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Short-Baseline neutrino oscillation 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 ν_e 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 overhaul at CERN, the T600 detector has been installed at Fermilab. In 2020 cryogenic commissioning began with detector cool down, liquid argon filling and recirculation. ICARUS has started operations and is presently in its commissioning phase, collecting the first neutrino events from the Booster Neutrino Beam and the NuMI off-axis. After the first year of operations, ICARUS will commence its search for evidence of a sterile neutrino jointly with the SBND near detector, within the Short Baseline Neutrino (SBN) program. The ICARUS exposure to the NuMI beam will also give the possibility for other physics studies such as light dark matter searches and neutrino-argon cross section measurements. The article will address 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.

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1. Introduction

In the last decades different experiments, in particular LSND [1], reported anomalies signals across very different neutrino sources and energy ranges, that cannot be explained in the standard three flavour picture. These anomalies could be described by the existence of a fourth neutrino state associated with a large $\Delta m^2_{new} \sim 1\ eV^2$ and a small mixing angle. The sterile neutrino puzzle anomalies are still not fully understood [2] and require a new definite experiment to measure simultaneously the possible ν_e appearance and ν_μ disappearance signals by comparing the neutrino spectra collected in two detectors located in different positions along the neutrino beam line.The Short Baseline Neutrino (SBN) [3] program at Fermilab is expected to give an important contribution to clarify these anomalies. The SBN program is exploiting three LAr-TPC detectors located at different location from the target along the Booster Neutrino Beam (BNB, average $E_\nu \sim 800$ MeV) [4]: SBND acting as near detector, with 112 tons active volume, at 110 m from the target, MicroBooNE as intermediate detector, with 89 tons active volume, at 470 m, and ICARUS as far detector, with 476 tons active volume, at 600 m. The ICARUS experiment demonstrated the performance of LAr-TPC detection technique that will provide, for the SBN experiment, the unambiguous identification of the neutrino interactions and a strong rejection of the possible backgrounds.

2. The ICARUS T600 detector and the SBN experiment

The ICARUS T600 detector, the first large scale operating liquid argon TPC (LAr TPC) detector [7], is expected to give an important contribution to clarify the sterile neutrino puzzle. This detection technique, first proposed by C. Rubbia in 1977 [5], allows for a detailed study of neutrino interactions combining the collected charge and the scintillation light signals produced by ionizing particles in LAr. A detailed description of the T600 detector can be found in [6]. ICARUS concluded in 2013 a three years long run in the LNGS underground laboratories exposed to the CNGS neutrino beam [7]. The recorded neutrino events associated to the CNGS beam were studied to identify a possible ν_e excess related to the LSND anomaly. As a result the LSND signal was constrained to a narrow parameter region at $sin^2 2\theta \sim 0.005$, $\Delta m^2 < 1eV$ [8] where all experimental results can be coherently accommodated at 90 % C.L.. Neutrino interactions have been also studied to develop and tune the algorithms for the reconstruction of the events [9]. After the data taking at LNGS, the T600 detector was transported to CERN where it underwent a significant overhauling phase in view of the new exploitation in the SBN experiment. The SBN multi-detector configuration allows simultaneous observation of neutrino interaction at difference distances, by independently measuring both ν_e appearance and ν_μ disappearance oscillation channels, covering the LSND 99% C.L. allowed region at $\sim 5\sigma$ C.L.. In addition, during SBN operations high-statistics measurements of neutrino-argon cross-sections will be also performed. The ICARUS detector will also be exposed to the off-axis NuMI neutrino beam [10], characterised by a few percent component of ν_e in the 0-3 GeV energy range. The studies of these events will be relevant also for the future long baseline experiment with the multi-kt DUNE LAr TPC detector [11].The experimental condition in SBN is more challenging with respect to the underground conditions of the LNGS laboratory. ICARUS at Fermilab is expected to collect about one million neutrino interactions and it will collect data on

surface, where cosmic rays can become a serious source of background in particular for the electron neutrino search. In fact, muons traversing the detector can produce electromagnetic showers that might mimic a genuine ν_e event. In addition, also primary cosmic photons and neutrons can induce in the detector "neutrino-like" interactions. In order to mitigate these sources of backgrounds, an overburden layer of concrete of 2.85 m thickness will be placed above the detector. This overburden will effectively remove all the primary photons, reduce the neutrons by a factor 200, while the primary muons and their associated showers will be suppressed by ~25%. As a result, the total number of cosmic induced backgrounds will be strongly reduced, making the overburden a fundamental element for the experiment. With the presence of the overburden, primary cosmic muons will be the dominant source of cosmic backgrounds inside ICARUS. Incoming cosmic charged particles will be tagged in time and position with an expected 95% efficiency by an external $\sim 4\pi$ segmented Cosmic Ray Tagging System (CRT) surrounding the detector, composed by 3 subsystems each one with two layers of plastic scintillators.
The combination of the CRT signal and the scintillation light signals can help to disentangle the particles entering in the detector from the particles generated by the neutrino interactions in the LAr active volume and exiting. The light detection system was upgraded during the overhauling phase and it is composed by 90 photomultipliers (PMT) in each TPC [12]. This new light detection system will provide a $\sim$ 1 ns time resolution and a sensitivity below 100 MeV of deposited energy, helping to recognize the events associated with the neutrino beam and reject the cosmic interactions out-of-time with respect to the beam spill. The PMTs gain equalization and timing are performed by 405 nm laser pulses flashing the PMTs via a fiber system.Also the TPC read-out electronics has been updated during the overhauling phase, in order to obtain a better event reconstruction [13, 14].
The reactor Neutrino-4 experiment has recently shown evidence at 2.7σ for an oscillatory pattern with best fit parameters Δm^2_{N4}= 7.30 eV^2 and $sin^2\theta_{N4}$ = 0.36 [15]. Due to a similar L/E ratio, ICARUS may provide a verification of this claim collecting neutrino events both from BNB and NuMI beams in one year of data taking [16].

3. Commissioning phase and Run 0

The ICARUS detector is presently running and recording data both from BNB and NuMI beams. After the arrival at Fermilab in August 2018, all the feedthrough flanges, the new TPC readout electronics components were installed and the noise conditions are being continuously monitored. Between February and April 2020, the detector was filled with LAr and all the different subsystems activated. The light detection system has been completed in 2019 and it has been activated after the detector filling with liquid argon. Also the preparation, installation and calibration of the modules of the three CRT subsystems is progressing rapidly and at the moment the bottom and side CRT panels are installed and commissioned while the top CRT installation is ongoing. The cryogenic system is stable and performing well and the LAr argon purity in the two modules is continuously and automatically monitored. In fact, the presence of electron trapping impurities, mostly O_2 , in liquid argon produces an exponential attenuation of the electron signal recorded on the wires along the drift coordinate. The measurement of the electron lifetime (τ_D) provides the correction for this effect improving the calorimetric event reconstruction. During June 2021, a full time ICARUS neutrino beam run as BNB primary user ("Run0" data taking) has been performed, collecting approximately 2.8×10^{19} proton on target (p.o.t) from the BNB and 5.2×10^{19} p.o.t. from the NuMI beam with a 95% efficiency. In this period the τ_D reached up to ~4.5 ms in the East cryostat and ~3 ms in the West one, allowing efficient signal detection over the full LAr volume. The development and commissioning of the trigger system has been performed recording initially each spill associated to the BNB and NuMI beams and then requiring also the presence of the scintillation light detected by the PMTs in coincidence with the beam spill. After the trigger commissioning, neutrino events from both beams have been collected to setup the data processing workflow and the event reconstruction tools.In figure 1 two neutrino events recorded in the ICARUS detector are shown.

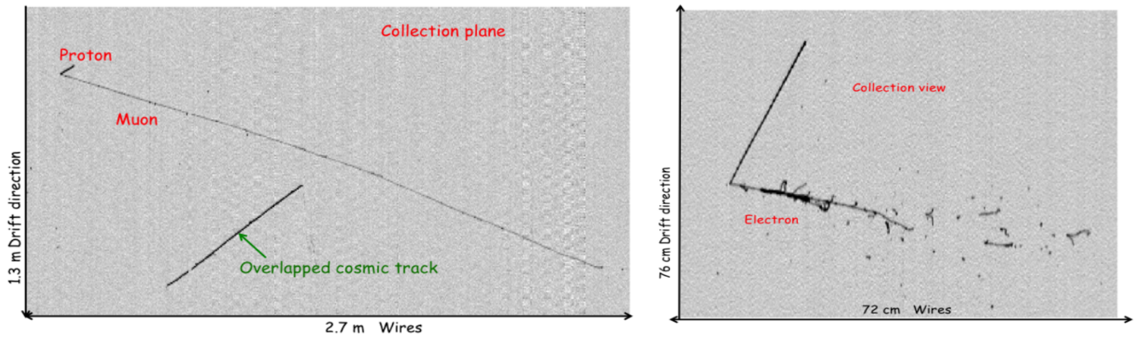

Figure 1: Neutrino events recorded in the ICARUS T600. Left: example of a fully contained ν_μ quasi-elastic interaction associated to the BNB beam. Right: ν_e event associated to the NuMI beam.

The ν_μ CC in figure 1 left is characterised by the presence at the primary vertex of a short track with high ionization (proton), together with a longer track (muon), also stopping inside and whose dE/dx is fully compatible with a m.i.p. . In figure 1 right, one of the first electron neutrino events associated with the NuMI beam is shown displaying a ~600 MeV energy deposition by the primary electron.In parallel with all these activities, also the tools for the event reconstruction and analysis are continuously under development to improve the performance in particular for the neutrino selection. The analysis of the events collected during the commissioning and related to cosmic rays and neutrino interactions is presently ongoing. These events will be used to better understand the detector response and systematics. For example, the selection of muon tracks crossing both the anode and the cathode in one TPC will allow one to measure the few mm distortions along the tracks due to the space charge effects [17]. In addition the study based on the dE/dx versus residual range relation along stopping cosmic muon tracks can be used to perform a first absolute calibration of the wire signal response.

4. Conclusion

The ICARUS T600 detector is expected to help clarifying the sterile neutrino puzzles as a key element of the SBN project at Fermilab. The detector installation and the filling with the Liquid Argon has been completed in 2020 and despite the pandemic situation the commissioning of the detector has been largely successful. ICARUS has recently recorded the first neutrino interactions both from the Booster and the NuMI beams and the data taking for physics is ongoing.

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References

[1] A. Aguillar et al. (LSND Collaboration), *Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam*, Phys. Rev. D 64, 2001, 112007.

[2] C. Giunti, T. Lasserre, *eV-Scale Sterile Neutrinos*, Ann. Rev. Nucl. Part. Sci. 2019, 69, 163-190.

[3] R. Acciarri et al.*A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*, arXiv:1503.01520 (2015).

[4] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), *Neutrino flux prediction at MiniBooNE*, Phys. Rev. D 79, 072002

[5] C. Rubbia, *The Liquid Argon Time Projection Chamber: A New Concept for Neutrino Detector*, CERN-EP/77-08 1977

[6] M. Antonello et al., (ICARUS Collaboration), *Design, construction and tests of the ICARUS T600 detector*, Nucl. Instrum. Methods Phys. Res. A 527 (2004) 329–410

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

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

[9] M.Antonello et al. (ICARUS Collaboration), *Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector*, Advances in High Energy Physics 2013, 260820

[10] P. Adamson et al., *The NuMI Neutrino beam*, Nucl. Instrum. Meth. A 806 (2016) 279-306

[11] B.Abi et al. (DUNE Collaboration), *Long-baseline neutrino oscillation physics potential of the DUNE experiment*,Our.Phys.J.C (2020) 80:978

[12] B. Ali-Mohammadzadeh et al., *Design and implementation of the new scintillation light detection system of ICARUS T600*, JINST 2020, 15, T10007

[13] L. Bagby et al., *New read-out electronics for ICARUS-T600 liquid Argon TPC. Description, simulation and tests of the new front-end and ADC system*, JINST 2018, 13, P12007

[14] L.Bagby et al., 2021, *Overhaul and installation of the ICARUS-T600 liquid argon TPC electronics for the FNAL Short Baseline Neutrino program*, JINST 2021, 16(1), P10307

[15] A. Serebrov,R.M. Samoilov, *Analysis of the Results of the Neutrino-4 Experiment on the Search for the Sterile Neutrino and Comparison with Results of Other Experiments*, JETP Lett. 112 (2020) 4

[16] C. Rubbia, *Experimental searches of neutrino anomalies*, talk at NEUTEL 2021

[17] M.Antonello et al., *Study of space charge in the ICARUS T600 detector*, JINST 2020, 15, P07001

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