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Dedicated study of the automatic event reconstruction in the ICARUS experiment

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Abstract

The three-flavor neutrino mixing minimal extension of the Standard Model (SM) has been established by a number of experiments in the past two decades. However, a series of experimental anomalies were observed, indicating a possible hint of the existence of a fourth neutrino, called *sterile neutrino* because it does not undergo weak interaction.

This 3 + 1 extension of the SM is the main physics target of the ICARUS experiment as part of the Short-Baseline Neutrino (SBN) program at Fermilab. The ICARUS-T600 760-ton detector is a Liquid Argon Time Projection Chamber (LAr-TPC) successfully employed at the LNGS laboratories for a three-year physics run and now collecting data at Fermi National Accelerator Laboratory (FNAL). The physics program of the ICARUS experiment also includes the measurement of neutrino-Argon cross sections employing the off-axis Neutrino at the Main Injector (NuMI) beam and several Beyond Standard Model studies.

The automatic TPC event reconstruction in ICARUS is performed using the Pandora Pattern Finding Algorithm framework that performs a 3D reconstruction of the image recorded in the collected event, including the identification of interaction vertices and the classification of tracks and showers inside the TPC.

In view of the standalone ICARUS oscillation ν_μ analysis and of the future combined SBN oscillation analysis, a thorough evaluation of the performances of reconstruction chain, as well as the systematic uncertainties induced on the reconstructed neutrino energy spectrum is essential. The main objective of this work is to evaluate the performances of single steps of the reconstruction sequence, while possibly testing improvements of the machine learning algorithms employed in specific stages of the chain.

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Introduction

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Active and sterile neutrinos

Chapter 2

The ICARUS Detector at the Fermilab SBN program

Firstly proposed by Nobel laureate Carlo Rubbia [1], the concept of Liquid Argon Time Projection Chambers (LArTPCs for short) was implemented in the Gran Sasso National Laboratories (LNGS) near L'Aquila (Italy) in the ICARUS (Imaging Cosmic And Rare Underground Signals) detector [2–5], which collected data between 2006 and 2011 [6], alongside the OPERA, LVD and BOREXINO detectors from the CERN Neutrinos to Gran Sasso (CNGS) neutrino beam [7]. The main detectors for this project were the OPERA and ICARUS experiments, and were therefore called respectively CNGS1 and CNGS2.

After the results of the CNGS analysis were published the ICARUS detector moved in 2018 from LNGS, to the CERN facility, where it underwent a series of upgrades, both for electronics and in the liquid Argon purification system; serious upgrades were also performed on the exterior of the experiment where a cosmic ray tagger module was added; in 2020 the detector arrived to its current location in the SBN facility at Fermilab, where it has been detecting neutrinos since: mainly $\nu\mu$ and some ν_es, from the Booster Neutrino Beam (BNB, on axis with the z direction of the detector frame of reference) and from the Neutrino Main Injector (NuMI).

At the Short Baseline Neutrino (SBN) facility, the ICARUS experiment started its data run taking period in 2022 and has since ran thrice [8], with the latest data expected to be ready for the end of 2024 for the official analysis. Its younger brother, the SBND (Short Baseline Near Detector) experiment, finished the cryostat commissioning with some delays in 2023 and is now completing the commissioning of the cosmic ray tagger (CRT) modules, with the analysis on veto efficiency for the top CRT modules ongoing.

Joint efforts of the SBND and ICARUS detectors in the SBN collaboration will provide a highly efficient identification of neutrino interactions, strongly mitigating the possible sources of background and reducing the impact of systematics.

The combination of two nearly identical detectors allows for the measurement of neutrino oscillations over the distance in between the experiments, comparing the νs flux at 110 m (SBND) and at 600 m (ICARUS).

A third and a fourth experiment were also active in the BNB baseline, MiniBooNE (mBooNE) and MicroBooNE (µBooNE). The former completed its data taking period in 2018, and the latter was active between 2015 and 2021. Those two experiments provided strong ($\sim 5\sigma$) evidence of event excess [9] in respect to what was expected (see figure **??**). The main goal of the SBN collaboration is therefore to test this anomaly using data from BNB neutrinos.

In addition to this anomaly, ICARUS will also test the oscillation signal reported by the Neutrino-4 collaboration, hinting towards $\Delta m^2 \simeq 7.26\,\mathrm{eV}^2$ and $\sin^2 2\theta = 0.38$ (3.5σ CL), both in ν_e and ν_μ channels from BNB and NuMI.

Chapter 3

Automatic event recontruction in TPC using Pandora

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