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ICARUS T600: Latest physics results

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Summary. — The ICARUS T600 detector is the largest Liquid Argon (LAr) Time Projection Chamber (TPC) ever built and operated to date. The detector, assembled underground in the Hall B of the Gran Sasso Laboratory (LNGS), has been collecting neutrino events with the CERN to Gran Sasso (CNGS) beam and from cosmic rays from May 2010 to June 2013. The ICARUS excellent spatial and calorimetric resolution, coupled to very refined 3D event reconstruction techniques, allows to search, among others, for $\nu_\mu \rightarrow \nu_e$ transitions which may be related to the "LSND anomaly". Though no evidence of this is detected, an important region of the parameter space remains unexplored. For this reason the joint ICARUS-NESSiE collaboration is proposing an experiment, at the new foreseen CERN-SPS neutrino beam facility (CENF), to solve the sterile neutrino puzzle.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `14.60.Pq` – Neutrino mass and mixing.

1. – ICARUS T600: description and performance

The ICARUS T600 detector is the largest Liquid Argon (LAr) Time Projection Chamber (TPC) ever built [1]. It was successfully operated in the Hall B of the underground Gran Sasso Laboratory (LNGS) for more than three years with neutrinos from both the CERN-Neutrino-to-Gran-Sasso (CNGS) beam and cosmic rays. The detector is made of a large cryostat housing two identical half-modules each of which is made of two TPCs sharing a common cathode. The half-modules are $3.6 \times 3.9 \times 19.6\,\mathrm{m}^3$ in internal dimensions and are filled with a total of 760 tons of ultrapure Liquid Argon. Each TPC has maximal drift length of 1.5 m.

Charged particles travelling in LAr produce scintillation light and ionization electrons, which are then drifted toward the anode by a constant electric field ($E_D = 500\,\mathrm{V/cm}$). The anode consists of three planes of parallel wires with a 3 mm pitch facing the drift volumes. Each of these planes is oriented at a different angle (0°, +60°, −60°) with respect to the horizontal direction, and a total of about 54000 wires are instrumented as a whole. The absolute measured drift time, combined with drift velocity information ($v_D = 1.59\,\mathrm{mm}/\mu\mathrm{s}$), provides the primary track position with respect to the anode. Matching the wire coordinates of the three planes for a given drift time value allows to find the position in space of the track (*i.e.* full 3D track reconstruction) with a precision of about $1\,\mathrm{mm}^3$.

Electronics is designed to allow for continuous read-out, with a 400 ns sampling, digitization (10-bit FADC) and independent waveform recording for each wire signal of the four TPCs. The trigger relies on detection of the scintillation light produced by the primary track (with 74, 8″ photomultipliers mounted behind the wire planes) in coincidence with the CERN-SPS proton extraction time for the CNGS beam.

A continuous gas and liquid recirculation system, and the use of standard commercial Hydrosorb/Oxysorb$^{\mathrm{TM}}$ filters, allowed to maintain the concentration of electronegative impurities (O_2, N_2, H_2O) far lower than the desired value of 0.1 ppb-O_2 equivalent, necessary to allow ionization charges to travel through the entire drift volume.

Through charge collection on the last wire plane, it is possible to study the behaviour of the track local energy deposition ($\mathrm{d}E/\mathrm{d}x$) as a function of its range, and perform particle identification. Moreover, the resolution of the detector is about 2% of the photon radiation length. This means that it is possible to perform e/γ separation and distinguish between ν_e Charged Current (CC) event candidates and π^0 decays in Neutral Current (NC) events.

As of December 2012, the ICARUS T600 detector has collected a final sample of 8.6×10^{19} protons on target (pot), which allowed, among others, to test the OPERA results on superluminal neutrinos [2]. The ICARUS Collaboration results are compatible with a value of the neutrino velocity equal to c [3-5].

2. – Search of an LSND anomaly signal with the CNGS beam

The high quality performance of the ICARUS T600 detector allows the testing of puzzling results related to non-standard neutrino oscillations. In particular, starting from B. Pontecorvo first suggestion in 1957 [6], the hypothesis of the presence of at least one additional heavier neutrino state appeared. This new neutrino is interacting only via gravity with other SM particles (hence *sterile*), but can mix with the three known ν states via the mass term.

The LSND collaboration found an anomalous excess of $\bar{\nu}_e$ production in a $\bar{\nu}_\mu$ beam at short distances. This result, later confirmed by MiniBooNE, would imply an oscillation behaviour driven by a new mass difference $\Delta m^2_{new} \approx 10^{-2} \div 1\,\mathrm{eV}^2$. The reported statistical evidence for this appearance signal is of $3.8\,\sigma$ [7].

Similarly, measurements from reactors and tests on very intense electron-capture neutrino sources used in gallium experiments reported a $\nu_e/\bar{\nu}_e$ disappearance, with an inferred value of $\Delta m^2_{new} \gg 1\,\mathrm{eV}^2$ [8].

In such a framework, ICARUS Collaboration started a dedicated search of ν_e appearance in the ν_μ CNGS beam ($10 \leq E_\nu \leq 30\,\mathrm{GeV}$). In the L/E range of our experiment ($\approx 36.5\,\mathrm{m/MeV}$) the mass-related term in the oscillation probability relation averages out to 1/2, thus having $\langle P(\nu_\mu \to \nu_e)\rangle \approx \frac{1}{2}\sin^2(2\theta_{new})$.

The excellent e/γ separation capabilities of the ICARUS T600 detector becomes therefore fundamental in identifying ν_e CC events. So far the data sample from 2010-2011 has been analysed, yielding 1091 neutrino events, compatible within 6% with the numbers expected from Monte Carlo simulations.

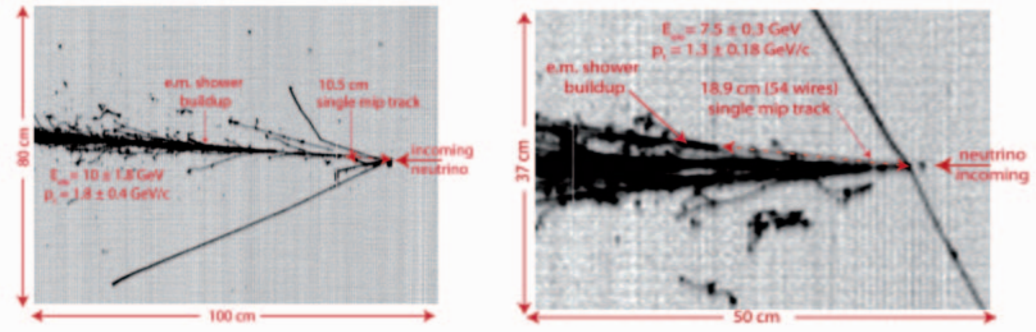

Fig. 1. – The two ν_e CC events found in the 2010-2011 data sample. In both events the single electron shower is visible.

The expected number of ν_e CC events in the sample was obtained considering "standard" effects, *i.e.* ν_e beam contamination, electrons coming from θ_{13} oscillations and from τ decays, and it was estimated to 5.0 ± 0.6 events. This value was weighted with reconstruction efficiency η, evaluated both for human scanners and for an automatic event selection algorithm. In both cases $\eta = 0.74$ was obtained, yielding 3.7 ± 0.6 expected events in the data sample.

The selection criteria for ν_e events, other than energy and fiducial volume cuts, consisted in detecting a single m.i.p. track at least 8 wires long and later developing into a shower. Moreover a minimal spatial separation (150 mrad) of other tracks from vertex was requested in at least one view.

Data analysis led to two ν_e CC events (shown in fig. 1), which is compatible with the absence of an appearance signal. With such results, one can set a limit on the number of events expected due to the "LSND anomaly", *i.e.* ≤ 3.4 (90% C.L.) and ≤ 7.1 (99% C.L.), which yield respectively the following oscillation probabilities:

$$(1) \quad P(\nu_\mu \to \nu_e) \leq 5.4 \times 10^{-3} \text{ (90\% C.L.)}, \qquad P(\nu_\mu \to \nu_e) \leq 1.1 \times 10^{-2} \text{ (99\% C.L.)}.$$

This result [9] restricts the region in the parameter space where it is still possible to obtain agreement between this and the other positive measurements, namely LSND, MiniBooNE and KARMEN [8, 10] (see fig. 2). This region has been later constrained by the OPERA Collaboration [11]. An improvement is also expected with the updated ICARUS results with almost doubled statistics [12].

3. – ICARUS-NESSiE at CERN-SPS new neutrino beam

Given the different results hinting at non-standard oscillation phenomena, it is necessary to investigate the whole oscillation parameter space. In order to do this, the ICARUS and NESSiE Collaborations have recently proposed [13] a new experimental program to be carried out at the foreseen CERN-SPS Neutrino beam Facility (CENF, 2 GeV mean neutrino energy). Such program will employ two LAr-TPCs followed by magnetic spectrometers in a near-far configuration. The T600, moved from Gran Sasso to CERN, will

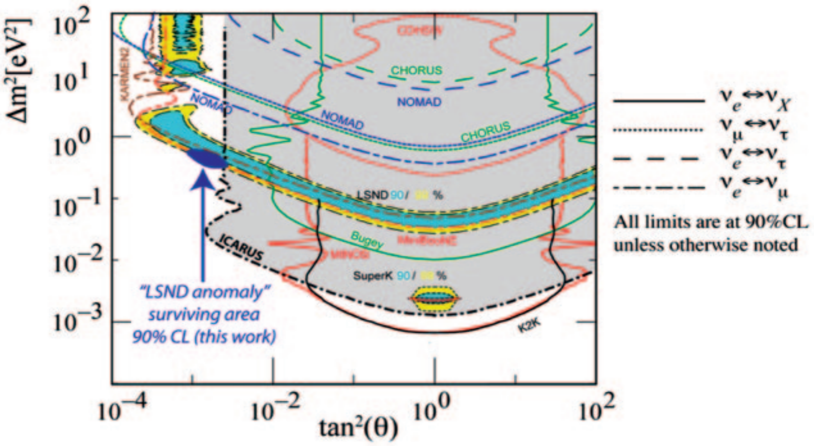

Fig. 2. – Exclusion plot summarising most oscillation measurements in different channels. The region for non-standard ν_e appearance surviving after ICARUS results is highlighted.

serve in the far position (1600 m from beam target), while a new scaled-down detector (T150) will be constructed and deployed as near station (450 m).

The new experiment will rely on:

- a more appropriate L/E ratio to match the Δm^2_{new} range expected for the anomalies;
- a simultaneous observation at different distances from the ν source, allowing to independently measure both parameters of interest: $(\Delta m^2_{new}, \sin^2(2\theta_{new}))$;
- an unambiguous detection of all reaction channels, thanks to imaging "bubble chamber"-class LAr-TPCs;
- very high rates, due to detectors large masses and short baseline, yielding relevant effects detectable at the percent level ($> 10^6 \nu_\mu \rightarrow \approx 10^4 \nu_e$);
- interchangeable $\nu/\bar{\nu}$ focused beams.

Such conditions, along with the experience on LAr technology gained during the years of operation at LNGS, will allow to greatly increase e recognition capability (up to 90%), while simultaneously lowering the π^0 mis-identification probability. A positive ν_e appearance signal should then manifest itself in two different ν spectra in the near and far detectors. On the contrary, overlapping spectra would directly imply no oscillation signal. According to MC predictions, the sensitivities, reached by operating one year in ν_μ mode and two years with $\bar{\nu}_\mu$, will be sufficient to explore the whole parameter space indicated by the reported anomalies, both for appearance and disappearance experiments (see fig. 3).

The smooth operation of the ICARUS T600 detector at LNGS for more than three years sets the detector as a milestone of LAr technology, and it paths the way towards the realization of a new generation of multi-tons mass detectors. Moreover the T600 gives the possibility to set up a dedicated search of non-standard oscillation signals, for

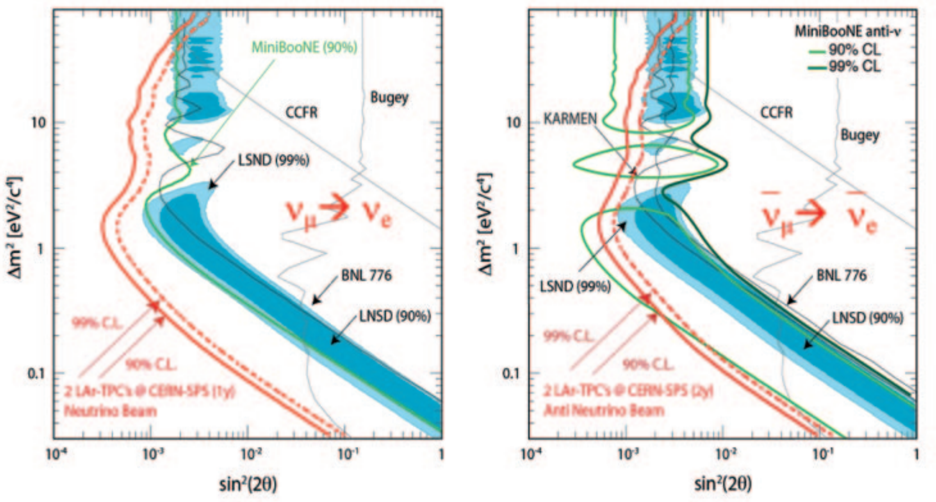

Fig. 3. – Expected sensitivity on all channels for e appearance (1 year ν_μ beam + 2 years $\bar{\nu}_\mu$ beam). The parameter space region will be fully explored.

which there have been reported indications from different experiments around the world in the last few years. The ICARUS-NESSiE joint collaboration proposes a new CERN-SPS based program that will be able to provide full coverage of the parameter space for neutrino anomalies.

REFERENCES

[1] Amerio S. *et al.* (ICARUS Collaboration), *Nucl. Instrum. Methods A*, **527** (2004) 527.
[2] Adam T. *et al.* (OPERA Collaboration), *JHEP*, **10** (2012) 093.
[3] Antonello M. *et al.* (ICARUS Collaboration), *Phys. Lett. B*, **713** (2012) 17.
[4] Antonello M. and Cohen A. G. *et al.* (ICARUS Collaboration), *Phys. Lett. B*, **711** (2012) 270.
[5] Antonello M. *et al.* (ICARUS Collaboration), *JHEP*, **11** (2012) 049.
[6] Pontecorvo B., *Zh. Eksp. Teor. Fiz.*, **53** (1967) 1717 (*Sov. Phys. JETP*, **26** (1968) 984).
[7] Aguilar-Arevalo A. A. *et al.*, arXiv:1207.4809v1 (2012) [hep-ex] and references therein.
[8] References on the cited results can be found in [9] (refs. 2-6). Also relevant papers on sterile neutrinos can be found at `https:/www.nu.to.infn.it/Sterile_Neutrinos/`.
[9] Antonello M. *et al.* (ICARUS Collaboration), *Eur. Phys. J. C*, **73** (2013) 2345.
[10] Armbruster B. *et al.* (KARMEN Collaboration), *Phys. Rev. D*, **65** (2002) 112001.
[11] Agafonova N. *et al.* (OPERA Collaboration), arXiv:1303.3953v1 (2013).
[12] Antonello M. *et al.* (ICARUS Collaboration), *Eur. Phys. J. C*, **73** (2013) 2599.
[13] ICARUS and NESSIE Collaboration, *Search for "anomalies" from neutrino and anti-neutrino oscillations at* $\Delta m^2 \approx 1\,\text{eV}^2$ *with muon spectrometers and large LAr-TPC imaging detectors*, CERN-SPSC-2012-010 and SPSC-P-347; Medinaceli V. E., these proceedings.