PROCEEDINGS OF SCIENCE

PoS(GSSI14)019

Hands on ICARUS: reconstruction of ν_μ charged-current events

Gonzalo Martínez-Lema[b], **Lakshmi S. Mohan**[a], **Maddalena Antonello**[c] **and Izabela Kochanek**[c]
On behalf of the ICARUS Collaboration

[a] *Institute of Mathematical Sciences*
C.I.T Campus, 4th Cross Street, Taramani, Chennai, Tamil Nadu 600113, India
[b] *Universidade de Santiago de Compostela*
Praza do Obradoiro, s/n, 15782 Santiago de Compostela, A Coruña, Spain
[c] *INFN - Laboratori Nazionali del Gran Sasso*
Via G. Acitelli, 22, 67100 Assergi, Italy
E-mail: slakshmi@imsc.res.in, gonzalo.martinez.lema@usc.es, maddalena.antonello@lngs.infn.it, iza.kochanek@lngs.infn.it

This article presents the hands-on activity carried on in the framework of the ICARUS T600 experiment during the Gran Sasso Summer Institute 2014. Exploiting the excellent performances in term of spatial resolution, calorimetry and particle identification offered by this 600 tons LAr-TPC detector, two CNGS-beam ν_μ CC events were fully reconstructed. The results of the analysis are reported here along with a brief description of the reconstruction procedure.

Gran Sasso Summer Institute 2014 Hands-On Experimental Underground Physics at LNGS - GSSI14,
22 September - 03 October 2014
INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy

1. Introduction

Neutrino interactions are very rare processes due to the neutral character of these leptons. Hence, large volume detectors are necessary in order to have a significant amount of statistics in a relatively short term. One attractive technological solution for such a detector is the Liquid Argon Time Projection Chamber (LAr-TPC), proposed for the first time by Carlo Rubbia in 1977 [1]. The ICARUS T600 detector [2] is a developed construction of the LAr-TPC concept, devoted to the study of neutrino interactions and other rare phenomena. For three years, from May 28th 2010 to June 26th 2013, it was operated in Hall B at the Gran Sasso Underground Laboratory, in Italy, exposed to the CNGS neutrino beam and to cosmics. This detector, the largest LAr-TPC ever built, offers great detection capabilities, such as good spatial resolution, excellent calorimetry and particle identification, features to be discussed later. This article reports two examples of full reconstruction of ν_μ charged current events which occurred in the ICARUS LAr-TPC. The report begins with a brief description of the detector followed by a detailed explanation of the reconstruction procedure. Finally, results and conclusions are presented.

2. Detector description

The ICARUS T600 detector (see Figure 1-left) consists of two identical adjacent modules of $3.6 \times 3.9 \times 19.6\ m^3$ filled with 760 tons of ultra-pure LAr at 89 K [3]. Each module contains two TPCs that share the cathode and house a uniform electic field of 0.5 kV/cm (see Figure 1-right). Each TPC is made of three parallel planes of wires, 3 mm apart with 3 mm wire pitch, facing the drift path (1.5 m). Wires are oriented on each plane at a different angle (0°, +60° and -60°) with respect to the horizontal direction. The working principle of the LAr-TPC relies on the ionization electrons produced by charged particles propagating in the medium. Electrons are drifted towards the wires, where the signal is recorded. An appropriate voltage biasing of the wire planes provides induced signals in the first two planes (Induction-1 and Induction-2) in a non-destructive way, thus allowing the electrons to reach the last plane (Collection) where full charge is collected. Thanks to the different wire orientation, it is possible to obtain three two-dimensional projections ("views") of the event, as represented in Figure 1-right. Combining the wire coordinate on each view at a given drift time, a three-dimensional image of the ionizing event can be reconstructed. Given the low transversal diffusion in LAr, the paths of the particles remain unaltered and a remarkable spatial resolution of about 1 mm^3 is uniformly achieved over the whole active volume ($\sim$340 m^3). When a charged particle crosses LAr, along with ionization, VUV scintillation light ($\lambda = 128\ nm$) is also produced, providing the information of the absolute time of the ionizing event (t_0). The absolute time, combined with the electron drift velocity information ($v_D \sim 1.6\ mm/\mu s$ at $E_D = 0.5\ kV/cm$), allows to reconstruct the track position along the drift. Scintillation photons are detected by arrays of Photo Multiplier Tubes (PMTs), placed behind the wire planes and coated with wavelength shifter to get sensitivity in the VUV range. A number of triggers have been applied for the acquisition of different classes of events during the detector operation. The PMT system acts as an independent trigger for cosmics or, whether in delayed coincidence with the beam spill, for CNGS neutrino events. A more detailed description of the detector as well as its performance may be found in [2, 3, 4, 5].

PoS(GSSI14)019

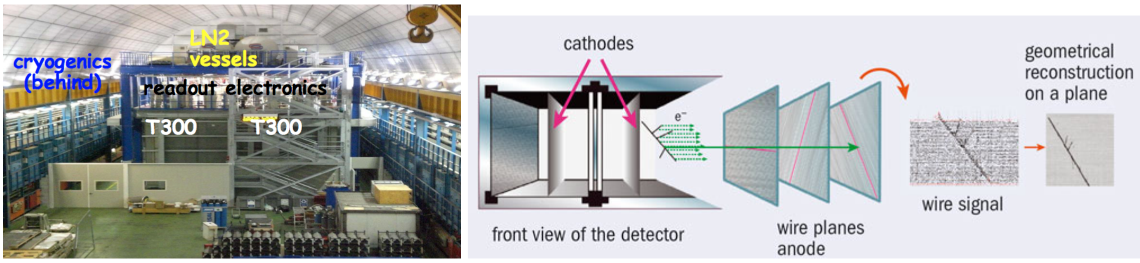

Figure 1: Left: The ICARUS T600 detector installed at the Gran Sasso Underground Laboratory. Right: Illustration of the ICARUS T600 detection principle: a charged particle interacts within the LAr active volume leaving a trail of electrons that produce the signal in the wires.

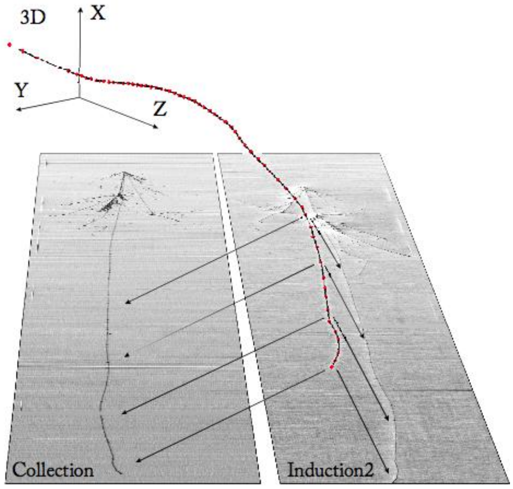

Figure 2: Example of three dimentional reconstruction of a track, obtained applying the polygonal-line algorithm to its Collection and Induction-2 views.

3. Neutrino event reconstruction

The LAr-TPC technology, thanks to its good spatial resolution and excellent calorimetry allows for the full reconstruction of ionizing events within its active medium. The reconstruction of the final state of a neutrino interaction in LAr consists of the following steps: 1) 3D geometrical reconstruction of the event topology; 2) Particle Identification (*PID*); 3) momentum reconstruction; 4) total neutrino energy reconstruction. For the reconstruction of the three dimensional topology of the event, a dedicated program based on the polygonal-line algorithm [6] is used; this procedure is illustrated in Figure 2 and is based on the idea of constructing a 3D track by simultaneous optimization of its 2D projections to match data in the wire planes (for example using Collection and Induction-2 views). Particle identification is achieved by studying the event topology and the energy deposition per track length unit as a function of the residual particle range for muons/pions, kaons and protons stopping within the LAr active volume. A dedicated program based on a neural network for particle identification was used for this purpose. Electrons are fully identified by the characteristic electromagnetic showering; minimum ionizing tracks travelling in LAr at least 2.5 *m* ($\sim$3 times the interaction length in LAr) are identified as muons. The momenta of stopping particles can be reconstructed knowing their kinetic energy and identity. The kinetic energy is measured through calorimetry (see section 3.1). For muons escaping the detector the momentum is determined exploiting the Multiple Coulomb Scattering along the track. All the particle momenta are summed up to obtain the total momentum. Finally, total neutrino energy is computed as the sum of the muon energy and the energy related to the non-leptonic part of the event, using a proper correction factor, evaluated through MC simulation, to account for nuclear binding energy loss, escaping particles, neutral particles and nucleon mass production.

3.1 Calorimetry

Charged particles cause ionization in the detector. Ionization electrons, which drift towards the detector anode, are finally gathered by the Collection wire plane. The deposited charge is actually less than the initial ionization charge due to various losses in the detector. Processes such as charge attenuation and charge quenching reduce the effective charge and, therefore, correction factors must be applied to get an unbiased calorimetric measurement of the event energy. Quenching is the phenomenon in which the ionization electron, soon after its production, recombines with its ion or with ions in the neighborhood. On average, 36% of electrons recombine and only 64% of the actual charge remains. Charge attenuation occurs because drifting electrons can be captured by electronegative impurities diluted in LAr. Free electron capture reduces the charge as $Q = Q_0 e^{-t/\tau_{ele}}$, where t is the drift time and τ_{ele} is the so called "free electron lifetime'', that is the average capture time of a free electron by an electronegative molecule such as O_2, CO_2 or H_2O. LAr purity is hence one of the key points of the LAr-TPC technology. The typical value of τ_{ele} for the ICARUS T600 detector during the CNGS run was $\sim$7 *ms*, corresponding to the impressively low impurity concentration of about 40 *ppt*.

3.2 π^0 reconstruction

Neutrino interaction in LAr, among other particles, may lead to neutral pion production. The LAr-TPC technology can distinguish the ν_μ NC π^0 and $\Delta \to N\gamma$ events from ν_e CC events. This feature, exploited by the LAr-TPC ν_e appearance oscillation experiments, lays on the e/γ separation and on the π^0 invariant mass reconstruction capabilities. Both γs and electrons may create electromagnetic showers; the discrimination is performed by dE/dx measurement in the first centimeters of the cascade: for electron-initiated showers dE/dx is $\sim$ 2.1 MeV/cm (1 mip) while for γ-initiated showers this value is doubled.

The π^0 decay produces 98.8 % of times a couple of γs, while in the remaning 1.2 % of times a γ is produced along with an electron-positron pair (Dalitz decay). The invariant mass of a neutral pion decaying into two γs is given by

$$m_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta_{12})}, \tag{3.1}$$

where E_1 and E_2, reconstructed through a calorimetric measurement, are the energies of the two γs and θ_{12} is the angle between their initial directions, reconstructed exploiting the already mentioned 3D reconstruction polygonal-line algorithm. The two ICARUS T600 neutrino events reconstructed in this hands-on activity and presented hereafter contain two examples of π^0 decaying into two γs.

4. Results

Neutrinos from the CNGS beam interact with the LAr in the detector, yielding a number of final state particles. Two of such events were fully reconstructed and identified as charged current muon-neutrino interactions.

Event number 1387 from run 9831 (Figure 3) was fully reconstructed and classified as ν_μ CC event. At the primary vertex, four minimum ionizing tracks are observed. They are identified as being produced by a muon, travelling at least 3.7 meters ($\sim$ 4.4 interaction lengths) before excaping the detector, and by three charged pions, interacting within one interaction length and giving secondary interaction vertices. Secondary interactions produce heavily ionizing particles that are identified as protons by the *PID* algorithm; it is also produced one charged pion, lately decaying into muon, in turn decaying into electron. Two distinct electromagnetic showers, pointing to the primary vertex, have been identified as being produced by two γs converting at distances $d_1 = 49\ cm$ and $d_2 = 58\ cm$ from the primary vertex and both showing an ionization signal equivalent to $\sim$2.5 mips in the first centimeters of the shower. The two γs deposit energies $E_1 = 329 \pm 21\ MeV$ and $E_2 = 705 \pm 32\ MeV$ respectively. The opening angle between their initial directions is θ_{12} =15.8^o $\pm$ 0.5^o. The associated invariant mass is reconstructed to be $m^*_{12} = 132 \pm 6\ MeV/c^2$, and it is compatible with the π^0 mass. The short highly ionizing track that appears, isolated, in the Induction-2 view has been identified as a proton and interpreted as the product of an inelastic interaction of a neutral particle with an Argon nucleus. The total momentum resulted to be $p_{tot} = 9.8\ GeV/c$ with a transverse momentum $p_T = 277\ MeV/c$, compatible with the theoretical expectation of the Fermi momentum of the target nucleon. The total incoming neutrino energy has been evaluated to be $E_\nu \sim 10.7\ GeV$. in agreement with the total momentum and the possible partial uncontainment of the neutral component of the event final state.

Event number 284 from run 9722 (Figure 4) was also fully reconstructed and identified as ν_μ CC event, given the presence of a 4 *m* long minimum ionizing track at the primary vertex, attributed to the charged lepton. The primary neutrino interaction generates also three charged pions: the first gets scattered before escaping the detector from the wire plane boundary; the second interacts inelastically before decaying into muon and the muon into electron; the third, after short range, gives a secondary vertex producing one decaying particle and two heavily ionizing particles. A neutral particle, probably a neutron produced at the primary vertex, after a path of 46 *cm*, interacts inelastically with an Argon nucleus giving a heavily ionizing particle identified as a proton. Two electromagnetic contained showers pointing to the primary vertex have been identified as generated by two γs converting at $d_1 = 33.9\ cm$ and $d_2 = 11.7\ cm$ from the primary vertex, with energy deposition per unit length of approximately 2 and 2.6 mips respectively in the first centimeters from the conversion points. The energy deposited by each γ amounts to $E_1 = 698 \pm 59\ MeV$ and $E_2 = 565 \pm 48\ MeV$ respectively and the opening angle between them is $\theta_{12} = 12.5^o \pm 0.4^o$; the reconstructed invariant mass is $136.3 \pm 4.7\ MeV/c^2$, in agreement with the π^0 mass. The total reconstructed momentum for the event is $p_{tot} = 13.7\ GeV/c$, with a transverse momentum of $p_T = 274\ MeV/c$. The total incoming neurtrino energy has been evaluated to be $E_\nu \sim 15\ GeV$.

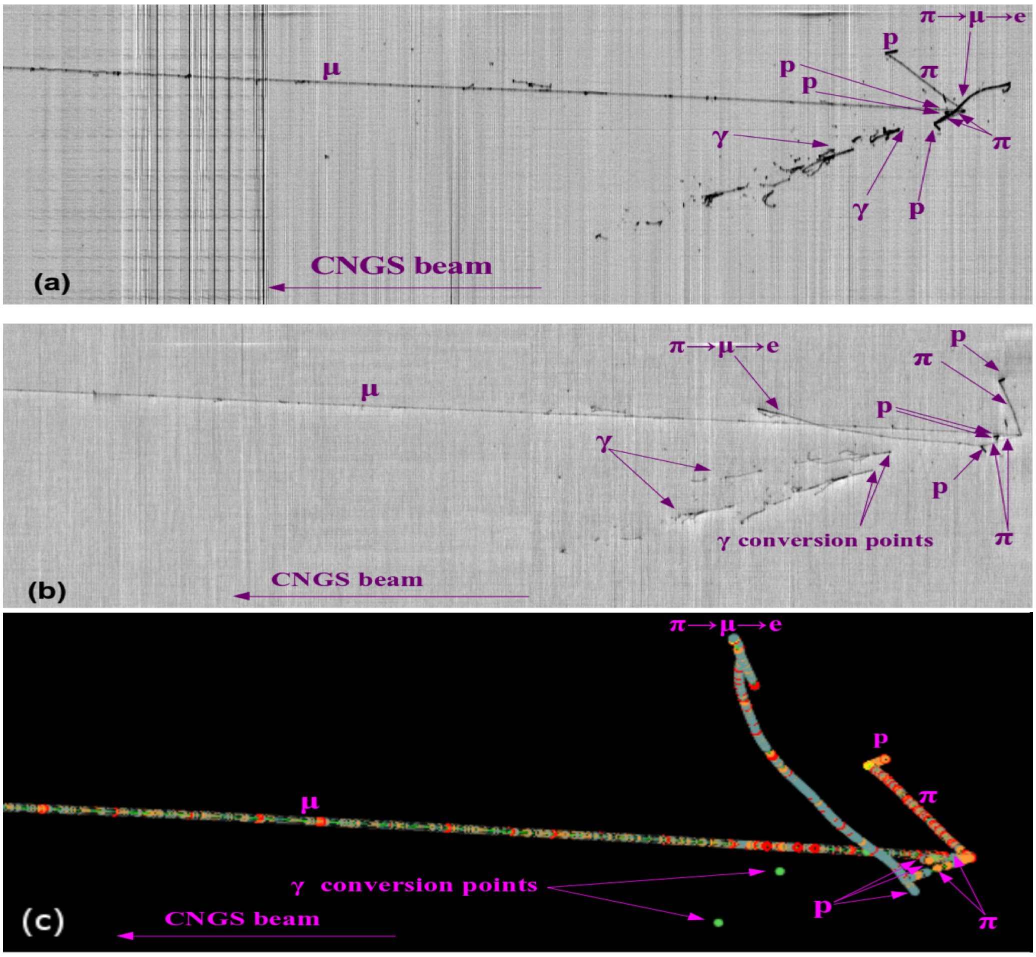

Figure 3: Collection (a) and Induction-2 (b) views of the event 1387 from run 9831. Identified interaction products are tagged. 3D reconstruction of the event in (c); the green dots represent the γ's conversion points.

PoS(GSSI14)019

5. Conclusions

The reconstruction method used in ICARUS was applied to two ν_μ CC events that were fully reconstructed and identified as such. The final state particles were identified using the dE/dx characterization. The energy and momenta of these particles were also measured taking into account the discussed correction factors and a three-dimensional reconstruction was also performed. The composition of this information lead to a precise determination of the event topology, including the products of the Final State Interactions following the primary neutrino interaction. These two examples demonstrate to which level of details particle interactions can be inspected within a LAr-TPC detector.

References

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

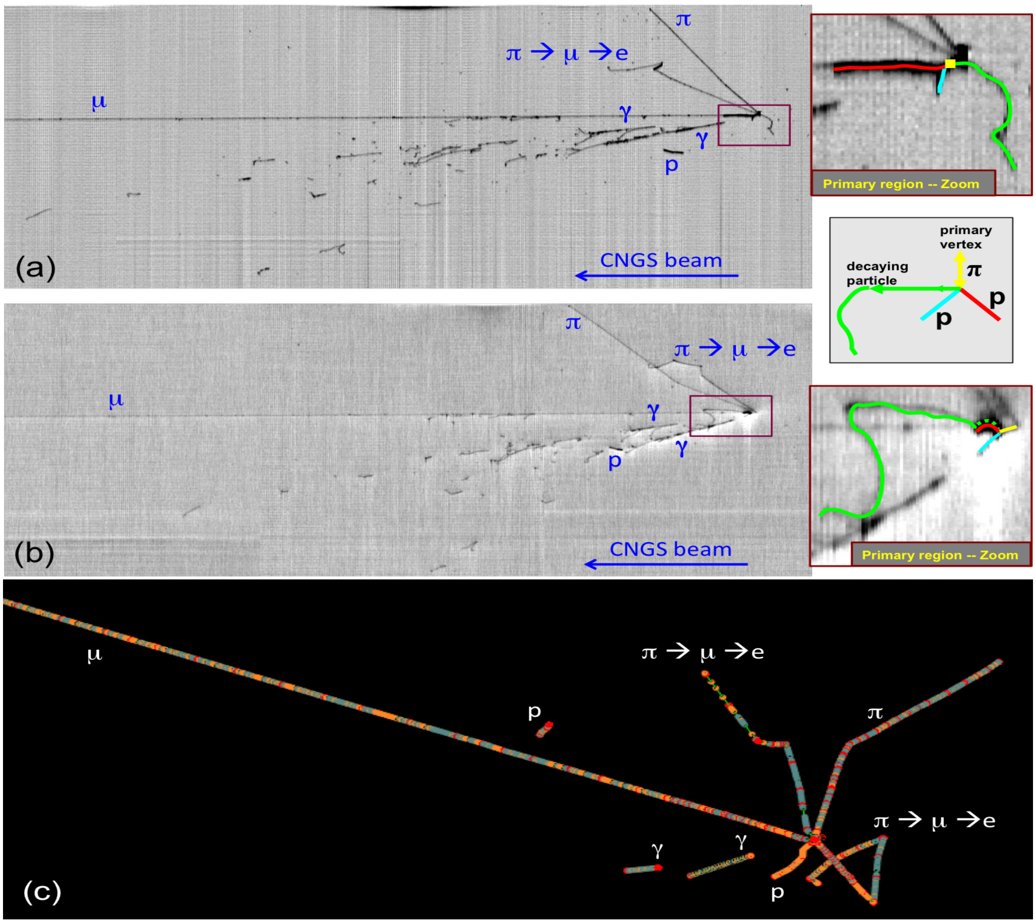

Figure 4: Visualization of the event 284 from run 9722 ocurring in the left TPC of the east module of the ICARUS T600 detector. Collection (a) and Induction-2 (b) views of the event are presented, where vertical axes correspond to the time coordinate while the horizontal axis represents the wire number. Identified tracks are tagged with the particle name. On the right, a zoom of the primary vertex region is given for both views. The event 3D reconstruction is shown in (c).

[2] S. Amerio et al., *Design, construction and tests of the ICARUS T600 detector*, *Nucl. Instrum. Methods* **A527**, 329 (2004).

[3] M. Antonello et al., *Experimental observation of an extremely high electron lifetime with the ICARUS-T600 LAr-TPC*, *Nucl. Instrum. Meth.* 2014 JINST 9 P12006.

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

[5] M. Antonello et al., *The trigger system of the ICARUS experiment for the CNGS beam*, *2014 JINST 9 P08003*.

[6] M. Antonello *et al.*, *Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector*, *Adv. High Energy Phys.* **2013** 260820 [arXiv:1210.5089 [physics.ins-det]].