ICARUS status and near future

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Abstract. The successful run of ICARUS-T600 at LNGS underground laboratory, receiving CNGS beam and atmospheric neutrinos, represents the first large-scale example of a liquid Argon TPC in a neutrino physics experiment. The relevant physics and technological results proved the maturity of the LAr-TPC technique. Updated results on the search for LSND-like $\nu_e$ appearance in CNGS beam neutrinos are presented. The ICARUS-T600 detector will take part in the SBN project at the Booster beam at FNAL, that has the goal to provide a definitive answer to the sterile neutrino puzzle by measuring both $\nu_e$ appearance and $\nu_\mu$ disappearance. The detector is currently undergoing an extensive overhauling at CERN, involving especially the development of a new light detection system; installation at FNAL is scheduled for the beginning of 2017.

1. The physics case for sterile neutrinos
In the last twenty years, many experiments using neutrinos from various sources (solar, atmospheric, accelerators, reactors) confirmed the existence of neutrino oscillations and established a coherent phenomenological picture. This scenario is characterized by three active neutrino flavours ($\nu_e, \nu_\mu, \nu_\tau$) corresponding to three mass eigenstates ($\nu_1, \nu_2, \nu_3$) with small mass differences ($\Delta m^2_{12} \sim 2.4 \cdot 10^{-3} eV^2, \Delta m^2_{23} \sim 8 \cdot 10^{-5} eV^2$), while mixing angles are relatively large ($\sin^2 \theta_{13} \sim 0.02$).

However, in recent years a number of anomalies were observed, that point out to possible non-standard oscillations with $\Delta m^2 \sim 1 eV^2$, and would imply the existence of (at least) a fourth, sterile neutrino, weakly mixed with the active ones. The first of these anomalies was recorded by the LSND experiment [1], which reported a $\sim 3.8\sigma$ excess of $\nu_e$ events in a $\nu_\mu$ beam, that was partially confirmed by MiniBooNE [2]. Signals of $\bar{\nu}_e$ disappearance were also observed in reactor experiments, where a global analysis points to a ratio $0.938 \pm 0.023$ between observed and expected antineutrino events [3], and in neutrinos from K-capture calibration sources in solar experiments [4]. Cosmological results from Planck [5] disfavor but not exclude the existence of sterile neutrinos, allowing for one neutrino species with mass smaller than $\sim 0.2 \ eV$.

These anomalies, while not compelling, represent one of the main puzzles in the present neutrino physics scenario, which calls for a definitive clarification.

2. ICARUS-T600: features and performances
The liquid Argon TPC, essentially an electronic bubble chamber, represents one of the leading detection technologies in neutrino and rare event physics. It was initially proposed in 1977 by C. Rubbia and reached full maturity with the ICARUS-T600 experiment at the LNGS underground laboratory, taking data from 2010 to 2013 with the CNGS beam neutrinos from
CERN and cosmic rays; the successful data-taking campaign collected $7.23 \cdot 10^{19}$ pot, recording 2650 CNGS neutrinos, in agreement with expectations within 6%.

The T600 detector contained $\sim 500$ t of active LAr mass, separated into two independent modules; each module was divided in two TPCs by a central cathode, with 1.5 m drift distance, corresponding to $\sim 1$ ms drift time ($E=500$ V/cm). The sampling time of 400 ns allowed a sub-millimeter resolution in the drift coordinate. The electron signal was read out by three parallel wire planes, with a 3 mm pitch between wires. The third plane collected the drift electrons, producing a signal proportional to charge and allowing to measure deposited energy. The scintillation light produced in LAr was collected by an array of PMTs, in order to produce trigger signals [6].

A crucial feature of LAr-TPCs is an exceptionally high liquid Argon purity: even small fractions (parts per billion) of electronegative impurities can absorb drifting electrons and degrade the signal-to-noise ratio. In ICARUS-T600, such a high purity was ensured by industrial purification methods, both in the liquid and gas phases [8]. The resulting electron lifetime was exceeding 7 ms (corresponding to an impurity concentration of $\sim 40$ parts per trillion $O_2$-equivalent) during the whole data-taking run, for a maximum attenuation of $\sim 12\%$ through the whole drift length [7]. In the final weeks of the run in 2013, the installation of a new pump allowed to improve the lifetime to $\sim 15$ ms. These results confirm the effectiveness of the single-phase LAr-TPC technique, paving the way for a future generation of larger detectors, such as DUNE, with drift lengths that could reach 5 meters.

Tridimensional reconstruction of a wide variety of ionizing events is possible with a resolution of a few millimetres (see a T600 example in Figure 1), while calorimetric measurements have a resolution of $\sim 3\% / \sqrt{(GeV)}$ for contained electromagnetic showers and $30\% / \sqrt{(GeV)}$ for hadronic ones.

Figure 1. Image (in the 2D Collection wire-plane) of a $\nu_e$ CNGS event in ICARUS-T600. The region close to the neutrino interaction vertex is zoomed on the right.

2.1. Measurement of muon momentum by multiple Coulomb scattering

A large fraction of muons from $\nu_\mu$ CC interactions in ICARUS-T600 are not contained within the LAr volume: the only way to measure their momentum is through multiple Coulomb scattering (MCS). The measurement algorithm has been validated by using muons from CNGS $\nu_\mu$ CC interaction in the rock upstream of T600, stopping in the LAr volume; this represents an ideal validation sample, since the MCS momentum estimate can be compared with calorimetry.

The measurement algorithm is based on a statistical evaluation of the average deflection angle between segments of the muon track, projected on the 2D Collection wire-plane. The segment length (19.2 cm) is optimized to enhance the effect of MCS while reducing the apparent deflections due to spatial measurement errors, which are dominated by the ones on the drift coordinate ($\sim 0.7$ mm on average).

Figures 2 and 3 show that MCS and calorimetric estimates of the momentum are well correlated on average; the resolution of the MCS measurement is $\sim 15\%$ on the stopping muon
sample. Some small underestimation, due to the non-perfect planarity of the TPC cathode, appears for p>3.5 GeV/c.

Figure 2. Scatter-plot of muon momentum obtained by MCS vs. calorimetry, on the full stopping muon sample (~400 events). The first 4 m of each muon track were used for the MCS measurement.

Figure 3. Ratio between MCS and calorimetric estimates of muon momentum in the full stopping muon sample. The red line corresponds to a Gaussian fit.

3. ICARUS search for LSND-like oscillations at CNGS
The most unique feature of the LAr-TPC technology is the capability to distinguish electrons and photons and reconstruct $\pi^0$s, which is critical in order to reduce backgrounds in $\nu_e$ appearance searches. The precise measurement of ionization density (dE/dx) in the interaction vertex region, before the onset of an electromagnetic shower, allows to identify $\nu_e$CC events, where a single m.i.p. electron exits the neutrino interaction vertex, from the background of NC events with emission of a $\pi^0$, as shown in Figure 4. A search for $\nu_e$ appearance in the CNGS beam, due to LSND-like sterile neutrino oscillations, has been performed with a total exposure of $7.23 \cdot 10^{19}$ pot (updating the last published result [9]); results are in agreement with known backgrounds, dominated by the intrinsical contamination in the CNGS beam. This result, also confirmed by OPERA[10], provides limits on the oscillation probability, as illustrated in Figure 5; only a small region in the parameter space, around $\Delta m^2 \sim 0.5 eV^2$, $\sin^2 2\theta \sim 0.005$, allows to accommodate all available experimental results at 90%CL [9].

Figure 4. Evolution of ionization density dE/dx in the first wires of the $\nu_e$CC event in Figure 1. The shower onset is marked by the red arrow, and the expected dE/dx for 1 and 2 m.i.p. in liquid Argon are shown on the right side.
Figure 5. Summary of experimental information on LSND-like oscillations in the $(\Delta m^2, \sin^2 \theta)$ parameter space. The region excluded by ICARUS-T600 is shown in yellow and compared with results from other experiments.

4. The Short Baseline Neutrino experiment

The Short Baseline Neutrino project (SBN) [11] is one of the main experiments that will attempt to provide a definitive answer to the sterile neutrino puzzle (see also [12]). It will perform a search for oscillation signals at the Booster beam at FNAL, with an average neutrino energy of 0.8 GeV. Three LAr-TPCs will be positioned along the beamline: ICARUS-T600 at a distance of 600 m from the target, MicroBooNE at 470 m, and a new purpose-built near detector (SBND) at 100 m. The experiment will precisely and independently measure both $\nu_e$ appearance and $\nu_\mu$ disappearance; the use of three LAr detectors will strongly reduce both beam-related and detector-related systematics.

The sensitivity in the $\nu_e$ appearance channel for 3 years of run with positive (neutrino) focusing is shown in Figure 6; the LSND 99%CL region is fully covered at the 5$\sigma$ level. The $\nu_\mu$ disappearance sensitivity will also be extended by about one order of magnitude beyond the present level (see Figure 7).

Figure 6. Expected sensitivity of the SBN experiment to oscillations in the $\nu_e$ appearance channel, for 3 years of run ($6.6 \cdot 10^{20}$ pot) with positive focusing.

Figure 7. Expected sensitivity of the SBN experiment to oscillations in the $\nu_\mu$ disappearance channel, for 3 years of run ($6.6 \cdot 10^{20}$ pot) with positive focusing.
The experimental conditions in which ICARUS-T600 will run at shallow depth at FNAL will be vastly different from the ones at LNGS, since \( \sim 12 \) cosmic muons will hit the detector in each drift time window and be superposed to every neutrino interaction. It will be necessary to unambiguously identify the timing of the neutrino interaction with respect to trigger time (or equivalently, its absolute position along the drift coordinate). Moreover, photons associated to cosmic muons could represent a serious background to \( \nu_e \) appearance searches, since electrons generated in LAr via Compton scattering or asymmetric pair production can mimic a genuine \( \nu_e \) signal. In order to mitigate this problem, a Cosmic Ray Tagger system made of plastic scintillators will surround the T600 detector, and allow to identify incoming cosmic muons, providing their timing and spatial position.

5. ICARUS-T600 refurbishing: the WA104 project
The ICARUS-T600 detector is currently being refurbished at CERN in view of its use at SBN, in the context of the WA104 project, according to an MoU between CERN and INFN. During this phase, a few parts of T600 are being overhauled while preserving present detector performances: new cold vessels with purely passive insulation are under construction, the planarity of the cathode is being improved, and new, faster, read-out electronics is being developed.

The light collection system will be greatly extended (90 PMTs per chamber) in order to increase the detection coverage to be sensitive to low energy deposition (100 MeV), to have a higher granularity and allow matching light and charge deposition, and to improve time resolution (~1 ns) to take advantage of the bunched beam structure. Localization will be possible within 30 cm for \( \sim 95\% \) of events; a neural network algorithm will be able to separate cosmic muons from \( \nu_\mu \) CC events and showers with a wrong-ID fraction of \( \sim 2\% \).

The refurbishment phase is expected to be completed by the end of 2016, with transportation to FNAL scheduled for the first months of 2017.

6. Conclusions
The successful run of ICARUS-T600 at Gran Sasso proved the maturity of the LAr-TPC technology for large-scale neutrino physics experiments, providing numerous physics and technical results. The detector is currently being refurbished at CERN and will be a crucial part of the SBN experiment, in order to provide a final answer to the sterile neutrino puzzle. This experiment will also be a crucial step in LAr-TPC development in view of future long baseline projects such as DUNE.

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