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Opening Pandora's box

A dedicated study of the automatic event reconstruction in the ICARUS-T600 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_μCC 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

Neutrinos are the most abundant particle in the universe, with billions of neutrinos passing trough each square centimeter each second, primarily coming from our neighbour star, the Sun: within nuclear reactions inside the Sun's core, billions of neutrino are created, and, due to their weakly interactive nature they travel unaltered to Earth. Other neutrino sources are also core-collapse supernovae, interacting cosmic ray within Earth's atmosphere, and, nonetheless, nuclear reactors and accelerator complexes.

The discovery of neutrino oscillations, hence the evidence for neutrino masses, is a striking proof of Beyond the Standard Model (BSM) physics. Generating neutrino masses is qualitatively different from generating masses for any other fermionic particle content of the Standard Model (SM). Several are the possible scenarios for introducing neutrino masses in the SM: in general, the mechanism of neutrino masses would require addition of new particle state to the SM that have never been observed. The addition of this particle states would modify substantially neutrino-related observables, and would have effects, for example, on oscillation phenomenology.

Interest in this direction has been fanned, more recently, by a series of neutrino anomalous measurement at short-baseline oscillation experiments, at accelerating complexes, like the LSND and MiniBooNE collaborations, at Gallium-based experiments, like GALLEX, SAGE and BEST collaborations, and at reactors baselines, like the Neutrino-4 collaboration.

None of these short-baseline experimental anomalies, hovewer, proved to be definitive, even if the global picture shows a strong tension with the current model. An individual program aiming at a $> 5\sigma$ sensitivity, on multiple short-baseline oscillation channels experiment is needed to test these results and draw a complete picture for these short-baseline experimental anomalies.

The Short Baseline Neutrino (SBN) program at Fermilab is a three detector, short-baseline, multiple oscillation channel experimental effort, located along the Booster Neutrino Beam (BNB) baseline. All the three detectors in the beamline are Liquid Argon Time Projection Chambers (LArTPC(s)), exploiting on the high precision calorimetric power and mm-scale three dimensional tracking capabilities of such detectors to archive unprecedented sensitivity on the sterile neutrino search.

The ICARUS T600 detector acts as the SBN Far Detector (SBN-FD) at a baseline of 600 m. The location of both the ICARUS detector and of the SBN Near Detector, SBND, where chosen to optimize neutrino oscillation sensitivity and minimize the impact of flux systematics. Among the Booster Neutrino Beam, the ICARUS T600 detector is also on the baseline of the Neutrino from the Main Injector (NuMI) Beam, crossing the detector 6° off-axis wih respect to the detector principal axis. The ICARUS detector is now finishing its fourth physics run, three of which were done while the SBN near detector was preparing to start its physic operation. With all this data the collaboration has started to look into ν_{μ}-disappearance studies, with the simplest topologies being $1\mu 1\mathrm{p}$ and $1\mu N\mathrm{p}$.

In order to reduce the systematic uncertainties related to the reconstruction efficiency, a detailed study of the event reconstruction inside the ICARUS TPC is needed, alongside an effort to align the ICARUS and SBND detectors signal processing and event reconstruction chain, in view of the future SBN joint analysis.

Of all steps involved in the event processing and reconstruction, one of great importance is related to the particle objects building from the signals left on the wireplanes, and the subsequent event hierarchy creation (that is defining which are the primary particles originating from the interaction vertex and the interaction *structure*), which is the centerpiece of many further analysis. This process is performed by a set of algorithms shared across the LArTPC technology detectors. The common framework is based on the Pandora Patter Finding Algorithm software. This feature, alongside the various algorithms suited for the reconstruction, a set of tools that can be used to perform studies on the reconstruction efficiency, previously unused by the ICARUS collaboration.

The goal of this thesis is to validate this set of tools for further use in the ICARUS collaboration, and show their power by performing a detailed efficiency analysis of the TPC reconstruction chain. This will likely serve both as a validation for the current analysis, as wall as a foundation for later works — such as the future ν_{e}-appearance analysis — where these tools can be used to validate the reconstruction for the shower-like particles, where the reconstruction hit a big wall due to the particle-argon interaction topology and the signal that it produces.

The thesis structure is as follows

- chapter 1 is devoted to introducing the theoretical framework of the Standard Model of Particle Physics, with a great interest on the physics of neutrinos, their *classical* picture, the phenomenology of neutrino oscillator behaviour and some of the anomalies driving the sterile neutrino picture.

- chapter 2 tries to get a detailed description of the ICARUS T600 detector, its three sub-systems, the Liquid Argon Time Projection Chamber, the light collection system and the cosmic ray tagging system, and its role in the Fermilab Short Baseline Neutrino Program.
- chapter 3 is dedicated to an overview of the event reconstruction in all the T600 sub-detectors, with a primary focus on the TPC event reconstruction.

1

Active and sterile neutrinos

1.1. Neutrinos

Dating back to 1914, the history of neutrions began with the first paper published by Sir James Chadwick [1], who, investigating the phenomena of beta decays, discovered that the emitted electron energy spectra was not a single vertical emission line (delta shaped), but a continuous spectrum.

The β decay process, up until then, was though to be just the emission of a single electron from a neutron decaing at rest to a proton

$$\mathrm{n} \to \mathrm{p} + \mathrm{e}^-,$$

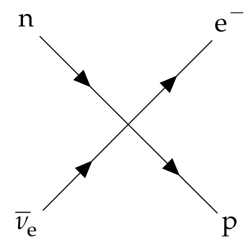
and so it was expected the electron to carry all of the neutron energy. A continuous e^- spectrum broke this expectation. W. Pauli in 1930 proposed the idea that the emission of the electron occurred along the emision of another fermionic particle, way less massive — massless even — than the electron, carrying no electric charge [2]

$$\mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}.$$

Though not calling this particle neutrino yet, its idea was all contained in Pauli's letter.

Enrico Fermi, a prominent scientist of that era, developerd on Pauli's idea, calling this new particle *neutrino* [3, 4] — from *neutron*, the only chargeless particle discovered so far, aside from photons, adding the suffix *-ino*, meaning smaller (and lighter). Fermi's idea was the first *field theory* of quantum mechanics, suggesting that the β decay was to be formalized as a four-fermion point interaction, involving a neutron, decaying to a proton, to produce an electron and a neutrino,

$$\beta^- : \quad \mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}. \implies \tag{1.1}$$



Fermi's effective theory was able to explain the β decay electron energy spectrum successfully, even preserving the angular momentum conservation. The value of the coupling measured by Fermi for this interaction, called G_F, was

$$G_F^{(\beta)} \simeq 1.166 \times 10^{-5}/\mathrm{GeV}^2, \tag{1.2}$$

implying that this type of inteaction was extremely small, which justified calling this type of interaction *weak*. Up until now however the neutrino was yet to be "directly" observed. It took twenty-six years of experimental efforts to actually detect the traces of this "ghostly" particle. The first experimental observation of electron anti-neutrinos produced by beta decays from the Savannah River reactor happened in 1956; a team led by F. Reines and C. L. Cowan observed the signature of inverse beta decay process (IB)

$$\overline{\nu}_\mathrm{e} + \mathrm{p} \to \mathrm{n} + \mathrm{e}^+ \tag{1.3}$$

in a water tank, detecting the two gamma rays from proton annihilation in water with a liquid scintillator [5].

The world of particle physics was discovering new particles very fast, and putting together the picture we today now as the Standard Model (SM) of particle physics: in the same years the electron neutrino was discovered, a team led by Carl D. Anderson and Seth Neddermeyer was discovering the muon, which they described as a heavier relative to the electron, since it showed a less prominent curvature than the electron when passed through a magnetic field; this discovery was later confirmed [6–8]. With the discovery of the muon, some started to question the true nature of neutrinos. In 1959 Bruno Pontecorvo examined this problem, and wondered wheter neutrions produced alongside electrons where the same as neutrinos produces alongside muons [9].

$$
\begin{aligned}
P(\nu_{\mathrm{e}} \to \nu_{\mathrm{e}}) &\simeq 1 - 4|U_{\mathrm{e}4}|^2(1 - |U_{\mathrm{e}4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \\
&\equiv 1 - \sin^2(2\theta_{ee})\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right), \qquad (1.4) \\
P(\nu_\mu \to \nu_\mu) &\simeq 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \\
&\equiv 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right), \qquad (1.5) \\
P(\nu_\mu \to \nu_{\mathrm{e}}) &\simeq 4|U_{\mu 4}|^2|U_{\mathrm{e}4}|^2\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \\
&\equiv \sin^2(2\theta_{\mu e})\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right). \qquad (1.6)
\end{aligned}
$$

2

The ICARUS Detector at the Fermilab SBN program

Firstly proposed by Nobel laureate Carlo Rubbia [10], 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 [11–14], which collected data between 2006 and 2011 [15], alongside the OPERA, LVD and BOREXINO detectors from the CERN Neutrinos to Gran Sasso (CNGS) neutrino beam [16]. The main detectors for this project were the OPERA and ICARUS experiments, and were therefore called respectively CNGS1 and CNGS2.

Today, the ICARUS T600 detector is one of the longest running LArTPC in existence.

3

Event reconstruction in the ICARUS T600 detector

3.1. Wireplanes signal processing

3.2. Light reconstruction

3.3. Cosmic ray tagging

3.4. TPC automatic event reconstruction

4

Validating the automatic Pandora-based reconstruction

5 Conclusions and future outlook

A
Acronyms

Throughtout the thesis multiple acronyms or concepts are presented and used, here are the most common with some context

ICARUS ***or SBN-FD***	The name stands for *Imaging Cosmic And Rare Underground Signals*, as it was called in the Gran Sasso era. It is the 760 t Far Detector in the SBN experiment
BNB	Booster Neutrino Beam, the main beam feeding the SBN experiment
SBN	The Short Baseline Neutrino experiment, consisting of the three detectors on the BNB baseline
SBND	Short Baseline neutrino Near Detector

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