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The ICARUS experiment and the neutrino velocity measurement

M.Antonello for the ICARUS Collaboration

INFN - Laboratori Nazionali del Gran Sasso, Assergi, Italy

Abstract

ICARUS T600 Liquid Argon (LAr) Time Projection Chamber (TPC) is located in the HALL B of the Gran Sasso National Laboratory, on axis with the CNGS neutrino beam. It is smoothly and continuously operating since June 2010. The experiment has proved to be well suited to address the superluminal neutrino problem firstly raised by the OPERA experiment. As A.G.Cohen and S.L.Glashow argued, Super-luminal muon neutrinos should lose their energy by producing photons and e^+e^- bremsstrahlung pairs, in analogy with Čerenkov radiation. The lack of observation of such a radiative process in the ICARUS T600 detector, using the CNGS beam neutrino events, immediately refuted a superluminal interpretation of the OPERA result. Moreover the ICARUS collaboration, profiting of two short periods of CNGS beam operation in bunched mode, repeatedly performed a high precision measurement of the neutrino time-of-flight which resulted to be compatible with the time-of-flight of a particle traveling at the speed of light: the difference between the expected value based on the speed of light and the measured value is $\delta t = tof_c - tof_\nu = 0.10 \pm 0.67_{stat} \pm 2.39_{syst}$ ns.

Keywords: superluminal, neutrino velocity, LAr-TPC, ICARUS

1. Introduction

ICARUS T600 is the largest Liquid Argon (LAr) Time Projection Chamber (TPC) ever built [1]. The detector (600 tons of LAr) is located in the HALL B of the Gran Sasso National Laboratory, on axis with the CNGS REF CNGS neutrino beam and it is smoothly and continuously operating since June 2010 with a live-time over 93%. The main goal of the ICARUS experiment [2] is the search for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the CNGS beam. On the same beam the search for sterile neutrinos in LNSD parameter space is also performed, looking for an excess of $\nu_e CC$ events [3]. Moreover, ICARUS T600 is studying atmospheric neutrinos and will possibly play a role in proton decay some exotic channels not accessible to Čerenkov detectors. Beyond its initial physics program, the experiment has proved to be well suited also for the precise determination of the neutrino velocity giving its contribution to address the superluminal neutrino problem firstly raised by the OPERA experiment [4]. This report will focus on this last issue and, specifically, on the search for the analogue to the Čerenkov radiation in the ICARUS T600 detector and on the direct measurement of the CNGS neutrino velocity using a dedicated neutrino bunched beam.

2. Detector

The ICARUS T600 detector consists of a large cryostat split into two half-modules filled with $760t$ of ultrapure LAr. Each half-module houses two Time Projection Chambers (TPCs) separated by a common cathode. An uniform electric field ($E_D = 500V/cm$) makes ionization charge drift over the $1.5m$ maximum drift distance in $1ms$. Each TPC is made of three parallel wire planes (53248 wires in total), $3mm$ apart, oriented at 0^o and $\pm 60^o$ w.r.t. the horizontal direction. Opportunely biased, the first two planes sense the signal induced by drifting electrons which can travel unperturbed until they get collected by the last plane. Combining the wire coordinate on each plane at a given drift time, a three-dimensional image of the ionizing event is reconstructed with the remarkable resolution of $1mm^3$.

Scintillation light is abundantly produced in LAr by ionizing events ($\sim 2.5 \times 10^4 \gamma/MeV$ at $128nm$). In ICARUS T600 the light signal is recorded by 4 arrays of photomultipliers tubes (74 PMT's in total) located behind the wire planes. The 4% of the γ are emitted within $1ns$ from the ionizing event, corresponding to about $50-100 phe/GeV/D^2$, where D is the distance from the closest PMT. PMT signals from each array are summed and ,in coincidence with the beam "Early Warning" signal, generate the ICARUS-CNGS trigger. The ICARUS T600 light detection system is equipped with a dedicated PMT-DAQ based on six 2-channel, 8-bit, 1-GHz ACQIRIS AC240 digitizers, triggered by the ICARUS-CNGS trigger. The PMT-DAQ records the PMT-sum signals along with the timing signals available for the event absolute UTC time stamp (see section 4). The delay between the PMT-Sums and the timing signals allows to determine the absolute time of the light pulse onset with few ns of precision.

3. Search for the analogue to Čerenkov radiation by super-luminal neutrinos.

Super-luminal muon neutrinos should lose their energy by producing photons and e^+e^- bremsstrahlung pairs, through Z^0 mediated processes analogous to Čerenkov radiation, as argued by A.G.Cohen and S.L.Glashow [5]. Both pair emission rate Γ and neutrino energy loss dE/dx are proportional to δ^3 where $\delta = (v_\nu^2 - c^2)/c^2$, being v_ν and c the neutrino and light velocity respectively.

A full Fluka Monte Carlo simulation of the CNGS neutrino propagation to Gran Sasso was been performed, including the superluminal radiating process kinematics, as a function of δ. Expectations for $\delta = 5 \times 10^{-5}$, corresponding to the first OPERA claim, are: (1) full ν event suppression for $E_\nu > 30GeV$; (2) about 10^7 e^+e^- pairs/10^{19}p.o.t./kt with a very clear signature: isolated e.m. shower ($E_{dep} > 200MeV$) within $150mrad$ from CNGS beam axis.

The raw energy deposition E_{dep} for CC and NC muon neutrino events was measured calorimetrically and its experimental distribution was compared with the MC expectations: no spectrum suppression was found in both NC and CC data (see Fig. 1) and no e^+e^- pair brehmstrahlung event candidates were found. This lack of events was translated into a 90% CL limit for $\delta < 2.5 \times 10^{-8}$ [6].

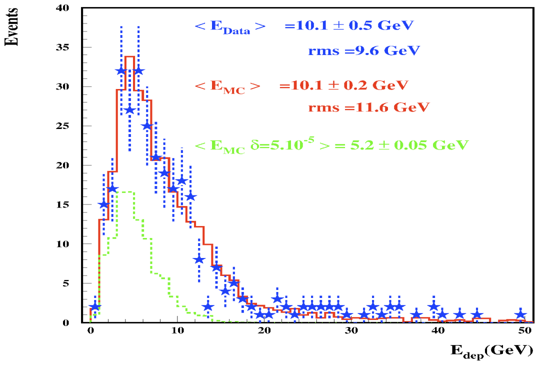

Figure 1: Experimental raw energy E_{dep} distribution for ν_μ and $\overline{\nu_\mu}$ CC interactions in ICARUS (blue) compared with Monte Carlo expectations for an unperturbed spectrum (red), and for $\delta = 5 \times 10^{-5}$ (green). 1.53×10^{19} p.o.t. were used for the analysis.

4. Direct neutrino velocity measurement

4.1. The 2011 neutrino bunched beam

At the end of the 2011 run, the CERN CNGS neutrino beam briefly operated in lower intensity mode ($\sim 10^{12}$ p.o.t./pulse) with a proton beam structure made of narrow bunches $\sim 3ns$ wide. This very tightly bunched beam allowed a very accurate time-of-flight (tof) measurement of neutrinos on an event-by-event basis. During this period the ICARUS T600 detector collected 7 beam-associated events, consistent with 2.2×10^{16} p.o.t. The neutrino velocity measurement is performed combining the accurate determination of the baseline and of the tof. The baseline measurement was performed based on old geodetic measurement available for the OPERA detector combined with recent optical triangulations providing the distance between the OPERA origin and the ICARUS detector entry wall along the beam direction. The baseline was estimated in $731222.3 \pm 0.5m$. The origin of the neutrino tof measurement is the Beam Current Transformer (BCT) detector (BFCTI.400344), located upstream of the CNGS neutrino target; the reference end-point is set at the upstream wall position of the ICARUS T600 active volume. The proton beam time-structure at the BCT is recorded by a 1 GS/s waveform digitizer. Every acquisition is time-tagged with respect to the SPS timing system, associating each neutrino event at LNGS to a precise proton bunch. The absolute UTC timing signal at CERN and at LNGS is provided by two identical systems: an ESAT 2000 GPS receiver coupled with a high accuracy GPS PolaRx2e receiver for time-transfer applications, operating in common-view mode, and a Cs atomic clock Symmetricom Cs4000. The systematic error for their synchronization is ~ 2.0 ns. All the timing signal transmission paths, including the $8km$ optical fiber driving the UTC time stamp from the outside LNGS buildings to the underground hall have been carefully measured within ~ $1ns$. On the detector side, several corrections have been included in order to measure the neutrino arrival time. The propagation time of the scintillation light signals from the PMT window to the PMT-DAQ system has been carefully calibrated. It includes the PMT transit time, overall cabling (~ $44m$) and the delay through signal adders and preamplifier. The associated uncertainty is $\pm 5.5ns$, dominated by PMT transit time fluctuations due to different bias voltages. All measurements have been done directly using PMT-sum signals. In addition, the distance of each event from the closest PMT and the position of the interaction vertex inside the detector active volume have been evaluated leading to the relative time correction within $1ns$. The difference $\delta t = tof_c - tof_\nu$ between the expected tof based on the speed of light ($tof_c = 2439098 \pm 1.7$ ns) and the neutrino tof resulted to be, on average, $\delta t = +0.3 \pm 4.9_{stat} \pm 9.0_{syst}$ ns with an r.m.s. of $10.5ns$ [7].

4.2. The 2012 neutrino bunched beam

With the aim of improving the neutrino tof measurement significance, in 2012 two additional weeks of bunched beam were provided. The new beam had 64 bunches with a narrow width of $4ns$ FWHM.

For this measurement four CERN-LNGS time syncronization/distribution systems were available:

1. the existing LNGS timing system, used in the 2011 campaign.
2. The High Precision Timing Facility (HPTF): a new independent system, setup by the Borexino Collaboration, using a Rb clock combined with PolaRx4 GPS receiver. One replica of the ICARUS trigger signal is sent to the HPTF for time-stamping through a ~ $9km$ calibrated optical fiber.
3. The "White Rabbit" systems (WR-2 and WR-4). White Rabbit is an open source protocol for reliable, fast and deterministic transmission of control information. It intrinsically accounts for signal propagation delay. WR-2 and WR-4 systems, set up both at CERN and LNGS by CERN staff, use two different, inter-calibrated GPS receivers (PolaRx2 and PolaRx4). They provide a synchronization signal to the ICARUS PMT-DAQ and perform the ICARUS trigger signal time-stamping as well.

All the time links were accurately calibrated by the metrology institutes INRiM, ROA, METAS, PTB.

With respect to the 2011 setup the PMT-DAQ system has been also improved by augmenting the granularity of PMT-sum signal recording (9 PMTs instead of 27). Moreover a new calibration campaign has been performed with improved accuracy allowing to infer, with the precision of $1ns$, the transit time of each single PMT as a function of the bias voltage applied.

In 2012, a high precision geodesy campaign by Politecnico di Milano re-evaluted the neutrino baseline in $731222.03 \pm 0.10m$, in agreement with the previous value.

During the 2012 bunched beam run, ICARUS T600 collected 25 beam-associated events, consistent with 1.8×10^{17} p.o.t. The final evaluation of tof_ν was obtained, event by event, as weighted average of all the available timing paths. The distribution of $\delta t = tof_c - tof_\nu$ is shown in Fig. 2 and the resulting average value is $\delta t = +0.10 \pm 0.67_{stat} \pm 2.39_{syst}$ ns, fully compatible with the neutrino propagation at the speed of light, excluding neutrino velocities exceeding the speed of light by more than 1.35×10^{-6} c at 90% C.L. [8].

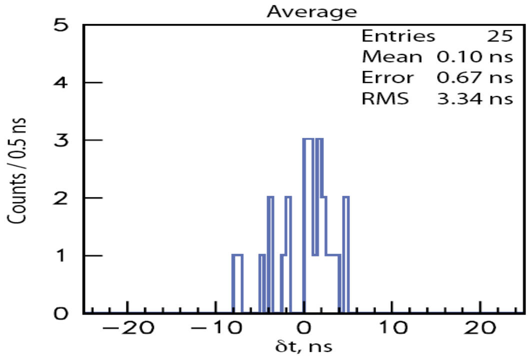

Figure 2: Event distribution in ICARUS T600 for $\delta t = tof_c - tof_\nu$, according to the averaging procedure of all synchronization paths.

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