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Sterile neutrino searches with the ICARUS detector

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The ICARUS collaboration employed the 760-ton T600 detector in a successful three-year physics run at the underground LNGS laboratories studying neutrino oscillations with the CNGS neutrino beam from CERN, and searching for atmospheric neutrino interactions. ICARUS performed a sensitive search for LSND-like anomalous νe appearance in the CNGS beam, which contributed to the constraints on the allowed parameters to a narrow region around 1 eV^2, where all the experimental results can be coherently accommodated at 90% C.L. After a significant overhauling at CERN, the T600 detector has now been placed in its experimental hall at Fermilab where installation activities are in progress. It will be soon exposed to the Booster Neutrino Beam to search for a sterile neutrino within the Short Baseline Neutrino (SBN) program, devoted to definitively clarify the open questions of the presently observed neutrino anomalies. ICARUS achievements, its status and plans for the new run at Fermilab and the ongoing developments of the analysis tools needed to fulfill its physics program are addressed .

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1. The ICARUS T600 detector and the Gran Sasso run

The Liquid Argon Time Projection Chamber (LAr-TPC) is a continuously sensitive and self triggering detector that can provide an excellent 3D imaging and calorimetric reconstruction of any ionizing events. First proposed by C. Rubbia in 1977 [1], this detection technique allows for a detailed study of the neutrino interactions, spanning a wide energy spectrum (from few keV to several hundreds GeV).
The ICARUS T600, with a total active mass of 476 ton, is the first large-scale operating LAr-TPC detector [2]: it consists of a large cryostat split into two identical, adjacent modules. Each module houses two LAr-TPCs separated by a common cathode and the maximum drift distance is 1.5 m, equivalent to ~ 1 ms drift time for the nominal 500 V/cm electric drift field. The anode is made of three parallel wire planes. Behind them there are located PMTs to collect the scintillation light produced by the charged particles in LAr and used for the trigger of the detector [3]. ICARUS concluded in 2013 a very successful 3 years long run in the Gran Sasso underground laboratory. During the data taking the liquid argon was kept at an exceptionally high purity level (< 50 ppt of O_2 equivalent contaminants) reaching in 2013 a 16 ms lifetime corresponding to 20 ppt O_2 equivalent LAr contamination [6], paving the way to the construction of huge LAr-TPC detectors with drift distances up to 5 m. The detector has been exposed to the CNGS neutrino beam and to cosmic rays and the recorded events demonstrate the high-level performances and the physical potentialities of this detection technique: the detector shown a remarkable e/γ separation and particle identification exploiting the measurement of dE/dx versus range [4].Furthermore the momentum of escaping muons has been measured studying the multiple Coulomb scattering with ~ 15% average resolution in the 0.4-4 GeV/c energy range, which is relevant to the next generation neutrino experiments [5]. The events related to cosmic rays have been studied to identify also the atmospheric ν interactions: 6 ν_μCC and 8 ν_eCC events in a 0.43 kton y exposure have been identified and reconstructed, demonstrating that the automatic search for the ν_eCC in the sub-GeV range of interest for the future short and long baseline neutrino experiments is feasible [7].

2. The sterile neutrino puzzle and the SBN experiment

Recent experiment, in particular LSND [8] and MiniBooNE [9], have reported anomalous signals that may imply the presence of an additional mass-squared difference $\Delta m^2_{new} \sim 1.0$ eV^2 driving oscillations at small distances and pointing toward the possible existence of non standard heavier sterile neutrino(s). A sensitive search for a possible ν_e excess related to the LSND anomaly in the CNGS ν_μ beam has been performed using the neutrino events collected in the T600 detector during the Gran Sasso run. 2650 CNGS neutrino interactions, identified in 7.9 10^{19} pot exposure, have been studied in details to identify the ν_e interactions. Globally 7 electron-like events have been observed to be compared with the 8.5 ± 1.1 expected from the intrinsic beam contamination and standard 3-flavor oscillations: this study constrained the LSND signal to a narrow parameter region at $\sin^2 2\theta \sim 0.005$, $\Delta m^2 < 1eV^2$ that should be definitely investigated. [10].
The SBN Short-Baseline Neutrino program at Fermilab can provide the required clarification of the LSND anomaly. It is based on three LAr-TPC detectors (ICARUS-T600, MicroBooNE with 89 t active mass and SBND with 82 t active mass) exposed at shallow depth to the ~ 0.8 GeV Booster

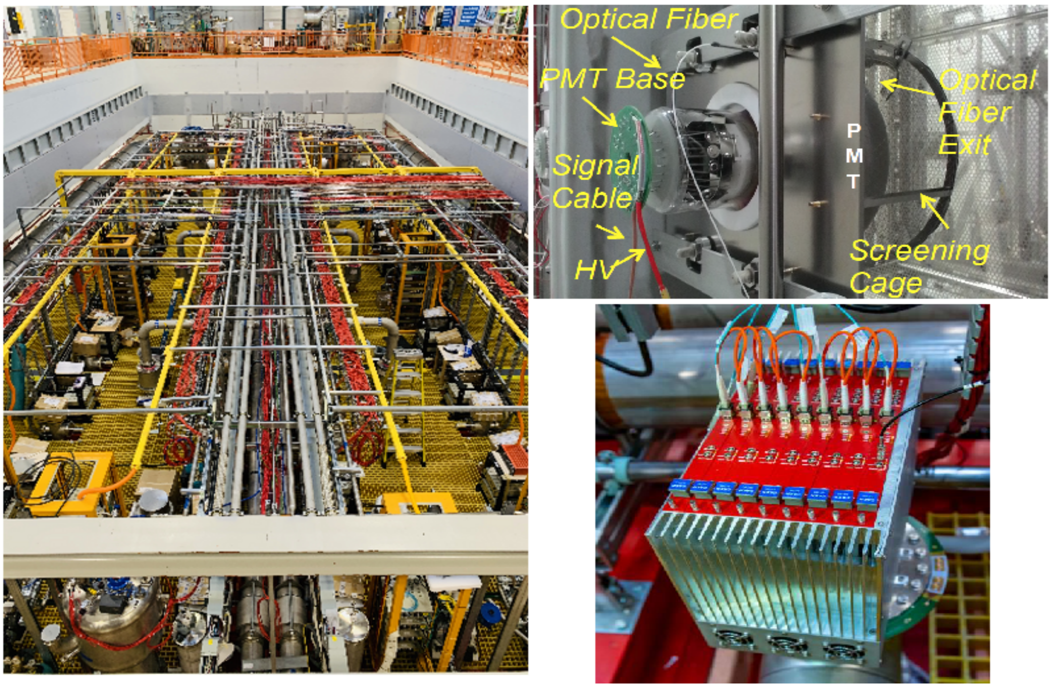

Figure 1: Left:ICARUS installation at SBN. Top Right: one of the PMT installed inside the detector. Bottom Right: one of the new mini-crates containing 9 CAEN A2795 boards used to collect the TPC wire signals.

neutrino beam at different distances from the target (600m, 470 m and 110 m respectively). The used detection technique will provide an unambiguous identification of the neutrino interactions, the measurement of their energy and a strong mitigation of the possible sources of background. In addition the study with almost identical detectors at different distances from the source will allow to identify any variation on the spectra, that will be a clear signature of neutrino oscillations. For these reasons, this experiment will allow for a very sensitive search for $\nu_\mu \rightarrow \nu_e$ appearance signals, covering the LSND 99% C.L. allowed region at $\sim 5\sigma$ C.L.. The high correlations between the event samples of the three LAr-TPC's and the huge event statistics at the near detector will also allow for a simultaneous sensitive search in the ν_μ disappearance and in the ν_e appearance channels.

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÷3 GeV energy range, with an enriched component of electron neutrinos (few %). The analysis of these events will provide useful information related to the detection efficiencies and to the neutrino cross-sections at energies relevant to the future long baseline experiment with the multi-kt DUNE LAr-TPC detector.

3. The T600 in the SBN experiment: overhauling and present status of the detector

The ICARUS-T600 detector at Fermilab will take data at shallow depth, protected by a 3 m concrete overburden: $0(10^6)$ ν interactions should be recognized amongst the $\sim$ 11 cosmic muons that are expected to cross the detector randomly in the 1 ms drift time corresponding to each triggered event. In addition the associated photons produced by cosmic rays can become a serious background source for the ν_e search since the electrons produced via Compton scattering and pair production can mimic ν_e CC events. In order to prepare the detector for this new SBN data taking, the T600 underwent an intensive overhauling at CERN in the Neutrino Platform framework before being shipped to US in 2017, introducing several technology developments while maintaining the already achieved performance.

The T600 is now equipped with an upgraded inner light detection system with 360 new 8" photo-multipliers, installed behind the TPC wire planes (90 PMTs in each TPC)[12, 13]. The PMTs gain equalization and timing will be performed by 405 nm laser pulses flashing the PMTs via a fiber system. This new light detection system will provide a sensitivity below 100 MeV of deposited energy, a ∼1 ns time resolution with a high granularity: all these features are fundamental to effectively identify the events associated to the neutrino beam and to measure the time of occurrence of each cosmic interaction crossing the detector.

The overhauling of the T600 gave also the opportunity to design an upgraded "warm" TPC read-out electronics, finalized to a better event reconstruction quality. This includes a front-end based on analog low noise - charge sensitive pre-amplifier, serial 12 bit ADCs, one per channel, with 400 ns synchronous sampling [14]. A $\sim 1.5\mu$s faster shaping time allows to match the electron transit time in the wire plane spacing, providing a better physical signals position separation, a drastic reduction of the undershoot in the preamp response as well as the low frequency noise while maintaining a S/N $\geq$ 10 ratio as demonstrated with a 50 liter LAr-TPC prototype exposed to cosmics at CERN. Finally a new compact design allow to host both the analogue and digital electronics in a new A2795 CAEN board, directly mounted on ad-hoc signal feed-through flanges and on each flange a custom mini-crate hosts nine boards, corresponding to 576 channels.

In order to reject the cosmic background, during the new data taking the T600 will be surrounded also by an external $\sim 4\pi$ segmented Cosmic Ray tagging system, composed by 3 subsystems each one with two layers of plastic scintillators ($\sim$ 1100 m^2). This additional system, in conjunction with the T600 internal PMT system, will allow to unambiguously identify cosmic rays entering the detector: the few ns time resolution provided by this system, combined with the activity in the LAr volume will allow measuring the direction of the particle propagation via time of flight and discriminate the incoming/outcoming particles.

After the placement in the pit of the two ICARUS modules in August 2018, all the feedthrough flanges for the TPCs and PMTs signals and for the injection of the laser flashes used to calibrate the PMTs have been installed (December 2018). The gain and the dark rate for all the 360 PMTs have been measured as a function of the applied voltage at room temperature. All the new TPC readout electronics in the 96 mini-crates and the low noise power supplies have been installed and verified: in particular the full readout chain has been tested injecting test pulses at far end of the chamber wires and reading out the signals by the A2795 boards on the other end, to check the full system for noise monitoring purposes. In parallel all the cryogenic equipment has been installed, welded and the complete system has been tested at 350 mbar overpressure. Then the cold vessels have been successfully evacuated at 10^{-5} mbar residual pressure.

The detector installation has been completed at the beginning of 2020 and between February and April the detector has been filled with Liquid Argon and the liquid and gas recirculation that is needed to purify the Argon have been activated. During the filling period ten mini-crates for the TPC read-out electronics have been continuously recorded to monitor the noise conditions: a steady

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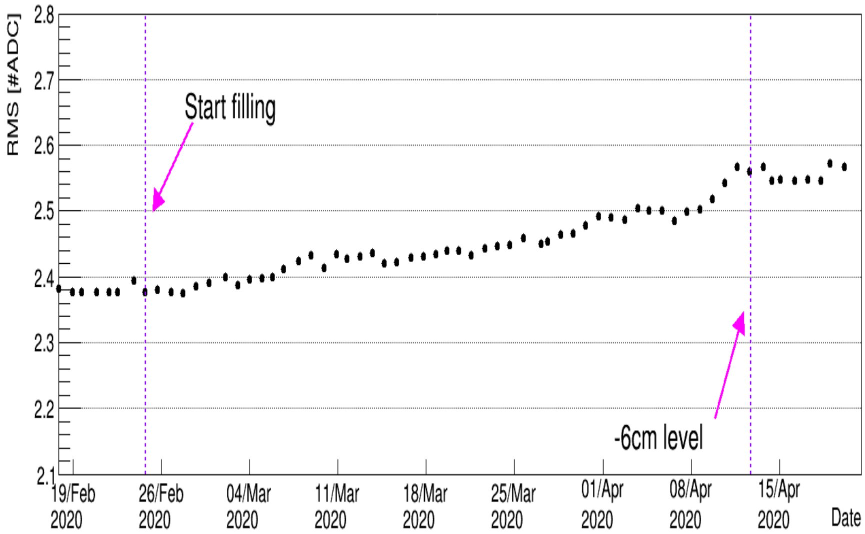

Figure 2: Variation of the noise level during the filling with liquid argon (1 #ADC ~ 550 electrons). The noise has been measured in one of the TPC read-out electronics mini-crates and has been evaluated removing the coherent noise component, common to each group of 32 channels.

increase of the noise level has been observed, in agreement with the expected variation of the wire capacitance due to the increase of the level of Liquid Argon inside the TPCs (see fig. 2). After the filling completion, the PMTs has been activated and the calibration at LAr temperature is ongoing. Also the preparation and installation of the modules of the 3 CRT subsystems is progressing rapidly and at the moment the commissioning of two side walls is ongoing with cosmics.

In parallel with the activities related to the installation, also the tools needed for the reconstruction and analysis of the collected events have been completely renewed. In particular, common reconstruction tools in the SBN detectors will be a key element to understand the detector related systematics and their correlation across the near and far detector. Starting from the experience cumulated also during the Gran Sasso run the neutrino event selection and reconstruction is under development: the combined signals from the TPC, PMTs and CRT will play a crucial role to reject the backgrounds in particular from cosmics.

4. Conclusions

The ICARUS-T600 successful run at LNGS proved that LAr-TPC technology is mature and ready for large-scale neutrino physics experiments. This detector, after an overhauling phase, is expected within the SBN project at FNAL to help clarifying the sterile neutrino puzzle, by looking at both appearance and disappearance channels with the combined signals from three LAr-TPCs. The installation and the Liquid Argon filling has been recently completed and the commissioning is starting: ICARUS will see the first new neutrinos from Booster at the end of 2020 and the data taking for physics is expected by beginning of 2021.

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