# The ICARUS Experiment at Gran Sasso Underground Laboratory

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**Abstract:** The ICARUS Experiment is the first example in a novel detector generation, able to provide on a large mass scale the imaging capabilities of the old famous ”bubble chamber” together with ionization energy measurement. The T600 detector operates at GranSasso Underground Laboratory, studying cosmic rays, neutrino oscillation, proton decay and supernova neutrino. Potentialities of this novel electronic imaging telescope are presented through preliminary data analysis results on events reconstructed with unprecedented details.

**Keywords:** Liquid Argon TPC, Neutrino oscillation, Supernova neutrino, Proton decay.

## 1 Introduction

The ICARUS T600 cryogenic detector is the biggest Liquid Argon TPC realized ever, with the cryostat containing 600 tons of Liquid Argon. The ICARUS Experiment represents the result of a many year effort in R&D studies along a path of increasing mass and complexity laboratory and industrial prototypes. At the same time, the ICARUS detector marks a major milestone towards the realization of a multi kiloton LAr detector.

The ICARUS T600 addresses a wide physical program operating as a continuously sensitive general-purpose observation instrument. It is collecting a wide variety of events from the Universe, namely cosmic rays (atmospheric and solar neutrino interactions), but also neutrinos from the CNGS beam, produced at CERN and reaching Gran Sasso after a flight of about 730 km under the Earth surface. Neutrinos still play a key role in fundamental physics since clarifying the neutrinos nature and the pattern of the mixing between different flavors could unveil possible extensions of the present Standard Model of particle interactions and could also shed light on fundamental questions like Dark Matter and baryon asymmetry in the Universe. ICARUS T600 could also provide interesting results on supernova explosion mechanism in case of a galactic supernova event. ICARUS opens a completely new way to explore the unknown too. In particular it will be searching for rare unobserved up to now events like the long sought for proton decay (in particular into exotic channels), with zero background in one of its $3^{32}$ nucleons. Relying on the LAr-TPC three-dimensional, high granularity imaging and calorimetric capabilities, few proton decay events may be enough to discover matter instability.

## 2 The ICARUS detector

The ICARUS detector is the first large scale realization of the Liquid Argon Time Projection Chamber (LAr-TPC) technique. It can be considered the large scale modern version of the old-famous bubble chambers because of its high granularity the 3D imaging capabilities and the excellent calorimetric properties. The LAr-TPC concept was proposed by C. Rubbia in 1977 [1] and is based on the possibility to drift in high purity Liquid Argon free electrons over long distances in an electric field. The LAr-TPC thus successfully reproduces the extraordinary imaging features of the bubble chamber with the further achievement of being a fully electronic detector, continuous sensitive, self triggering and potentially scalable to huge masses. The ICARUS T600 is now installed in the Hall B of the Gran Sasso underground National Laboratory (LNGS) of Istituto Nazionale di Fisica Nucleare (INFN), shielded against cosmic rays by about 1400 meters of rock. Smoothly running under stable conditions since months, the detector is demonstrating high-level technical performances, as will be shown in the following.

The ICARUS T600 detector consists of a large cryostat split into two identical, adjacent half-modules with internal dimensions $3.6 \times 3.9 \times 19.6$ m$^3$ and filled with about 760 tons of ultra-pure liquid Argon. An uniform electric field ($E_{\rm drift}$ = 500 V/cm) is applied to the LAr bulk: each half-module houses two TPCs separated by a common cath-

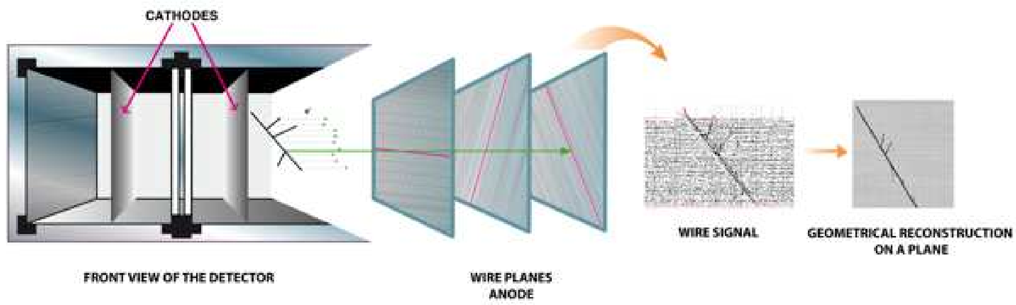


Figure 1: Icarus Liquid Argon TPC working principle: ionization electrons are drifted in the active volume and collected by the anode wire plane.

ode. Charged particles crossing the medium produce ionization and scintillation light along their path. Scintillation light has a wavelength of about 128 nm (UV) with a yield of about 5000 $\gamma$/mm for a mip particle; this provides a prompt signal that can be used for triggering purposes by means of Photo Multiplier Tubes (PMTs), suitable to detect VUV scintillation light and operating at the LAr cryogenic temperature. Ionization on the other hand has a yield of about 5000 electrons per mm; these electrons are drifted by the uniform electric field towards three wire planes where the signal is recorded, ensuring a redundant tridimensional track reconstruction. Thanks to the low transverse diffusion of charge in LAr, the electron images of ionization tracks are preserved along the 1.5 m maximum drift distance, as shown in figure 1. Wires are spaced by 3 mm and wire planes are oriented at a different angles ($0^o$, $+60^o$, $-60^o$) with respect to the horizontal direction. Therefore, combining the wire coordinates on each plane at a given drift time, a three-dimensional image of the ionizing event can be reconstructed. A remarkable resolution of about 1 $mm^3$ is uniformly achieved over the whole detector active volume (about 170 $m^3$).

Globally, 53248 wires with length up to 9 m are installed in the detector and individually readout by the data acquisition electronics; the DAQ design allow to continuously read-out and digitize independent waveforms of signals from each wire of the TPCs. The data are stored in multi-event circular buffers which are frozen and readout when a trigger signal occurs, minimizing the dead time. The average electronic noise achieved with the custom designed low noise front-end is of about 1500 electrons r.m.s. to be compared with about 15000 free electrons produced by a minimum ionizing particle in 3 mm (S/N about 10).

## 3 Detector operation and performances

A fundamental requirement for the performance of a LAr-TPC is the high purity of the Liquid Argon with respect to electronegative impurities (mainly $O_2$, $H_2O$ and $CO_2$); a very low concentration level, less than 0.1 ppb, is required in order to safely operate the drift chamber. To this aim, each half-module is equipped with two gas argon and one liquid argon recirculation/purification systems. Argon gas is continuously drawn from the cryostat ceiling and, once re-condensed, drops into Oxysorb$^{TM}$ filters to finally get back into the LAr containers. LAr instead is recirculated by mean of an immersed, cryogenic pump and is purified through standard Hydrosorb/Oxysorb$^{TM}$ filters before being re-injected into the cryostats. Electron lifetimes exceeding 6 ms are reached after few months of operation.

During summer 2010 the first events from the CNGS neutrino beam and cosmic rays were detected. The trigger system relies on both, the scintillation light signals provided by the internal PMTs and the CNGS proton beam extraction time. As a starting layout, for each of the four chambers, the analog sum of signal from PMTs is exploited with a discrimination threshold set at around 100 photo-electrons, guaranteeing an almost full efficiency for the interactions induced by CNGS neutrinos. The trigger for the CNGS neutrino interactions is based on the presence of the PMT signal within a CNGS related gate.

The CNGS run started in stable conditions on October 1st and continued till the beam shutdown, on November 22$^{nd}$; in this period $5.8 \times 10^{18}$ pot were collected out of the $8.0 \times 10^{18}$ delivered by CERN, with a detector lifetime up to 90% since November 1$^{st}$. The 78% of the whole collected sample of events, corresponding to $4.54 \times 10^{18}$, has been preliminarily analyzed: 94 $\nu_\mu$CC and 32 NC events have been identified by means of visual scanning into a 434 ton fiducial volume, while 6 events need for further analysis to be classified (being at edges the muon track is too short do be visually recognized); this result is in full agreement with the number of interactions predicted in the whole energy range up to 100 GeV (2.6 $\nu_\mu$ CC and 0.86 $\nu$ NC for each $10^{-17}$/pot), accounting for fiducial volume and DAQ dead-time. Examples of CNGS beam neutrino interaction is shown in figure 2.

Identification of the nature of particles is obtained by studying the event topology and the energy deposition per track length unit as a function of the particle range (dE/dx versus range) for muons/pions, kaons and protons [2, 3, 4, 5]. A dedicated reconstruction program based on the polygonal line algorithm [6] for 3D reconstruction, and on neural network for particle identification has been recently developed by the ICARUS Collaboration to this purpose.

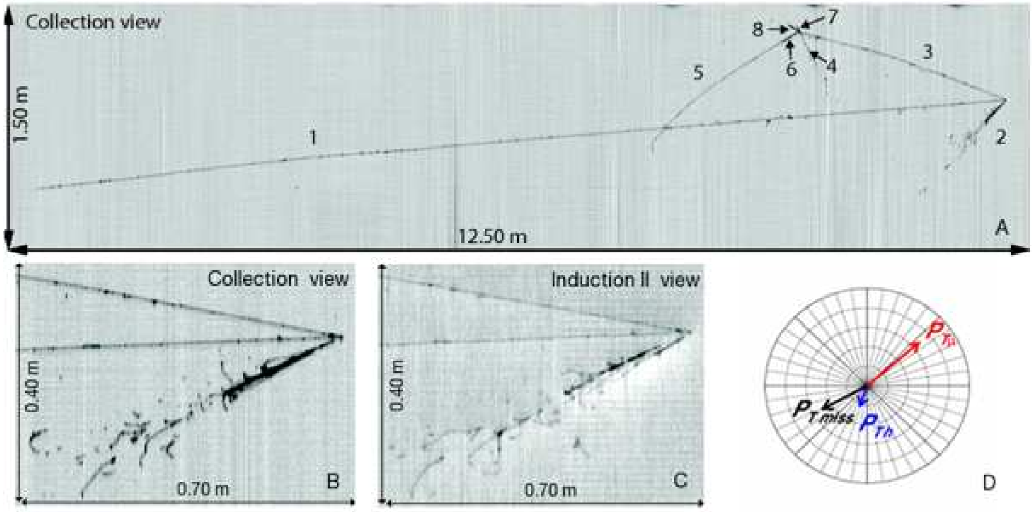


Figure 2: Example of $\nu_\mu$CC interaction from the CNGS beam.

Electrons are fully identified by the characteristic electromagnetic showering, well separated from $\pi^0$ via $\gamma$ reconstruction, dE/dx signal comparison and $\pi^0$ invariant mass measurement at the level of $10^{-3}$. This feature guarantees a powerful identification of the CC electron neutrino interactions, while rejecting NC interactions to a negligible level. The electromagnetic energy resolution $\sigma(E)/E = 0.03/\sqrt{E(\mathrm{GeV})} \oplus 0.01$ is estimated in agreement with the $\pi^0 \rightarrow \gamma\gamma$ invariant mass measurements in the sub-GeV energy range [7]. The measurement of the Michel electron spectrum from muon decays, where bremsstrahlung photons emission is taken into account [8], provided the energy resolution below critical energy ($E_c$ 30 MeV), $\sigma(E)/E = 0.11/\sqrt{E(\mathrm{MeV})} \oplus 0.02$. At higher energies the estimated resolution for hadronic showers is $\sigma(E)/E = 0.3/\sqrt{E(\mathrm{GeV})}$. However the LAr-TPC detector allows to identify and measure, track by track, each hadron produced in interactions, through ionization and range, leading to a much better energy resolution. For long muon track escaping the detector, momentum is determined exploiting the multiple scattering along the track, studying its displacements with respect to a straight line. The procedure, implemented as a Kalman filter technique and validated on cosmic rays stopping muons, allows a resolution $\Delta p/p$ that can be as good as 10%, depending mainly on the track length [9].

## 4 Future developments: the sterile neutrino puzzle

Recently an increasing number of experimental anomalies together with indication from cosmology on the role of a fourth family of neutrino raised the interest on the existence of a sterile neutrino. In-fact, the $3.8\sigma$ $\bar{\nu}_e$ excess signal in a $\bar{\nu}_\mu$ beam observed by LSND for the first time has been confirmed by the MiniBooNE experiment, suggesting a possible $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation ($0.2 < \Delta m^2 < 2.0$ eV$^2$, $\sin^2(2\theta) < 10^{-3}$) beyond the three neutrino flavour oscillation scheme as observed in solar/atmospheric neutrino experiments [10]. At the same time a recent re-evaluation of the $\bar{\nu}_e$ reactor spectra (about 3% of flux increase) brought out a $\bar{\nu}_e$ deficit at many short-baseline reactor experiments [11] and revived the SAGE/GALLEX $\nu_e$ deficit from the MegaCurie radioactive source [12], hinting at a fast disappearance rate ($\Delta m^2 > 1.5$ eV$^2$, $0.02 < \sin^2(2\theta) < 0.23$ at 99.7% C.L.). Furthermore, the latest WMAP data seem not to exclude, or even to prefer, a scenario with more than three neutrinos since recent analysis of the CMB lineshape performed by the WMAP Collaboration [13] gives the number of effective neutrino as $N_{\mathrm{eff}} = 4.34 + 0.86 - 0.88$; although only a one sigma effect, this estimate suggests the number of degrees of freedom at radiation-matter decoupling time could be larger than expected, leaving room for an extra light particle. At the same time recent results on $^4$He abundance bring Big Bang Nucleosynthesis to favor more than the three known neutrino species [14], being the number of relativistic degrees of freedom directly related to the expansion rate of the Universe in the radiation dominated expansion phase.

In such a situation the use of two identical LAr-TPC detectors on a short baseline refurbished neutrino beam at the CERN-PS could represent a way to solve the puzzle [15]. The neutrino beam would be a low energy $\nu_\mu$ beam produced by 19.2 GeV protons of at least $1.25 \times 10^{20} pot/yr$ intensity. The far detector, located at about 850 m from the target, could be ICARUS-T600 itself, while the near detector, at 127 m, would be a 150 ton active mass LAr-TPC (possibly a clone of one ICARUS-T600 semi-module having the length reduced by a factor of two). The LAr-TPC technique appears the ideal detector for the study of low energy neutrino events thanks to its very high $\nu_e$ detection efficiency combined with an extremely high-level rejection of associated NC background events. Moreover the usage of two identical detectors together with the very similar intrinsic $\nu_e$ spectra in the two positions, ensure that

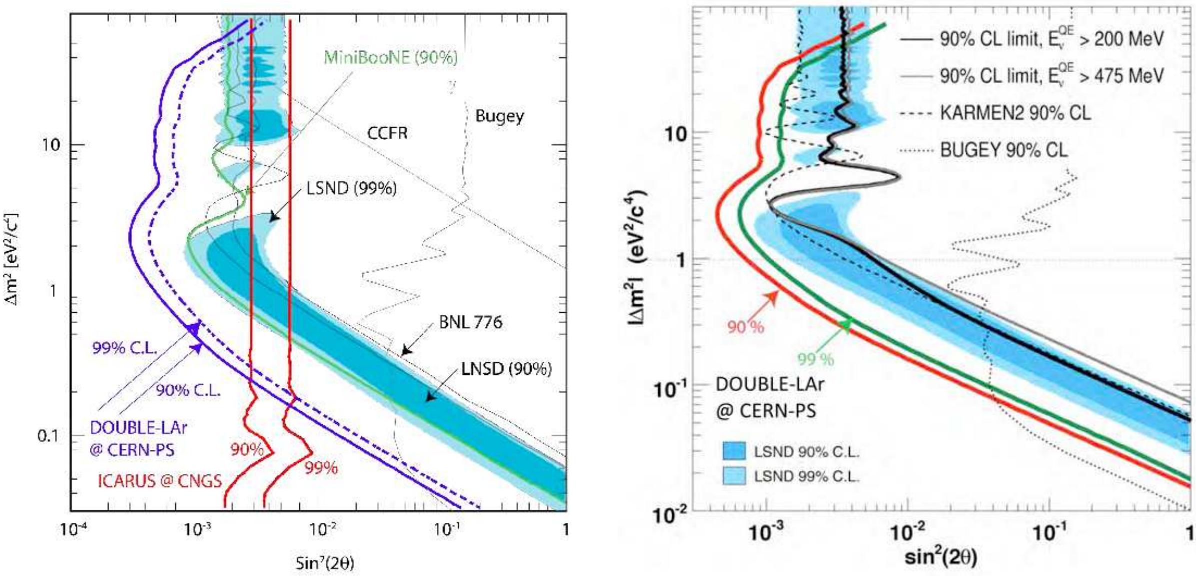


Figure 3: Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) and anti-neutrino (right) for $2.5 \times 10^{20}$ pot. The LSND allowed region is fully explored both for neutrinos. In the neutrino case, the expectations from CNGS2/ICARUS T600 at LNGS are also shown.

experimental and cross-section biases cancels out. It would thus be possible to perform the search for both $\nu_\mu \to \nu_e$ LSND appearance signal and $\nu_\mu \to \nu_x$ reactor disappearance anomaly, with promising sensitivity in only 2(4) years data taking in neutrino (antineutrino) mode, as shown in figure 3.

## 5 Conclusions

The ICARUS-T600 detector, installed underground at the LNGS laboratory, has started data taking during 2010 after a long R&D and installation phase. The successful assembly and operation of this LAr-TPC is the experimental proof that this technique is mature. It has demonstrated to have unique imaging capability, spatial and calorimetric resolutions and the possibility to efficiently distinguish electron from $\pi^0$ signals, thus allowing to reconstruct and identify events in a new way with respect to the other neutrino experiments. After a short commissioning phase this experiment is ready for the 2011-2012 run, addressing a wide physics programme. The main goal is to collect events from the CNGS neutrinos beam from CERN-SPS to search for the $\nu_\mu \to \nu_\tau$ oscillation, but also to study solar and atmospheric neutrino and explore in a new way the nucleon stability in particular channels beyond the present limits. Furthermore ICARUS-T600 is so far the major milestone towards the realization of a much more massive LAr detector. Actually the employment of this technique at a refurbished CERN-PS $\nu$ beam has been proposed after the ICARUS-T600 exploitation at LNGS to definitely solve the sterile neutrino puzzle.

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