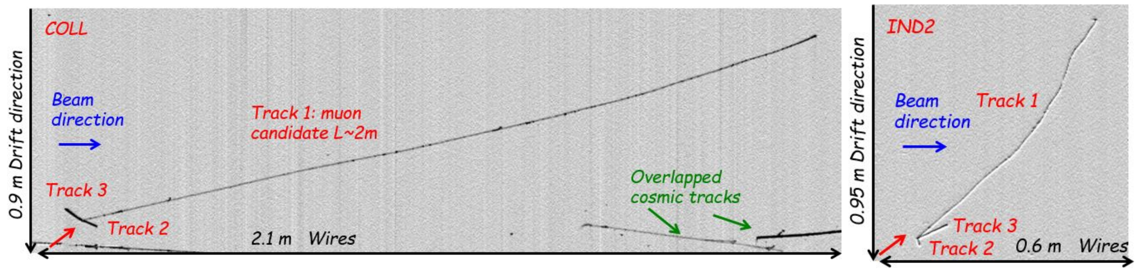

Figure 4: Display of a ν_μ CC QE interaction of a BNB neutrino in ICARUS detector. Track 1 is a stopping muon candidate with a length L = 2 m, track 2 and 3 are proton track candidates with L = 4.6 cm and L = 12.9 cm, respectively. The total deposited energy is ~ 600 MeV.

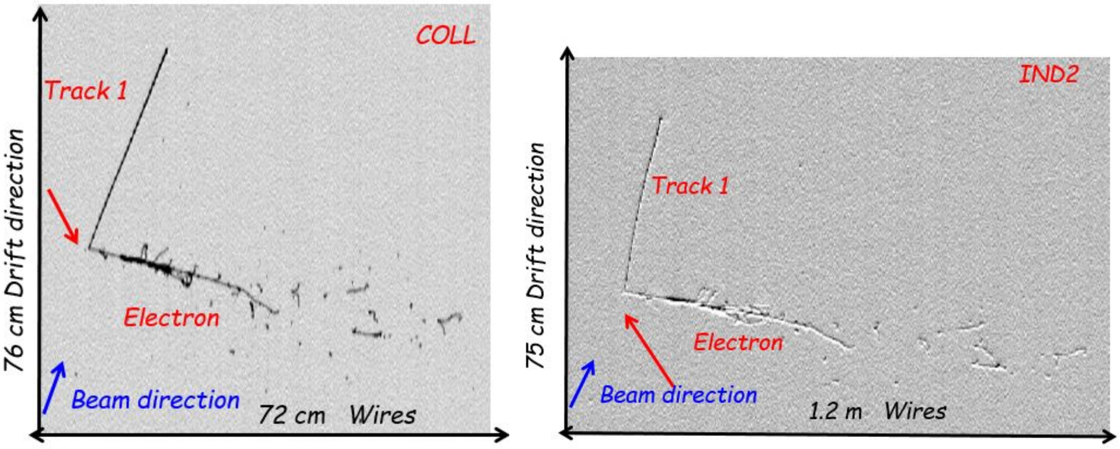

Figure 5: Display of a contained ν_e CC QE interaction of a NuMI neutrino in ICARUS detector with two tracks at the primary vertex: the electron generating the electromagnetic shower and a hadron (a proton's or pion's track) candidate stopping in L = 43 cm. The total deposited energy is ~ 600 MeV.

signal distortion due to space charge effects. The TPC track reconstruction algorithm is based on multiple steps: a pre-processing of the raw data, wire signal identification to reconstruct the hits and track/shower like particle reconstruction. A visual scanning procedure is foreseen to study the detector behaviour and to identify neutrino events candidates. An automatic event selection procedure is still under development and is tuned and tested by means of the neutrino events selected by visual scanning. The particle identification is performed exploiting the dE/dx versus range measurement [7]. Some examples of collected neutrino events identified with the visual scanning are shown in Fig. 4 and Fig. 5 for ν_μ CC QE and ν_e CC QE candidates, respectively, where the left picture is the event projection on collection plane and the right picture is the event projection on one of the induction planes. The excellent spatial resolution of these reconstructed event images combined with energy loss measurement at the beginning of the shower allows a clear e/γ separation.

4. Conclusions and perspectives

The SBN program at Fermilab will provide the ultimate solution to the sterile neutrino puzzle by measuring the ν_e appearance and ν_μ disappearance oscillation channels in 3 years of data taking. The ICARUS detector started operations since summer 2020 collecting data on cosmic muons and beam neutrinos. These data allowed an accurate detector calibration and tuning of simulation and reconstruction tools. The detector commissioning was completed in May 2022. The new physics run data taking is expected to start in autumn 2022.

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