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To cite this article: Christian Farnese and (for the Icarus collaboration) 2011 *J. Phys.: Conf. Ser.* **335** 012074

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# ICARUS-T600 and beyond: LAr-TPC for neutrino physics and proton decay search

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**Abstract.** Liquid Argon TPCs are performing detectors for neutrino and astroparticle physics thanks to their high granularity, good energy resolution and 3D imaging, allowing a precise event reconstruction. At the end of May 2010 the ICARUS-T600, the first underground large mass LAr-TPC devoted to the experimental study of neutrinos, matter stability and, more generally, rare phenomena, recorded the first CNGS neutrino interaction and is presently taking data at INFN Gran Sasso Laboratory. ICARUS-T600 represents also an important step of the Liquid Argon technique towards the realization of much larger LAr-TPC detectors for future neutrino and matter stability projects.

## 1. Introduction

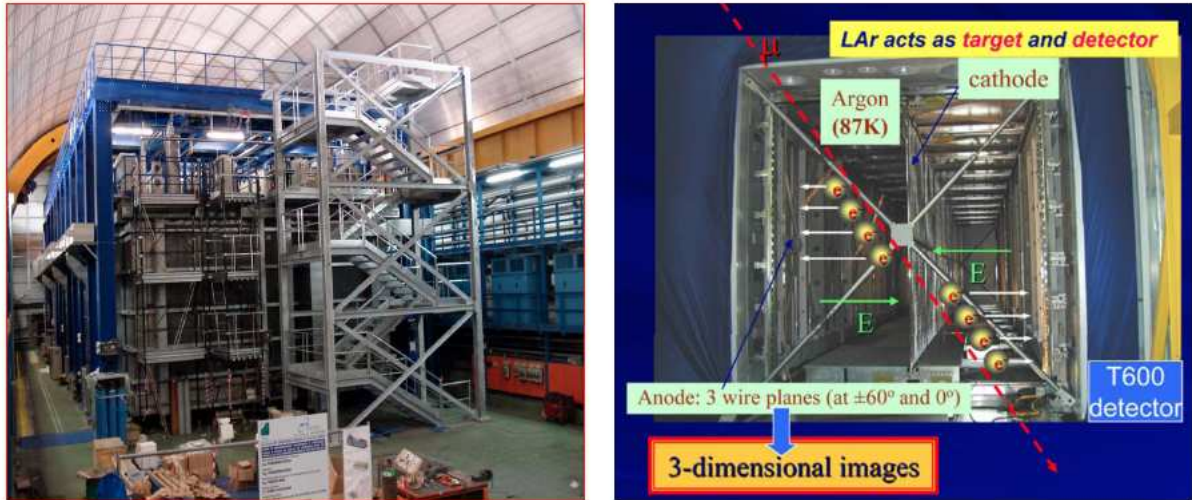
The Liquid Argon Time Projection Chamber (LAr TPC), first proposed by C. Rubbia in 1977 [1], is a powerful detection technique that can provide a 3D imaging of any ionizing event. This continuously sensitive and self triggering detector is characterized by an high granularity and spatial resolution, similar to a bubble chambers. Moreover it is an excellent calorimeter that allow also an efficient particle identification based on the energy deposition vs range measurements.

The operating principle of the Liquid argon TPC is rather simple: a ionizing event taking place in highly purified LAr can be transported practically undistorted by an appropriate uniform electric field over macroscopic distances. Three parallel wires planes, oriented with different directions and placed at the end of the drift path record the signals induced by the drifting electrons providing simultaneous different projections of the same event. The informations from these three projection allow a precise reconstruction of the recorded particle trajectory and a precise calorimetric measurement.

The ICARUS T600 LAr-TPC detector presently taking data in Hall B of LNGS underground laboratory is the largest liquid Argon TPC ever built, with a size of about 600 t of imaging mass. Its detection technique offers the possibility to detect “bubble chamber like” neutrino events due first of all to the CNGS neutrino beam from the CERN-SPS to Gran Sasso to look for the  $\nu_\mu \rightarrow \nu_\tau$  oscillations. At the same time ICARUS can study events due to solar and atmospheric neutrino and finally it can be used to search for proton decay in a background free mode.

In the following the T600 detector and its physics potentials are presented. Finally a new proposal based on LAr-TPC detectors is described.

## 2. The ICARUS T600 detector



**Figure 1.** The ICARUS T600 detector in Hall B at the LNGS underground laboratory (left) and a simple scheme of the LAr-TPC working principle for one of the two semi-module of the T600.

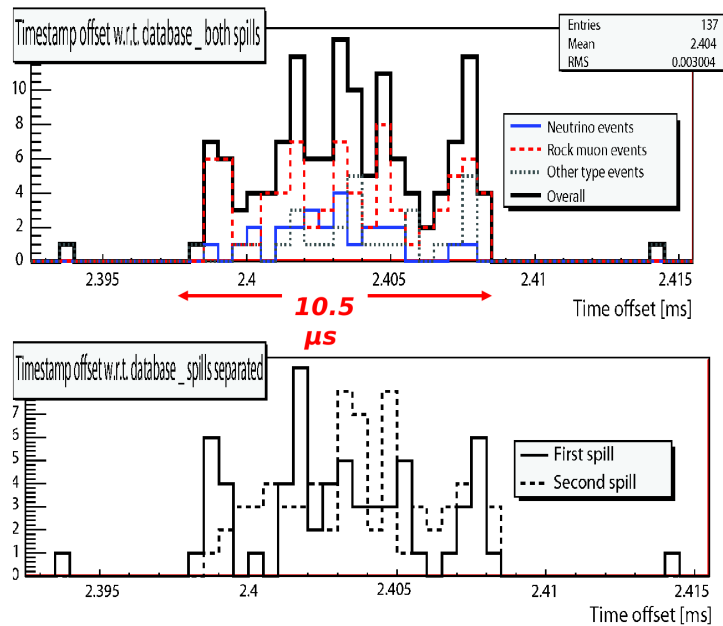
The ICARUS-T600 detector [2] (see Fig.1) consists of a large cryostat split into two identical, adjacent half-modules, with internal dimensions  $3.6 \times 3.9 \times 19.9 \text{ m}^3$  each. Each half-module houses two Time Projection Chambers (TPC) separated by a common cathode, a field shaping system, monitors and probes. Each TPC is made of three parallel wire planes, 3 mm apart, the first with horizontal wires and the other two at  $\pm 60^\circ$  from the horizontal direction. The distance between the cathode and the wire planes, corresponding to the maximal drift length, is 1.5 m equivalent to 1 ms drift time and the nominal drift field 500 V/cm. By appropriate voltage biasing, the first two planes faced to the drift region (Induction planes) provide signals in non-destructive way: the charge is collected in the last wire plane called Collection View. The signals coming from each wire are continuously read and digitized every 400 ns and recorded into a circular buffer. The total number of wires in the T600 detector is about 54000.

### 2.1. ICARUS Trigger

The passage of charged particles through the LAr ionizes it and generates a copious scintillation signal, with emission of 128 nm photons. This signal can be collected by an array of PMTs [3] coated with TPB wavelength-shifter and located behind the wire planes and used in the trigger of this detector.

The trigger rate is dominated by cosmic rays muons and it is  $\sim 40 \text{ mHz}$ . In addition, using the information about the absolute time provided by an LNGS atomic clock, the early warning signals provided by CERN before each CNGS proton extraction is used to trigger in coincidence with PMT signals the CNGS neutrino events with a  $10^5$  suppression of cosmic rays. The analysis of the time distributions of the neutrino interactions, recorded during the CNGS spill gate, allows to reconstruct the  $10.5 \mu\text{s}$  spill width of the two CNGS proton spill and at the same time the  $\sim 2.4 \text{ ms}$  delay is in agreement with the neutrino travel time from CERN to Gran Sasso (fig 2).

Moreover the PMT signals are used to establish the “ $T_0$  time”, i.e. the time of the ionizing event: this information, combined with the knowledge of the electron drift velocity, provides the absolute position of the ionizing event along the drift coordinate.



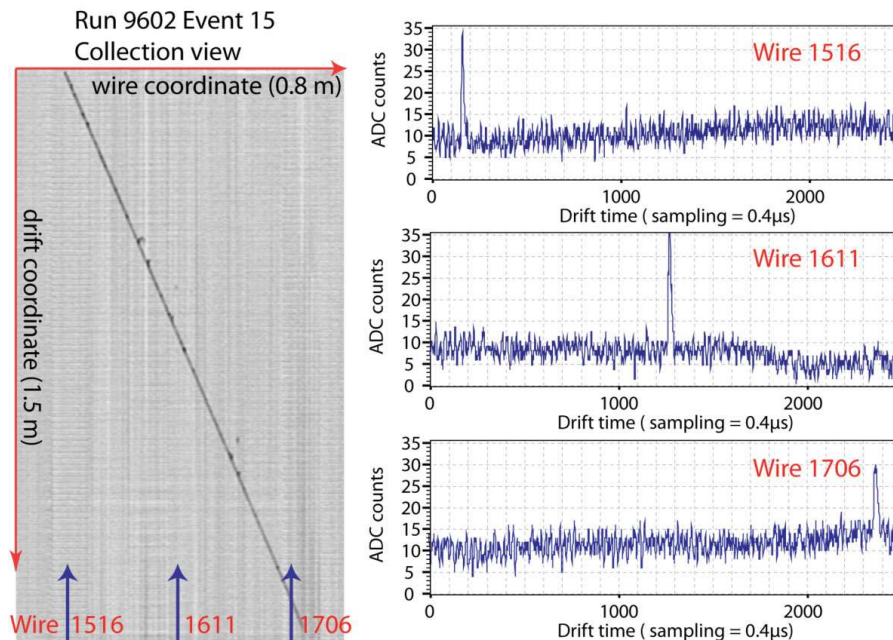
**Figure 2.** Distributions of the difference between the neutrino interaction ICARUS timestamp and the time of the corresponding CNGS proton extraction separated for different event type (top) or different spill (bottom).

### 2.2. Electron Lifetime in ICARUS

The main technological challenge of the development of the LAr-TPC is the capability to ensure and maintain a sufficiently long free electron lifetime. The ICARUS detector is equipped with both a gas and liquid recirculation system to reduce and keep at an exceptionally low level the electro-negative impurities, especially Oxygen and Nitrogen, in order to obtain free electron lifetime of several milliseconds. The electron lifetime is continuously measured in real time studying the charge signal attenuation vs drift time along through-going muon tracks without evident associated  $\delta$ -rays and  $\gamma$ 's in Collection view (Fig. 3). A precise and systematic measurement of the electron lifetime in LAr was initiated soon after the liquid recirculation in the two half-modules started. Thanks to the liquid recirculation system in the first 5 months of data taking the LAr purity reaches  $\sim 7$  ms in the West module, corresponding to a free electron charge attenuations less than 13% in the maximal drift length, and 2.8 ms in the East module, corresponding to a signal attenuation  $\sim 30\%$ .

### 3. Physics potentials and performances of ICARUS T600

ICARUS T600 is the major milestone towards the realization of a much more massive multi-kiloton LAr-TPC detector. Thanks to its high resolution and  $\sim$  mm granularity, the information redundancy and the particle identification capability, ICARUS can address some interesting physics in itself, both in underground physics (proton decay search and cosmic neutrino measurements) and long base-line and high precision neutrino physics [6]. The particle ID capabilities allow to identify the interacting neutrino flavour and provide a powerful discrimination of the  $\nu_e$  CC from the  $\nu_\mu$  NC interactions with high efficiency, by identifying and measuring the electrons emitted in the primary vertex. Overall, exploiting the event topology study, the  $dE/dx$  signal



**Figure 3.** A muon track candidate for the purity measurement and three different wire signals.

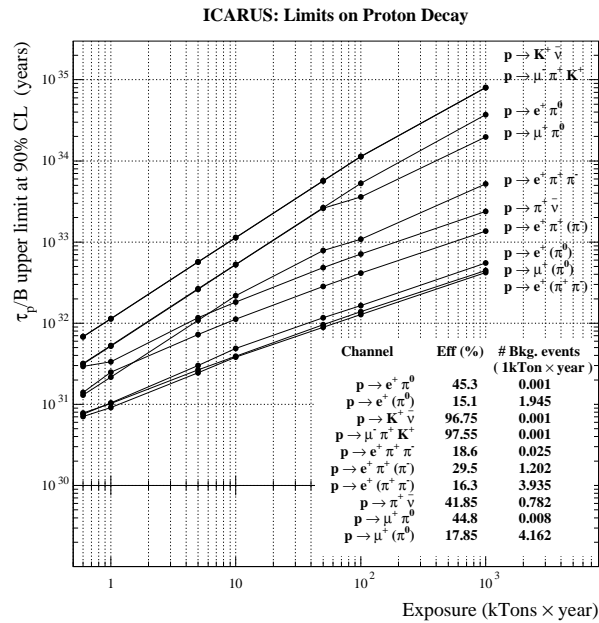
comparison and the  $\pi^0$  invariant mass measurement, it is possible to obtain a  $10^{-3}$  electron -  $\pi^0$  separation with a 90% electron identification efficiency [4].

ICARUS will observe  $\sim 1200$  CNGS neutrino CC interaction per year ( $4.5 \cdot 10^{19}$  pot) with an efficiency of 90% inside the fiducial volume that means  $\sim 2800$  CNGS neutrino events for  $10^{20}$  pot will be collected. It is possible to measure the muon momentum by the study of the multiple scattering within  $\sim 10 \div 15\%$  accuracy for the  $\nu_\mu$  CC from CNGS [5]. The  $\nu_\mu \rightarrow \nu_\tau$  oscillation will be searched in the CNGS neutrino beam recognizing the  $\tau$  decay on the basis of kinematical criteria; in addition ICARUS can also search for sterile neutrino in LNSD parameter space looking at a deep e-like inelastic CC events excess. ICARUS can also study cosmic neutrino events: at least 100 CC atmospheric neutrino interaction per year are expected and also solar electron neutrino interaction with an energy greater than 8 MeV will be studied. Finally, thanks to the powerful background rejection, ICARUS can perform exclusive nucleon decay modes measurements in a background free mode, in particular for interesting channels not accessible to Čerenkov detectors due to the complicated events topology or because the emitted particles are below the Čerenkov threshold. For this reasons with an exposure of a few years ICARUS can improve the knows limits on some “super-symmetric favored” nucleon decay channel (fig. 4).

An example of CNGS  $\nu_\mu$  CC event detected in ICARUS T600 is shown in fig. 5: in this interaction a long muon track,  $\sim 4$  meters, is clearly visible. In addition, looking near the vertex in the Collection and Induction II views, the two photons emitted in a  $\pi^0$  decay are visible. Another example of low energy neutrino interaction is shown in figure 6: the total visible energy is  $\sim 890$  MeV.

#### 4. ICARUS T600 after CNGS-2: a new proposal for a future neutrino experiment at CERN-PS

The operation of ICARUS T600 demonstrate the important milestones achieved, opening the way to the development and the realization of much larger LAr-TPC detectors, for a next



**Figure 4.** The proton decay limit as a function of the exposure

generation of experiments.

A detector of the same size as the T600, i.e. requiring in practice no R.&D. to become operative soon, would be an ideal device to solve the anomalies that have been found by the LNSD and MiniBooNE experiments thanks to its detection capability of  $\nu_e$ . For these reasons a new experimental search based on two strictly identical LAr-TPC detector and on the observation of the  $\nu_e$  signal using a refurbished  $\nu$  beam at CERN-PS has been proposed [7]. The neutrino beam is a low energy  $\nu_\mu$  beam produced by 19.2 GeV protons of intensity  $1.25 \cdot 10^{20}$  pot/yr. The far detector, located at  $\sim 850$  m from the target, will have the same size of the ICARUS T600 while the near detector, at  $\sim 127$  m, will have a active mass of  $\sim 150$  ton (fig. 7). A possible solution for these two detector is to transport, at the end of the CNGS neutrino beam, the ICARUS-T600 and to use it as Far detector. At the same time to ensure the maximum similarity between Near and Far detectors, the Near one will be a clone of a module of T600 with length reduced by a factor 2, keeping untouched the inner detector layout. The energy resolution and granularity of these detectors, largely adequate for the study low energy neutrino events (below 3 GeV), allow to obtain a very high  $\nu_e$  detection efficiency maintaining at the same time an extremely high level of rejection of associated NC background events, in particular due to  $\pi^0$ .

In absence of oscillations, apart some small beam related spatial corrections, the two experimentally observed event distributions in the Near and Far detector must be a precise copy of each other and can be compared without any need of Monte Carlo corrections. Therefore an exact observed proportionality between the two  $\nu_e$  spectra implies directly the absence of neutrino oscillations over the measured interval of  $L/E$ . At the same time any difference between the Near and Far observed event spectra would be a direct proof of neutrino oscillations allowing to determinate separately both the mixing angle and the mass difference. As shown in fig. 8, very different and distinguishable pattern can be obtained for different values in the  $(\Delta m^2, \sin^2 2\theta)$  plane: in any case, the magnitude of the LSND expected oscillatory behavior, for the moment completely unknown, is well above the background, also considering the very high statistical impact and resolution of the experimental measurement. The expected sensitivity in a two-



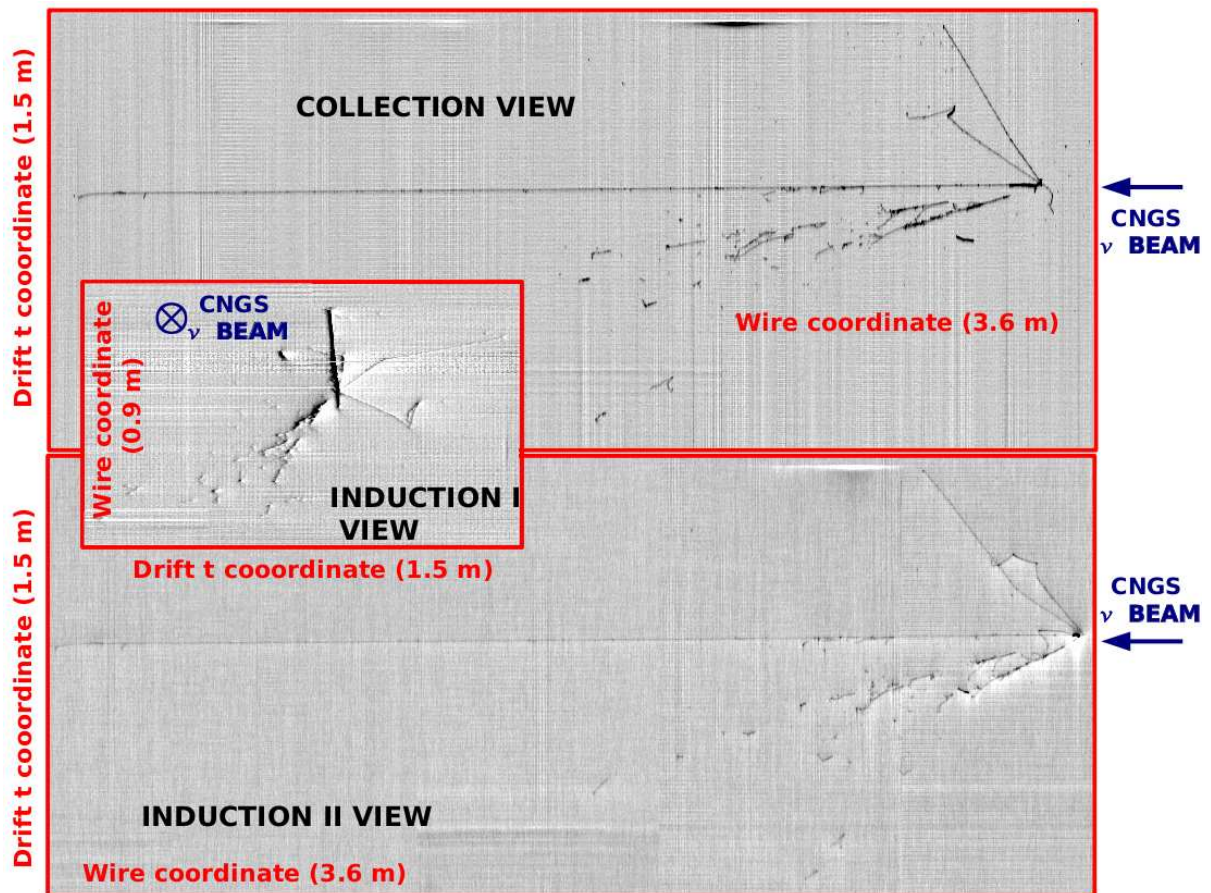


Figure 5. Example of CNGS  $\nu_\mu$  CC event.

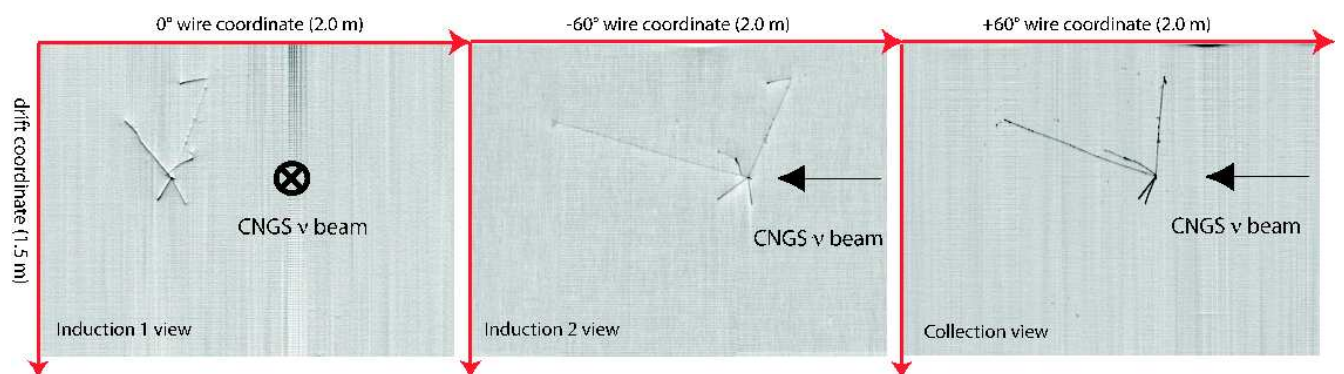
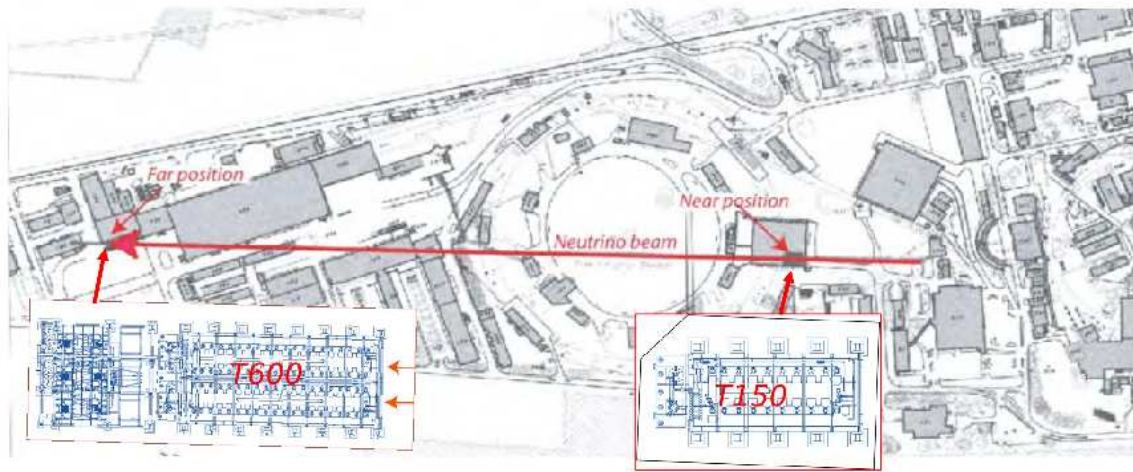


Figure 6. Example of low energy neutrino interaction.



**Figure 7.** Neutrino beam from the CERN-PS and positions of the two LAr-TPC detectors.

flavour oscillation scheme for the neutrino beam considering  $2.5 \cdot 10^{20}$  pot, shown in fig. 8, extends well over the region explored by LSND and MiniBoone. Even in anti-neutrino mode, 2 years of data taking would be sufficient to cover the whole LSND region.

## 5. Conclusions

The ICARUS-T600 detector is presently taking data at the LNGS underground laboratory. Neutrino interactions have been observed and collected for 6 months. The successful assembly and operation of this LAr-TPC is the experimental proof that this technology is mature: this experiment is so far the most important milestone for the LAr-TPC technology and acts as a full-scale test-bed located in a underground environment. The unique imaging capability of this detector, its spatial and calorimetric resolutions and the powerful separation between the electron and  $\pi^0$  signals allow to reconstruct and identify events in a new way with respect to the other neutrino experiments. Its high imaging granularity and resolution allow to address a wide physics programme. ICARUS-T600 is collecting events from the CNGS neutrinos beam from CERN-SPS to search the  $\nu_\mu \rightarrow \nu_\tau$  oscillations. In addition ICARUS-T600 will study with few year data taking the solar and atmospheric neutrino and explore in a new way the nucleon stability in particular channels beyond the present limits. Finally the LAr-TPC technology can be employed to solve the LSND/MiniBooNe anomalies : for this reason a novel search with a refurbished  $\nu$  beam at the CERN-PS has been proposed after the ICARUS T600 exploitation at LNGS.

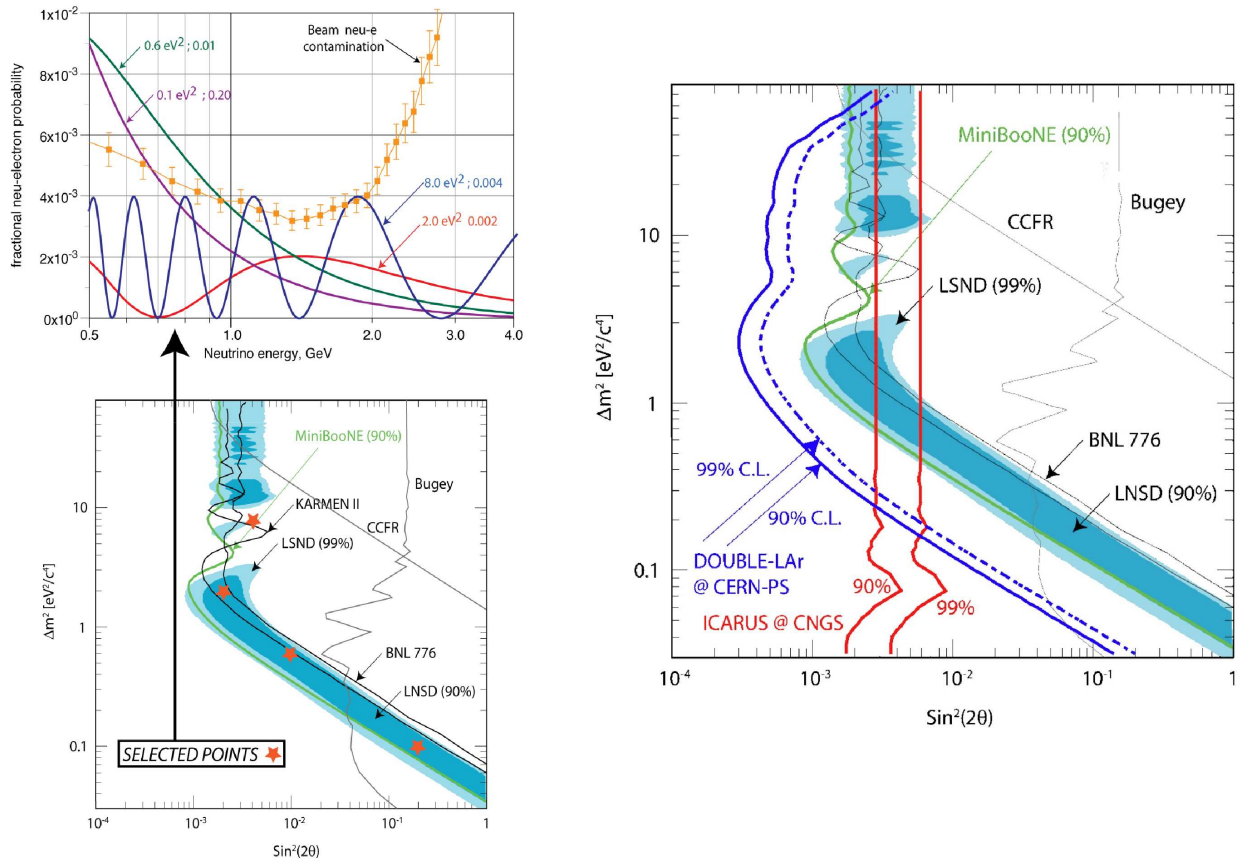
## 6. Acknowledgements

I thank all the ICARUS Collaboration for the contributions in the preparation of the talk and of this proceeding. In particular I wish to thank Prof. Milla Baldo Ceolin who introduces me in the neutrino physics and provides me precious advices for this talk. I would like also to thank the Organizing Committee for the possibility to present this talk during the DISCRETE 2010.

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**Figure 8.** Left: the experimentally expected oscillation patterns at 850 m are shown for some particular points of the LSND allowed region; the expected background is also shown. Right: expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam considering  $2.5 \cdot 10^{20}$  pot; the expectations from the ICARUS-T600 at LNGS are also shown.

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