PROCEEDINGS OF SCIENCE

The ICARUS experiment

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The ICARUS-T600 detector, the first large-scale liquid Argon TPC, took data in the underground LNGS laboratory, detecting both CNGS beam and atmospheric neutrinos, proving the full maturity of the LAr-TPC technology. A sensitive search for $\nu_\mu \to \nu_e$ oscillations mediated by possible eV-scale sterile neutrinos, as observed by LSND, allowed to strongly constrain the corresponding parameter space. A dedicated short-baseline experiment (SBN) with three LAr-TPCs, where ICARUS-T600 will act as far detector, is in preparation at FNAL to will fully address this issue by searching for sterile neutrino oscillations, both in appearance and disappearance.

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1. Introduction

The liquid Argon time projection chamber (*LAr-TPC*) is one of the most innovative and effective detection technologies in neutrino and nucleon decay physics; it works at the same time as a 3D imaging device with excellent granularity ($\sim$ mm^3) and as a homogeneous calorimeter, allowing to accurately reconstruct a wide variety of events with complex topology. ICARUS-T600 is the first large-scale LAr-TPC, with a total mass of 760 t; it took data from 2010 to 2013 in the underground LNGS laboratory in Italy, exposed to the CNGS ν_μ beam from CERN (average energy $\sim$ 17 GeV, $\sim$ 730 km distance) detecting also atmospheric neutrinos. This successful data-taking run matched the expected detector performance, confirming the full maturity of the LAr-TPC technology; it also provided relevant physics results, especially in the search for sterile neutrinos through $\nu_\mu \rightarrow \nu_e$ oscillations.

2. The ICARUS-T600 detector

The ICARUS detector [1] is composed by two identical and independent modules housing two TPCs with a common central cathode and a drift length of 1.5 m. The uniform electric field within the chambers ($\sim$ 500 V/cm) allows drifting ionization electrons with velocity $\sim$ 1.6 mm/μs towards the read-out system, composed by three wire planes, with wires oriented in different directions ($0°, \pm 60°$). The measurement of three independent 2D projections, therefore, results in a full 3D reconstruction with a $\sim$ *mm*-scale resolution (the wire pitch is 3 mm). The charge signal on the last (Collection) wire-plane is proportional to the deposited energy, permitting a calorimetric measurement of particle energy. The LAr scintillation light in the VUV range (128 nm), provides a fast signal that is used for triggering purposes; it is detected by photomultipliers immersed in the liquid, coated with TPB (tetraphenyl butadiene) wavelength shifter to convert the light to the visible range.

In order to prevent the absorption of the drifting electrons by electronegative impurities such as oxygen, which would result in a reduction of the signal, the concentration of these impurities must be kept at an exceptionally low level. The continuous Argon recirculation, both in the liquid and gaseous phase, allowed reaching an equivalent O_2 residual concentration of $\sim$ 20 parts per trillion, corresponding to a few percent maximum signal attenuation [2]. This will permit a very precise calorimetric measurement of the energy of contained particles, with a typical resolution of $\sim 3\%/\sqrt{\mathrm{E(GeV)}}$ for high-energy electromagnetic showers.

Momentum of non-contained muons is measured by multiple Coulomb scattering (MCS), by statistically analyzing track deflection angles, which are inversely proportional to momentum. This measurement algorithm has been validated in the few-GeV/c range on a sample of $\sim$ 500 CNGS muons, interacting in the upstream rock and stopping in the detector, by comparing the MCS momentum with calorimetry (Figure 1). After correcting for the $\sim$ cm observed non-planarity of the TPC cathode, that distorts the drift field, the MCS and calorimetric estimates of momentum agree on average within the errors, confirming the viability of the measurement. A $\sim$ 15% average resolution in the 1-5 GeV/c range has been determined, depending on the muon track length and momentum [3].

PoS(EPS-HEP2017)142

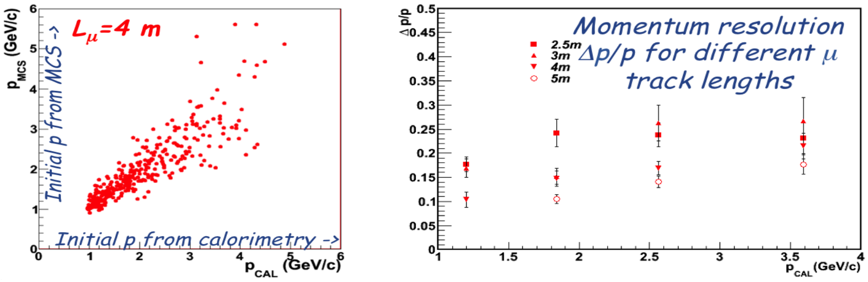

Figure 1: Scatter-plot comparing MCS and calorimetric estimates of momentum on the stopping muon sample before the cathode planarity correction (left). MCS muon momentum resolution, as a function both of muon momentum and of muon length L_μ used in the measurement (right).

The most relevant feature of liquid Argon TPCs is given by their high efficiency and precision in detecting electron-like events in the neutrino oscillation studies, identifying ν_e interactions and rejecting the background of neutral currents, in particular with production of π^0's. This separation makes use of the very fine signal sampling of the LAr-TPC (0.02 X_0), ensuring excellent reconstruction capabilities; in particular, the identification of the photon conversion vertex and the precise measurement of the ionization density in the first few centimeters from the vertex, before the shower onset, allow to suppress NC background by a $\sim 10^4$ rejection factor. A further handle is provided by the reconstruction of the π^0 invariant mass.

3. Atmospheric neutrinos in ICARUS-T600

Atmospheric neutrinos collected during the LNGS run, for an exposure of $\sim$ 0.73 kt year, are being analyzed; they are also of interest for the future SBN project, covering a similar energy range. Moreover, a similar analysis could also address nucleon decay searches, particularly in channels involving kaons, with a preliminary efficiency of $\sim$ 80%. Dedicated filters have been developed to reject cosmic rays and preselect neutrino candidates to be scanned visually. About 0.25 kt year exposure has been scanned so far, identifying 7 ν_μ and 8 ν_e candidates; an example of electron neutrino is shown in Figure 2.

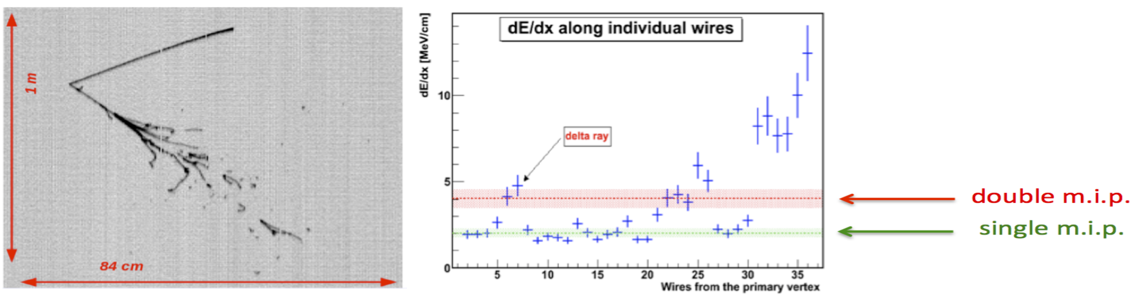

Figure 2: Example of an atmospheric ν_e event in ICARUS-T600. A 2D image of the event in Collection plane is shown on the left. On the right, the ionization density is plotted as a function of the wire number: in the first $\sim$ 20 wires ($\sim$ 6 cm) before the shower onset, dE/dx is compatible with a single m.i.p. signal, identifying the event as a ν_e interaction. .

4. Search for sterile neutrinos

While the 3-neutrino oscillation scenario is largely confirmed by experimental data, a few anomalous results [4] at accelerators, reactors and radioactive sources appear to point to neutrino oscillations with a much smaller L/E, possibly implying the existence of a fourth (necessarily sterile) neutrino flavor with a mass ~ 1 eV/c^2. ICARUS-T600 searched for a possible LSND-like effect through the appearance of ν_e in the CNGS ν_μ beam; in the $\sim 7.9\ 10^{19}$ pot exposure, the number of observed ν_e events was 7 (see Figure 3), while the expected background (mainly due to the $\sim$ 1% intrinsic ν_e contamination in the beam) was ~ 8.5. This negative result [6], confirmed by OPERA [7], allowed to define a very small parameter region, around $\Delta m^2 \sim 1eV^2$, in agreement with all available positive and negative results, as illustrated in Figure 4 (left).
However, some recent results [5] appear to disfavor this interpretation, making the sterile neutrino scenario inconclusive and calling for a definitive experiment.

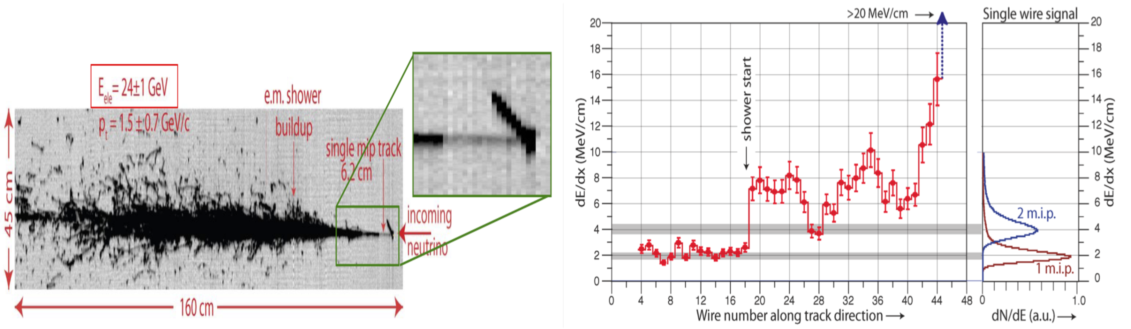

Figure 3: Example of an electron neutrino event identified in the CNGS beam. Similarly to Figure 2, a 2D picture is shown on the left, while the ionization density is plotted on the right.

5. The SBN experiment

In the Short Baseline Neutrino program (SBN), three liquid-Argon TPC detectors (SBND, MicroBooNE, ICARUS-T600, with active masses of 82, 89 and 476 ton) will be exposed to the Booster ν_μ beam at FNAL (average $E_\nu \sim$ 800 MeV) at different distances (110, 470, 600 meters respectively) from the target. SBN is expected to clarify the LSND anomaly with a single experiment. The use of similar near and far detectors will allow to strongly reduce systematics; in absence of anomalies, the observed neutrino spectra would essentially be the same. It is expected to cover the LSND parameter region with 5σ significance in 3 years of data-taking (6.6 10^{20} pot) both in the $\nu_\mu \to \nu_e$ appearance and in the ν_μ disappearance channels, as shown in Figure 4.
ICARUS-T600, like the other SBN detectors, is located at shallow depth, exposed to a large cosmic ray background. While a 3 m concrete overburden is enough to suppress the hadronic component and reduce muons by $\sim$ 30%, the T600 detector will still record ~ 11 uncorrelated cosmic muons per event in the $\sim$ ms acquisition time, that could mimic ν_e interactions by Compton scattering or asymmetric pair production. In order to reject this additional background, a cosmic ray tagger, made of scintillating bars, will surround the TPC. Moreover, a much-improved light detection system (360 PMTs with $\sim$ 2 ns time resolution) will allow identifying incoming cosmic rays.

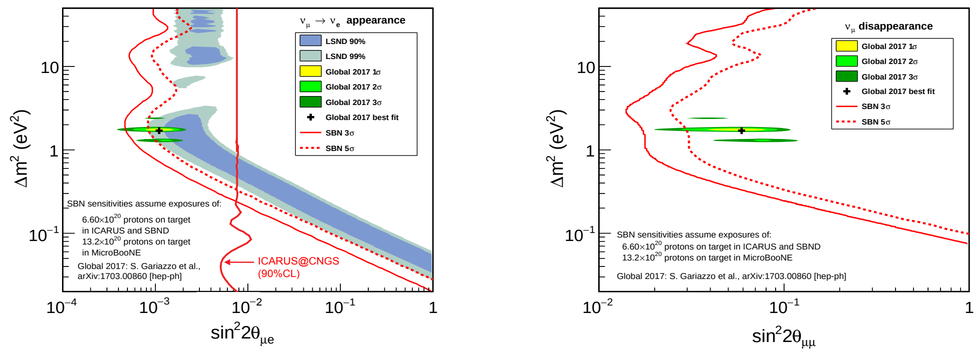

Figure 4: Sensitivities of the SBN experiment: on the left $\nu_\mu \rightarrow \nu_e$ appearance sensitivity, compared with LSND allowed region and current global best fit [8] The 90% C.L. limit obtained by ICARUS-T600 with CNGS beam neutrinos is also shown. On the right, sensitivity in the ν_μ disappearance channel.

The ICARUS-T600 detector underwent an extensive overhauling phase at CERN [9]. This included the installation of an improved PMT system, a flattening of the TPC cathode, reducing non-planarities by a factor $\sim$ 10, and new more performing read-out electronics. The two T600 modules were transported to FNAL in July 2017 and are currently being installed in the far position at the FNAL Booster beam; the detector commissioning is expected in the summer of 2018.

References

[1] C. Rubbia et al., *Underground operation of the ICARUS-T600 LAr-TPC: first results*, JINST **6** (2011) P07011 [arXiv:1106.0975]

[2] M. Antonello et al., *Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC*, JINST **9** (2014) P12006 [arXiv:1409.5592]

[3] M. Antonello et al., *Muon momentum measurement in ICARUS-T600 LAr-TPC via Multiple Scattering in few-GeV range*, JINST **12** (2017) P04010 [arXiv:1612.07715]

[4] A. Aguilar et al. [LSND Coll.], *Evidence for neutrino oscillation from the observation of $\overline{\nu_e}$ appearance in an $\overline{\nu_\mu}$ beam*, Phys. Rev. D **64** (2001) 112007 [hep-ex:0104049]; ?G. Mention et al., *The reactor antineutrino anomaly*, Phys.Rev. D **83** (2011) 073006 [arXiv:1101.2755]; C. Giunti et al., *Statistical significance of the Gallium anomaly*, Phys. Rev.C **83** (2011) 065504 [arXiv:1006.3244]

[5] P.A.R. Ade et al., *Planck 2015 results. XIII. Cosmological Parameters*, A&A **594** (2016) A13 [arXiv:1502.01589]; M.G. Aartsen et al., *Searches for sterile neutrinos with the IceCube detector*, PRL **117** (2016) 071801 [arXiv:1605.01990]; Y. Ko et al., *A sterile neutrino search in NEOS experiment*, PRL **118** (2017) 121802 [arXiv:1610.05134]

[6] M. Antonello et al., *Search for anomalies in the ?e appearance in a ν_μ beam*, EPJ C **73** (2013) 2599 [arXiv:1307.4699]

[7] N. Agafonova et al., *Search for $\nu_\mu \rightarrow \nu_e$ oscillation with the OPERA experiment in the CNGS beam*, JHEP **1307** (2013) 004 [arXiv:1303.3953]

[8] S. Gariazzo et al., *Updated global 3+1 analysis of short-baseline neutrino oscillations*, JHEP **06** (2017) 135 [arXiv:1703.00860]

[9] G.L. Raselli, *The upgrading of the ICARUS-T600 detector*, this conference