IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11143-7

Colloquia: LaThuile11

# Icarus and status of Liquid-Argon technology

A. Fava for the ICARUS Collaboration
*INFN, Sezione di Padova - Via Marzolo 8, I-35131, Padova, Italy*

(ricevuto il 29 Settembre 2011; pubblicato online il 25 Gennaio 2012)

**Summary.** — ICARUS-T600 at the INFN-LNGS Gran Sasso Laboratory is the first underground large-mass Liquid-Argon TPC: exposed to the CNGS neutrino beam from CERN, it has been taking data since May 2010. Thanks to its excellent resolution and 3D imaging, it allows an unprecedented event visualization quality combined with a good calorimetric reconstruction and the electronic event processing. After a first commissioning phase, it has started an interesting physics program, ranging from $\nu_\mu \rightarrow \nu_\tau$ oscillation search in appearance to matter stability study, thus demonstrating the feasibility and effectiveness of the Liquid-Argon TPC technique. Furthermore, ICARUS-T600 represents a major milestone towards the realization of much larger Liquid-Argon detectors for future rare events physics. The idea to use a LAr-TPC experiment at a refurbished CERN-PS neutrino beam is presented as a possible solution to the sterile neutrino puzzle.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `13.15.+g` – Neutrino interactions.
PACS `07.05.Fb` – Design of experiments.

## 1. – LAr TPC technique: working principle and performance

The idea of a Liquid-Argon Time Projection Chamber (LAr-TPC) was first proposed by C. Rubbia in 1977 [1] as a powerful detection technique to provide a 3D imaging of any ionizing event. Nowadays LAr-TPC can be considered the heir of the bubble chamber detector, because of the high granularity and excellent spatial resolution and calorimetric properties; but it has some interesting additional features, being continuously sensitive and self-triggering detector, and the advantage of being scalable to bigger masses.

The working principle of the LAr-TPC (fig. 1) is based on the two processes by which charged particles loose energy in liquid argon, *i.e.* scintillation and ionization. Scintillation light, emitted in the infrared at 128 nm wavelength with $5000\,\gamma$/mm yeld, provides a prompt signal made by a fast ($\sim 6$ ns) and a slow ($\sim 1.6\,\mu$s) component. By means of ionization, instead, each charged particle produces $\sim 6000$ electrons per mm, which are drifted by a uniform and intense electric field towards several (transparent)

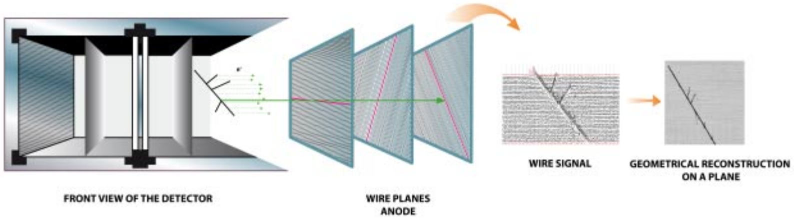

Fig. 1. – Simple scheme of the LAr-TPC working principle: from the interaction of the incoming particle with LAr to the readout system.

wire arrays where the signal is recorded in a nondestructive way, ensuring a redundant tridimensional track reconstruction. A key feature for LAr-TPC experiments is the level of purity of liquid argon, since electro-negative molecules (mainly $O_2$, $H_2O$ and $CO_2$) could eventually capture the drifting electrons before they reach the anode plane.

The high resolution and granularity of this detection technique (less than $1\,\mathrm{mm}^3$) allows a precise reconstruction of events topology and the recognition of the particles produced in interactions in LAr. Calorimetric measurement is also possible over a very wide energy range, from MeV to several tens of GeV, allowing particle identification via $\mathrm{d}E/\mathrm{d}x$ ionization signal.

For long muon tracks escaping the detector, momentum is determined exploiting their multiple scattering by a Kalman filter algorithm, *i.e.* studying the track displacements with respect to a straight line; this procedure, validated on cosmic rays stopping muons, allows a resolution $\Delta p/p$ down to 10%, depending mainly on the track length [2]. Electrons, instead, are identified with full efficiency by the characteristic electromagnetic showering, well separated from $\pi^0$ combining $\gamma$ reconstruction, $\mathrm{d}E/\mathrm{d}x$ signal comparison and $\pi^0$ invariant-mass measurement at the level of $10^{-3}$ [3]. This feature guarantees a 90% efficiency identification of the leading electron in $\nu_e$ CC interactions, while rejecting NC interactions to a negligible level.

The electromagnetic energy resolution $\sigma(E)/E = 0.03/\sqrt{E(\mathrm{GeV})} \bigoplus 0.01$ is estimated in agreement with the $\pi^0 \to \gamma\gamma$ invariant mass measurements in the sub-GeV energy range. The measurement of the Michel electron spectrum from muon decays, where bremsstrahlung photons emission is taken into account [4], provided the energy resolution below critical energy ($\sim 30\,\mathrm{MeV}$), $\sigma(E)/E = 0.11/\sqrt{E(\mathrm{MeV})} \bigoplus 0.02$. At higher energies the estimated resolution for hadronic showers is $\sigma(E)/E = 0.30/\sqrt{E(\mathrm{GeV})}$. 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.

## 2. – ICARUS-T600 experiment

The ICARUS T600 LAr-TPC detector, presently taking data in the Hall B of the INFN Gran Sasso underground National Laboratory (LNGS), is the largest Liquid-Argon TPC ever built, with the cryostats containing more than 600 tons of LAr. Its detection technique offers the possibility to collect “bubble chamber like” events to address a wide physics program: the main goal is the observation of the $\nu_\mu \to \nu_\tau$ oscillation in the CNGS neutrino beam from CERN to Gran Sasso, but this detector can also be used to study solar and atmospheric neutrino events and to improve the limit on proton decay in some background free channels.

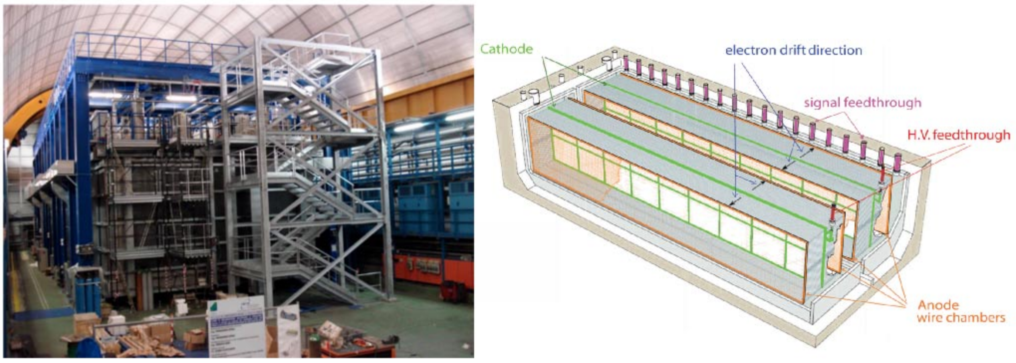

Fig. 2. – The ICARUS T600 detector in Hall B at the LNGS underground laboratory (left) and a simple sketch of the inner TPCs structure (right).

**2**·1. *Detector overview.* – The ICARUS-T600 detector [5] (see fig. 2) consists of a large cryostat split into two identical, adjacent and independet half-modules, with an overall volume of about 760 tons of ultra-pure liquid Argon at 89 K temperature. Each half-module, with internal dimensions $3.6 \times 3.9 \times 19.6\,\mathrm{m}^3$, houses two Time Projection Chambers (TPC) separated by a common cathode. The anode of each TPC is made of three parallel wire planes, 3 mm apart, oriented at 0° and ±60° w.r.t. the horizontal direction: in all 53248 wires, with length up to 9 m, are installed. By appropriate voltage biasing, the first two planes (Induction-1 and Induction-2 planes) are transparent to drift electrons and measure them in a non-destructive way, whereas the ionization charge is finally collected by the last one (Collection plane). The application of an electric field $E_D = 500\,\mathrm{V/cm}$, kept uniform by appropriate field shaping electrodes, ensures that the 1.5 m maximum drift distance is covered in 1 ms. The signals coming from each wire are continuously read and digitized at 25 MHz (thus 1 t-sample $\sim 400\,\mathrm{ns}$) and recorded in multi-event circular buffers.

A prompt detection of the scintillation light is also necessary to determine the absolute time of the ionizing events. For this purpose arrays of Photo Multiplier Tubes (PMTs), operating at the LAr cryogenic temperature [6] and made sensible to VUV scintillation light ($= 128\,\mathrm{nm}$) by applying a wavelength shifter layer (TPB), are installed behind the wire planes.

**2**·2. *The Liquid-Argon purity.* – The main technological challenge in the development of a large mass LAr-TPC is the capability to ensure and maintain a high LAr purity level. In ICARUS-T600 detector an elaborate cryogenic plant, comprehensive of Oxysorb/Hydrosorb filters, performs both gas and liquid recirculation to reduce and keep at an exceptionally low level the electro-negative impurities, especially water and oxygen, in order to obtain free electron lifetime of several milliseconds.

The electron lifetime is continuously monitored studying the attenuation of the charge signal as a function of the drift time along "clean" through-going muon tracks in Collection view, *i.e.* straight tracks without clear $\delta$-rays and associated $\gamma$'s; the negative signal induced by the PMTs on the wires (fig. 3) marks the time at which the track entered the detector. About 50 muon tracks are sufficient to measure day-by-day the electron charge attenuation within a 3% precision, dominated by residual Landau charge fluctuations.

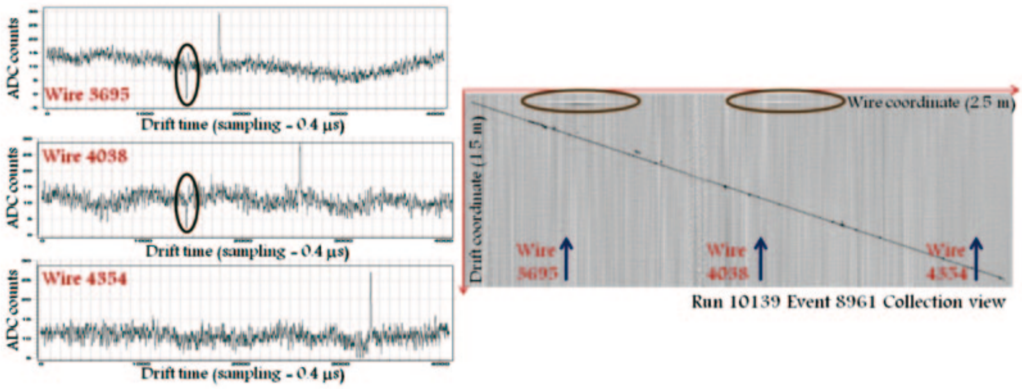

Fig. 3. – A muon track candidate for the purity measurement (right) and three different wire signals (left) in Collection view. The $t = 0$ signal, induced by PMTs on the wires, are circled.

With the liquid recirculation turned on, the LAr purity steadily increased, reaching values of free electron lifetime ($\tau_e$) exceeding 6 ms in both half-modules after few months of operation (fig. 4). This corresponds to 0.05 ppb $O_2$ equivalent impurity concentration, producing a maximum 16% charge attenuation, at the maximum 1.5 m drift distance.

**2**˙3. *Physics programme.* – ICARUS-T600 is the major milestone towards the realization of a multikiloton LAr-TPC detector [7], but it can also address some interesting physics in itself, thanks to its high resolution, $\sim \text{mm}^3$ granularity, information redundancy and particle identification capability [8].

The main goal is the search for $\nu_\mu \to \nu_\tau$ oscillation in the CNGS beam, *i.e.* a beam almost pure in $\nu_\mu$ with average energy $E_\nu \sim 17.4\,\text{GeV}$, traveling over 732 km from CERN to Gran Sasso. ICARUS-T600 looks for $\nu_\tau$ appearance in the electron decay channel $\tau \to e\nu\nu$ of the $\tau$ produced by $\nu_\tau$CC interaction in LAr: in 2011–2012 run almost 3000 $\nu_\mu$CC interactions are expected ($1.1 \cdot 10^{20}$ pot), leading to 3 $\tau \to e$ events over 7 $\nu_e$CC

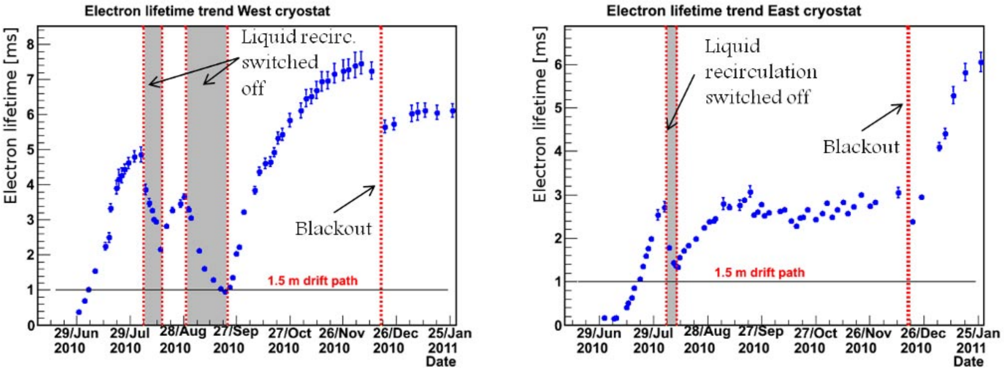

Fig. 4. – Free electron lifetime monitoring in 2010 run, for both cryostats.

background events due to the intrinsic beam contamination. The background can be rejected with kinematical selection criteria based on missing transverse momentum, thus eventually allowing to detect 1-2 $\nu_\tau$ CNGS events in next 2 years. On the same beam the search for sterile neutrinos in LNSD parameter space can be also performed, looking at an excess of $\nu_e$ CC events.

ICARUS-T600 is studying also neutrinos from natural sources: $\sim 80$ unbiased CC atmospheric neutrino interactions are expected per year, and solar electron neutrino interactions with energy greater than 8 MeV can be detected.

Finally, thanks to the powerful background rejection and its $3 \times 10^{32}$ nucleons, ICARUS-T600 can play a role in the long sought for proton decay search, in particular in interesting exotic channels not accessible to Čerenkov detectors. With an exposure of a few years its sensitivity on some "super-symmetric favored" nucleon decay channels will exceed the present known limits.

**2**˙4. *2010 physics run.* – ICARUS-T600 started its operation in May 2010, after a long R&D and installation phase, collecting right from the beginning both cosmic rays and CNGS neutrino events. The trigger system relies on the scintillation light signals, with a starting layout based, for each of the four TPC chambers, on the analog sum of signal from PMTs with a 100 photo-electron discrimination threshold. The trigger for cosmic rays exploits the coincidence of the PMTs sum signals of the two adjacent chambers in the same half-module, relying on the 50% transparency of the cathode mechanical structure: this allows an efficient reduction of the spurious signals maximizing the detection of low energy events. An overall acquisition rate of 25 mHz has been achieved well below the maximum allowed DAQ rate, resulting in about 83 cosmic events per hour. For CNGS neutrino events the proton extraction time information is also available, since an "early warning" signal is sent from CERN to LNGS 80 ms before the first proton spill extraction. Thus, accounting for the CNGS SPS cycle structure, *i.e.* two spills 50 ms apart and lasting 10.5 $\mu$s each, a dedicated trigger strategy has been chosen for the CNGS neutrino interactions, based on the presence of the PMT signal within a $\sim 50\,\mu$s gate opened in correspondence to the predicted extraction times delayed by the neutrino time of flight (2.44 ms) from CERN to LNGS. A trigger rate of about 1 mHz is obtained, including neutrino interactions inside the detector and muons from neutrino interactions in the upstream rocks.

The CNGS run 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 the $8 \cdot 10^{18}$ delivered by CERN, with a detector lifetime up to 90% since November 1st (fig. 5, top). The 78% of the whole collected sample of events, corresponding to $4.52 \cdot 10^{18}$, has been preliminarly analyzed: 94 $\nu_\mu$CC and 32 NC events have been identified by means of visual scanning into a 434 tons fiducial volume, while 6 events need for further analysis to be classified (being at edges, with $\mu$ track 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 $+\ 0.86\ \nu$ NC$)\cdot 10^{-17}$/pot), to be corrected for fiducial volume and DAQ dead-time.

The analysis of the time distributions of this event sample, compared with the CNGS proton extraction time, allows to reconstruct the 10.5 $\mu$s spill duration (fig. 5, bottom), suggesting an excellent precision in the events timestamp.

The neutrino interaction events are then fully 3D reconstructed: muons, pions, protons and kaons are identified by studying the event topology and the energy deposition per track length unit as a function of the particle range ($\mathrm{d}E/\mathrm{d}x$ *versus* range) with

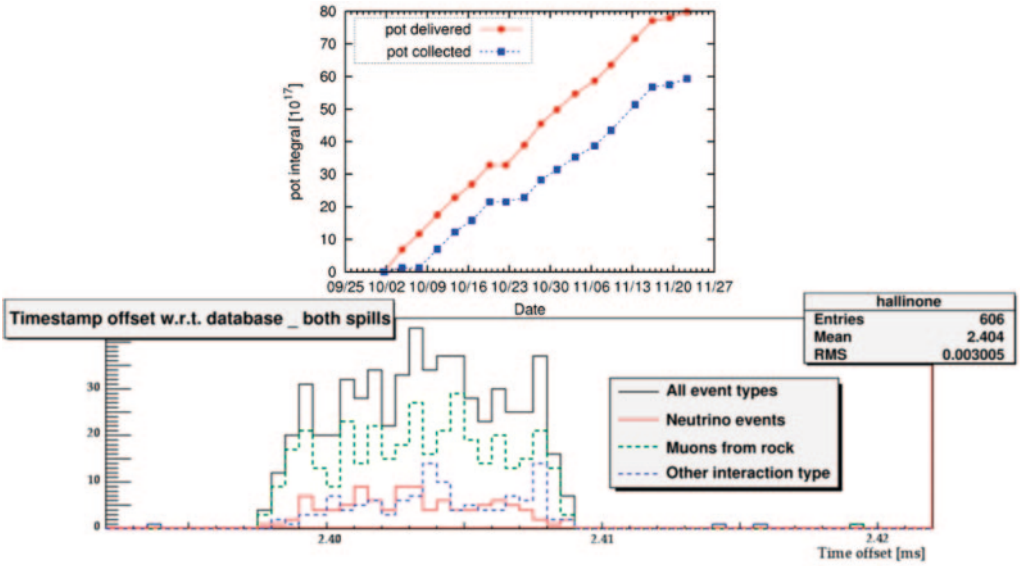

Fig. 5. – Top: number of pot collected by ICARUS-T600 in the Oct.1st–Nov.22nd run compared with the beam intensity delivered by CERN. Bottom: distribution of the difference between the neutrino interaction timestamp and the corresponding CNGS proton extraction time.

a dedicated reconstruction program based on the polygonal line algorithm [9] and on neural network. Electrons are recognized by the characteristic electromagnetic showering. Momentum of long muon tracks escaping the detector momentum is determined by multiple scattering. An example of event reconstruction is reported in fig. 6.

## 3. – A two LAr-TPC experiment at a CERN-PS neutrino beam to solve the sterile neutrino puzzle

Recently a sterile neutrino puzzle is growing, catching the interest of the particle physics community, due to the increasing number of experimental anomalies. On one side the 3.8 $\sigma \overline{\nu}_e$ excess signal in a $\overline{\nu}_\mu$ beam first observed by LSND has been confirmed by the MiniBooNE experiment, suggesting a possible $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation with large $\Delta m^2$ ($0.2 < \Delta m^2 < 2.0\,\mathrm{eV}^2$, $\sin^2 2\theta < 10^{-3}$) beyond the $3\nu$ flavour oscillation scheme

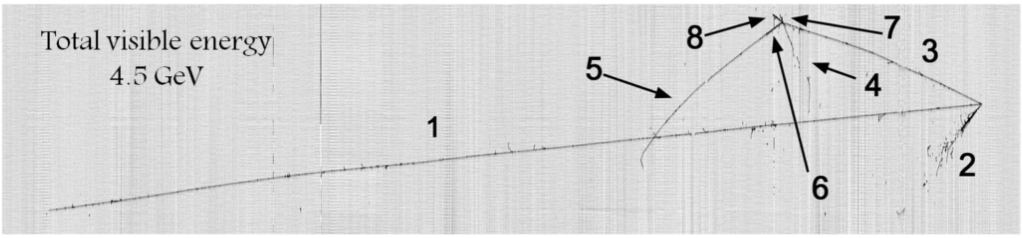

Fig. 6. – Example of a fully reconstructed CNGS $\nu_\mu$CC event, collected in 2010 run.

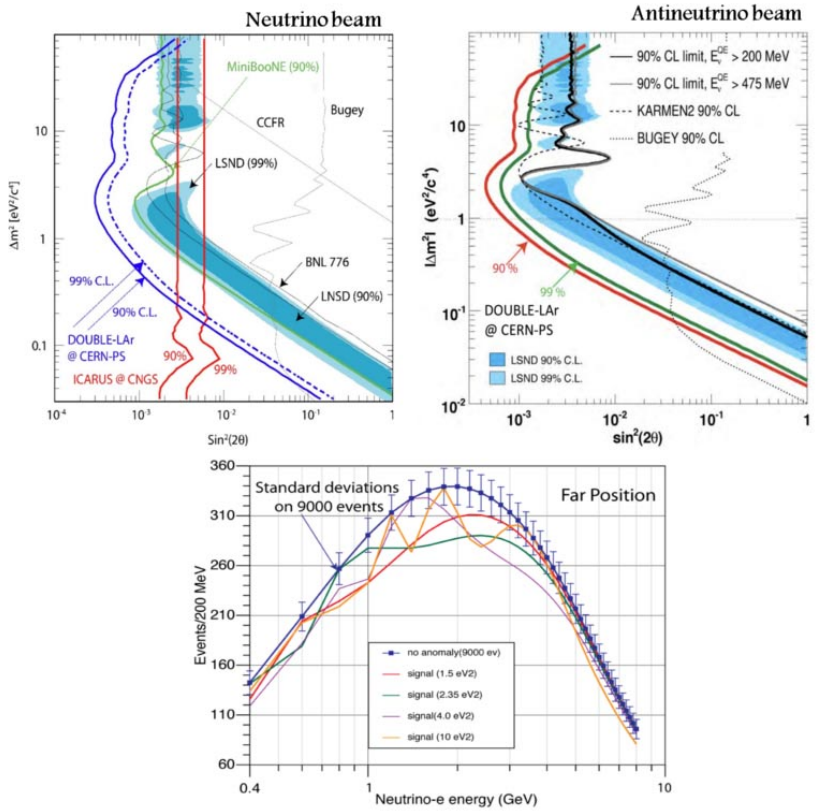

Fig. 7. – Top: sensitivity of the CERN-PS experiment to the $\nu_e$ appearance signal in 2 years (left) and 4 years (right) data taking with in neutrino and antineutrino beam mode, respectively. Bottom: sensitivity to the disappearance reactor anomaly at the far detector.

as observed in solar/atmospheric neutrino experiments. On the other side, a recent re-evaluation of the $\overline{\nu}_e$ reactor spectra ($\sim 3\%$ flux increase) brought out a $\overline{\nu}_e$ deficit at many short-baseline reactor experiments and revived the SAGE/GALLEX $\nu_e$ deficit from the MegaCurie radioactive source, hinting at a fast disappearance rate ($\Delta m^2 > 1.5\,\mathrm{eV}^2$, $0.02 < \sin^2 2\theta < 0.23$ at 99.7% C.L.). Finally, the latest WMAP data seem not to exclude, or even to prefer, a scenario with more than 3 neutrinos.

To clarify the situation a definitive experiment is envisaged: the proposal to use 2 strictly identical LAr-TPC detectors on a refurbished neutrino beam at the CERN-PS represents a possible solution [10]. The neutrino beam would be a low energy $\nu_\mu$ beam produced by 19.2 GeV protons of at least $1.25 \cdot 10^{20}$ pot/y intensity. The far detector, located at $\sim 850$ m from the target, could be ICARUS-T600 itself, while the near detector, at $\sim 127$ m, would be a $\sim 150$ tons active mass LAr-TPC (possibly a clone of a ICARUS-T600 semi-module with length reduced by a factor 2). 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 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 the canceling out of experimental and cross-section biases. It would thus be possible to perform the search for both $\nu_\mu \rightarrow \nu_e$ LSND appearance signal and $\nu_e \rightarrow \nu_x$ reactor disappearance anomaly, with promising sensitivity in only 2(4) years data taking in $\nu(\overline{\nu})$ mode (fig. 7).

## 4. – 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 $\nu_\mu \rightarrow \nu_\tau$ oscillation and LSND-like $\nu_e$ excess, 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.

## REFERENCES

[1] Rubbia C., *The Liquid-Argon Time Projection Chamber: A new Concept for Neutrino Detector*, CERN-EP/77-08 (1977).

[2] Ankowski A. *et al.* (ICARUS Collaboration), *E. Phys. J. C*, **48** (2006) 667.

[3] Ankowski A. *et al.* (ICARUS Collaboration), *Acta Phys. Polon. B*, **41** (2010) 103.

[4] Amoruso S. *et al.* (ICARUS Collaboration), *E. Phys. J. C*, **33** (2004) 233.

[5] Amerio S. *et al.* (ICARUS Collaboration), *Nucl. Instrum. Methods A*, **527** (2004) 329.

[6] Ankowski A. *et al.*(ICARUS Collaboration), *Nucl. Instrum. Methods A*, **556** (2005) 146.

[7] Baibussinov B. *et al.*, *Astropart. Phys.*, **29** (2008) 174.

[8] Arneodo F. *et al.* (ICARUS Collaboration), *ICARUS initial physics program*, LNGS P28/01, LNGS-EXP 13/89 add. 1/01.

[9] Kegl B., Krzyzak A., Linder T. and Zeger K., *IEEE Trans. Pattern Anal. Machine Intell.*, **22** (2000) 281.

[10] Baibussionov B. *et al.*, *A new search for anomalous neutrino oscillations at the CERN-PS*, arXiv:0909.0355; Rubbia C. (ICARUS/CNGS2-P323 Collaboration), *Physics Programme for ICARUS after 2012*, CERN-SPSC-2011-012, SPSC-M-773 (2011).