# ICARUS T600 experiment in the underground laboratory in Gran Sasso

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The multipurpose ICARUS T600 detector, with its large sensitive volume, high granularity, excellent tracking and particle identification capabilities, is an ideal device for searching for phenomena beyond the Standard Model. The ICARUS T600 addresses a wide physics program. It is simultaneously collecting a wide variety of ,,self-triggered" events of different nature, such as cosmic ray events and neutrino interactions associated with the CNGS neutrino beam.

## 1 Introduction

The Liquid Argon Time Projection Chamber (LAr-TPC), first proposed by C. Rubbia in 1977 [1], is a powerful detection technique that can provide a 3D imaging of any ionizing event. LAr-TPC provides excellent calorimetric measurements of particle energy. The ICARUS T600 is 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 1400m of rock. The description of ICARUS T600 detector and its underground operation in 2010-2011 are presented in this paper. A fully reconstructed neutrino interaction collected by T600 will be discussed.

## 2 The ICARUS T600 detector

The ICARUS T600 detector [2] consists of a large cryostat split into two identical, adjacent and independent half-modules, with an overall volume of about 760 tons of ultra-pure liquid Argon at temperature of 89K. Each half-module houses two TPCs separated by a common cathode. The anode of each TPC is made of three parallel wire planes, $3mm$ apart, oriented at $0°$ and $\pm 60°$ with respect to the horizontal direction. The operational principle of the LAr-TPC relies on ionization electrons that can be transported practically undistorted by the application of an uniform electric field ($E_D = 500V/cm$) over macroscopic distances - see illustration in Figure 1. The signals coming from each wire are continuously read and recorded in multi-event circular buffers. The measurement of the absolute time of the ionizing event, combined with the electron drift velocity information ($v_D \sim 1.6mm/\mu s$ at $E_D = 500V/cm$), provides the absolute position of the track along the drift direction. The determination of the absolute time of ionizing event is accomplished by the prompt detection of the scintillation light produced in LAr by charged particles. For this purpose arrays of Photo Multiplier Tubes (PMTs) are installed behind the

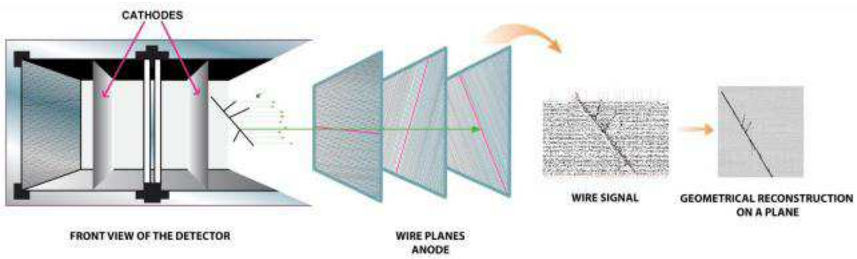


Figure 1: Illustration of the ICARUS T600 working principle: a charged particle ionization path in LAr and its geometrical reconstruction on a plane.

wire planes. The PMTs are coated with wavelength shifter to allow the detection of VUV scintillation light ($\lambda = 128nm$) and they are operating at the LAr cryogenic temperature [3].

### *2.1 LAr Purity*

The detector imaging capability and a correct estimation of the energy deposition from the ionization charge signal relies on a liquid Argon purity. Purity is continuously monitored measuring the charge attenuation along ionizing clean through-going cosmic muon track. The drifting electrons, before they reach the anode planes can be captured by the electronegative contaminants (mainly $O_2$, $H_2O$ and $CO_2$). With the liquid recirculation turned on, the LAr purity steadily increased, reaching values of free electron lifetime [a] ($\tau_e$) exceeding $6ms$ in both cryostats. Pump maintenance required some stops of the LAr recirculation lasting several days which resulted in a degradation of the purity suddenly recovered as soon as pumps were back on. The $\tau_e$, however, never droped below 1ms.

### *2.2 CERN Neutrinos to Gran Sasso - CNGS*

The CNGS project aims at directly detecting $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations. A muon-neutrino beam ($10^{17}\nu_\mu$/day) is generated at CERN and directed towards the Gran Sasso National Laboratory, 732km away. A beam of this type is generated from collisions of protons in a beam with nucleons in a graphite target. The products of such interactions (mostly pions and kaons) are not stable particles. In most of the cases they decay to $\nu_\mu$ neutrinos and muons. The muon-neutrino energy spectrum is the key feature for the ICARUS T600 experiment. The average muon-neutrino energy is $\sim 17GeV/c$.
The trigger system relies on the scintillation light signals provided by the internal PMTs and on the SPS proton extraction time for the CNGS beam. For every CNGS cycle two proton spills, lasting $10.5\mu s$ each, separated by 50ms, are extracted from the SPS machine.

### *2.3 CNGS data taking*

The CNGS run 2010 started in stable conditions on October 1st and continued till the beam shutdown, on November 22nd.

In this period $5.8 \cdot 10^{18}$ pot were collected out of $8 \cdot 10^{18}$ pot delivered by CERN (left plot on Figure 2), with the detector lifetime up to 90% since November 1st. ICARUS T600 detector smoothly started data taking on March 18th 2011 receiving the CNGS neutrino beam operating in high dedicated mode. In the time interval from March 18th to Novenmer 20th CNGS delivered $4.78 \cdot 10^{19}$ pot (right plot on Figure 2). The detector lifetime in this period was about 93%, allowing the collection of about $4.44 \cdot 10^{19}$ pot.

[a] Free electron liftime is the average capture time of a free ionization electron by an electronegative impurity in LAr. It can be expressed as $\tau_e[ms] \sim 0.3/N[ppb]$, N being the Oxygen equivalent impurity concentration.

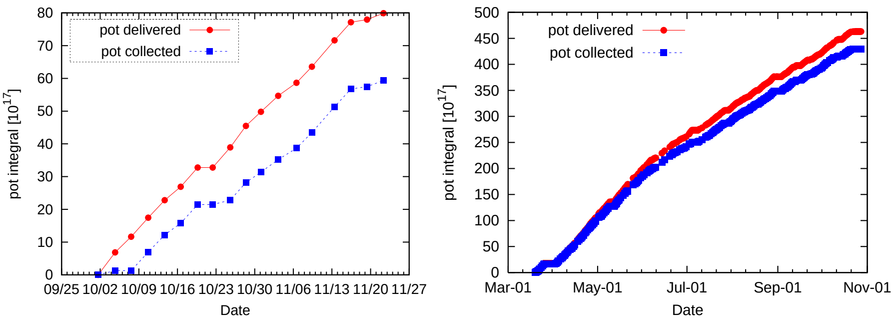


Figure 2: Number of pot collected by ICARUS T600 during 2010 (left) and 2011 (right) compared with the beam intensity delivered by CERN.

## 3 Neutrino events

The T600 at LNGS is detecting neutrino interaction events both from the CNGS beam and from cosmic interactions. The 3D track reconstruction is based on the Polygonal Line Algorithm fit in 3D space[4], optimized to all available hits in 2D wire planes and identified 3D reference points (interaction vertices, peculiar points like delta rays). The main advantage is that 2D hit to hit associations are not needed and therefore missing track parts in single view are accepted as well as horizontal tracks except for pathological situations such as long missing segments at the track ends. Improvements in the PID algorithm allow for a reduction of the systematic effects due to trajectory and charge measurement errors. Stopping particle identification is based on the dependency of reconstructed dE/dx versus track residual range. A shower measurement algorithm providing the reconstruction of shower geometry, initial dE/dx and total energy has been developed on MC and is being validated with real data. The available analysis tool allow a complete kinematical reconstruction of the neurino interactions.

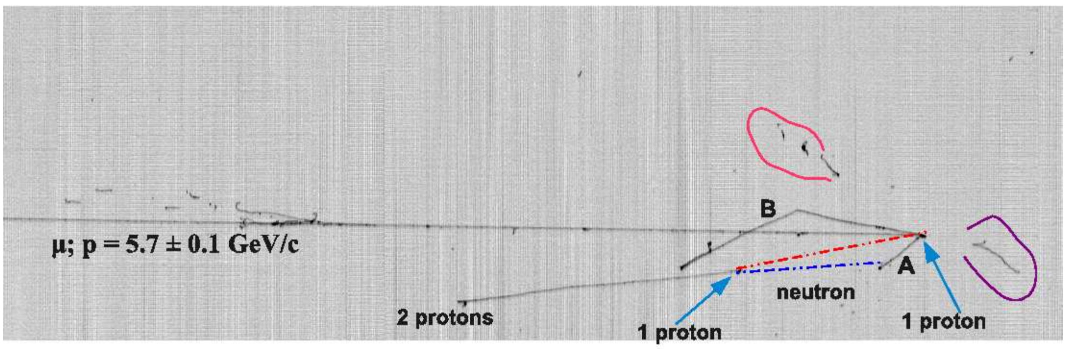


Figure 3: An example of CC neutrino interaction in Collection view

An example of CNGS CC event is shown in Figure 3. The use of two different views allows the recognition of the presence of two distinct electromagnetic showers pointing to the primary vertex. The corresponding conversion distances are measured to be $15cm$ and $61cm$ respectively. The invariant mass $m^*_{\gamma\gamma} = 117 \pm 15 MeV/c^2$, associated with electromagnetic showers, compatible with the $\pi^0$ particle mass, is determined, under the assumption of equally shared energy between the two photons, from their opening angle $\theta = (129.1 \pm 2.5)^\circ$. In the primary vertex one can see also a long muon track with its momentum calculated as $5.7 \pm 0.1 GeV$ via multiple scattering. The values of energy of interacting pions are listed in Table 1.

The transverse and total momentum of presented event were calculated as in Table 2.

| TRACK | E [MeV] | p [MeV/c] | range [cm] |
|---|---|---|---|
| A ($\pi$) | $62 \pm 5$ | $145 \pm 7$ | 18 |
| A ($\pi$) | $337 \pm 32$ | $455 \pm 32$ | 18 |
| B ($\pi$) | $429 \pm 36$ | $550 \pm 38$ | 92 |

Table 1: Reconstructed values of energy, momentum and range for pions created in primary vertex.

| $p_T[MeV/c]$ | $p_{tot}[GeV/c]$ |
|---|---|
| 78 | 7 |
| 154 | 6.5 |

Table 2: Values of transverse momentum and total momentum for the event.

## 4 Conclusions

The ICARUS T600 detector is so far the biggest LAr detector ever built. It has been successfully installed in the Gran Sasso underground National Laboratory (Italy) and, after having smoothly reached the optimal working conditions, it is presently collecting data for its second year of CNGS neutrino beam. ICARUS T600 represents the final milestone of a series of fundamental technological achievements in the last several years. Its underground operation demonstrates that T600 technology is mature and scalable to much larger masses, in the range of tens of kton, as required to realize the next generation experiments for neutrino physics and proton decay searches. The examples of neutrino interaction event preliminary analyzed in this paper show that reconstruction precedures and particle identification are correctly performed, fully exploiting the physical potentiality of this technology.


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