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PROCEEDINGS OF SCIENCE

Searching sterile neutrinos with ICARUS at FNAL

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The ICARUS T600 detector completed in 2013 a successful three-year physics run at the underground LNGS laboratory and after a significant overhaul at CERN, it has been installed at Fermilab. In June 2022 a new data taking started and ICARUS is presently recording neutrino events from BNB and NuMI off-axis beams. ICARUS aims at first to investigate the claim by Neutrino-4 short-baseline reactor experiment and to perform with the NuMI beam measurements of neutrino cross sections in LAr and several BSM searches. ICARUS will soon jointly search for evidence of sterile neutrinos with the Short-Baseline Near Detector (SBND). In this proceeding the status of the T600 detector and preliminary results from the ICARUS data analysis with the BNB and NuMI beams will be shortly described.

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1. The SBN experiment

In the last decades different experiments (for example LNSD[1]) have reported evidences of neutrino oscillations that seems to indicate the possible existence of a fourth state of neutrino, the so called "sterile neutrinos", associated to large Δm^2_{new} of the order of the eV^2 and small mixing angles, driving oscillations at short distances. Recently an anomalous $\overline{\nu}_e$ disappearance signal with a clear modulation on L/E at about 1-3 m/MeV has been observed also by the Neutrino-4 experiment and the combined analysis of its result with the results from BEST, GALLEX and SAGE experiments seems to indicate a $\Delta m^2_{new} \simeq 7.3 eV^2$ with a 5.8 σ confidence level [2].
The mentioned sterile neutrino puzzle is still far from being fully understood: the Short Baseline Neutrino (SBN) [3] program at Fermilab will provide soon a definitive clarification of these anomalies. This experiment is based on two fundamental elements: it will measure at the same time the possible ν_μ disappearance and ν_e appearance signals by comparing the neutrino spectra recorded in two detectors located in different positions along the Booster neutrino (BNB) beam line (average Eν ~ 800 MeV). The SBN experimental configuration, in fact, involves the SBND detector located at 110 m from the target and ICARUS-T600 operated as far detector and located at a 600 m distance from the target. In addition this project is exploiting Liquid Argon (LAr) TPC detection technique, that provides excellent neutrino identification and reconstruction capabilities, precise measurement of the neutrino energy and a strong mitigation of the possible sources of background for the neutrino search. In this way, the oscillation signals can be identified directly as differences in the measured spectra, since identical spectra are expected in the absence of oscillation. The adoption of the same detection technology for the detectors allows also to drastically reduce most of the systematic uncertainties for the oscillation analysis. For all these reasons, SBN will allow for a very sensitive search for $\nu_\mu \to \nu_e$ appearance signals, covering the LSND 99% C.L. allowed region at $\sim 5\sigma$ C.L..
During the SBN operations, in addition to the search for sterile neutrinos, high-statistics ν-Ar cross-section measurements will be also performed: in particular the T600 is also exposed to the NUMI Off-axis neutrino beam, with an enriched component of electron neutrinos (few %) in the 0÷3 GeV energy range. The analysis of these events will provide useful information related to the neutrino detection, identification and reconstruction efficiencies and to the neutrino cross-sections at energies relevant to the future long baseline experiment with the multi-kt DUNE LAr-TPC detector [4].

2. ICARUS T600 data taking at Fermilab

The ICARUS T600 detector, with a total active mass of about 476 ton, is the first large scale operating LAr-TPC detector ever built and it has been successfully operated for three years in the Gran Sasso underground National Laboratory of Istituto Nazionale di Fisica Nucleare (INFN), demonstrating the full maturity of this detection technique. After the Gran Sasso data taking the T600 has been moved to CERN and it underwent an intense overhauling phase in view of the new shallow depth operation within the SBN program. It has been then moved to Fermilab, installed in the far detector building and in 2020 it restarted to collect new interesting events. A detailed description of the T600 detector and of the commissioning activities can be found in [6].
At Fermilab, ICARUS is facing a more challenging experimental condition with respect to the previous LNGS physics run: the detector is presently installed essentially at Earth surface and then

cosmic ray particles can become a serious source of background for the neutrino event search. For this reason the T600 is presently surrounded by a $\sim 4\pi$ Cosmic Ray Tagger system that can tag the incoming cosmic muons with ~ 95% efficiency. The CRT is composed by 3 subsystems (*"top", "side"* and *"bottom"*) each one made of two layers of plastic scintillators, with a total surface of ~1100 m^2, and it has been completed and is fully operational since December 2021. In addition ICARUS is shielded also by a ~ 3 m thick concrete overburden installed on the top of the CRT, providing a strong suppression of the cosmic gamma and neutrons that can in principle mimic in the detector ν_e interactions.

RUN	**Date**	**BNB** Positive Focusing	**NUMI** Positive Focusing	**NUMI** Negative Focusing
RUN-1	June 9^{th} - July 10^{th} 2022	0.41×10^{20}	0.68×10^{20}	-
RUN-2	Dec. 20^{th}, 2022 - July 14^{th}, 2023	2.05×10^{20}	2.74×10^{20}	-
RUN-3	March 15^{th} -July 12^{th} 2024	1.36×10^{20}	-	2.82×10^{20}
TOTAL		3.82×10^{20}	3.42×10^{20}	2.82×10^{20}

Table 1: Collected Protons on Target (POT) for the different ICARUS physics Runs.

ICARUS data taking for physics started on June 9^{th} 2022, soon after the completion of the concrete overburden installation, with TPC, PMT and CRT systems fully operational. Table 1 summarizes the different physics data taking period with the total amount of proton on target (POT) collected for both BNB and NuMI beams: the last physics run (Run-3) concluded in July 12^{th} 2024 with a collection efficiency, defined as the ratio between the protons on target collected and delivered, exceeding 97%. In figure 1 two recently collected neutrino interactions from the BNB beam are shown, demonstrating how the LAr-TPC detection technique allows to record and study the neutrino interactions with unprecedent details.

A key element for the successful operation of a LAr-TPC detector is the purity of the liquid Argon: the presence of electronegative impurities produces an exponential attenuation of the electron signal recorded on the wires along the drift coordinate. The measurement of the electron lifetime τ_{ELE} provides the proper correction for this effect, improving the precision of the deposited energy measurement. During the ongoing data taking the ICARUS cryogenic and purification system performed smoothly, keeping τ_{ELE} stable and adequate in particular during the physics runs, as shown in figure 2 for the Run-3 period.

3. ICARUS stand-alone physics program

Before the start of the joint operation with SBND within the SBN experiment to address the sterile neutrino puzzle, ICARUS is focusing on a stand-alone physics program, that will be also fundamental in preparation for the joint SBN oscillation analysis.

One of the major ongoing investigation is related to Neutrino-4: the study of a possible ν_μ disappearance signal in the BNB beam, later complemented with the search for a possible ν_e appearance in the NuMI beam, will allow to either confirm or refute the Neutrino-4 claim. The main focus for the ν_μ disappearance in the BNB beam is presently on *1μNp events*, neutrino interactions fully contained

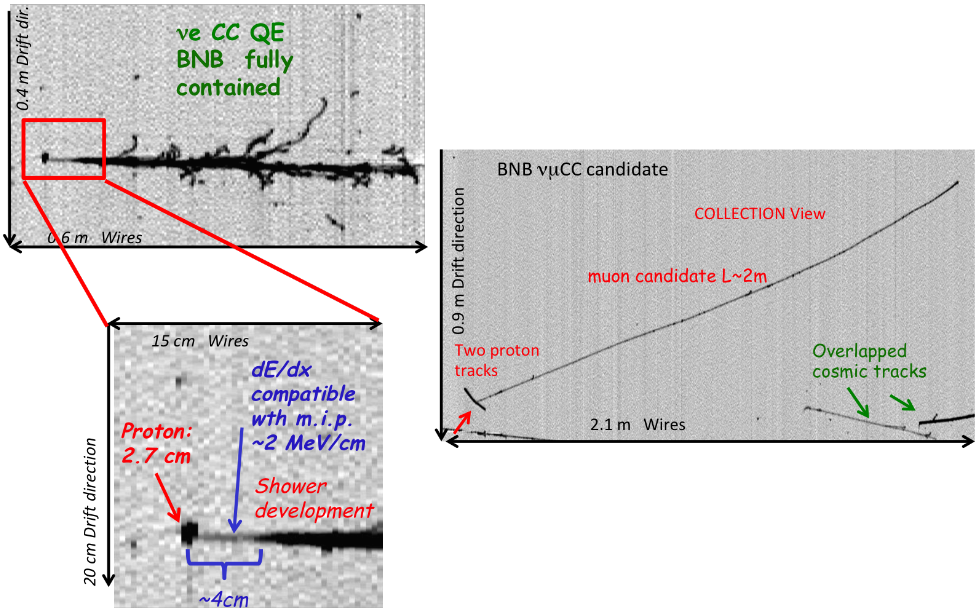

Figure 1: On the left an example of a fully contained quasi-elastic ν_e interaction. The study of the vertex allows to demonstrate that the ionization at the beginning of the shower is fully compatible with a minimum ionizing particle. On the right an example of a fully contained ν_μCC: at the primary vertex, two short proton tracks with high ionization and a longer muon track, also stopping inside the detector, are visible.

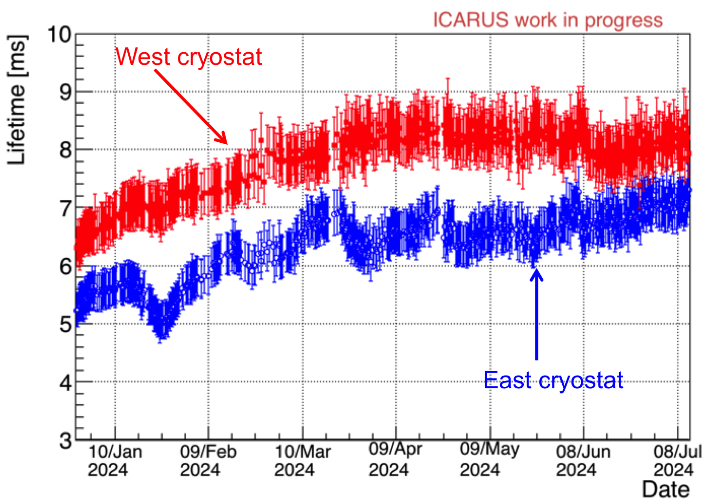

Figure 2: Electron lifetime measurements performed in the first part of 2024 in the West (red points) and East (blue points) cryostats. τ_{ELE} is measured studying the charge signal attenuation as a function of the drift time along cosmic muon tracks.

in the active volume and characterized by the presence at the primary vertex of a single muon with a track length exceeding 50 cm and at least one proton with a kinetic energy exceeding 50 MeV. An example of a candidate collected with BNB beam is shown in Figure 1 on the right. This analysis

is currently performed only on the 10% of the Run-2 statistics, corresponding to about 1.9 $\times 10^{19}$ POT. The neutrino selection and reconstruction is performed using two different multi-algorithm automatic reconstruction and selection chains: Pandora, a recognition software commonly used in LAr-based detectors, and SPINE, a machine-learning based pattern recognition tool developed for ICARUS. The performance of these procedures has been studied using MC events and directly on the data, using a sample of neutrino interactions visually selected. All the possible source of systematics and related to flux, cross section and detector effects, has been studied and a preliminary evaluation has been taken into account in the analysis. The first results for this *$1\mu Np$* events analysis are shown in Figure 3: the neutrino energy for the selected events in the studied collected data results in good agreement with the expectations from MC events within the systematics.
In parallel to this analysis, the study of the neutrino events from the NuMI beam will allow also to obtain precise cross sections measurements and to optimize neutrino identification and reconstruction tools in an energy range of interest for DUNE. Presently the 15% of the Run-1 and Run-2 are under study and the focus is on the selection and reconstruction of neutrino candidates characterized by the presence at the primary vertex of a muon with at least 226 MeV/c momentum and of any proton with momentum between 400 MeV/c and 1 GeV/c, without any neutral or charged pions in the final state. Within systematics, a good agreement is observed in the data/MC comparison for the considered reconstructed event variables, as shown in figure 4. Finally the off-axis NuMI beam can also be exploited to investigate sub-GeV Beyond Standard Model signals. In particular a search for long-lived particles that decay to two muons fully contained inside the detector has been recently completed and no new physics signal was observed. A detailed description of this results can be found in [7].

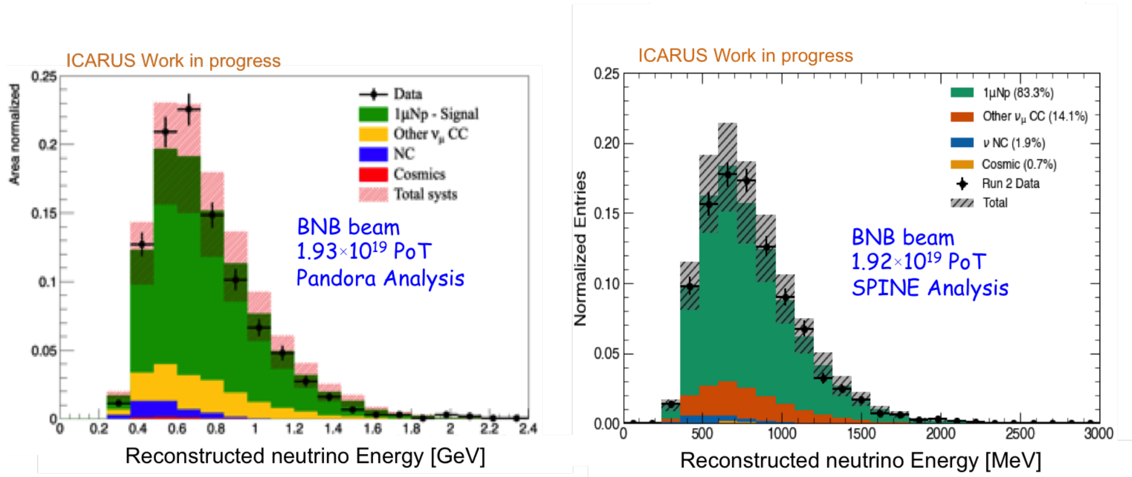

Figure 3: Data/MC comparison for the reconstructed neutrino energy distribution on the left for the events selected using the Pandora chain, while on the right for the events selected by SPINE.

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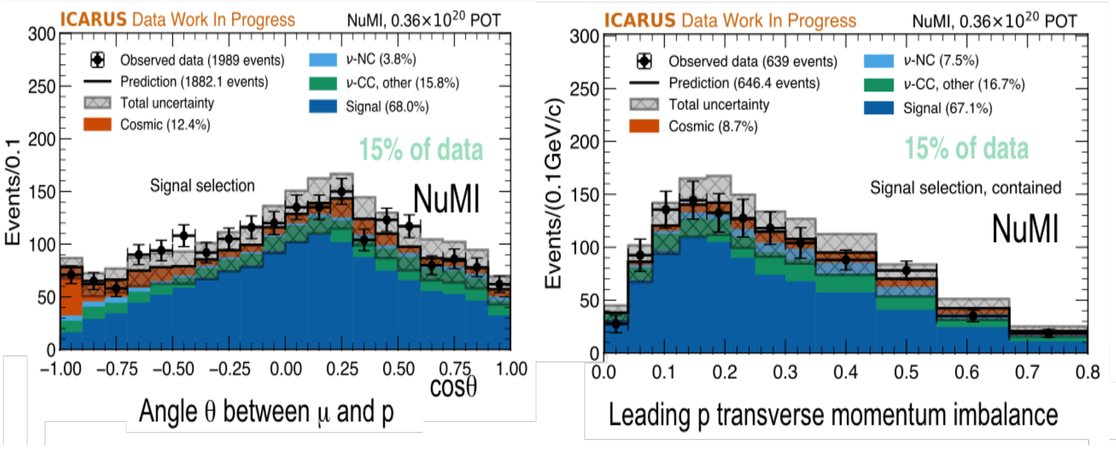

Figure 4: First Data/MC comparison considering the 15% of the recorded Run-1 and Run-2 NuMI events: the reconstructed angle between the muon and the leading proton candidate produced at the primary vertex on the left and for the transverse momentum imbalance (in GeV/c) for the leading proton on the right.

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