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ICARUS T600: Status and perspectives of liquid-argon technology for neutrino physics

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Summary. — ICARUS T600 is the largest Liquid-Argon (LAr) Time Projection Chamber (TPC) ever built: the detector, assembled underground in the Hall B of the Gran Sasso laboratory (LNGS), is collecting neutrino events with the CERN-to-Gran Sasso CNGS beam since May 2010. The excellent spatial and calorimetric resolutions and the three-dimensional visualization capabilities make the detector a sort of "electronic bubble chamber": for these reasons ICARUS T600 represents a major milestone towards the realization of future LAr detectors for neutrino physics and for the search of rare events, such as the idea to use two identical LAr-TPCs in a "near-far" configuration at the foreseen new CERN-SPS neutrino beam to solve the sterile neutrino puzzle.

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

1. – ICARUS T600: description and performance

ICARUS T600 is the largest Liquid Argon (LAr) Time Projection Chamber (TPC) ever built [1]: it consists of a large cryostat split into two identical adjacent half-modules with $3.6 \times 3.9 \times 19.6\,\text{m}^3$ internal dimensions and filled with a total of 760 tons of ultra-pure LAr. Each half-module houses two TPCs separated by a common cathode, with a drift length of 1.5 m.

Charged particles, along their path in LAr, produce ionization electrons which are drifted under a uniform electric field ($E_D = 500\,\text{V/cm}$) towards the TPC anode made of three parallel wire planes, facing the drift volume. A total of ≈ 54000 wires are deployed, with a 3 mm pitch, oriented on each plane at different angles ($0°, +60°, -60°$) with respect to the horizontal direction. The drift time of each ionization charge signal, combined with the electron drift velocity information ($v_D \approx 1.59\,\text{mm}/\mu\text{s}$), provides the position of the track along the drift coordinate. Combining the wire coordinate on each plane at a given drift time, a three-dimensional image of the ionizing event can be reconstructed with a resolution of about $1\,\text{mm}^3$.

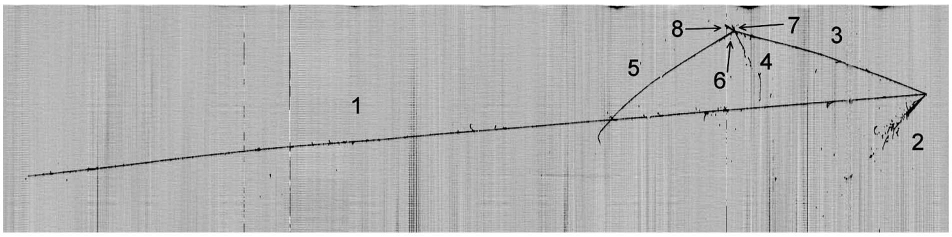

Fig. 1. – Example of a ν_μ Charged Current event from CNGS beam. All the secondary particles are identified by means of $\mathrm{d}E/\mathrm{d}x$ and the associated energies and momenta are extracted: 1) muon from the CC conversion; 2) electromagnetic showers from π^0 decay; 3) pion; 4) multiple tracks from secondary vertex; 5) muon 6) kaon; 7) proton; 8) escaping particle. The reconstructed total energy is $12.6 \pm 1.2\,\mathrm{GeV}$, within the energy range of the CNGS beam; the missing transverse momentum $\approx 250\,\mathrm{MeV/c}$ is consistent with the theoretical expectation from Fermi motion of target nucleon.

The electronics for data acquisition allows a continuous read-out (400 ns sampling), digitization (10 bit) and independent waveform recording of signals from each wire of the TPCs. The trigger relies on the scintillation light signals provided by 74 Photo-Multiplier-Tubes (PMTs) installed in LAr behind the wire planes and on the CERN-SPS proton extraction time for the CNGS beam.

In order to allow electrons produced by ionizing particles to drift "unperturbed" from the point of production to the wire planes, electronegative impurities (mainly O_2, H_2O and CO_2) in LAr must be kept at a very low concentration level (less than 0.1 ppb). Therefore, both gaseous and liquid Argon are continuously purified by recirculation through standard Hydrosorb/Oxysorb$^{\mathrm{TM}}$ filters.

The ICARUS T600 detector was pre-assembled in Pavia (Italy), where one of its two 300 tons half-modules was brought to operation and tested with cosmic rays at the Earth surface. A number of ancillary works to build the cryogenic plant and other technical infrastructures inside the LNGS Hall B were accomplished after the transfer. The final assembling of the detector was achieved in 2010 and ICARUS T600 was finally brought into operation with its commissioning [2].

2. – Operation in 2011

During 2011, the ICARUS experiment took data on the CNGS neutrino beam with very high efficiency. The collected event statistics corresponds to 4.44×10^{19} p.o.t. over the 4.78×10^{19} p.o.t. delivered by CERN from March 19$^{\mathrm{th}}$ to November 14$^{\mathrm{th}}$ 2011, with 93% of detector live-time for CNGS exploitation. Cosmic events, or in general events whose acquisition was triggered out of the CNGS spill, were also recorded.

The high resolution and granularity of the LAr-TPC imaging allow precise reconstruction of events topology (see the example in fig. 1): particle identification is obtained through $\mathrm{d}E/\mathrm{d}x$ *versus* the range analysis and the decay/interaction topology.

Data collected in 2011 were exploited to contribute to the solution of the super-luminal neutrino problem. This activity was motivated by the earlier, later corrected, OPERA claim that CNGS muon neutrinos arrive at Gran Sasso, after covering a distance of about 732 km, earlier than expected from luminal speed [3]. The ICARUS analysis focused on two different issue: 1) the direct measurement of the neutrino time-of-flight; 2) a search for the analogue to Cherenkov radiation by neutrinos at super-luminal speeds.

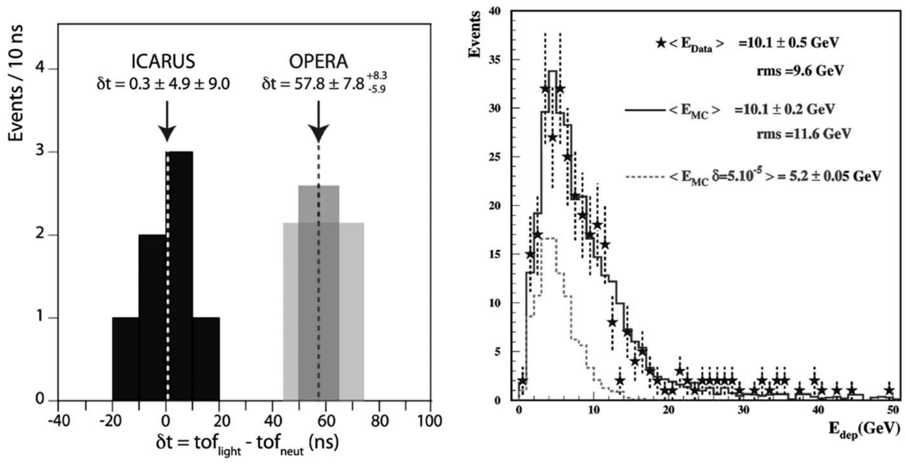

Fig. 2. – Left: time of flight difference between the speed of light and the arriving neutrino at LNGS [4]. Right: neutrino energy deposition in ICARUS compared with Monte Carlo expectation [5]. Both results are in agreement with Lorentz dependent velocities of neutrinos and of light and are not compatible with the earlier OPERA claim of super-luminal neutrinos [3].

2˙1. *Direct measurement of the neutrino time-of-flight*. – The measurement was carried out from October 31st to November 6th 2011, with the use of very tightly bunched, low-intensity, beam with four $\approx 3\,\text{ns}$ extractions separated by $524\,\text{ns}$.

Seven beam-associated events were recorded during this period: this number is consistent with the CNGS delivered neutrino flux (2.2×10^{16} p.o.t.) and the ICARUS T600 detection efficiency. The sample consists of two Charged Current (CC) and one Neutral Current (NC) with the vertex contained within the detector active volume, whereas four events represent muons coming from neutrino interactions with the upstream rock.

For each event the actual neutrino time of flight was obtained from $tof_{neut} = T_{stop} - T_{start}$, where T_{stop} is the event time in ICARUS T600 corrected for the PMT and vertex positions, T_{start} is the proton transit time at the SPS/CNGS beam-current-transformer (BCT) accounting for the additional time related to the nearest proton bunch. The resulting time-of-flight difference $\delta t = \text{tof}_{\text{light}} - \text{tof}_{\text{neut}}$ between the speed of light and the arriving neutrino is $\delta t = (0.3 \pm 4.9(\text{stat}) \pm 9.0(\text{syst}))\,\text{ns}$ in agreement with Lorentz dependent velocities of neutrinos and of light (fig. 2, left [4]); this result is not compatible with $\delta t = (57.8 \pm 7.8(\text{stat})^{+8.3}_{-5.9}(\text{syst}))\,\text{ns}$ earlier reported by OPERA [3].

2˙2. *Search for the analogue to Cherenkov radiation by neutrinos at super-luminal speeds*. – Super-luminal muon neutrinos should lose their energy by producing photons and e^+e^- bremsstrahlung pairs, through Z^0 mediated processes analogous to Cherenkov radiation, as argued by Cohen and Glashow [6]. The pairs emission rate Γ and neutrino energy loss $\mathrm{d}E/\mathrm{d}x$ are both proportional to δ^3 where $\delta = (v_\nu^2 - c^2)/c^2$, being v_ν and c the neutrino and light velocity, respectively. The former OPERA result corresponds to the value of $\delta \approx 5 \times 10^{-5}$ with small variations over the detected neutrinos energy domain.

About 1.53×10^{19} p.o.t. were used for the analysis. The measured raw energy deposition E_{dep} for CC and NC muon neutrino events was obtained from a calorimetric measurement corrected for signal quenching. The experimental distribution was compared with a full Fluka Monte Carlo simulation of the neutrino propagation to Gran

Sasso for two values of δ, namely $\delta = 0$, and $\delta = 5 \times 10^{-5}$. The experimental spectrum agrees very well with the simulations for the unaffected CERN neutrino beam (fig. 2, right) and is not compatible with the spectrum resulting from the former OPERA claim. In addition, no candidate of e^+e^- pair event was found following the bremsstrahlung production criteria: this lack of events was translated into 90% CL limit of $\delta < 2.5 \times 10^{-8}$ for multi-GeV neutrinos [5].

3. – Perspectives for 2012 and beyond

On March 23$^{\rm rd}$ 2012, data taking with the CNGS beam was resumed and the detector started to collect events. The main item of physics that will be addressed with the CNGS beam are: ν_τ search, ν_e CC identification/measurement and NC rejection capability. On the same beam, the search for sterile neutrinos in the LSND/MiniBooNE allowed parameter space region [7] can be also carried out, looking for an excess of ν_e CC events. ICARUS-T600 will also study neutrinos from natural sources (atmospheric, solar, supernovae) and it can play a role in the long sought for nucleon decay search, in particular in exotic channels not accessible to Cherenkov detectors.

ICARUS-T600 is a major milestone towards the realization of future massive LAr detectors. Recently, the exploitation of this technique at the foreseen new CERN-SPS neutrino beam in the CERN north-area has been proposed after the ICARUS-T600 exploitation at LNGS to definitely solve the sterile neutrino puzzle searching for some reported anomalies, which might be due to the presence of "sterile" neutrino. Two identical LAr-TPCs followed by magnetized spectrometers can be used to observe electron and muon neutrino events in a "near-far" configuration of the foreseen new beam ($E_p = 100\,\mathrm{GeV}$, $E_\nu \approx 2\,\mathrm{GeV}$, $I = 4.5 \times 10^{19}$ p.o.t./y) [8]. This project will exploit the actual ICARUS T600 LAr-TPC, moved from Gran Sasso to the CERN "far" position, ≈ 1600 m from the beam target. A new detector (about 150 tons of LAr) will be located in a "near" position, $\approx 330\,\mathrm{m}$ away from the proton target. The experiment will offer the capability to measure both appearance and disappearance for electron and muon neutrinos and antineutrinos, allowing the unambiguous measurement of oscillation at $\Delta m^2 \approx 1\,\mathrm{eV}^2$. The expected sensitivities operating for one year in neutrino mode followed by two years in antineutrino mode will be sufficient to fully explore the Δm^2–$\sin^2(\Theta)$ parameter space region indicated by the reported anomalies.

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