PROCEEDINGS OF SCIENCE

Short-baseline neutrino oscillation searches with the ICARUS detector

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The ICARUS detector represents the first large-scale example of the LAr-TPC detection technique for neutrino and rare event physics. Its underground run at LNGS (2010-13) provided important results in the search for sterile neutrinos.
The Short Baseline Neutrino program at Fermilab will further address the sterile neutrino puzzle, confirming or disproving the existence of a fourth neutrino flavour in both appearance and disappearance channels. ICARUS will act as the SBN far detector, taking advantage of the excellent reconstruction capability of LAr-TPC.
The ICARUS commissioning phase, culminating in the "Run 0" in June 2021, has largely been successful, confirming that ICARUS is able to take physics data continuously with high live-time. The first physics run is planned to start in October 2021.

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1. The sterile neutrino puzzle

The sterile neutrino puzzle is one of the most urgent open questions in the current neutrino physics scenario. While most experimental results in the last 20 years agree with the 3-flavor oscillation paradigm, a few results [1] appear to point to flavor change characterized by an $L/E \sim 1m/MeV$, corresponding to a possible fourth neutrino mass eigenstate with a mass in the region of a few electron-volts. This neutrino would necessarily be sterile, i.e. not involved in the known Standard Model weak interaction.

No phenomenological model, however, appears to be able to accommodate this possible evidence of sterile neutrinos with the negative results coming from other experiments [2]; the issue remains far from being fully understood, and a definitive clarification is needed. Moreover, a recent result from the Neutrino-4 experiment [3] claims a signal from the disappearance of reactor anti-neutrinos with a large $\Delta m^2 \sim 7eV^2$ and a relatively large mixing angle $\sin^2\theta \sim 0.26$.

2. SBN and ICARUS physics goals

Several experiments both at reactors and accelerator are proposed or already running with the goal of confirming or disproving the sterile neutrino hypothesis. Among them, the Short Baseline Neutrino (*SBN* [4]) project at Fermilab has the capability of studying it in both appearance and disappearance channel, with the same beams and detectors. SBN will exploit two well-characterized ν_μ beams (BNB and NUMI off-axis), searching for both ν_e appearance and ν_μ disappearance.

Neutrino beams will be observed by very similar near and far detectors, both based on the Liquid Argon Time Projection Chamber (*LAr-TPC*) technology. The near detector (SBND) will characterize the beam at a short distance ($\sim$ 100 m) from the target, before oscillation effects can take place, while the far detector (ICARUS) will observe neutrinos at a distance of 600 m, allowing an L/E ratio in the sterile neutrino range. Any difference observed in the spectra at the near and far detectors, except for the expected solid-angle corrections, will be an evidence of new physics.

The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5σ sensitivity, both for appearance and disappearance channels, in 3 years of data taking (see Fig. 1).

In addition, SBN will provide high-statistics samples of neutrino cross-section measurement with both BNB and NuMI beams, which will be greatly useful for the future DUNE experiment [5]. Even before SBND (whose commissioning is expected in 2022) starts taking data, ICARUS alone will be able to confirm or refute the recent Neutrino-4 claim in less than one year (see fig.2). The verification of the Neutrino-4 claim will be performed both in the ν_μ disappearance channel with the BNB neutrinos, and in the ν_e disappearance channel, making use of the contamination component in the NuMI beam. In the first case, $\sim$ 11500 events are expected in 3 months of data-taking, allowing to observe the Neutrino-4 oscillation pattern, as shown in Fig. 2.

3. The ICARUS-T600 detector and its commissioning at FNAL

ICARUS-T600, with $\sim 760t$ of total mass, represents the first large-scale example of the LAr-TPC technology The charge signals generated by drifting electrons from LAr ionization provide a

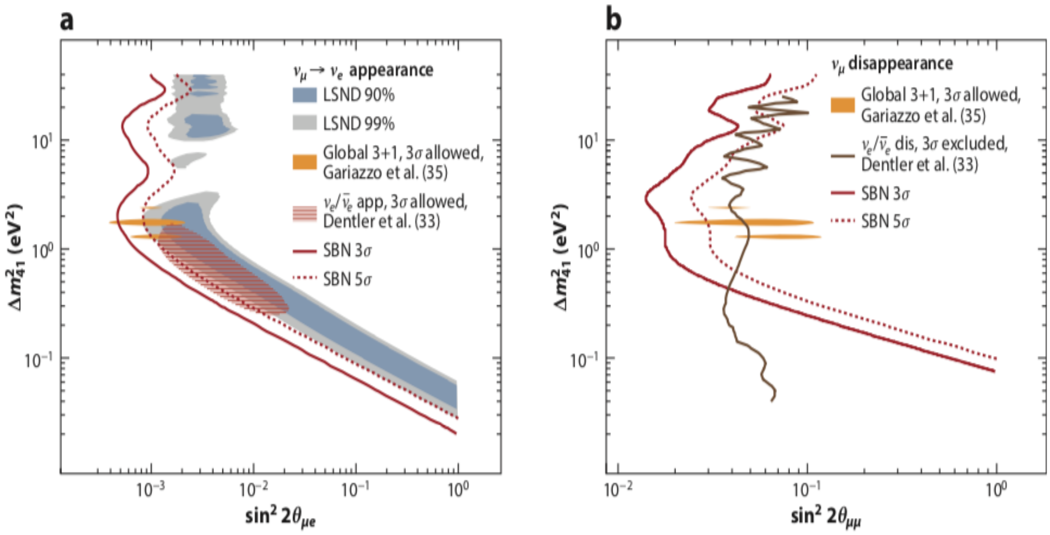

Figure 1: Left: sensitivities of SBN after 3 years for appearance (left) and disappearance (right) channels, compared with LSND allowed region and global fits (see [6] and references therein for detail).

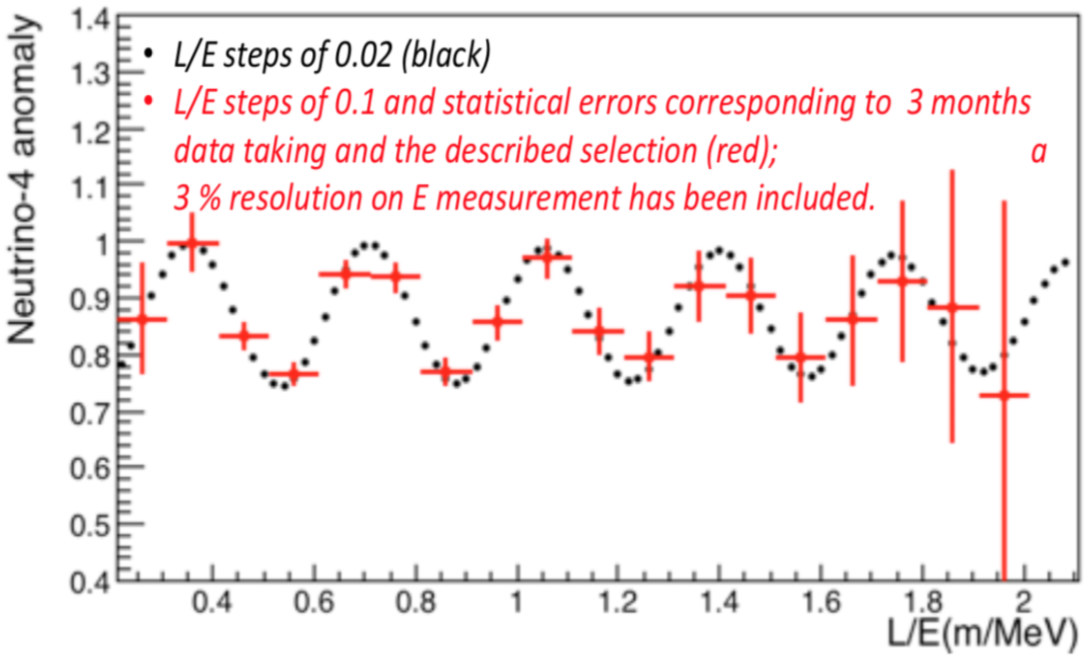

Figure 2: Expected disappearance probability for BNB muon neutrinos, as a function of L/E, for 3 months of ICARUS data-taking, assuming the best-fit Neutrino-4 oscillation parameters.

3D reconstruction capability with high (~ 3 mm) resolution, with homogeneous calorimetry, for a large variety of ionizing events. In particular, the accurate measurement of ionization density (dE/dx) allows distinguishing electron- and photon-generated electromagnetic showers, resulting in a very good identification of ν_e interactions. Moreover, the LAr scintillation light, read out by PMTs immersed in Argon, provide fast signals for triggering and timing purposes. Further details on the ICARUS detector features and performances can be found in [7].
The data-taking of ICARUS-T600 in the underground LNGS laboratory with the CNGS neutrino beam, from 2010 to 2013, proved for the first time the maturity of the Liquid Argon technology for a large-scale neutrino experiment. It also provided important physics results, including a search for sterile neutrinos through $\nu_\mu \to \nu_e$ oscillation that helped constrain the allowed parameter space (see [8]).
Unlike at LNGS, The ICARUS operation at Fermilab is taking place on the Earth's surface, resulting in a more challenging environment for a LAr-TPC, due to the cosmic rays impinging into the detector volume. This problem will be mitigated by the installation of a concrete overburden of ~ 2.85 m thickness on top of the detector, that will reduce primary cosmic neutrons and photons by a factor ~ 200 and muons by ~ 25%; the residual muon rate has been estimated as ~ 11 cosmic muons during the ~ 1 ms ICARUS drift window. In particular, photons associated to those muons, through Compton scattering or asymmetric pair production, can mimic the ν_e signal searched in oscillation studies, resulting in a significant background.
In order to reduce the impact of this background on physics, the incoming cosmic rays should be clearly identified in time and space, including determining unambiguously their position along the TPC drift coordinate. This can be obtained both by with a more efficient light detection system, and by adding a Cosmic Ray Tagger sub-detector.
The ICARUS PMT system has greatly been improved during the refurbishing of the detector at CERN, increasing the number of photomultipliers to 260 (90 per TPC, for a 5% coverage). This will allow not only the use of PMT signals for triggering, but also their timing with a ns-level resolution and the localization of events based on light information alone, with a of ~ 50 cm precision. All ICARUS PMTs have been activated in LAr at FNAL; the commissioning allowed to characterize the single photoelectron response and perform gain calibration with lasers.
The CRT system is composed by a double layer of plastic scintillator surrounding the ICARUS detector for an almost 4π coverage ($\sim 1100 m^2$), allowing to tag any incoming charged particle with an efficiency estimated in ~ 95%, with a time resolution of a few ns and a spatial granularity of some tens of cm. Bottom and side CRT planes are installed and commissioned, while the top planes will follow during summer and fall 2021.
New read-out electronics has also been installed in ICARUS in view of SBN, with significant improvements on the one used in the LNGS run. In particular, a short $\sim 1.3\mu$s shaping time was chosen for all wire planes, allowing better signal reconstruction in dense regions. This electronics has been fully installed and commissioned at FNAL.
Since the detector filling with liquid Argon in spring 2020, the cryogenic system ensured stable detector conditions; liquid Argon purity, as measured by looking at the signal attenuation in anode-cathode crossing cosmic muon tracks, has reached ~ 4.5(3) ms in the West(East) cryostat, allows an efficient signal reconstruction in the whole volume (see Fig.3).
The trigger system will be based on BNB and NuMI beam spills, distributed via a White Rabbit

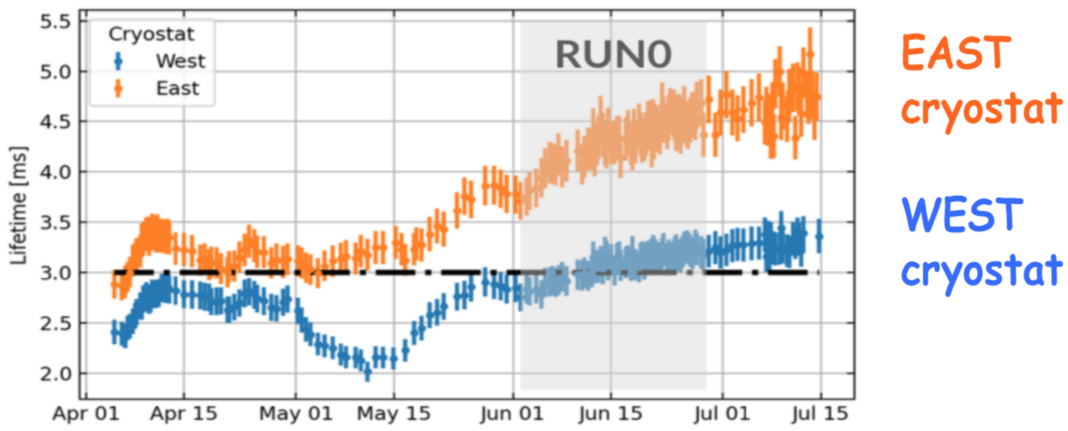

Figure 3: Evolution of ICARUS electron lifetime from April to July 2021. East cryostat in orange, West in blue.

network, and scintillation light signals, involving a majority of PMT pairs in coincidence with the beam gate. Trigger commissioning is ongoing and allowed the observation of beam neutrino events since March 2021, in order to exercise data processing and reconstruction. As an example, a ν_μ charged current interaction of a BNB neutrino is shown in Fig.4.

The *Run 0*, with ICARUS as the primary BNB beam user, lasted for all June 2021, allowing

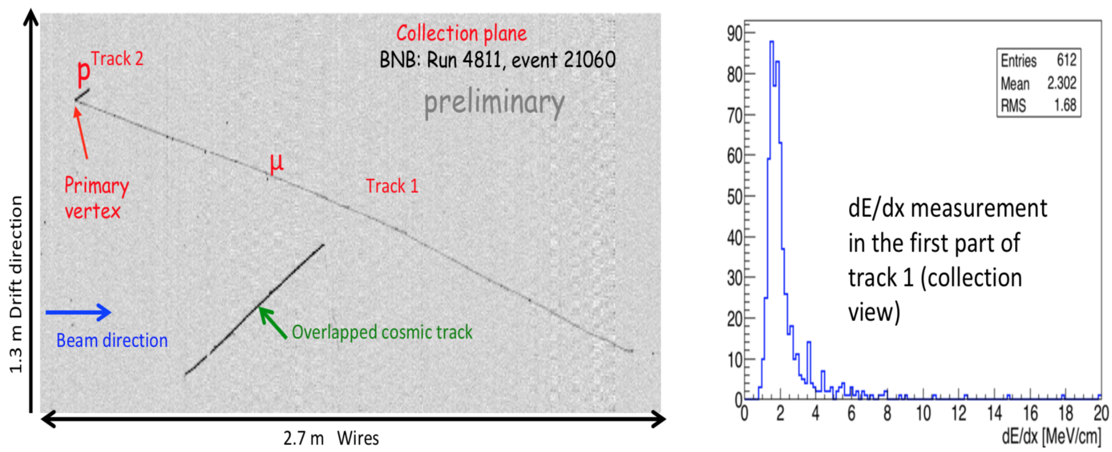

Figure 4: A ν_μCC interaction of a BNB neutrino in ICARUS. On the left, the 2D projection on the Collection plane is shown: Track 1 is a stopping muon candidate, with length ~ 2.8 m and E_{dep} ~ 650 MeV, while Track 2 is likely a proton with length ~ 11 cm and E_{dep} ~ 100 MeV. The plot on the right shows the dE/dx distribution in the first 2 m of the muon, compatible with expectations for a single MIP.

to receive 2.7 $\times 10^{18}$ protons on target from BNB and 2.7 10^{18} from NuMI, with 95% efficiency. Physics data-taking will begin in October 2021.

In parallel with detector commissioning, reconstruction and analysis tools are being developed and calibrated with real data. As an example, cosmic muons crossing from anode to cathode are being used to provide an absolute calibration of the wire signal response and to quantify the distortion due to space charge effects.

4. Conclusions and perspectives

The commissioning phase of ICARUS-T600 at FNAL was largely successful, despite the work limitations due to the current pandemic. The *Run 0* in June confirmed the capability to acquire data continuously with high live-time and allowed observation of beam neutrinos. The LAr purity is adequate for high-quality physics data-taking.
The bottom and side CRT installation is complete, while the top modules will be installed shortly. This will be followed by the construction of the concrete overburden, which will allow a significant reduction of cosmic backgrounds. The start of physics data-taking is expected in October 2021.

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