PROCEEDINGS OF SCIENCE

Sterile neutrino searches with the ICARUS detector

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The ICARUS collaboration employed the 760-ton T600 detector in a successful three-year physics run at the underground LNGS laboratory studying neutrino oscillations with the CNGS neutrino beam from CERN and searching for atmospheric neutrino interactions. ICARUS performed a sensitive search for LSND-like anomalous ν_e appearance in the CNGS beam, contributing to constraint the allowed parameters to a narrow region around $\Delta m^2 \sim \mathrm{eV}^2$, where all the experimental results could be coherently accommodated at 90% CL. After a significant overhauling at CERN, the T600 detector has now been placed in its experimental hall at Fermilab where installation activities are in progress. It will be soon exposed to the Booster Neutrino Beam to search for sterile neutrino within the Short Baseline Neutrino (SBN) program, devoted to clarify in a definitive way the open questions of the presently observed neutrino anomalies. The contribution will address ICARUS achievements and plans for the sterile neutrino search at Fermilab.

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1. Introduction

Imaging detectors have always played a crucial role in particle physics. In the past century successive generations of detectors realized new ways to visualize particle interactions driving the advance of physical knowledge and the discovery of unpredicted phenomena, even on the basis of single fully reconstructed events. In 1977 C. Rubbia [1] conceived the idea of a Liquid Argon Time Projection Chamber (LAr-TPC), i.e. the calorimetric measurement of particle energy together with three-dimensional track reconstruction from the electrons drifting in an electric field in sufficiently pure liquid Argon. The LAr-TPC is a continuously-sensitive and self-triggering detector, characterized by high granularity and spatial resolution, providing 3D imaging of any ionizing event starting from the electrons produced by each charged particle crossing highly-purified LAr. Moreover, this detector is an excellent homogeneous calorimeter which also provides efficient particle identification based on the density of the energy deposition.

2. ICARUS T600 LAr-TPC detector

The ICARUS T600 LAr-TPC detector consists of two large identical modules with internal dimensions $3.6 \times 3.9 \times 19.6$ m^3 filled with $\sim$ 760 tons of ultra-pure liquid Argon, surrounded by a common thermal insulation [2]. Each module houses two TPCs separated by a common central cathode for an active volume of $3.2 \times 2.96 \times 18.0$ m^3. A uniform electric field (E_d = 500 V/cm) is applied to the drift volume. Each TPC is made of three parallel wire planes, 3 mm apart, with 3 mm pitch, facing the drift path (1.5 m) and with wires oriented at 0°, ±60° with respect to the horizontal direction. Globally, 53248 wires with length up to 9 m are installed in the detector.
After a long phase of R&D at INFN and CERN, in 2010 the ICARUS T600 detector was put into operation in the underground Laboratori Nazionali del Gran Sasso (LNGS, Italy) of INFN, where it was exposed to CNGS (CERN to Gran Sasso) beam and cosmic rays [3]. The ICARUS T600 detector concluded in 2013 a very successful three years long run at LNGS collecting 8.6×10^{19} pot with a detector live time exceeding 93%, recording 2650 CNGS neutrino, in agreement with expectations. ICARUS T600 demonstrated the effectiveness of single phase TPC technique for neutrino physics [4], providing a series of results, both from the technical and from the physical point of views, which represent a crucial step towards future larger LAr-TPC detectors (see Fig. 1): a high electron lifetime, exceeding 7 ms (impurity concentration < 40 ppt) over the whole run [5]; an excellent spatial and calorimetric reconstruction, with accurate dE/dx measurement with fine sampling (0.02 X_0) and particle ID from dE/dx versus range [6]; the momentum of escaping muons measure by multiple Coulomb scattering, with an average $\sim$ 15% resolution on stopping muons (0.5÷5 GeV/c) [7].

3. Sterile neutrino searches at LNGS

Experimental observations of neutrino oscillations have established a picture consistent with the mixing of three neutrino flavors (ν_e, ν_μ, ν_τ) with three mass eigenstates (ν_1, ν_2, ν_3) whose mass differences turn out to be relatively small, with $\Delta m^2_{31} \simeq 2.4 \times 10^{-3} eV^2$ and $\Delta m^2_{21} \simeq 7.5 \times 10^{-5} eV^2$ [8]. However, in recent years, several experimental anomalies have been reported which, if experimentally confirmed, could be hinting at the presence of additional neutrino states with larger

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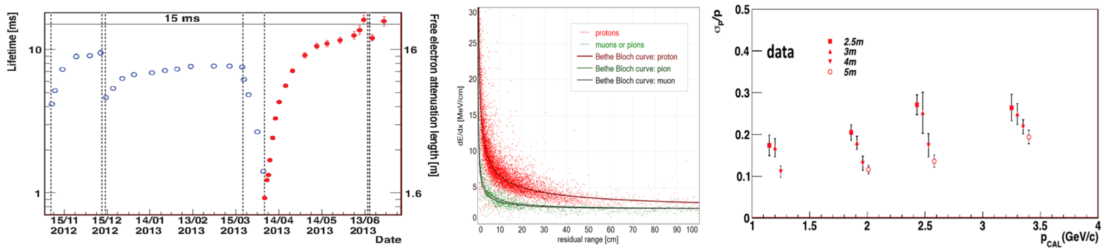

Figure 1: Performance of the ICARUS T600 detector at LNGS in terms of drift electron lifetime (left), particle ID from dE/dx versus range (center) and momentum of escaping muons measure by multiple Coulomb scattering (right).

mass-squared differences participating in the mixing [9]. These anomalies may be distinguished into two classes, namely: 1) the apparent disappearance signal in low energy electron anti-neutrinos from nuclear reactors beyond the expected θ_{13} effect [10] and from Mega-Curie radioactive electron neutrino sources in the Gallium experiments [11, 12] originally designed to detect solar neutrinos; 2) the evidence for an electron-like excess in interactions coming from muon neutrinos and anti-neutrinos from particle accelerators in LSND and MinoBooNE experiments [13, 14]. The sterile neutrino physics scenario is far from understood: hints to flavor transitions at short distance in the $\Delta m^2 \sim 1eV^2$ range are inconclusive. Moreover there is no evidence of oscillations in ν_μ disappearance data [15, 16], bringing a tension between ν_e appearance and ν_μ disappearance results.
The ICARUS LAr-TPC detector is well suited for these kind of searches, not only for its excellent performance as tracking device and as homogeneous calorimeter, but also for its remarkable capability in electron/photon separation and particle identification exploiting the measurement of dE/dx versus range. The tiny intrinsic ν_e component in CNGS muon neutrino beam indeed allowed to perform a sensitive search for anomalous LSND like $\nu_\mu \to \nu_e$ oscillations with the LNGS run beam data. Globally, seven electron-like events were observed, which are consistent with the 8.5±1.1 events expected from intrinsic beam ν_e component and standard oscillations, providing the limit on the oscillation probability $P(\nu_\mu \to \nu_e) \leq 3.86 \times 10^{-3}$ at 90% CL and $P(\nu_\mu \to \nu_e) \leq 7.76 \times 10^{-3}$ at 99% CL (see Fig. 2) [17].
Fig. 3 shows one of the seven electron-like events, where the unique detection properties of LAr TPC technique to identify unambiguously individual e-events with high efficiency is evident: the evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires, see Fig. 4.

4. The ICARUS-SBN deployment at Fermilab

Many global analyses of experimental results have been performed fitting to models including one or more sterile neutrinos [18]. However, even after 20 years, the LSND result is still the dominating one in terms of significance in all global sterile neutrino fits, but it has not been fully confirmed or rejected yet.
The Short Baseline Neutrino (SBN) [19] program is then being developed at Fermilab to provide the definitive clarification at the 5σ level of the puzzle related to the existence of sterile neutrinos. This new project is exploiting the LAr-TPC technology, which provides excellent visualization

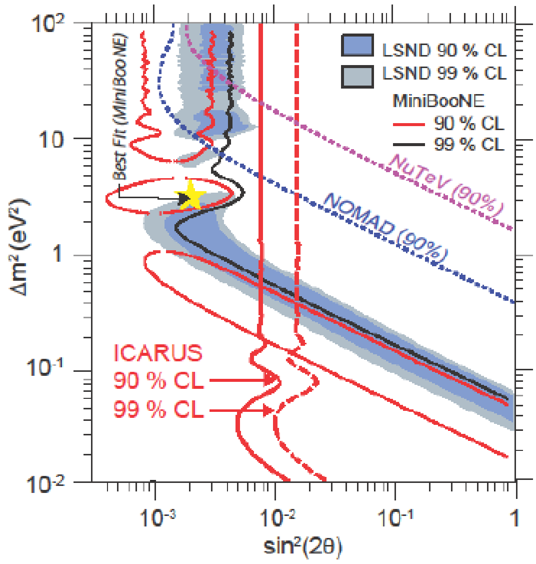

Figure 2: Δm^2 as a function of sin$^2(2\theta)$ for the main experiments sensitive to the $\nu_\mu \to \nu_e$ anomalies and for the ICARUS T600 result (continuous red lines). The yellow star marks the best fit points of MiniBooNE at the time. The ICARUS limits on the oscillation probability for $\nu_\mu \to \nu_e$ are P $(\nu_\mu \to \nu_e) \leq 3.86 \times 10^{-3}$ and P $(\nu_\mu \to \nu_e) \leq 7.76 \times 10^{-3}$ at 90% and 99% CL.

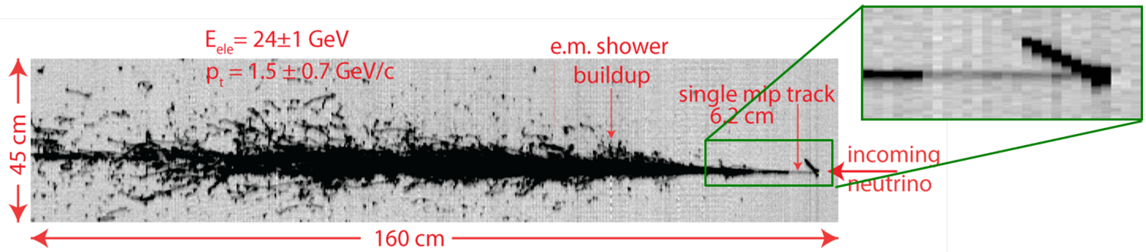

Figure 3: CNGS ν_eCC event: a high energy CC electron is evident, as well as a short, highly ionizing proton starting from the main vertex of the neutrino interaction.

tracking and reconstruction capabilities. In addition, a key element of the program is the possibility to measure the neutrino spectrum at different positions along the beam line. The SBN experimental configuration will, in fact, involve three LAr-TPC detectors installed on axis along the Booster Neutrino Beam (BNB, average $E_\nu \sim 800$ MeV): the SBND detector located at 110 m from the target, the MicroBooNE detector at 470 m, and ICARUS-T600 operated as the far detector and located at a 600 m distance from the target. In this way, the oscillation signals will be identified directly as differences in the measured spectra, while virtually identical spectra would be expected in the absence of oscillation, helping, together with the adoption of the same detection technology for the different stations, to reduce most of the systematic uncertainties.

Fig. 5 presents the experimental sensitivity of the proposed Fermilab SBN program to $\nu_\mu \to \nu_e$ appearance signals in the (Δm^2, $\sin^2 2\theta$) plane with a comparison to the original LSND allowed region [17]. The LSND 99% C.L. allowed region is covered at $> 5\sigma$ level above $\Delta m^2 = 0.1$ eV^2 and $> 4.5\sigma$ everywhere. Note that the region below $\Delta m^2 = 0.1$ eV^2 is already ruled out at more

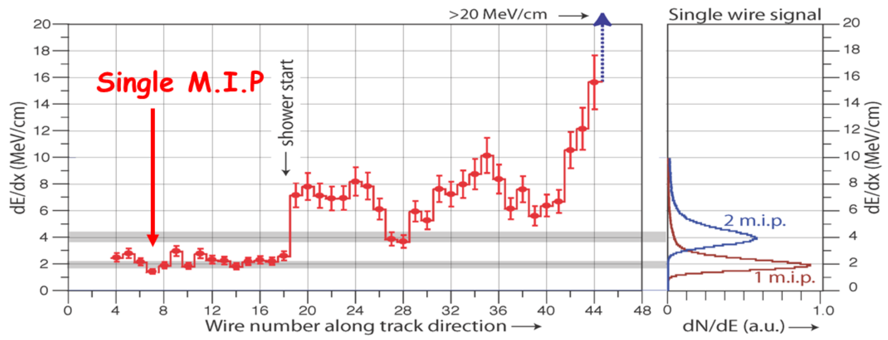

Figure 4: Evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower of Fig. 3: a single m.i.p. track of about 6 cm is evident.

than 5σ by the previous results of ICARUS at Gran Sasso [17].

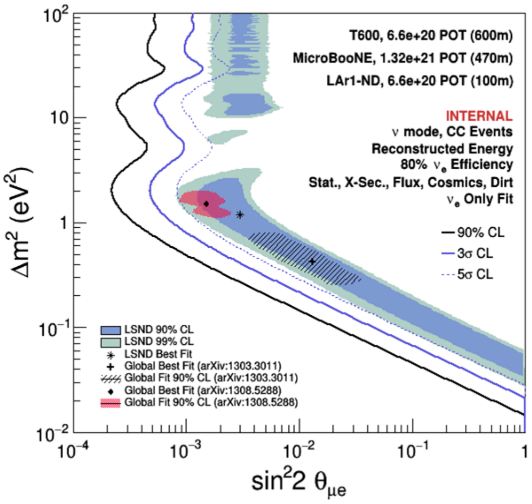

Figure 5: Sensitivity of the SBN Program to $\nu_\mu \to \nu_e$ oscillation signals.

A new situation the ICARUS T600 detector has to face at Fermilab is its deployment at shallow depths condition rather than the deep underground situation of LNGS operations. This requires the recognition of O(10^6) neutrino interactions among 11 kHz of cosmic rays, representing a new problem compared to underground operation at LNGS: the reconstruction of the true position of each track requires associating to each element of TPC image the occurrence time with respect to trigger time. For this reason, before its shipment to USA, in the context of the WA104/NP01 project and according to an MoU between CERN and INFN, the ICARUS T600 detector underwent an intensive overhauling at CERN from 2015 to 2017. Several technology developments were introduced, while maintaining the already achieved performance at LNGS run:

- new cold vessels, with a purely passive insulation;
- renovated LAr cryogenics/purification equipment;

- improvement of the cathode planarity;
- upgrade of the PMT system: higher granularity and o(ns) time resolution;
- new faster, higher-performance read-out electronics.

Moreover, an external cosmic ray tagger (CRT) covering almost all the solid angle with layers of plastic scintillators is being installed to correlate residual muons with the inner TPC signals. Finally, a three meters concrete overburden will be placed on top of ICARUS to remove the contribution coming from charged hadrons and photons associated with cosmic radiation.
ICARUS modules were placed inside the warm vessel in August 2018 after their shipping to FNAL in 2017. Installation of the TPC and PMT feed-through flanges and connectivity tests were completed by February 2019. In sequence, leak tightness tests have been then performed and top cold shields and top CRT support have been installed, see Fig. 6 (Left). Side CRT installation is also ongoing. The installation of proximity cryogenics started in February 2019 and is presently completed. Evacuation of the detector started on June 2019 to reach a residual internal pressure of less than $\sim 10^{-4}$ mbar, which is suitable to start the cooling down operations, see Fig. 6 (Right). Connectivity has been checked on all feed-through flanges and a full readout chain test, from wires to DAQ, has been performed for all the mini-crates hosting the front-end electronics. This allowed to set the baseline for future noise monitoring and to measure the noise level on random triggers and test pulses: despite the grounding conditions were still far from optimal, a noise RMS of about 1700 electrons was found, not too far from the 1200 electrons previously measured in a dedicated read-out electronics test carried out at CERN with a 50 liters LAr-TPC. The subsequent ICARUS T600 detector cooling down and filling with LAr will mark the phase of the commissioning of the CRT, DAQ, trigger and slow controls. The data-taking for physics with the Booster Neutrino Beam will follow to collect neutrinos for at least three years. In parallel with the commissioning of ICARUS, the near detector SBND is being constructed to provide an absolute normalization for neutrino fluxes. In this way, the joint SBN project will definitively clarify the LSND anomaly after more than 20 years.

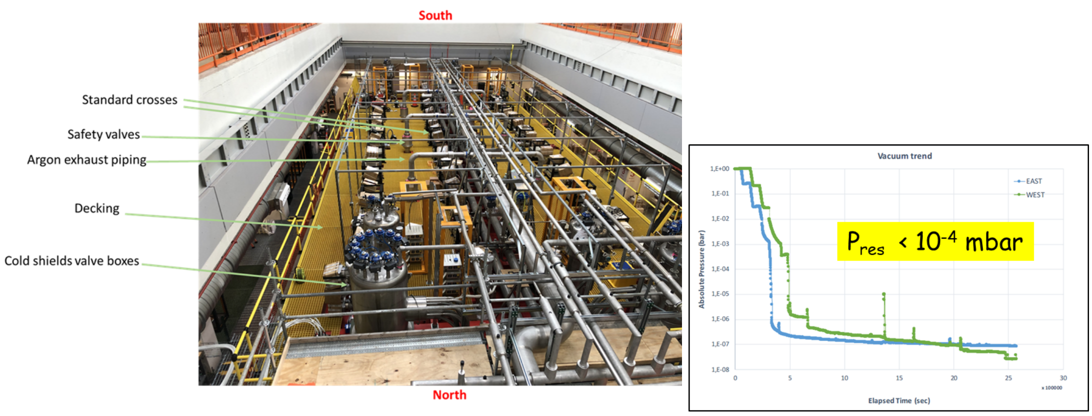

Figure 6: Left: residual pressure inside the two ICARUS T600 modules during the vacuum phase. Right: the present status of the ICARUS T600 plant.

5. Conclusions

The ICARUS T600 detector performed a successful three-years run at Gran Sasso underground laboratory, proving that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments. ICARUS searched for LSND-like anomaly via ν_e appearance in the CNGS beam, significantly constraining the allowed parameter region. The SBN project at Fermilab is then expected to clarify the sterile neutrino puzzle, by looking at both appearance and disappearance channels with three LAr-TPCs. After an extensive refurbishing, the ICARUS-T600 installation at Fermilab in the SBN far site is completed, and after the cryogenic plant commissioning, cool down and filling, ICARUS T600 will be operational to take data for physics for at least three years. Thus, the joint SBN project is expected to definitively clarify the LSND anomaly and the sterile neutrino puzzle after more than 20 years.

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