PROCEEDINGS OF SCIENCE

Short-Baseline neutrino oscillation searches with the ICARUS detector

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Liquid Argon Time Projection Chamber (LArTPC) imaging detectors provide an impressive capability to reconstruct neutrino interactions. After a successful three-year physics run at the underground LNGS - INFN laboratory, ICARUS was refurbished and subsequently moved to Fermilab to begin operating as the far detector in the Short-Baseline Neutrino (SBN) Program. ICARUS has entered the physics data taking phase and is presently collecting large statistical samples for its proposed physics analysis program. First studies have been performed with a well defined sample of ν_μCC quasi elastic interactions, showing promising and robust results of fully reconstructed neutrino events. A brief review of ICARUS' initial operations and its current activities are reported here.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August, 2023
Hamburg, Germany

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PoS(EPS-HEP2023)177

1. Short Baseline Neutrino program at Fermilab

The Short-Baseline Neutrino (SBN) program will carry out sensitive searches for new physics in neutrinos, recording millions of neutrino charged and neutral current interactions on argon to unveil its physics at the GeV energy scale. SBN is designed to address the possible existence of 1 eV mass-scale sterile neutrinos motivated by a set of anomalies seen in the past collected neutrino data, mainly driven by the result of LSND experiment. SBN will test this important problem using multiple, functionally identical detectors sitting along the same neutrino beam, which is the key point to the experiment's world-leading sensitivity. A discovery would reveal new physics and open the doors to further experimentation of this area, while a clear null result from SBN would help close the long-standing puzzle of anomalies in the neutrino physics field. The SBN program, consists of three large liquid argon time projection chambers (LArTPC) sitting along the Booster Neutrino Beam (BNB) line at Fermi National Accelerator Laboratory (Fermilab) in Illinois; where the near and far detector locations have been optimized for maximal sensitivity in the most relevant ranges of oscillation parameters, with $\Delta m^2 \sim 1eV^2$.

The Short-Baseline Near Detector (SBND) is a 112 t active mass LArTPC located at 110 m from the neutrino production target. It will be able to characterize the neutrino beam before any substantial oscillation, greatly reducing the systematic uncertainties in a search for oscillation signals downstream the BNB. The detector is in its final stages of installation and is getting ready for data-taking, expected to begin in early 2024. The MicroBooNE detector is an 89 t active mass LArTPC, sited at 470 m along the beam. The detector has been collecting data from BNB since October 2015 and completed its physics run in early 2020. The collaboration has published initial results on the LEE from 2016-2018 data [1] and further results are expected soon from the full data set. Finally the far detector is the ICARUS-T600 detector, of 476 t active mass and placed at 600 m from target, which has been refurbished and upgraded from its previous operation at Gran Sasso INFN underground laboratory for an optimal performance in SBN. The detector commissioning phase concluded in June 2022, and has been collecting physics data since that moment.

The joint effort among the three LArTPC detectors will provide a world-leading sterile neutrino search experiment. A very sensitive search of $\nu_\mu \longrightarrow \nu_e$ appearance signal will cover the full LSND 99% C.L allowed region at $\sim 5\sigma$. On the other hand, the huge event statistics at the near detector will also allow a simultaneous sensitive search in the $\nu_\mu \longrightarrow \nu_\mu$ disappearance channel. Precision oscillation studies are mandatory to observe a clean signal, hence SBN will exploit the highly correlated event rates in the near-far detector configuration to achieve a significant cancellation of the neutrino flux and cross section uncertainties.

2. The SBN Far Detector: ICARUS

The ICARUS-T600 cryogenic detector is the first large-scale operating LAr-TPC containing 760 tones of ultra-pure LAr, of which 476 tons are active. It consists of two large and identical adjacent modules with internal dimensions of 3.6 (W) × 3.9 (H) × 19.6 (L) m^3. Each module houses two LAr-TPC separated by a common central cathode with a maximum drift distance of 1.5 m, equivalent to 0.96 ms drift time at the nominal 500 V/cm electric drift field. The anode of each TPC is composed of three parallel wire planes placed 3 mm apart from each other and oriented at 0° and ±60° with respect to the horizontal direction. ICARUS light detection system is equipped with 360 8-inch diameter photomultiplier tubes (PMT) placed behind the anode planes. They are used to detect the prompt LAr scintillation light for the purpose of event triggering and absolute timestamp of the recorded events, reconstructing the interaction position along the drift coordinate.

In contrast to the clean and noiseless environment in which ICARUS operated at the underground Gran Sasso National Laboratories (LNGS) [2], the SBN program offers a completely different venue. The shallow depth at which ICARUS function at FNAL, exposes the detector to an abundant flux of cosmic rays which would overwhelm the detector, as these can induce several additional and uncorrelated triggers during the 1 ms drift time. On average $\sim$ 11 cosmic tracks are expected to cross the entire detector volume during each drift window, which need to be identified and suppressed. To cope with this challenging condition, the detector setup includes a $\sim$ 3m concrete overburden, to reduce the cosmic ray flux, complemented by a 4π coverage cosmic ray tagger (CRT) system, to tag the remaining incoming charged particles. Besides that, the coincidence of CRT signal with the light and charge signals of the chamber are also exploited to further suppress the backgrounds. Cosmic background rejection strategies are of uttermost relevance for the $\nu_\mu \longrightarrow \nu_e$ channel, as the oscillation study relies on the tiny intrinsic ν_e component in the BNB beam. Any additional contribution of background faking ν_eCC interactions would negatively affect the oscillation sensitivity.

ICARUS is also exposed $\sim 6^\circ$ off-axis to the higher energy Neutrinos at the Main Injector (NuMI) beam. Hence the detector will as well be able to record a large neutrino event sample, where most of the events are in the 0 – 3 GeV energy range and have an enriched component of ν_e (few %). The analysis of these events will provide useful information related to detection efficiencies, Beyond the Standard Model searches, and neutrino cross-sections at energies relevant to the future long baseline experiment, such as the multikiloton DUNE LArTPC detector.

3. ICARUS initial operations

After the arrival of ICARUS at FNAL, in August 2018, all subsystems were installed in the detector and the correct operation of its components was verified. Cryogenic commissioning started on January 2020, and detector activation took place on August 27, 2020 when the TPC wire planes and the cathode high voltage were taken to nominal voltage. The CRT system consists of a top, side and bottom scintillator panel subsystems, which were installed through the commissioning activities, but culminated in December with the placement of the last top CRT panel. ICARUS was first fully operational in June 2021, when the first neutrinos were collected, and took data stably with BNB and NuMI beams in parallel with commissioning activities. The overburden installation started once the Top CRT commissioning was completed, and finalized on June 7, 2022 marking the beginning of ICARUS physics data taking phase. Top CRT cosmic rates were monitored during the commissioning phase, showing a factor $\sim$ 2 reduction due to the overburden installation. Figure 1 shows the evolution of ICARUS towards a full detector assembly; further details about its first operation activities can be found in Ref [3].

Before the beam summer shutdown and with the detector in optimal physics conditions, data with both beams was collected during the first physics run, which spanned from June 9th to July 10th (2022). The dedicated month of data taking, showed an overall beam data collection efficiency of $\sim$ 93% with an excellent stability on long runs. The collected proton on target for Run 1 are

Figure 1: Assembly activities in the ICARUS detector: left shows TPC, PMT and part of the cryogenic subsystems installed, middle picture the fully completed CRT and finally the blocks of concrete overburden being put into place on the right.

$4.1 \cdot 10^{19}$ for BNB and $6.8 \cdot 10^{19}$ for NuMI. The summer pause provided an opportunity to carry out several activities in preparation for the subsequent neutrino physics run, mainly dedicated to improving the performance of the detector and the stability of data collection. ICARUS was brought back to physics data taking by the end of 2022 and has successfully concluded Run 2 on July 2023, collecting large statistics; Run 2 collected $2.1 \cdot 10^{20}$ for BNB and $2.8 \cdot 10^{20}$ for NuMI. The free electron lifetime is crucial to monitor the liquid argon purity in the TPCs and to ensure no ionization charge signal is lost, thus it has been monitored through the whole life of the detector. East cryostat has had a stable value of 4.5 ms during the whole commissioning phase and physics runs, whereas an increase from 3 ms to 8.5 ms was seen in the West cryostat after the regeneration of its cryogenic filter during the summer shutdown. The filter regeneration of the East module has been recently completed in September 2023, and should allow the module to reach values similar to those of the West cryostat in the near future.

Taking advantage of all the data collected so far, thorough studies were performed to evaluate the trigger performance. The ICARUS trigger system exploits the recognition of the prompt scintillation light signal detected by the PMT system in coincidence with the beam spill windows for both neutrino beams. Beam events are collected requiring at least 5 fired PMT pairs inside one of the five 6 m longitudinal slices, which includes 30 PMTs on the left TPC and 30 PMTs on the right TPC. This threshold was chosen as the best trade-off between an acceptable trigger rate to be sustained by the data acquisition system and a high trigger efficiency to neutrino interactions. A more stringent multiplicity of 9 PMT pairs is evaluated to record PMT signals within a 2 ms time window around the trigger time to recognize and tag cosmic rays which are crossing the detector during the electron drift time. Trigger efficiency was measured selecting vertical cosmic muons by matching TPC tracks to CRT signals, and showed an efficiency greater than 90% for events in coincidence with the neutrino beam spill and of at least ~ 100 MeV of deposited energy.

While SBND is preparing to join the SBN program, ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation hypothesis [4] in the same baseline over energy range ($\sim$ 1-3 m/MeV), but collecting ~ 100 times more energetic events. The Neutrino-4 oscillation-like signal for $\bar{\nu}_e$ events can be initially addressed by ICARUS at the BNB studying the ν_μ disappearance channel as a function of the neutrino energy, followed by an analogous search exploiting the NuMI enriched ν_e-signal. Therefore, Run 1 and 2 collected data sets are being analysed to understand detector performance and provide robust first physics results.

For this analysis, NuMI is currently focusing on contained electromagnetic (EM) showers coming from quasi-elastic ν_e CC interactions. LArTPC technology presents a unique electron vs photon discrimination exploiting the initial deposited energy along the trajectory of the shower. Therefore, the considered sample requires to have a clear EM shower from the primary vertex and an initial deposited energy of the aforementioned compatible with a minimum ionizing particle (corresponding to the primary electron). On the contrary, BNB studies focus on ν_μ CC quasi-elastic interactions looking for contained events with a single muon and at least a proton in the final state. The main goals of the analysis include the development and optimization of a solid strategy to automatically select a pure sample of well reconstructed ν event topology. In parallel, the particle identification tool performance and the kinematic reconstruction capability were first investigated by a visual selection of neutrino interaction inside the active LAr. For each visually scanned event, the 3D positions of the vertex, end muon, and end proton were saved allowing a comparison between the scan information and the automatic reconstruction variables. In $\sim 70\%$ of the cases the reconstructed vertex and end position of the muon were within 15 cm from the scanned information, showing the great performance of the reconstruction algorithms.

The identification of the neutrino interactions requires a Particle Identification (PID) tool, based on the energy loss (dE/dx) by ionisation, to effectively recognise the particles involved in the interaction. The current algorithm relies on the comparison between the measured deposited energy (dE/dx) along the track with theoretical profiles of different particles. A χ^2 fit is performed considering only the last 25 cm of the track, where the strongest discrimination power is achieved. Figure 2 shows a sample of data for muon and proton candidates together with its Bethe-Bloch theoretical prediction respectively, showing good agreement in both cases.

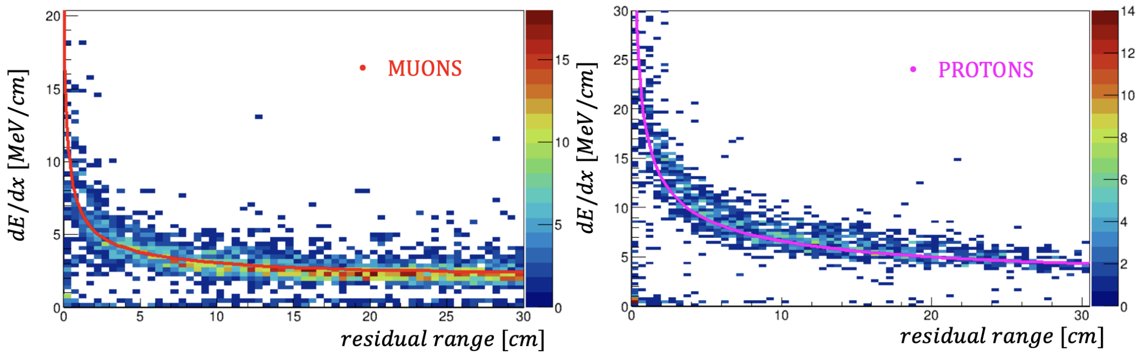

Figure 2: Deposited energy along the trajectory for muon and proton candidates. The theoretical stopping power for each particle is also shown.

From all the data available stringent quality selections were applied to all the tracks to guarantee that only well reconstructed events were selected. Such cuts mostly rely on scan information and good performance of the PID algorithm. For this analysis a simplified scenario was considered requiring that only one muon and exactly one single proton were present in the final state. In order to kinematically reconstruct the event, the muon and proton momenta were computed based on their range. It is known that for genuine ν_μ CC quasi-elastic events the total transverse momenta should be dominated by the Fermi momentum in argon nuclei, hence that variable was chosen to provide a first feedback on the purity of the sample.

Figure 3 left shows a typical ν_μ CC quasi-elastic candidate from BNB that passed all selections,

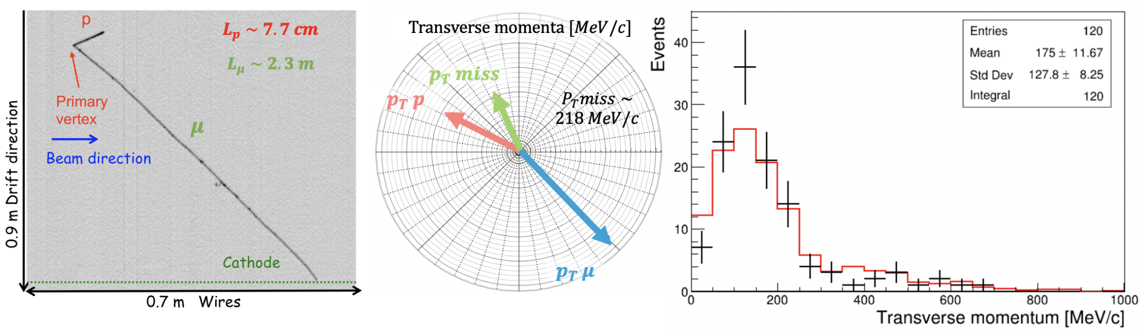

Figure 3: Left: ν_μ CC quasi-elastic event collected with BNB. Middle: transverse momentum reconstruction of the previous event. Right: neutrino transverse momenta distribution for all well reconstructed events in comparison to MC expectations.

while the middle plot represents the reconstructed muon and proton momenta in the transverse plane. The missing transverse momentum can be calculated if both vectors are summed together; thus the process was iterated all over well reconstructed events to provide the respective distribution, as shown in figure 3 right. Black dots indicate the available data, whereas the Monte Carlo prediction is highlighted with a red solid line. Reasonable agreement can be observed despite the low statistics, although great efforts are ongoing to increase the sample.

4. Conclusions

ICARUS installation and commissioning phases were completed by mid 2022. Run 2 smoothly finished in July 2023 collecting data from both Booster and NuMI beams with excellent data taking performance. All available statistics are actively being used to further develop and tune an automatic neutrino selection procedure while improving the actual reconstruction software tools to analyse the events. Preliminary results were obtained proving ICARUS' capability to perform calorimetric studies and particle identification, which are essential to carry out oscillation analysis. ICARUS early phase focuses mainly on Neutrino-4 claims searching for ν_μ disappearance with BNB and ν_e disappearance in the NuMI off-axis beam. On the other hand, SBND detector will soon be added at shorter distance from the BNB target to join ICARUS effort and perform a definitive 5σ analysis of sterile neutrinos.

References

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