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Communication

The ICARUS Experiment †

Christian Farnese and on behalf of the ICARUS Collaboration

Dipartimento di Fisica ed Astronomia, Università degli Studi di Padova, ed INFN, Sezione di Padova, 35131 Padova, Italy; christian.farnese@pd.infn.it

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Abstract: The 760-ton ICARUS T600 detector has completed a successful three-year physics run at the underground LNGS laboratories, searching for atmospheric neutrino interactions and, with the CNGS neutrino beam from CERN, performing a sensitive search for LSND-like anomalous ν_e appearance, which contributed to constraining the allowed parameters to a narrow region around $\Delta m^2 \sim$ eV^2, where all the experimental results can be coherently accommodated at 90% C.L. The T600 detector underwent a significant overhaul at CERN and has now been moved to Fermilab, to be soon exposed to the Booster Neutrino Beam (BNB) to search for sterile neutrinos within the SBN program, devoted to definitively clarifying the open questions of the presently-observed neutrino anomalies. This paper will address ICARUS's achievements, its status, and plans for the new run and the ongoing analyses, which will be finalized for the next physics run at Fermilab.

Keywords: neutrino physics; liquid argon; TPC

1. The ICARUS T600 Detector

A very promising detection technique for the study of rare events such as the neutrino interactions is based on the Liquid Argon Time Projection Chamber (LAr-TPC). These detectors, first proposed by C.Rubbia in 1977 [1], combine the imaging capabilities of the famous bubble chambers with the excellent energy measurement of huge electronic detectors. For this reason, they are particularly well suited to investigate a large variety of physical events, spanning a wide energy range (from a few keV to several hundred GeV). The LAr-TPC is a continuously-sensitive and self-triggering detector, characterized by high granularity and spatial resolution, providing 3D imaging of any ionizing event starting from the electrons produced by each charged particle crossing highly-purified LAr. Moreover, this detector is an excellent homogeneous calorimeter which also provides efficient particle identification based on the density of the energy deposition. The operating principle of LAr-TPCs is rather simple: the ionization electrons transported by a uniform electric field to a set of multiple wire planes with different orientations placed at the end of the drift path induce signals on the sensing wires and permit the simultaneous measurement of the same event in different projections. The combined information from these projections provide an accurate 3D reconstruction of the recorded particle trajectories and a precise calorimetric measurement. In addition, the copious scintillation light produced by charged particles in liquid argon can be collected by PMTs located behind the wire plane and used for triggering purposes [2].

The ICARUS T600 detector represents the state-of-the-art of this detection technique [3]. The construction and successful operation of this detector finalized many years of R&D studies: it represents the major milestone towards the realization of multi-kiloton LAr-TPC detectors. Operated for three years (2010–2013) in the Gran Sasso underground laboratory of Istituto Nazionale di Fisica Nucleare (I.N.F.N.), ICARUS, with a total active mass of 476 tons, consists of a large cryostat split into two identical, adjacent modules: each module houses two LAr-TPCs made of three parallel wire planes, 3 mm apart, the first with horizontal wires and the other two at ±60° from the horizontal direction. By appropriate voltage biasing, the first two planes facing toward the drift region (Induction planes) provide signals in a non-destructive way, and the charge is collected in the last wire plane, called Collection view. The two TPCs in each module are separated by a common cathode, and the maximum drift distance is about 1.5 m, equivalent to an ∼1-ms drift time for the nominal electric drift field of 500 V/cm.

One of the main technological challenges for the development of the LAr-TPC is the capability to ensure long drift paths for the ionization electrons. The presence of electronegative impurities in the liquid argon can strongly reduce the electron signal along the drift coordinate, resulting in ionization signals indistinguishable from the electronic noise. For this reason, the argon must be continuously filtered, and the impurity level in the liquid must be continuously monitored measuring the charge signal attenuation on the wires along cosmic-ray muon tracks crossing the LAr active volume. The LAr purity measurements during the Gran Sasso run show that an electron lifetime exceeding 7 ms (corresponding to <50 ppt of O_2 equivalent contaminants and to 12% maximum charge attenuation at the longest drift distance) has been obtained for the majority of the ICARUS data taking. In 2013, improvements in the recirculation system allowed an unprecedented 16-ms lifetime corresponding to 20 ppt O_2 equivalent LAr contamination [4,5], to be obtained demonstrating the effectiveness of single-phase LAr-TPC technique and paving the way toward the construction of huge LAr-TPC detectors with even longer drift distances (up to 5 m of drift).

From October 2010 to December 2012, ICARUS collected about 3000 neutrino events from the CNGS CERN to Gran Sasso neutrino beam corresponding to 8.6×10^{19} protons on target (POT). Neutrino events in the 10–30-GeV energy range have been recorded with unprecedented detail, demonstrating the high-level technical performances and the physical potentialities of this detection technique: the remarkable signal-to-noise ratio of about 10/1 on individual wires and the high density of sampling—∼2% of a radiation length—resulting in a very precise measurement of the dE/dx along the collected tracks in the detector, providing the particle identification for stopping particles [6] and also a powerful electron/photon separation. The events collected demonstrate also that the LAr-TPCs are very suitable detectors in particular for the study of rare events, such as neutrino oscillation physics and proton decay searches, thanks to the high spatial granularity (resolution of ~ 1 mm^3 in an overall active volume of 340 m^3 for the ICARUS T600) and to the good homogeneous calorimetric response ($\sigma_E/E \approx 3\%/\sqrt{E(\mathrm{GeV})}$ for the e.m.showers and $\sigma_E/E \approx 30\%/\sqrt{E(\mathrm{GeV})}$ for hadronic showers). In addition, the momentum of escaping muons can be determined by studying the multiple Coulomb scattering (MCS) along the muon track, providing an average resolution $\Delta p/p \sim 15\%$ in the 0.4–4 GeV/c energy range, which is relevant to next-generation neutrino experiments [7].

2. LSND-Like Search by the ICARUS Experiment at LNGS

Neutrinos have been the origin of an impressive number of "surprises" in the last few decades. The neutrino oscillation studies have established a picture consistent with the mixing of three mass eigenstates, whose actual mass values are so far unknown, in the three flavor neutrino states: electron, muon, and tan neutrinos. The observations of an electron excess in muon neutrino beams, made by the LSND [8] and MiniBooNE [9,10] experiments, of an additional apparent disappearance signal in the ν_e or $\overline{\nu}_e$ events collected by the reactor neutrino experiments [11,12], and in experiments dedicated to solar neutrinos during calibration runs with Mega-Curie k-capture calibration sources [13,14], seem to suggest the presence of invisible "sterile" neutrinos, in addition to the three well-known neutrino flavor states, with an additional mass-squared difference somewhere within a wide interval $\Delta m^2_{new} \sim 0.01$–$\sim 10.0$ eV^2, largely in excess of the predictions of the three-neutrino standard model. More recent experimental results, for example from NEOS [15], DANNS [16], and Neutrino-4 [17], still leave open questions, requiring a definitive clarification of the sterile neutrino puzzle.

The ICARUS Collaboration performed a sensitive search for a possible ν_e excess in the CNGS ν_μ beam related to the LSND anomaly. In total, 2650 CNGS neutrino interactions have been identified in 7.9×10^{19} POT statistics, consistent within 6% with MC predictions. These neutrino events have been studied in detail to identify the electron neutrino interactions: the capability to reconstruct the neutrino interaction vertex, to identify and measure e.m. showers generated by primary electrons and to measure accurately the invariant mass of photon pairs from π^0 decays provided by the LAr-TPC detection technology facilitate a high efficiency in the identification of the electron-neutrino events and allow rejecting to an unprecedented level the NC background for the study of $\nu_\mu \rightarrow \nu_e$ transitions [18]. In particular, electron neutrino interactions have been identified by the presence of a charged track from the primary vertex with a dE/dx compatible with a minimum ionizing particle (m.i.p.) and subsequently building up into a shower isolated from other ionizing tracks near the vertex. In addition, the muon neutrino CC events have been efficiently rejected by requiring the presence of a track from the primary vertex without any hadronic interaction and a visible length greater than 2.5 m. Globally, seven electron-like events have been observed (Figure 1) to be compared with the 8.5 ± 1.1 expected from the $\sim$ 1% intrinsic beam component and standard three-flavor oscillations, providing the limit on $\nu_\mu \rightarrow \nu_e$ oscillations $P < 3.85 \times 10^{-3}$ at 90% C.L. and $P < 7.60 \times 10^{-3}$ at 99% C.L. (Figure 2) [18–20].

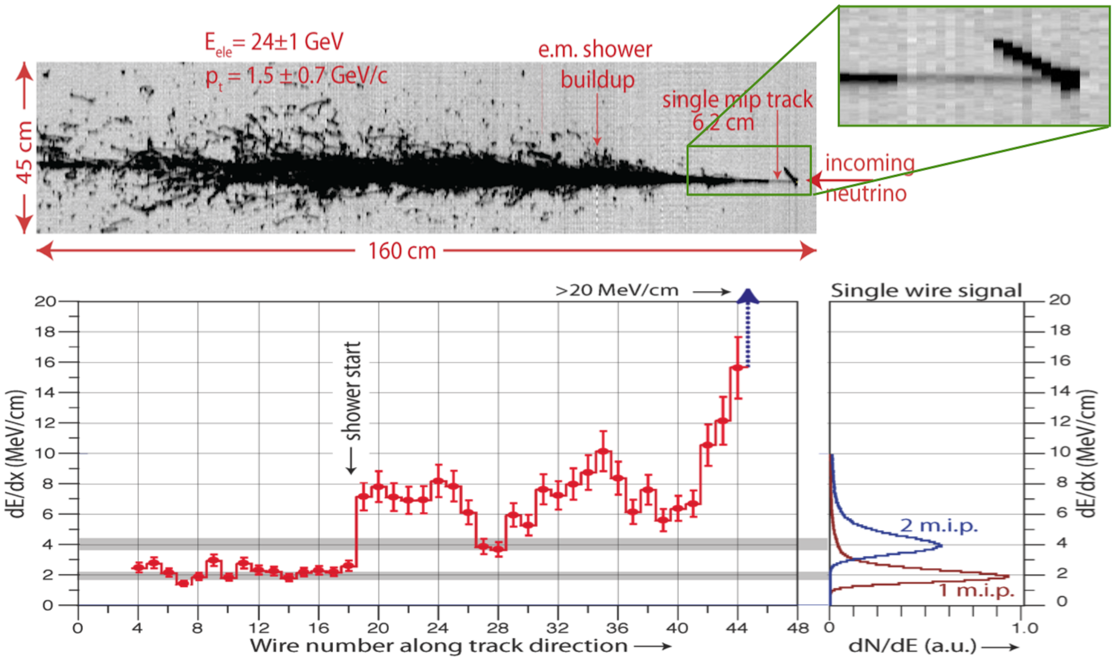

Figure 1. ν_eCC CNGS event in the 2D Collection view of ICARUS-T600 (**top**) with the corresponding evolution of ionization density, dE/dx, in the first wires with the marked shower onset (**bottom**). The expected dE/dx signals for 1 and 2 minimum ionizing particle (m.i.p.) are also shown [20].

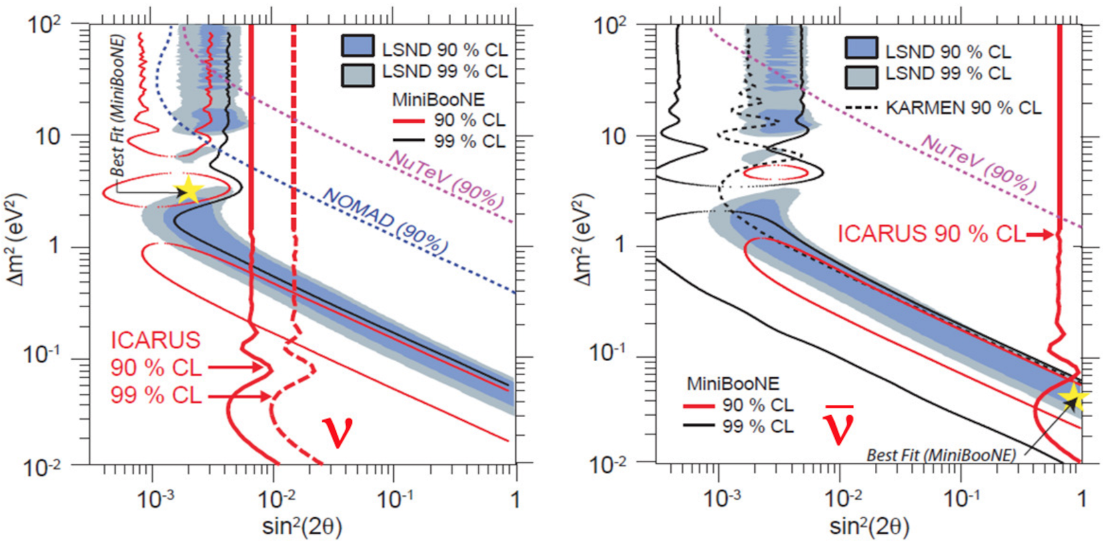

Figure 2. ICARUS-T600 exclusion plots on the search for anomalous $\nu_\mu \to \nu_e$ LSND-like oscillations with the CNGS beam compared to the LSND allowed region for the neutrino (**left**) and the antineutrino (**right**) case. Other experimental limits are also shown [19].

3. The New Short Baseline Neutrino Program at FNAL

The Short Baseline Neutrino (SBN) [21] program is being developed at Fermilab in order to provide the definitive clarification at the 5σ level of the puzzle related to the existence of sterile neutrinos. This new project is exploiting the LAr-TPC technology, which provides excellent visualization tracking and reconstruction capabilities. In addition, a key element of the program is the possibility to measure the neutrino spectrum at different positions along the beam line. The SBN experimental configuration will, in fact, involve three LAr-TPC detectors installed on axis along the Booster neutrino beamline (average $E_\nu \sim$ 800 MeV): the SBND detector located at 110 m from the target, the MicroBooNE detector at 470 m, and ICARUS-T600 operated as the far detector and located at a 600-m distance from the target. In this way, the oscillation signals will be identified directly as differences in the measured spectra, while virtually identical spectra would be expected in the absence of oscillation, helping, together with the adoption of the same detection technology for the different stations, to reduce most of the systematic uncertainties.

The ν_eCC event distributions expected in the near and far detectors corresponding to a total collected statistics of 6.6×10^{20} protons on target and with an oscillation signal corresponding to $\Delta m^2 = 0.43$ eV^2 and $\sin^2(2\theta) = 0.013$ are shown in Figure 3. The resulting experimental sensitivity of the SBN program to $\nu_\mu \to \nu_e$ appearance signals in the $(\Delta m^2, \sin^2(2\theta))$ plane is also shown in Figure 4, left: the LSND 99% C.L. allowed region is covered at the $\sim 5\sigma$ level everywhere; the region below $\Delta m^2 = 0.1$ eV^2 has been already ruled out at more than 5σ by the previous results of ICARUS at Gran Sasso. In addition, in order to confirm an observed ν_e appearance signal as related to sterile neutrino oscillations, the disappearance measurement is also needed since in this case, a genuine $\nu_\mu \to \nu_e$ appearance can also be accompanied by the disappearance of the intrinsic ν_e and ν_μ beam components. The simultaneous analysis of ν_e CC and ν_μ CC events in the SBN oscillation physics program will be a very powerful way to disentangle the effects of $\nu_\mu \to \nu_e$, ν_μ disappearance, and ν_e disappearance, if they exist, in this mass-splitting range. Even if the absolute neutrino flux and cross-section uncertainties in any detector are expected to be larger than 10%, the high correlations between the near detector and the MicroBooNE/ICARUS event samples combined with the excellent statistics at the near site will make the SBN program the most sensitive ν_μ disappearance experiment at $\Delta m^2 \sim 1$ eV^2 (Figure 4, right).

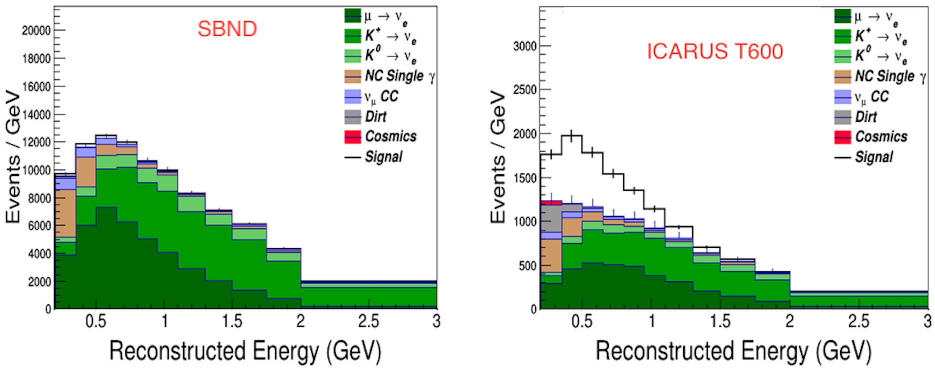

Figure 3. Expected ν_e CC event distributions at the near SBND (**left**) and far ICARUS-T600 (**right**) detectors, corresponding to a 6.6×10^{20} protons on target (POT) exposure at the Booster Neutrino Beam (BNB). The $\nu_\mu \rightarrow \nu_e$ oscillation signal refers to $\Delta m^2 = 0.43$ eV^2 and $\sin^2 2\theta_{\mu e} = 0.013$. The misidentified neutral-current and ν_μ CC events, out-of-detector beam-related backgrounds, and cosmogenic photon-induced electromagnetic shower backgrounds are also included [21].

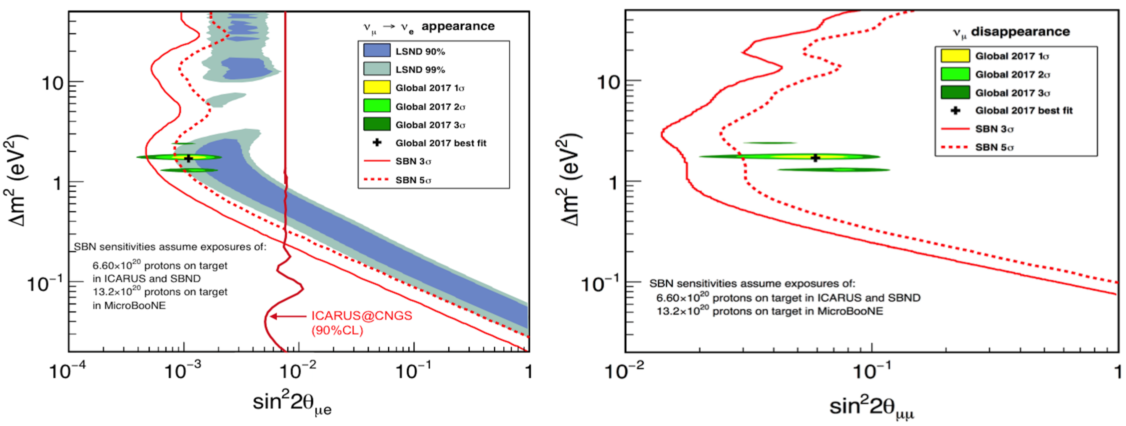

Figure 4. The expected sensitivity to $\nu_\mu \rightarrow \nu_e$ (**left**) and the corresponding expected sensitivity to ν_μ disappearance (**right**) provided by the SBN program, compared to the LSND positive result and to a global best fit expectation of all present neutrino anomalies [22]. A total exposure of 6.6×10^{20} POT at the BNB beam for the SBND and ICARUS detector and 1.32×10^{21} POT for the MicroBooNE detector have been considered [23].

During the data taking at Fermilab, the T600 detector will be also exposed to the off-axis neutrinos from the NuMI beam, in the $0 \div 3$-GeV energy range with an enriched component of electron neutrinos (several %) from the dominant three-body decay of secondary K. Statistics comparable to the one from the Booster beam will be collected: the careful and detailed analysis of these events will provide fundamental information related to the detection efficiencies, neutrino cross-sections, and interaction topologies at energies relevant to the future Long Baseline Neutrino Facility (LBNF) program with the multi-kt DUNE LAr-TPC detector [24].

4. Overhauling the T600 Detector at CERN

In order to prepare the detector for this new SBN data taking, the T600 has been transported to CERN and, starting from December 2014, underwent a significant overhauling phase in the framework of the CERN Neutrino Platform (WA104 project). The most important overhauling activities concerned:

- the flattening of the existing TPC cathode panels;
- the construction of new cold vessels, made of extruded aluminum profiles welded together;

- the preparation of the new purely-passive insulation for the detector;
- the refurbishment of the cryogenics and LAr purification system;
- new, higher-performance read-out electronics;
- the realization and installation of a new scintillation light detection system;

4.1. The New Light Detection System

At Fermilab, the T600 detector will take data at a shallow depth, protected by a 3-m concrete overburden, and so, $\sim$11 cosmic muons are expected to cross the detector randomly in the 1-ms drift time corresponding to the triggered event. The photons produced by cosmic rays crossing the overburden can become a serious source of background for the electron neutrino search since the showers produced by the Compton scattering and by pair production processes can mimic genuine ν_e CC interactions.

The realization of a new T600 scintillation light detection system [25] is a fundamental feature in order to reject this expected huge cosmic background. The new system consists of 360 Hamamatsu R5912-MOD PMTs installed behind the wire planes. All the PMTs have been tested at room temperature to verify the PMTs' compliance with the required functioning specifications, and 60 PMTs have been also tested in a liquid argon bath, to verify any feature variation (PMT gain, dark counts, and saturation). Then, the PMT glass windows have been coated by a fluorescent wavelength shifter (tetra-phenyl butadiene), which re-emits in the visible light frequencies, to make the PMT sensitive to the scintillation light produced in liquid argon (λ = 128 nm). Finally, the 360 PMTs have been installed behind the wire planes (90 PMTs in each TPC). The PMT is now enclosed in a wire screening cage in order to prevent the possible induction of PMT pulses on the facing TPC wires.

The new light detection system will provide, during the data taking at Fermilab, a sensitivity below 100 MeV of deposited energy, a time resolution of the order of 1 ns, and a high granularity: all these features are fundamental to identify effectively the events associated with the neutrino beam and to measure the time of occurrence of each interaction in the detector. The information provided by this system, combined with the signals from a 4π segmented cosmic muon tagging system (CRT) composed of plastic scintillation slabs read out by silicon PMTs surrounding the T600 (area $\sim$ 1200 m^2, coverage $\sim$ 98%), will allow the cosmic ray tracks entering the detector to be unambiguously identified and will help to select the genuine neutrino interactions, providing at the same time a strong reduction of the cosmic-related background for the electron neutrino search.

4.2. The New Read-Out Electronics for the ICARUS T600 Detector

The overhaul of the T600 gave the opportunity also to update the "warm" TPC read-out electronics, in order to obtain a better event reconstruction quality [26,27]. The new analogue front-end adopts a faster shaping time ($\sim$1.5 µs) for both induction and collection wires, achieves a better signal-to-noise ratio and provides a better hit separation together with a drastic reduction of the undershoot in the preamplifier response and of the low frequency noise. The introduction, after the amplifier associated with each channel, of a serial 12-bit ADC avoids the cumbersome use of multiplexers and most of all provides a synchronous sampling of the whole detector (sampling time: 400 ns), which is expected to help in the measurement of the muon momentum with multiple Coulomb scattering. The data stream of each channel is fed into a single high-performance FPGA, which performs data compression, buffering, and transmission to the DAQ. The throughput of the read-out system has been improved up to 10 Hz by using a modern switched I/O where transactions are carried over optical gigabit/s serial links. Finally, a new, more compact design allows both the analogue and digital part associated with 64 channels to be housed in a single board, and nine boards are housed directly on ad hoc detector feed-through flanges.

5. Status of the Activities in View of the New Data Taking at Fermilab

The T600 overhaul process was concluded in June 2017 with the installation of the two T600 internal detectors, completely refurbished, in the new aluminum vessels. The two ICARUS modules have been then transported to FNAL and safely arrived at the far site of the SBN experiment on 26 July 2017 (see Figure 5).

During August 2018, the detectors were inserted in the new Warm Vessel, which had been installed during 2017 in the new Far-Detector building. The detector commissioning should start at the beginning of 2019 with the vacuum pumping (1 month) followed by the cooling of the detector (15 days). The detector will be then filled with liquid argon, and approximately two months are needed to obtain a high purity level and a stable condition, in order to start the data taking. The commissioning of the TPC and PMT systems, including also the calibration of the different systems, the DAQ, and trigger commissioning, will require two months, and in parallel, also the commissioning of the Cosmic Ray Tagging System will start.

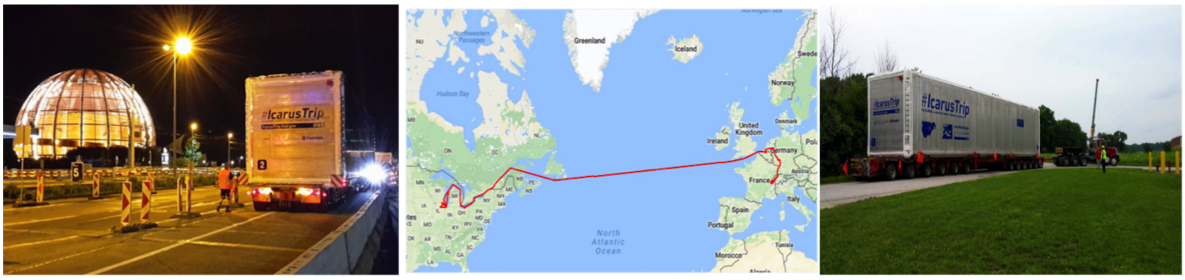

Figure 5. The so called icarustrip, the journey of the T600 detector from CERN to FNAL. In particular, on the left is a picture of the T600 detector leaving from CERN on 12 June 2017. In the middle, the map of the long journey of the detector, and finally, on the right, a picture of the T600 arriving at the SBN Far site building in Fermilab on 26 July 2017.

Status of the ICARUS Event Reconstruction in View of the New Data Taking at Fermilab

In parallel with the activities for the overhaul of the T600 detector, the software that will be used for the analysis of the collected events during the new SBN experiment has also been completely renewed. In particular, in the SBN program, a common software framework called LarSoft is adopted, providing important tools for the simulation, identification, and reconstruction of the events collected in the LAr-TPC detectors. In addition, in view of a common oscillation analysis, the events from the different detectors have to be analyzed side by side using the same tools to better exploit a cancellation of all common effects and to obtain a robust control and minimization of all the residual systematic effects. For all these reasons, LarSoft is now adopted also for the ICARUS T600 detector, implementing a detailed description of the geometry and structure of the setup (see Figure 6) together with all the components to realize first a full simulation and then a complete reconstruction of the signals from the TPC wires, as well as from the PMTs and the Cosmic Muon Tagging system, including the new wire electronic response, a realistic simulation of the noise, and the parametrization of the scintillation light in LAr.

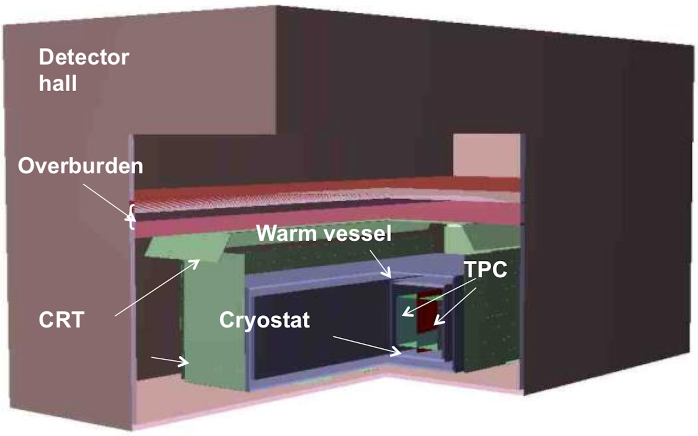

Figure 6. Sketch of the new geometry description of the T600 detector in LarSoft.

In parallel with the preparation and development of a very detailed simulation of the events, also the most important analysis tools developed and used during the Gran Sasso run have been imported and improved in view of the new analysis. For example, the method for the measurement and monitoring of the liquid argon purity condition, necessary as soon as the detector starts collecting events, has been updated taking into account the new experimental conditions: in fact, in the new data taking at FNAL, on average, ∼11 muon tracks are expected in each collected event, while in the Gran Sasso underground laboratory, only one muon was present in each triggered event [4]. In addition, the muon energy spectrum will also be different: in fact, ∼15% of the crossing muons will stop inside the detector. The first preliminary results provided by the updated method on a full simulation of cosmic rays events are shown in Figure 7 for different values of the electron lifetime.

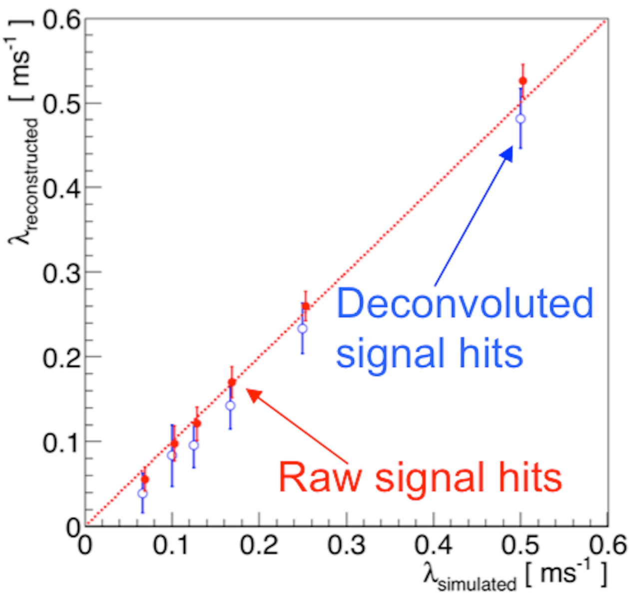

Figure 7. Preliminary results from the updated method for the measurement of the electron lifetime $\tau = 1/\lambda$ in liquid argon, to be used during the new data taking at Fermilab. Two different methods related to the identification and reconstruction of the physical signals on the TPC wires ("hits") have been tested: the "raw signal" analysis is based directly on the signal collected on the TPC wires, while in the "deconvoluted signal" case, the analysis is done after the application of an appropriate treatment on the collected signal to take into account the effects of the electronic response and of the electric field.

Since the identification and reconstruction of the electromagnetic showers are key elements in order to select and identify the electron neutrino events, a dedicated effort to improve the reconstruction of the electron shower was launched, starting from the methods used in Gran Sasso for the study of the electron neutrino events collected both in the CNGS beam and in the cosmic ray events. The first preliminary results obtained on the reconstruction of the shower direction for electrons at 800 MeV are shown in Figure 8: these methods will be improved in order to be ready for the reconstruction of the new neutrino events collected at Fermilab.

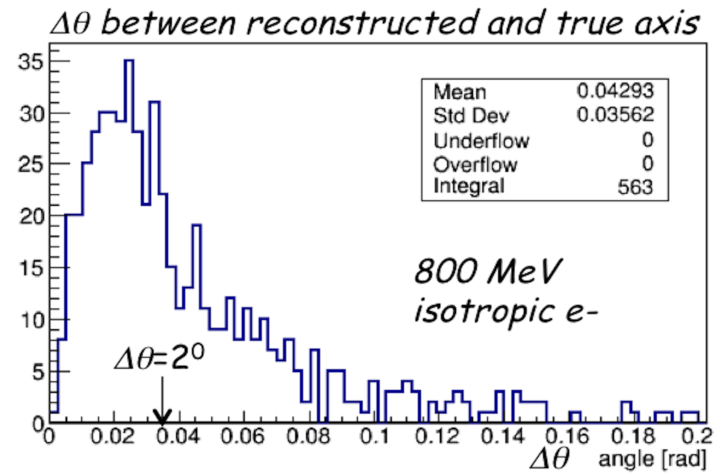

Figure 8. Preliminary results on the reconstruction of the direction of an electron shower with 800 MeV of deposited energy: in particular, the distribution of the angle between the real initial direction of the shower and the reconstructed direction is shown.

6. Conclusions

The LAr-TPC detection technique has been taken to full maturity with the ICARUS-T600 detector. After a successful continuous three-year run at LNGS exposed to CNGS neutrinos and cosmic rays, the T600 detector underwent an intensive overhauling phase at CERN and in July 2017 has been transported to Fermilab. During 2019, this detector will start again to take data exposed to the Booster Neutrino Beam and together with the SBND and MicroBooNE detector will provide the definitive answer to the anomalies related to the possible existence of sterile neutrinos with a mass $\sim$eV.

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Conflicts of Interest: The authors declare no conflict of interest.

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