Some recent results from the ICARUS experiment

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Abstract

ICARUS is the largest liquid Argon TPC detector ever built ($\sim$ 600 ton LAr mass). It was smoothly operated underground at the LNGS laboratory in Gran Sasso since summer 2010, up to June 2013, collecting data with the CNGS beam and with cosmics. ICARUS is internationally considered as a milestone towards the realization of next generation of massive detectors ($\sim$ tens of ktons) for neutrino and rare event physics. It permits, as a unique feature, the unambiguous identification of ν_e events. In particular an update of the experimental search for a ν_e signal in the LSND anomaly region in the CNGS beam will be here presented with the full statistics. The published result strongly limits the window of opened options for the LSND anomaly, reducing the remaining effect to a narrow region centered around $(\Delta m^2, \sin^2(2\theta)) = (0.5 \text{ eV}^2, 0.005)$ where there is an overall agreement (90% CL) between the present ICARUS limit, the published limits of KARMEN and the published positive signals of LSND and MiniBooNE collaborations. Moreover, new results will be shown concerning the analysis of a CNGS beam-related stopping muon sample with the purpose of the momentum reconstruction through multiple Coulomb scattering. Finally, the most recent result on the Argon purity analysis will be presented, which allowed to reach impressive results in terms of Argon purity and a free electron lifetime exceeding 12 ms, corresponding to about 25 parts per trillion of O_2-equivalent contamination: a milestone for any future project involving LAr-TPCs and the development of higher detector mass scales.

1. Introduction

The innovative liquid Argon Time Projection Chamber (LAr-TPC) detection technique, first proposed by C. Rubbia [1], observes ionizing events in neutrino processes or other rare events with a performance comparable to the one of a traditional bubble chamber. The LAr-TPC is fully electronic, continuously sensitive and self-triggering. Operated at atmospheric pressure with a cheap and abundant cryogenic noble liquid, it offers both visual and calorimetric determinations of the recorded events. The operating principle is based on the fact that in highly purified liquid Argon (or Xenon) free electrons from ionizing particles can be easily transported over macroscopic distances (meters) with the help of a uniform electric field to a multi-wire anodic structure placed at the end of the drift path.

The ICARUS Collaboration has developed the LAr-TPC technology from prototypal dimensions to the mass of nearly 1000 ton of liquid Argon with the so-called T600 detector [2], installed in the underground INFN-LNGS Gran Sasso Laboratory near Assergi. Its successful and extended operation has demonstrated the enormous potentials of this novel detection technique, developing a vast physics program [3, 4, 5] and the simultaneous observation of neutrinos both from the CNGS beam at a distance of 730 km from CERN and from cosmic rays.

The ICARUS T600 detector consists of a large cryostat filled with about 760 tons of ultra-pure liquid Argon and split into two identical, adjacent modules. A more detailed description can be found elsewhere [2, 3]. Each module houses two TPCs with 1.5 m maximum drift path, sharing a common central cathode. A uniform electric field (E_{drift} = 500 V/cm) drifts ionization elec-

trons with $v_D \sim 1.6$ mm/μs velocity towards the anode, consisting of three wire arrays and a stereoscopic event reconstruction. A total of 53248 wires are deployed, with a 3 mm pitch, oriented on each plane at a different angle (0°, +60°, -60°) with respect to the horizontal direction. By appropriate voltage biasing, the first two wire planes (Induction 1 and Induction 2) record signals in a non-destructive way; finally the ionization charge is collected and measured on the last plane (Collection). The electronics was designed to allow continuous read-out, digitization and independent waveform recording of signals from each wire of the TPC. The read-out chain is organized on a 32-channel modularity. Signals of the charge sensitive front-end amplifiers have been digitized with 10-bits ADCs with 400 ns sampling channels. The overall gain is about 1000 electrons for each ADC count, setting the signal of minimum ionizing particles (m.i.p.) to $\sim$ 15 ADC counts. The average electronic noise is 1500 electrons, compared with the $\sim$ 15000 free electrons produced by a m.i.p. in 3 mm, leading to a signal to noise ratio S/N $\sim$ 10. The gain uniformity has been measured with an accuracy of about 5%, determined by the uncertainties on the adopted calibration capacitances.

In order to determine the absolute position of the track along the drift coordinate, the measurement of the absolute time of the ionizing event provided by a conventional 8" cryogenic Photo-Multiplier Tubes (PMT) system detecting the prompt scintillation light in LAr has been combined with the information coming from the electron drift velocity.

One thermal insulation vessel surrounds the two modules: between the insulation and the aluminium containers a thermal shield is placed, with boiling Nitrogen circulating inside to intercept the heat load and maintain the cryostat bulk temperature uniform (within 1 K) and stable at 89 K. Nitrogen is stored into two 30 m^3 LN$_2$ reservoirs. The temperature is fixed by the equilibrium pressure in the tanks (2.1 bar, corresponding to about 84 K), which is kept stable in a steady state by a dedicated re-liquefaction system of twelve cryo-coolers (48 kW global cold power), thus guaranteeing the safe operation in a closed-loop. To keep the electronegative impurities in LAr at a very low concentration level, each module is equipped with two gas Argon and one liquid Argon recirculation/purification systems [3, 6]. Argon gas is continuously drawn from the cryostat ceiling and, re-condensed, drops into Oxysorb^{TM} filters to finally return in the LAr containers. LAr instead is recirculated by means of an immersed, cryogenic pump ($\sim$ 2 m^3/h, full volume recirculation in 6 days) and is purified through standard Hydrosorb^{TM} / Oxysorb^{TM} filters

before being re-injected into the cryostats. LAr is extracted at 1.5 m from the floor on one side of the vessel, purified and injected back at the opposite longitudinal side (20 m apart) through several nozzles uniformly distributed close to the floor of the vessel. Convective motions induced by heat losses from the module walls ensure a fast and almost complete LAr mixing, minimizing the fluctuations of the relevant parameters, such as LAr density, temperature and purity.

2. Updated results on the search for a ν_e signal in the LSND anomaly region

The LSND experiment [7] at the LANSCE Los Alamos accelerator and the MiniBooNE experiment [8] at the FNAL-Booster have previously reported significant evidence for an anomalous excess of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ at L/E$_\nu \simeq 0.5 \div 1.0$ m/MeV, where L is the distance from the target and E$_\nu$ is the neutrino energy. These results may imply the presence of an additional mass-squared difference somewhere within a wide interval $\Delta m^2_{new} \simeq 0.01$ to 1.0 eV^2 and with a corresponding associated value of $\sin^2(2\theta_{new})$, largely in excess of the predictions of the Standard Model and three neutrino mixing. Additional ν_e or $\overline{\nu}_e$ disappearance anomalies have been observed at similar Δm^2 new values in (a) nearby nuclear reactors [9] and (b) Mega-Curie k-capture calibration sources [10, 11]. In our case, such anomalies due to the appearance of ν_e in a ν_μ beam will be observed at much larger values of L/E$_\nu$, centered around L/E$_\nu \simeq 36.5$ m/MeV. These hypothetical anomalies will therefore produce very fast oscillations as a function of E$_\nu$, averaging over the observed spectrum to $\sin^2(1.27 \Delta m^2_{new}$ L/E$_\nu) \simeq 1/2$ and P ($\nu_\mu \rightarrow \nu_e$) = 1/2 $\sin^2 (2\theta_{new})$. An update of the search for such anomalies in the CNGS neutrino beam is here presented, based on an additional sample of 455 ν interactions, for a total of 2450 neutrino events within the sensitive LAr volume and 7.23×10^{19} protons on target (pot) out of the fully collected statistics of 8.60×10^{19} pot. The following results complete the already published searches of LSND-like anomalies in ICARUS T600 [5], which showed that there is a possible agreement of all published experimental results only for a narrow surviving region centered around $(\Delta m^2, \sin^2 (2\theta))_{new} = (0.5$ eV^2, 0.005).

Following the previous analysis [4], interaction vertices at a distance less than 5 cm from each side of the active volume of the TPC or less than 50 cm from its downstream walls have been discarded from the recorded sample. The "electron neutrino signature" has been defined [4] requiring:

- interaction vertex located inside the previously defined fiducial volume;

- event energy E < 30 GeV, in order to reduce the beam ν_e background;

- a primary charged track starting directly from the vertex, fully consistent over at least 8 wire hits with a minimum ionising relativistic particle (i.e. dE/dx < 3.1 MeV/cm on average after removal of visible delta rays) and subsequently building up into a shower;

- the electron candidate track has to be spatially separated from other ionising tracks within 150 mrad in the immediate proximity of the vertex in at least one of the two transverse views ($\pm 60°$), except for short proton like recoils due to nuclear interactions.

The expected number of ν_e events due to conventional sources in the energy range and fiducial volume are:

- 7.0 ± 0.9 events due to the estimated ν_e beam contamination;

- 2.9 ± 0.7 ν_e events due to the $\nu_\mu \rightarrow \nu_e$ oscillations from $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$;

- 1.6 ± 0.1 ν_τ with $\tau \rightarrow \nu_e$ events from the three neutrino mixing standard model predictions, giving a total of 11.5 ± 1.2 expected events, where the errors represent the uncertainty on the NC and CC contributions.

The selection efficiency for the search of a ν_e anomaly has been previously estimated as $\eta = 0.74 \pm 0.05$ [4] in the selected energy region. For the intrinsic ν_e contamination the slightly lower value 0.65 ± 0.06 has been estimated since its spectrum is harder than the one of the expected anomalies, based on a sample of 300 simulated events. The contribution from misidentified ν_μCC and νNC interactions is negligible, as discussed in [4]. The predicted visible background is then 7.9 ± 1.0 (systematic error only) events. A thorough discussion on the estimate of the systematic uncertainties on the predicted number of ν_e events was already presented in the previous ICARUS papers on the search for the LSND anomaly [4, 5].

In the newly added sample we have found two additional electron events that bring to six the total observed number of events. This is compatible with the expectation of 7.9 ± 1.0 due to conventional sources: the probability to observe a statistical under-fluctuation resulting in six or less ν_e events is 33%.

As an example, the first new event, shown in Fig. 1, has an electron with energy of 24.0 ± 1.0 GeV, which is clearly separated from the other tracks from the main vertex. The progressive evolution of the electron from the single ionising particle to an electromagnetic shower is clearly visible in the plot of dE/dx along the individual wires in Fig. 1.

Our previously published result [5] is therefore extended: at statistical confidence levels of 90% and 99% and taking into account the detection efficiency η, the limits are respectively 5.2 and 10.3 events. The corresponding new limits on the oscillation probability are $P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3}$ and $P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \times 10^{-3}$, respectively. The exclusion area of the ICARUS experiment referred to neutrino-like events is shown in Fig. 2 in terms of the two dimensional plot of $\sin^2(2\theta_{new})$ and Δm_{new}^2. In the interval $\Delta m_{new}^2 \simeq 0.1$ to > 10 eV^2 the exclusion area is independent of Δm_{new}^2 with $\sin^2(2\theta_{new}) = 2P(\nu_\mu \rightarrow \nu_e)$. In the Δm_{new}^2 interval from 0.1 to $\simeq 0.01$ eV^2, the oscillation is progressively growing and averages to about the above value of twice $P(\nu_\mu \rightarrow \nu_e)$.

As shown in Fig. 2, a major fraction of the initial two dimensional plot $(\Delta m^2, \sin^2(2\theta))_{new}$ of the main published experiments sensitive to the $\nu_\mu \rightarrow \nu_e$ anomaly [7, 8, 12, 13, 14] is excluded by the present result: ICARUS result strongly limits the window of parameters for the LSND anomaly to a narrow region ($\Delta m^2 \simeq 0.5$ eV^2, $\sin^2(2\theta) \simeq 0.005$) for which there is an overall agreement of experiments.

3. Results on Multiple Scattering

In the physics programme of ICARUS T600, as was first pointed out by C. Rubbia [15], a precise measurement of muon momentum in the range of a few GeV/c is a fundamental ingredient, necessary also to understand and to monitor the CNGS beam ν_μ spectrum. For non-contained events, which are expected to be the majority in T600, given the absence of a magnetic spectrometer, multiple scattering is the only method to measure the momentum. A charged particle propagating in a medium undergoes a random deviation from its direction, caused by the Coulomb interactions with the nuclei in the medium, known as multiple scattering. The distribution of the scattering angle for a particle trajectory of length l projected on a plane containing the trajectory, is characterized by a central gaussian region whose width θ_{RMS} depends on the particle momentum p:

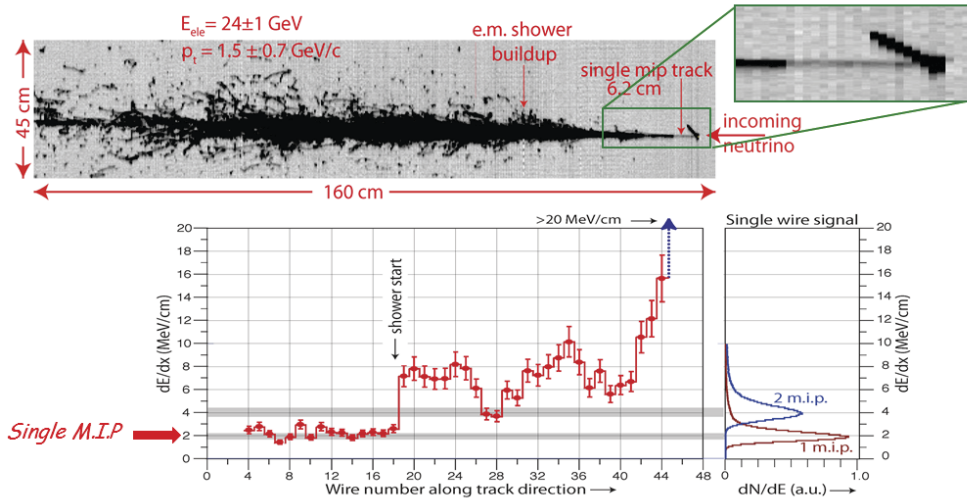$$\theta_{RMS} = \frac{13.6 MeV}{p} \sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}, \qquad (1)$$

Figure 1: Experimental pictures of the first of the two events with a clear electron signature found in the additional sample of 455 neutrino interactions. The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is shown along the individual wires. The event has an electron with energy E = 24.0 ± 1.0 GeV.
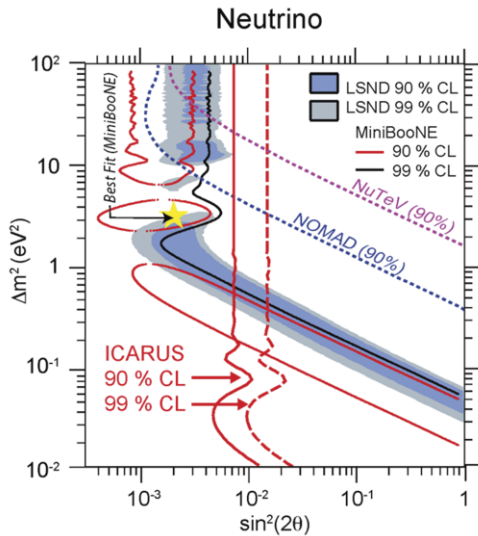

Figure 2: Neutrino oscillation exclusion plot for the main experiments sensitive to $\nu_\mu \to \nu_e$ anomalies [7, 8, 12, 13, 14] and for the present result (continuous red lines). The yellow star marks the best fit point of MiniBooNE [8]. The ICARUS limits on the oscillation probability for $\nu_\mu \to \nu_e$ are $\langle P(\nu_\mu \to \nu_e) \rangle \le 3.85 \times 10^{-3}$ and $\langle P(\nu_\mu \to \nu_e) \rangle \le 7.6 \times 10^{-3}$ at 90% and 99% CL, respectively.

where X_0 is the medium radiation length (14 cm in liquid Argon) [16] and σ the spatial resolution. To estimate precisely the contribution of multiple scattering to the muon propagation, a precise and undistorted track reconstruction is required. Moreover, to separate the multiple scattering contribution from the apparent track deviation given by measurement errors, a full understanding of all these experimental errors is also crucial. The method has been tested in T600 on ∼ 1000 stopping muon sample from CNGS ν interactions in the upstream rock, comparing the initial momentum measured by multiple scattering (p_{MS}) with the corresponding calorimetric determination (p_{CAL}), which is accurately measured with a resolution $\frac{\Delta p_{CAL}}{p_{CAL}} \sim 1\%$, see Fig. 3. The energy range of the selected muons (0.5 ÷ 4.0 GeV) is the appropriate one to study the feasibility of the method in view of the foreseen extension of the ICARUS activities at FNAL with both Short-Baseline and Long-Baseline neutrino beams.

Stopping muons have been visually selected amongst all the neutrino events recorded in coincidence with the CNGS beam spill, by requiring a track length $l_\mu \ge$ 2.5 m, corresponding to about three hadronic interaction lengths, the absence of nuclear interactions along the track and in general no other activity in the event. Tracks were then automatically reconstructed in the space, and delta rays and outliers were identified and removed before proceeding to fit the momentum p, which was extracted from measurement of deflection angle θ and from the χ^2 of the fit, according to:

$$\begin{cases} \theta_{MS} \propto \sqrt{l}/p \\ \theta_{det} \propto l^{-3/2}. \end{cases} \tag{2}$$

The actual momentum is iteratively generated starting

from an initial trial trajectory of $p_{trial} = 10$ GeV/c. Results are shown in Fig. 4, where p_{MS} is compared with the momentum from the observed range. Here the multiple scattering is measured on the first 4 m for stopping tracks with length $L > 5$ m. The plot show a good agreement between calorimetric and MS momentum measurement, with a resolution ~ 16%. Despite the goodness of the method, it has to be remarked that some bias still appears for larger momenta, see Fig. 5.
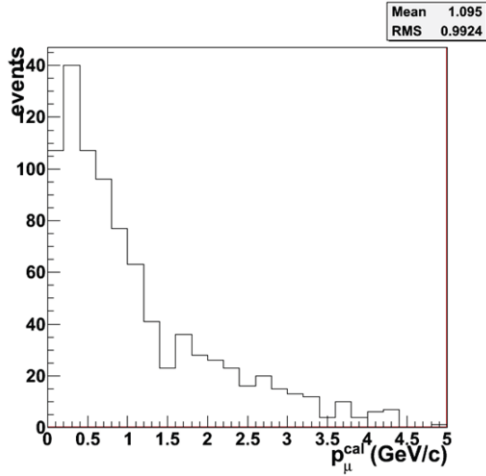

Figure 3: Distribution of the momenta p_{CAL} of stopping muons reconstructed by calorimetric measurement. The accuracy on the calorimetric reconstruction of p_{CAL} is ~ 1%.
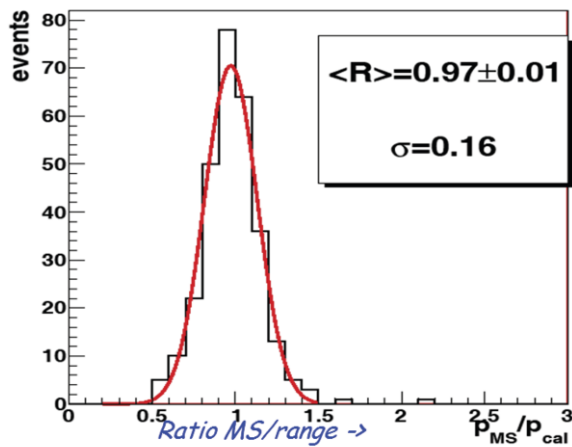

Figure 4: Distribution of the ratio $\frac{p_{MS}}{p_{CAL}}$: the plot shows a good agreement between MS momentum and calorimetric measurement, with a resolution ~ 16%.
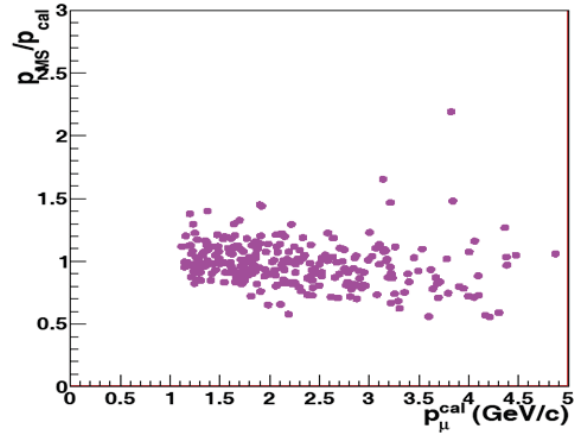

Figure 5: $\frac{p_{MS}}{p_{CAL}}$ as a function of p_{CAL}: despite the goodness of the method, some bias still appears for larger momenta.

4. Argon Purity achievements

The electron lifetime τ_{ele} in LAr-TPC has been measured with the help of the attenuation of the charge signal of traversing cosmic-ray muon tracks as a function of the electron drift distance. A new precise method has been introduced to measure the attenuation $\lambda = 1/\tau_{ele}$ of the actual energy deposition in the ICARUS T600 events, as a function of the drift distance from the wire planes [17].

The through going cosmic rays collected at the rate of ~ 3100 muons per day have been used to measure the free electron lifetime in the ICARUS-T600 providing an almost ideal source of continuous calibration. The LAr purity trend in the T600 East module (Fig. 6) is here shown for the last few months of operation; each data point and the related errors are obtained averaging over ~ 100 muon tracks collected in about half a day. The analysis of the LAr purity demonstrates that the ICARUS detector has operated correctly only when both circulation systems are operational. The interruption of the liquid recirculation system for pump maintenance resulted in a rapid decrease of the electron lifetime that was restored promptly as the recirculation system was reactivated. In April 2013 a major upgrade of the LAr recirculation system was performed in the East cryostat [6]. The ACD CRYO pump used during the first two years of run was replaced with a new Barber Nichols BNCP-32C-000 with an external motor similar to the ones used in the LN2 circuit, which worked in a very efficient and reliable way without frequent stopping. During the two week stop of the LAr recirculation, required for the new pump installation, τ_{ele} rapidly de-

creased below 1 ms. After the new pump was switched on, the electron lifetime started increasing at a rate faster than before (Fig. 6). At the end of the ICARUS data taking the electron lifetime was still rising and the last measurement before the detector stop exceeded $\tau_{ele} \sim$ 12 ms, corresponding to a maximum signal attenuation of 8% at 1.5 m drift distance. This preliminary τ_{ele} value has been improved with a refined analysis, as reported in a recent ICARUS Collaboration paper [17] submitted for publication. The remarkable LAr purity obtained in the large T600 detector approaches the result of $\tau_{ele} \sim$ 21 ms previously obtained with the smaller LAr-TPC prototype of INFN-LNL [18].
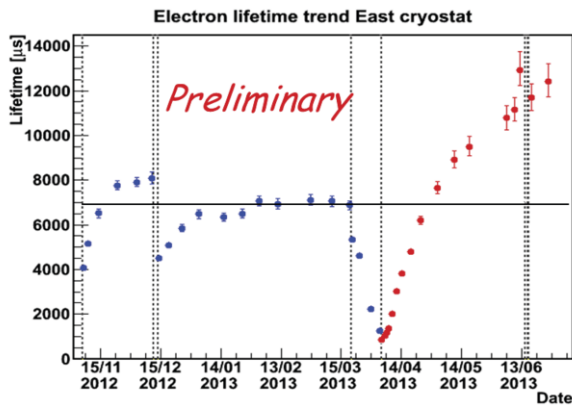

Figure 6: Electron lifetime τ_{ele} of the East module for the last part of the ICARUS data taking: in red full points the measurements with the new not immersed pump are shown.

5. Conclusion

The most recent results from the ICARUS T600 detector operation at LNGS have been presented: ICARUS T600 has successfully completed the CNGS-2 experiment, conclusively demonstrating that LAr-TPC is a leading technology for future Short and Long Base Line accelerator driven neutrino physics. The accurate analysis of the CNGS events and the identification of six ν_e events provides no evidence of oscillation into sterile neutrinos in ICARUS L/E interval. The global fit of all SBL data with ICARUS result limits the window of parameters for a possible LSND anomaly to a very narrow region around ($\Delta m^2 \simeq 0.5$ eV^2, $\sin^2(2\theta \simeq 0.005$) for which there is an overall agreement of experiments. Moreover, muon p measurement by Multiple Scattering techniques has been achieved with a 16% resolution in the momentum range of interest for future LAr TPC either at Short and Long Base Line. Finally, a

remarkable LAr purity, exceeding 12 ms, has been preliminarily measured, opening the way for future large TPC detectors at the scale of the tens of kton.

References

[1] C. Rubbia, *The liquid-argon time projection chamber: a new concept for neutrino detector*, CERN-EP/77-08 (1977).

[2] S.Amerio et al., *Design, construction and tests of the ICARUS T600 detector*, Nucl. Instr. Meth. **A**527 329-410 (2004).

[3] C. Rubbia et al., *Underground operation of the ICARUS T600 LAr-TPC: first results*, JINST 6 P07011 (2011).

[4] M. Antonello et al., *Experimental search for the "LSND anomaly", with the ICARUS detector in the CNGS beam*, Eur. Phys. J. **C**73 2345 (2013).

[5] M. Antonello et al., *Search for anomalies in the ν_e appearance from a ν_μ beam*, Eur. Phys. J. **C**73 2599 (2013).

[6] C. Vignoli, *The ICARUS T600 liquid argon purification system*, presented at the 25^{t}h International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25-ICMC (2014), in publication.

[7] A. Aguilar et al., Phys. Rev. **D**64, 112007 (2001).

[8] A. A. Aguilar-Arevalo et al., PRL 110, 161801 (2013) and references therein.

[9] G. Mention et al., Phys. Rev. **D**83 073006 (2011) and references therein.

[10] J. N. Abdurashitov et al., Phys. Rev. **C**80, 015807 (2009).

[11] F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, Phys. Lett. **B**685, 47 (2010) and references therein.

[12] B. Armbruster et al., Phys. Rev. **D**65, 112001 (2002).

[13] P. Astier et al., Phys. Lett. **B**570 19 (2003).

[14] S. Avvakumov et al., Phys. Rev. Lett. 89 011804 (2002).

[15] A. Ferrari, C. Rubbia, *Muon momentum determination by multiple scattering in Liquid Argon*, ICARUS-TM/99-09.

[16] Particle Data Book, W.M. Yao et al., Journal of Physics **G**33,1 (2006).

[17] M. Antonello et al., *Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC*, ArXiv:1409.5592, submitted to JINST.

[18] B. Baibussinov et al., *Free electron lifetime achievements in liquid Argon imaging TPC*, JINST 5 P03005 (2010).