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First results from the search of ν_μ disappearance with ICARUS

Maria Artero Pons on behalf of the ICARUS Collaboration
INFN Sezione di Padova, University of Padova,
Via Marzolo 8, 35131 Padova, Italy

This work presents a search for muon neutrino disappearance signal using the ICARUS detector. ICARUS is currently working as the far detector of the Short-Baseline Neutrino (SBN) program. Its main goal is to investigate the possible oscillation of a sterile neutrino state ($\Delta m^2 \sim \mathrm{eV}^2$), that would drive short baseline oscillations at the scale of L/E ∼ km/GeV. Neutrino interactions from the Booster Neutrino Beam (BNB) are investigated, looking for simple final state topology with a single muon and at least one proton (1μNp). This analysis tests the 3+1 model using the two flavor neutrino approximation, where careful consideration has been given to the systematic uncertainties arising from flux, neutrino interaction, and detector models. No statistically significant ν_μ disappearance is observed, hence 90% C.L. exclusion contours are reported in the $\Delta m^2_{41} - \sin^2 2\theta_{\mu\mu}$ parameter space.

1 Introduction

The standard three-flavor neutrino oscillation measurements are incompatible with short-baseline oscillation. However, a number of anomalous results suggest the existence of a new sterile neutrino state, characterized by an eV-scale mass state and a small mixing to the active flavors, that would produce short-distance oscillations. Definitive investigation of this hypothesis is one of the primary motivations of the Short-Baseline Neutrino (SBN) program, composed of three liquid argon time projection chambers (LArTPC). A key feature of this project is the shared detector technology, same nuclear target and similar flux across the different LArTPCs, resulting into a significant constraint of systematic uncertainty when multi-detector analysis are performed.

For this first ICARUS standalone analysis, only data from the far detector, located at 600 m, is exploited testing the 3+1 sterile neutrino model.

2 ICARUS within the SBN program

After a successful three-year physics data taking at the underground LNGS laboratories of Gran Sasso, in Italy, ICARUS was move to Fermilab (USA) to operate as the far detector of the SBN program. From 2022 ICARUS has been collecting data stably over the course of 5 physics runs, for a total collected proton-on-target (POT) of $\sim 10^{21}$ POT from the Booster Neutrino Beam (BNB). The analysis presented here uses data collected from winter 2022 to spring 2023 (the so called Run 2 period), corresponding to an exposure of $\sim 2.05 \times 10^{20}$ POT. Detector and beam data quality metrics were developed to ensure nominal performances and guarantee optimal physics data, reducing the available exposure to $\sim 1.6 \times 10^{20}$ POT.

3 Single detector ν_μ disappearance search

3.1 Motivation

To produce this early physics result, a simple final-state topology was chosen. The selection criteria were specifically designed to minimize sensitivity to ongoing detector calibrations and software developments while ensuring high-quality physics results. Consequently, the signal is defined as muon neutrino charged-current interactions yielding at least one muon and one proton ($1\mu Np$), with all final-state products reconstructed within the detector's fiducial volume. This final state offers several reconstruction advantages, as contained tracks allow for both reliable particle identification and precise momentum estimation via range. Even more, the requirement of a reconstructed vertex provides a powerful rejection of cosmic-ray backgrounds, which—unlike neutrino interactions—typically lack an interaction vertex within the fiducial volume.

Figure 1 shows en example event display of a target final state interaction, specifically an event with a muon and two identified protons. Instead the right-hand side plot shows the defined 1μNp true signal spectrum as a function of true ν visible energy [a], with contributions from each true interaction type. Many of the signal events are from quasielastic (QE) interactions, but there is also a significant contribution from meson exchange current (MEC) and resonant pion production (RES).

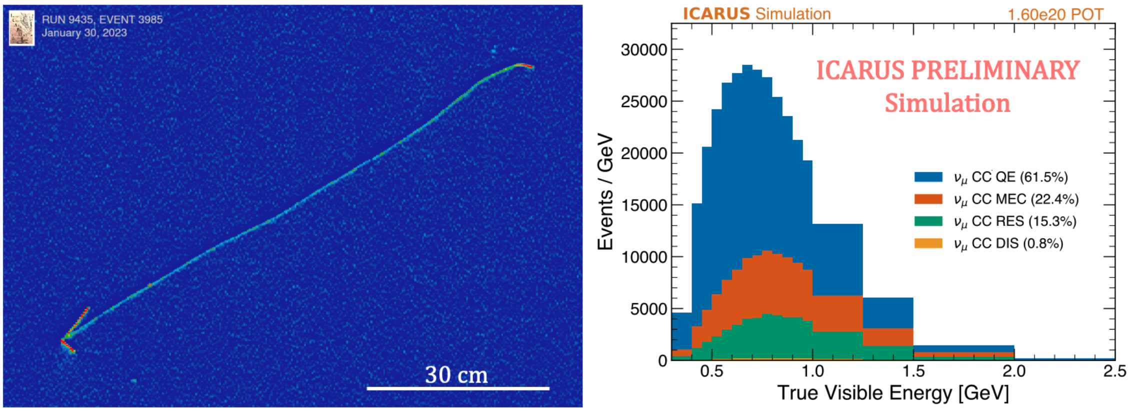

Figure 1 – Left: Example of 1μ2p candidate observed in the Run 2 data. The color scale indicates the energy deposition of each, red zones are more energetic than light blue. Right: True 1μNp visible energy spectrum selected by truth criteria. True interaction type is indicated by color together with its contribution.

3.2 Event selection and performance

Due to the large amount of data to analyze, an automatic procedure to select signal events while rejecting cosmic ray background is mandatory to handle the current statistics. Presently, the selection and reconstruction of neutrino candidates is performed using two different analysis streams based on Pandora[2] pattern recognition and SPINE[3], a machine learning-based algorithm developed for ICARUS. Nonetheless, the selection procedure to recognize 1μNp events in both cases is based on similar criteria. The interaction vertex needs to be in the fiducial volume [b], with exactly one muon coming out of it, longer than 50 cm, and at least one proton with deposited energy > 50 MeV. All reconstructed charged particles must be contained within 5 cm from the active volume, allowing a range-based measurement of particle momenta. The muon length cut reduces the contamination of neutral current interactions with a pion in the final state, while the proton energy threshold ensures a track long enough to be reconstructed and resolved with good efficiency. A veto is finally applied to remove interaction with additional charged particles or showers. A few specific algorithm selection criteria are also applied due to the intrinsic nature of both reconstruction paths. Pandora uses the correlation between charge, light and absence of interaction in the cosmic ray tagger to reject particles entering or exiting the cryostat. On the other hand, SPINE selected interactions are required to be match with an optical flash detected by the photon detection system consistent with the neutrino beam spill

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[a] The energy of the neutrino is reconstructed by adding the total energy of the muon, the kinetic energy of the proton(s), and an empirical average removal energy [1] of 30.9 MeV for each proton above 50 MeV.

[b] The fiducial volume is defined as more than 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls.

time. Pandora selection achieves a 48% efficiency and 82% purity, while SPINE sets these values to 77% and 92% respectively. Both calculations were computed using Monte-Carlo simulations, with statistics 10 times larger than those available for data, and validated through a small sample of visual scanning to cross check the results. The primary background in both cases are mis-identified true ν_μ interactions that have different true final state topology from the target sample. It is worth noting that even if ICARUS is operating at shallow depth, the overall cosmic background accounts for only $\sim$ 1% and $<$ 0.1% of the total selected events for Pandora and SPINE respectively.

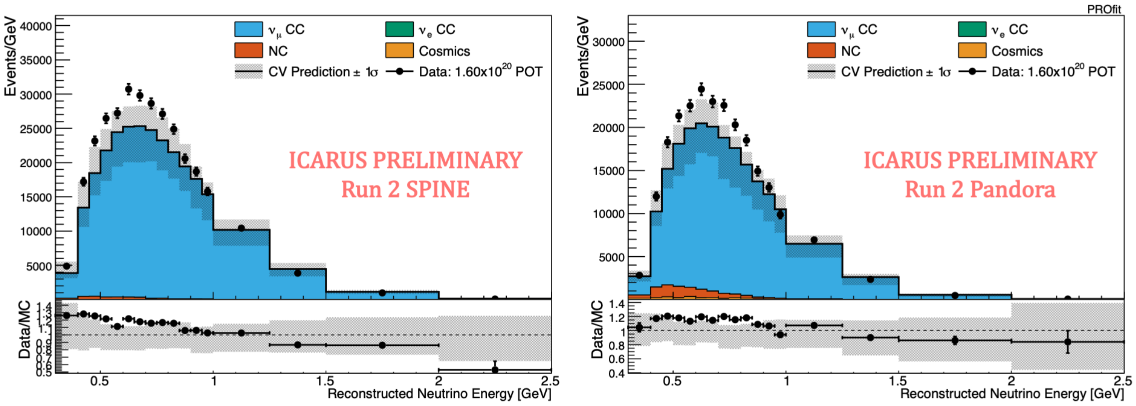

Figure 2 – Reconstructed neutrino energy distributions and data/MC ratios for selected events for Pandora (right) and SPINE (left).

A total of 13,914 and 19,124 events are selected from Run 2 for Pandora and SPINE, respectively. Figure 2 shows the reconstructed neutrino energy distribution for selected events in data and MC. The error bars on the data points represent the statistical uncertainty, whereas the shaded band represents the 1σ range of the central value MC prediction, based on the systematics uncertainties described in the following section. In general, the data points are above the central value (CV) MC prediction; this tendency of the CV MC to underpredict the number of events is expected based on comparisons of the interaction model used in this analysis to other neutrino datasets. Most of this known data-MC discrepancy is covered by the systematic uncertainties included in the analyses and the shapes of the distributions are generally in good agreement with simulation.

3.3 Systematic uncertainties and fitting

Potential neutrino oscillations between the neutrino production and detection points are studied by comparing the observed spectrum at ICARUS to a prediction based primarily on MC simulation. Uncertainties in modeling the neutrino beam and interactions, and the detector are reflected as uncertainties in the predicted spectrum, which are strongly correlated with the measured values of oscillation parameters. For this reason systematic uncertainties are included in the result presented here.

The ICARUS flux prediction and related uncertainties are inherited from past experiments that ran in the same beamline; MiniBooNE and MicroBooNE. These arise mainly from uncertainties in proton delivery, particle production, hadronic interactions, the horn magnetic field and beamline geometry. Additionally, there is a flat 2% uncertainty in the flux POT normalization. The fractional contribution of flux in both analysis are shown in figure 3.

For neutrino interactions, systematic uncertainties and prior constraints are taken directly from the used neutrino generator, GENIE AR23 [4]. Additional uncertainties, not available in GENIE, are implemented using the NuSystematics package [5]. Systematics are implemented in the fitter either by using random throws of parameter values to construct a covariance matrix in bins of reconstructed neutrino energy or by associating each spline with an additional nuisance parameter with its own prior uncertainty, which are then constrained in the fit. Systematics which are expected to be significant, non-Gaussian, or are important to understand which values the fit prefers, are treated using the latter method. The remaining, less significant ones, are included in a covariance matrix. The systematic uncertainties with the largest observed impact on the analysis are the random-phase approximation (RPA) suppression of the quasi-elastic (QE) channel, the z-expansion parameters describing the QE axial form factor and the shape and normalization of charged-current meson exchanged current (CCMEC). The QE contribution dominates at reconstructed neutrino energies below 0.6 GeV, after which the greatest uncertainty comes from the MEC interaction.

Finally, uncertainties arising from imperfections in the simulation of detector response are evaluated using alternative MC samples in which the detector model parameters are varied. These variations reflect specific modifications to individual components of the detector model and include: intrinsic noise simulation, TPC signal shape, spatial non-uniformities in the detector response, alternative recombination model and variation of electron lifetime. Other detector effects were considered but found to be less relevant with respect to the previous list.

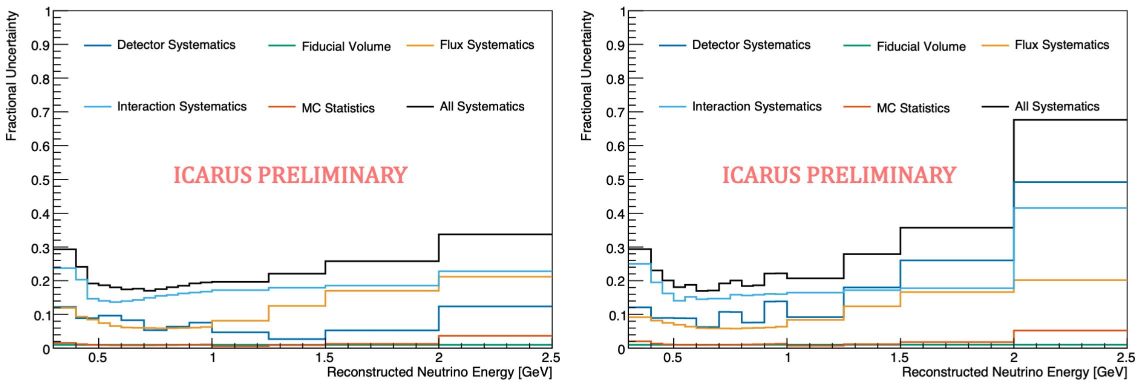

Figure 3 – Fractional size of systematic uncertainty as a function of reconstructed neutrino energy for SPINE (left) and Pandora (right).

The total uncertainty in the predicted event rate resulting from systematic variations is around 20% at the peak of the selected neutrino distribution, with the fractional contributions as a function of reconstructed neutrino energy shown in figure 3. The systematics coming from uncertainty in the neutrino interaction model are the largest contribution, while flux and detector models have approximately equal contributions for most energies.

All necessary statistical studies and analyses are performed using PROfit [6], a new general-purpose oscillation and fitting framework that has been developed for SBN analyses. PROfit finds the set of oscillation and systematic parameters best describing the data, given prior uncertainties on the models used in the simulation. This analysis is performed in the context of a two-flavor approximation within the 3+1 sterile neutrino model and results are presented in terms of Δm^2_{41} and $\sin^2 2\theta_{\mu\mu}$, with the assumption $\theta_{ee} = \theta_{\mu e} = 0$. Systematic uncertainties are incorporated as nuisance (pull-term) parameters governing the strength of correlated variations or through a covariance matrix. Minimization of the combined Neyman–Pearson (CNP) χ^2_{CNP} metric is performed and confidence intervals on the oscillation parameters are constructed using the Feldman-Cousins (FC) procedure. To avoid biases, signal unblinding follows a predetermined staged procedure supported by PROfit in which fits to both the SPINE and Pandora selections are performed simultaneously, with validation checks evaluated at each stage before proceeding, to ensure a robust result.

3.4 Results

No evidence for oscillation is observed in either the SPINE or Pandora fits. The best fit χ^2/ndof is 15.3/17 for Pandora and 17.3/17 for SPINE. The post-fit spectra and uncertainties are shown in Figure 4, where oscillation parameters are allowed to float. While the data do not show a statistically significant preference for sterile neutrino oscillations, the best-fit oscillation parameters and χ^2 values for both analyses are provided in Table 1. The higher significance for oscillation observed in the SPINE fit is attributed to its improved efficiency and reduced systematic uncertainties in the highest energy bins. Nonetheless, given the consistency with the null hypothesis in both fits, 90% confidence level exclusion contours are reported instead.

Table 1: Fit results for both reconstruction algorithms. No statistically significant oscillation is observed.

	Best fit $\sin^2 2\theta_{\mu\mu}$	Best fit Δm^2_{41}	χ^2 null	χ^2 osc	$\Delta\chi^2$	FC p-value
Pandora	0.07	10.2	15.7	15.3	0.4	0.91
SPINE	0.24	13.5	20.5	17.3	3.2	0.42

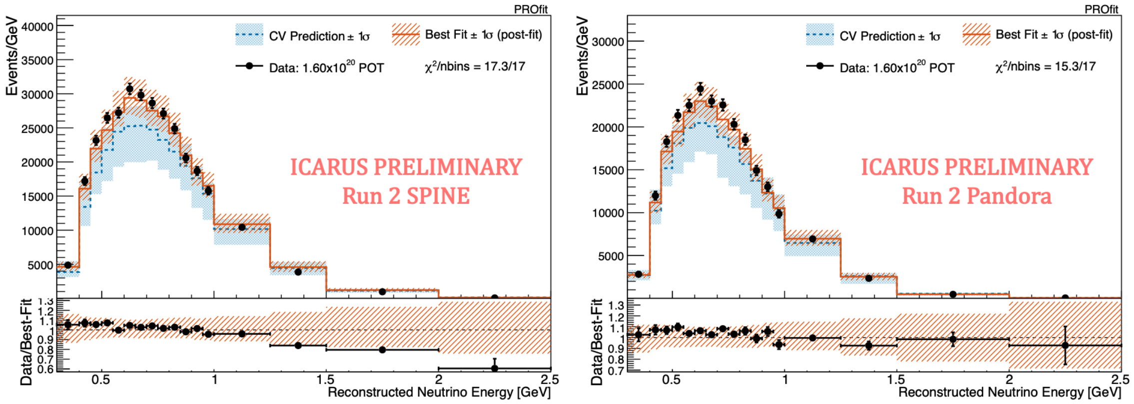

Figure 4 – SPINE (left) and Pandora (right) post fit spectra and data/best-fit ratios for the null fit in which oscillation parameters are allowed to float.

PROfit diagnostic plots are inspected to understand the impact of systematic uncertainties in the analyses. No outstanding values were found neither in the systematics pulls nor in the correlation matrices of both analyses. As observed in previous mock data studies, a couple of parameters related to the spectrum normalization were pulled to cover the differences between number of events in data and MC.

The final 90% C.L. sensitivity contours and exclusion band in Figure 5 are generated using FC corrected critical χ^2 value. For both analyses, the data contour falls within the 2σ sensitivity band for nearly all points. The spiky behavior in the data contour as a function of Δm^2 is typical of short-baseline oscillation exclusion contours and results from from the sinusoidal variation in oscillation probability. At high values of Δm^2, the data contour falls near the $+1$ to $+2\sigma$ boundary of the sensitivity band. Oscillations in this region of the parameter space would primarily manifest at ICARUS as a change in normalization. Because the observed data rate is slightly higher than the central value of the MC prediction — whereas an oscillation signal would predict a reduction in the event rate — the resulting data exclusion is stronger than the MC-based median sensitivity in this region.

4 Conclusions

ICARUS observes no evidence for ν_μ disappearance in the BNB in the Run 2 dataset, using both the Pandora and SPINE reconstruction frameworks to identify samples of 1μNp interactions. 90% exclusion contours are presented for both analyses in the context of the 3+1 sterile neutrino model, being consistent with previous single-detector ν_μ disappearance searches. For now, this analysis remains dominated by systematic uncertainties, as expected in the absence

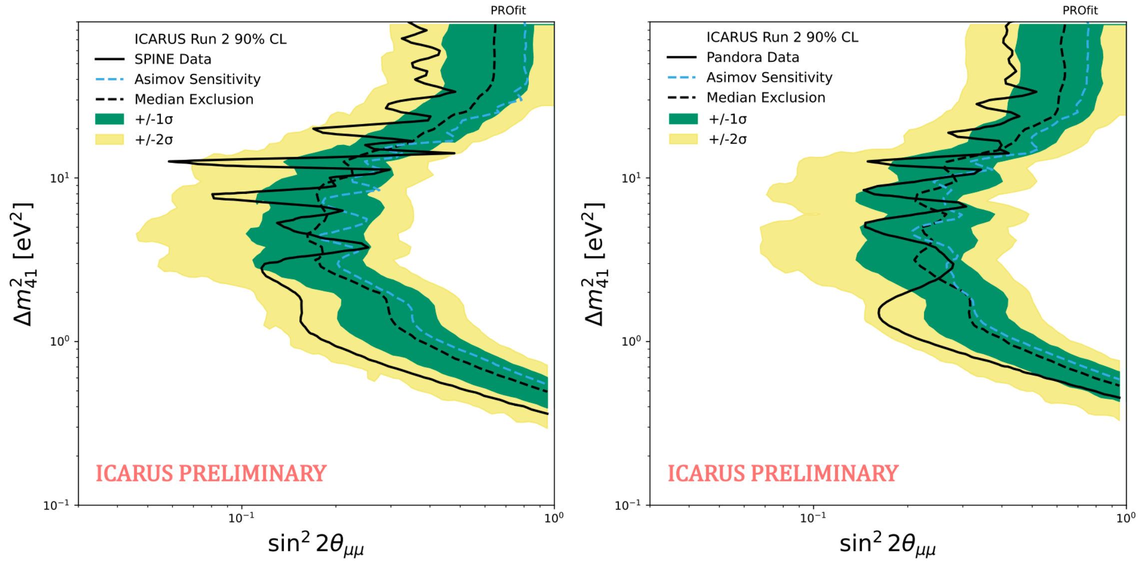

Figure 5 – Feldman-Cousins 90% C.L. exclusion contours for SPINE (left) and Pandora (right). The uncertainty bands represent the range of exclusion contours within which 68.3% and 95.4% of the universes that exclude oscillation are found.

of near-detector data. However, the SBN program is specifically designed to suppress these uncertainties; since flux and interaction model uncertainties are nearly 100% correlated between the two LArTPC detectors, they will be significantly constrained in a joint two-detector oscillation analysis. Furthermore, improvements to the detector simulation, many of which were developed as systematic variations in the analysis reported here, will remove many residual data-MC discrepancies in ICARUS. All these improvements will produce robust and world-leading two-detector oscillation analysis, giving definitive answers to the sterile neutrino puzzle.

The results presented here are based on a recently published article, where more detailed information can be found [7].

Acknowledgments

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