Detector Related Uncertainties in ICARUS

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This paper explores the challenges in neutrino detection and emphasizes the importance of understanding the ICARUS neutrino detector. It delves into the use of cosmic rays to bridge the gap between experimental and theoretical data, offering insights into the behavior of different components of neutrino detectors. This procedure sheds light on the intricate aspects of cosmic ray detection in ICARUS, contributing to an increased understanding of how this detector's uncertainties operate. More can be learned about neutrino physics in future experiments through this understanding.

I. INTRODUCTION

The basis of any scientific experiment is to determine the difference between a hypothesis and the experiment itself. This principle is just as true for the ICARUS detector as it is for testing $\vec{F} = m\vec{a}$. However, the ICARUS detector is much more complicated than measuring the time it takes for a block to move a certain distance. The tested theory requires complex Monte Carlo simulations that simulate the underlying QFT processes.

This paper seeks to show how to quantify the differences between the simulated predictions and the data. The point is to understand uncertainties that stem from the detector's geometry.

II. BACKGROUND

FIG. 1: A picture of the ICARUS detector[1]

Neutrinos are one of the most fascinating and elusive particles in the universe. They are a lepton that only interacts with the weak Nuclear Force and gravity. Despite being incredibly abundant, these interactions are so few and far between that even a light year of lead might not stop a single neutrino.

Neutrinos come in three types or "flavors" – electron neutrinos, muon neutrinos, and tau neutrinos – and can oscillate or change from one type to another. They are produced in various high-energy processes in the cosmos, such as in the nuclear reactions that power stars, during supernova explosions, and even through interactions cosmic rays have in the atmosphere. Particle accelerators produce them as well, of course.

An essential area of neutrinos research is studying their masses. Neutrinos each have a tiny mass, and we have only been able to measure the differences. Quantum Mechanics additionally complicates things[2]. The mass states, and the flavor states do not coincide. This state differential is unintuitive, but what is essential is that this means that when neutrinos interact, they do so in the flavor states, not the mass states. So, to research these complicated little scamps, it is vital to understand the detector used.

ICARUS stands for "Imaging Cosmic And Rare Underground Signals" (Figure 1). It is a Time Projection Chamber (TPC) detector. This means it uses a uniform electric field to drift the charged particles produced in interactions to create a 3D image of the particle tracks. Another critical attribute is that the detector is filled with liquid Argon. There are a few reasons for this: it is dense and can stop charged particles; it is an effective scintillator, meaning it produces light when charged particles travel through it, which gives more data on the trajectory; most importantly, it is stable and abundant[1].

All of this results in ICARUS being an excellent detector for studying neutrinos. It can effectively reconstruct the trajectories of the charged particles produced by neutrinos interacting with matter. ICARUS can detect more than just neutrinos, however. Cosmic rays also provide a plethora of events that can be analyzed. They are essential to understanding the detector.

III. MOTIVATION AND PURPOSE

Every scientific experiment comes with its collection of uncertainties. A detector like ICARUS, however, is quite complicated, so it is difficult to quantify the uncertainties that arise in its geometry. So, a helpful way to analyze the uncertainties is to compare the Monte Carlo simulations to the experimental data. More specifically, by creating histograms of the data, the ratio of the simulation and the experimental results can be taken.

An excellent method of accomplishing our goal is in[3] in the context of the MicroBooNE detector. This paper outlines many methods that can be applied to ICARUS, as the MicroBooNE and ICARUS detectors are very similar. Before moving forward, it is crucial to understand how the detector and its geometry work.

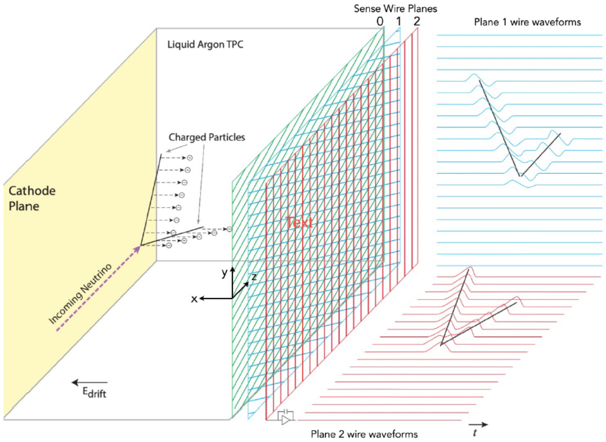

FIG. 2: Schematic of MicroBooNE Wire Planes[3]

Figure 2 gives a detailed schematic of how the MicroBooNE detector functions. A cathode and anode plane produce a uniform electric field that drifts the charged particles produced by an interaction. Three wire planes are labeled 0, 1, and 2 at the anode. During an event, charged particles induce signals on the induction planes of planes 1 and 2. The third plane (plane 2), the collection plane, directly measures the signals. It is also worth noting that the collection plane has its wires aligned vertically while the induction planes are oriented $\pm 60^{\circ}$ from the vertical. The signals themselves come in the form of waveforms that will be analyzed.

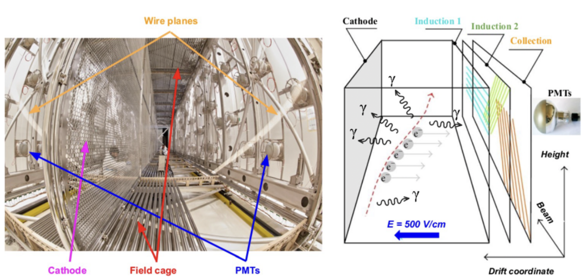

FIG. 3: Layout of ICARUS[1]

Figure 3 shows a layout of the ICARUS detector. As was previously stated, it is very similar to MicroBooNE. Two anodes with corresponding wire planes and a cathode in between them essentially create two regions with a uniform electric field in opposite directions. The photomultiplier tubes (PMTs) used to analyze the light signals produced are also worth noting.

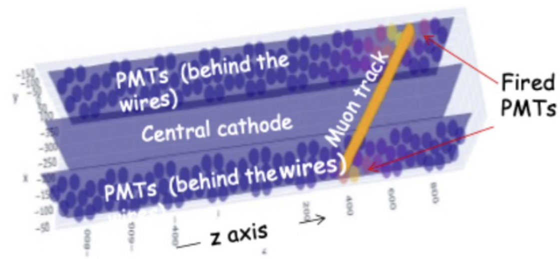

FIG. 4: Geometry of ICARUS[1]

In addition, figure 4 lays out the geometry of the ICARUS detector to give a clearer view of what will be analyzed. It is along the x-axis that most of the differences in the geometry come into play. The x-axis is perpendicular to the cathode, wire-planes, and PMTs

Even though ICARUS aims to study neutrinos, they are hard to detect. Luckily, cosmic rays exist (figure 5). Cosmic rays provide a far more convenient source of events than neutrinos. An apparent reason for this is that they fall out of the sky. Importantly, they interact exponentially more frequently with matter than neutrinos do. Therefore, there are far more cosmic ray events to study than neutrino events. So, they are a fantastic tool for analyzing the detector itself.

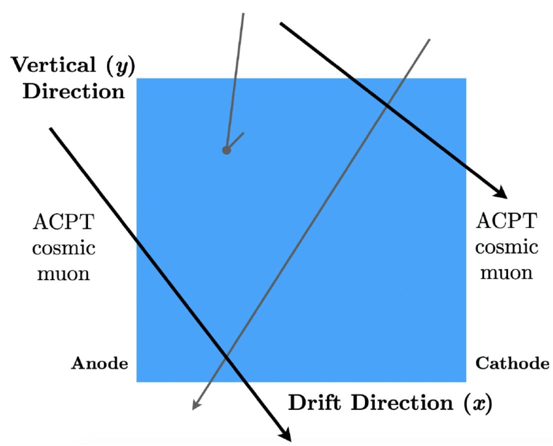

FIG. 5: Cosmic Rays in MicroBooNE[3]

IV. RESULTS

The simulation and experimental data were analyzed using ROOT and C++[4]. This data came in waveforms that passed attributes such as Amplitude and full width at half max (FWHM). Additionally, there are Gaussian fits to the signals, which come with a height and width. Therefore, we made histograms of these variables vs the positional variables of x, y, z, theta, and phi. Further, the plots are organized based on where the signal was in the detector. We organized the plots by four variables: the wire plane, the TPC (East or West), the cryostat (East or West), and whether an anode or anode was crossed (denoted selected hits). This method produced hundreds of histograms; we will only cover some of them in this paper due to sheer volume. Since it is the most important, we will look at the Amplitude of the hits vs the x variable. The complete set of plots is here.

Figure 6 shows one example of the histogram formed from experimental data. Of course, this is just one of many histograms that we made. Figure 7 shows the average Amplitude at each x point for each wire plane to understand the data better. Figures 8 and 9 show the same results but for the data from the Monte Carlo simulations. An interesting detail of this data is that one side of the detector has far more hits than the other. There are significantly more events in the negative x region than in the positive x region.

The histograms themselves are only part of the puzzle. What is important is the ratio of the experimental data histograms to the histograms derived from Monte Carlo simulations. Figure 10 shows this for all of the different parts of the detector.

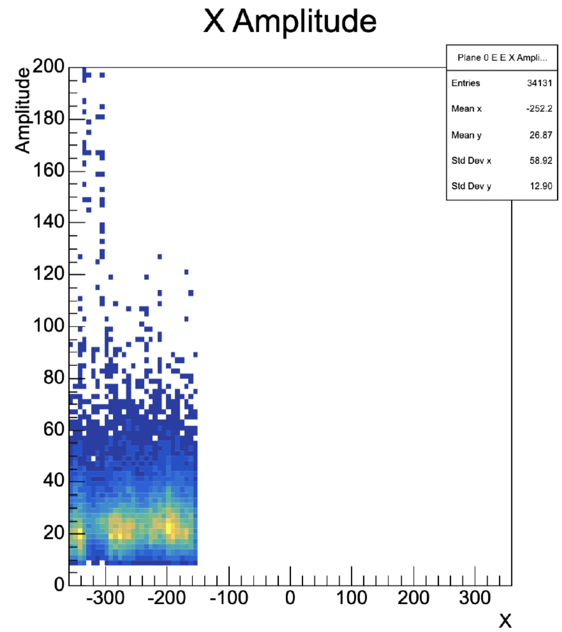

FIG. 8: 2D histogram for Monte Carlo data of X (cm) vs. Amplitude for plane 0 at TPC and cryostat East for all hits

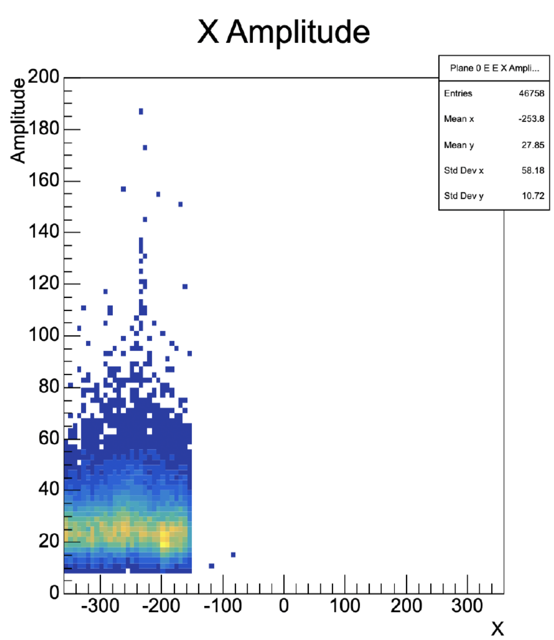

FIG. 6: 2D histogram for experimental data of X (cm) vs Amplitude for plane 0 at TPC and cryostat East for all hits

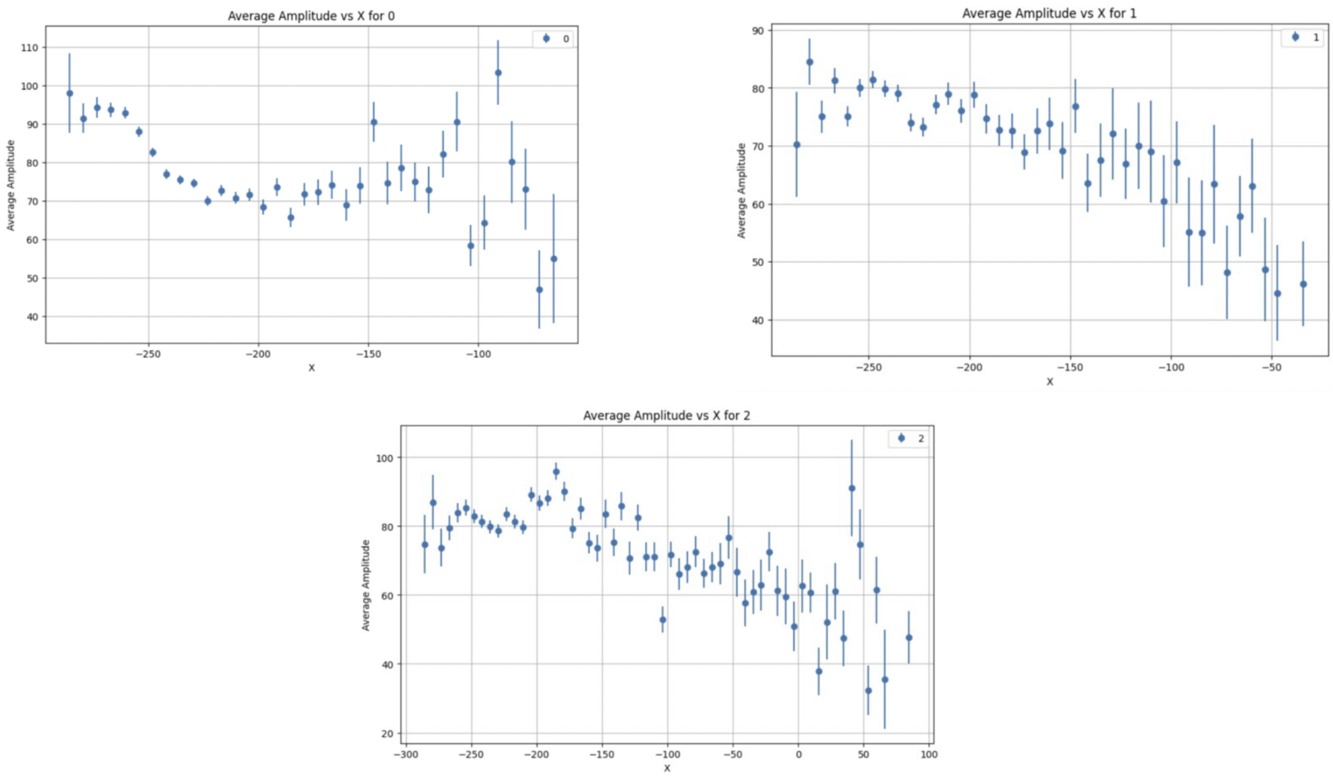

FIG. 7: X (cm) vs. Average Amplitude of experimental data for each plane

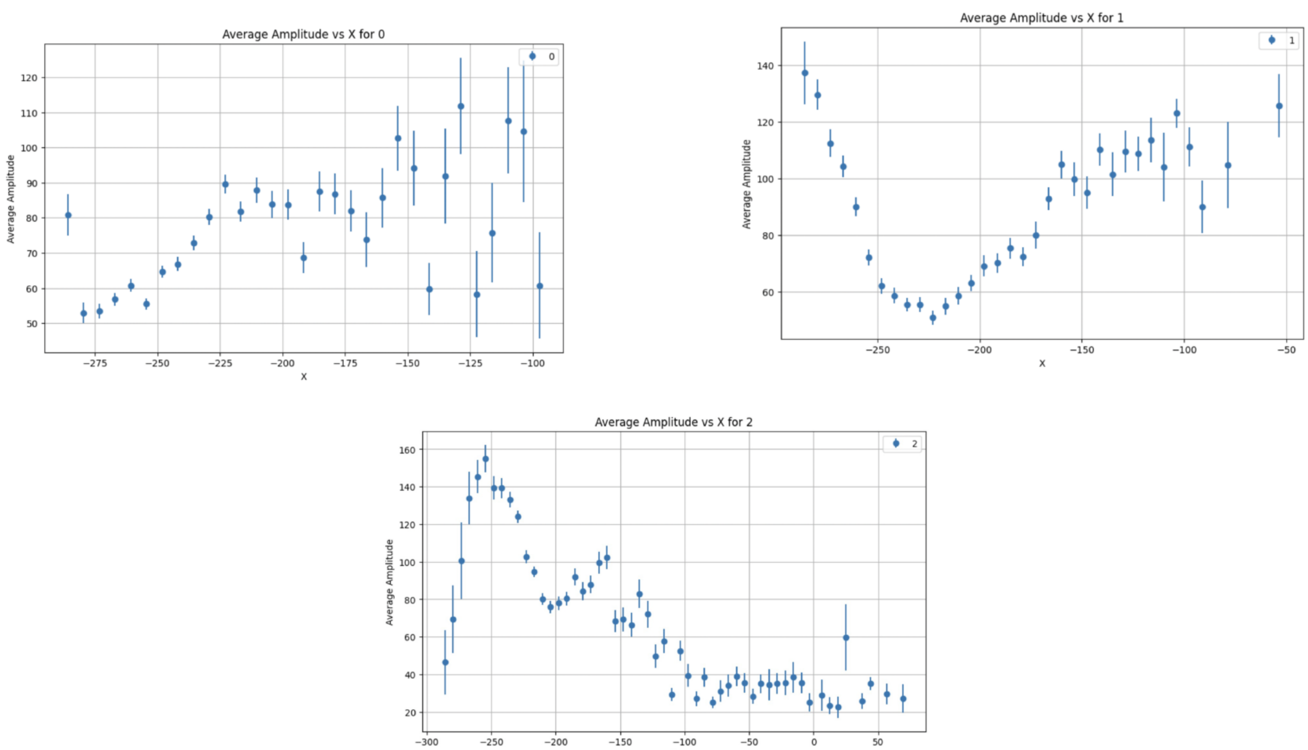

FIG. 9: X (cm) vs Average Amplitude of Monte Carlo data for each plane

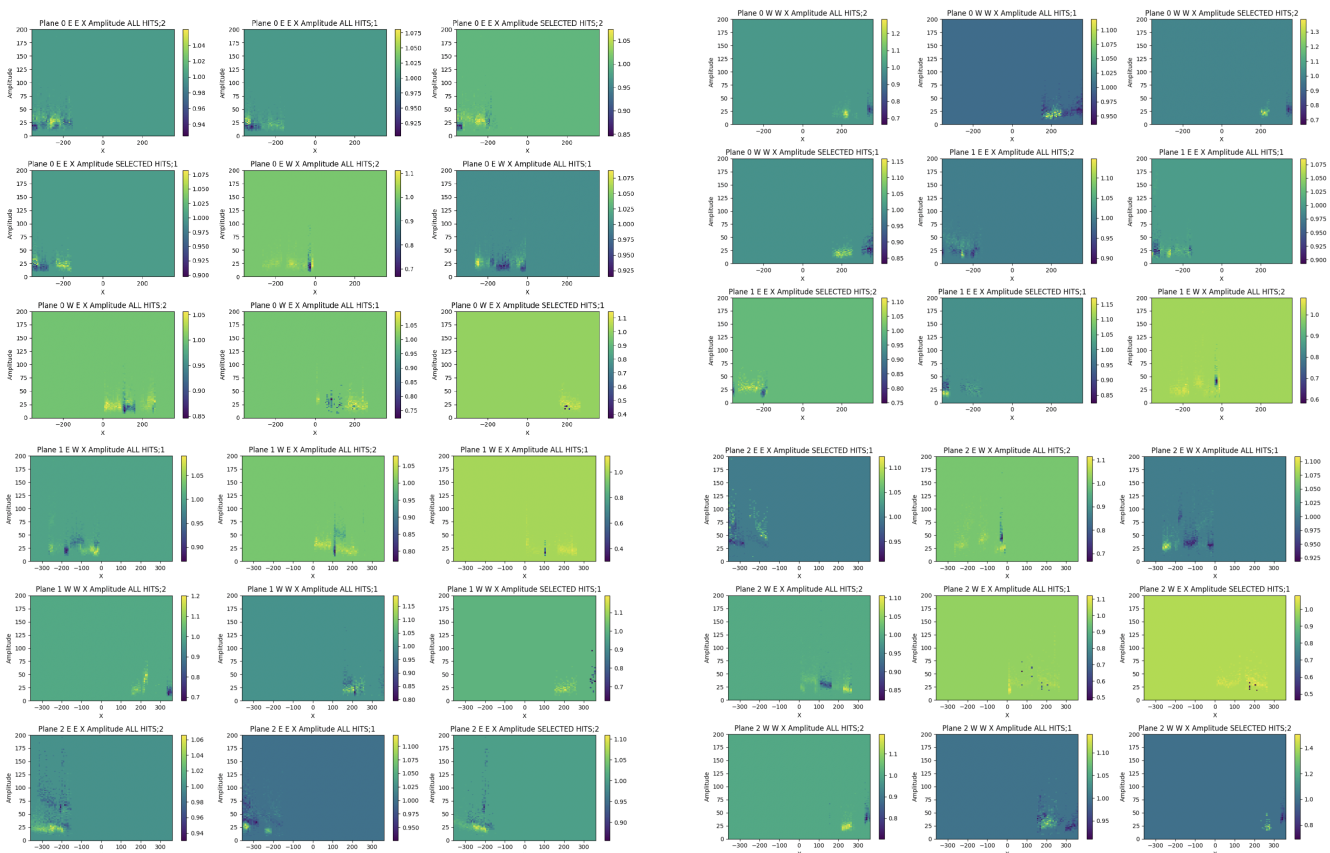

FIG. 10: 2D histograms of X (cm) and Amplitude for ratios of experimental data / MC data for each region of detector

V. CONCLUSION

The exploration into the enigmatic world of neutrinos can only be enhanced through cutting-edge research projects like ICARUS. Neutrinos, often called 'ghost particles' due to their weak interactions with matter, present a unique challenge in particle physics. This paper has underscored the importance of understanding the complexities and subtleties of neutrino detectors, mainly focusing on the ICARUS detector and its capabilities to capture the nuances of neutrino interactions.

Through detailed analysis and comparison with detectors like MicroBooNE, we have delved deeper into the uncertainties inherent in neutrino detection. Using cosmic rays as a proxy to bridge the experimental and theoretical data has opened new avenues in understanding the behavior of different components within these detectors. This approach has been crucial in elucidating the intricacies of cosmic ray detection in ICARUS, thereby enhancing our comprehension of the uncertainties and limitations of the detector.

In conclusion, the study of neutrinos through advanced detectors like ICARUS is not just a pursuit of understanding these ghostly particles but also a journey into the depths of particle physics. It challenges our current understanding, pushes the boundaries of technology, and expands our knowledge of the universe we inhabit.

[1]P. Abratenko, A. Aduszkiewicz, F. Akbar, M. A. Pons, J. Asaadi, M. Aslin, M. Babicz, W. Badgett, L. Bagby, B. Baibussinov, *et al.*, "Icarus at the fermilab short-baseline neutrino program: initial operation," The European Physical Journal C **83**, 467 (2023).

[2]M. D. Schwartz, *Quantum field theory and the standard model* (Cambridge university press, 2014).

[3]M. Collaboration *et al.*, "Novel approach for evaluating detector systematics in the microboone lartpc," Tech. Rep. (MICROBOONE-NOTE-1075-PUB. https://microboone. fnal. gov/wp-content/uploads . . . , 2020).

[4]"Sbn doxygen documentation," `https://sbnsoftware.github.io/doxygen/index.html`, accessed: 2023-12-04.