Elimination LArTPC Simulation Uncertainty With Modifications to TPC Wire Waveforms FERMILAB-PUB-24-0520-STUDENT

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This paper introduces a novel approach to reducing systematic uncertainties in LArTPC detector simulations, which arise from known detector effects that are challenging and computationally intensive to model. The proposed method involves modifying simulated waveforms based on observed discrepancies in ionization signals from the TPC between actual data and simulations. This approach reduces the sensitivity to detailed detector modeling and decreases the computational resources required for accurate simulations.

I. INTRODUCTION

Liquid Argon Time Projection Chambers (LArTPC) are extensively used to measure muons and neutrinos, providing detailed 3D imaging of particle interactions. Fast-moving particles collide with the argon, releasing electrons that drift towards the wire planes due to an applied electric field. These electrons induce current in the wires, which is measured and used to reconstruct the particle's path. LArTPCs are employed in various experiments, including the Short Baseline Neutrino (SBN) detector, which aims to study neutrino oscillations over short distances. The SBN measures neutrinos before they have time to oscillate and change flavors, offering critical insights into neutrino properties and interactions. Additionally, LArTPCs are used in nuclear physics studies and dark matter searches.

However, LArTPCs face several known effects that are difficult to model, such as electron-ion recombination, electron diffusion, and electron attenuation, all of which introduce uncertainties in signal strength and spatial resolution. The method outlined here seeks to close the gap between simulation and data caused by these effects by modifying the amplitude and width of signals on the TPC wires.

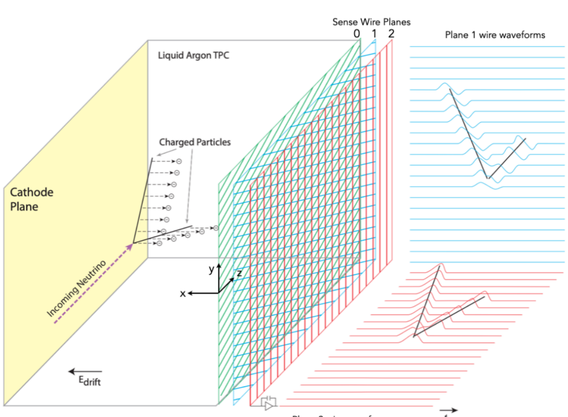

FIG. 1. A model of he MicroBooNE detector showing the 3 wire plans and the reconstructed neutrino path.

A. Background

Neutrinos are among the most intriguing and elusive particles in the universe. As leptons, they interact only via the weak nuclear force and gravity, making their interactions extremely rare. Despite their abundance, detecting and studying them is a significant challenge. Neutrinos exist in three "flavors"—electron, muon, and tau neutrinos—and have the unique ability to oscillate, or change, from one flavor to another. These particles are produced in various high-energy processes, such as nuclear reactions in stars, supernova explosions, and cosmic ray interactions in the atmosphere. Particle accelerators are another source of neutrinos.

A crucial aspect of neutrino research is understanding their masses. While neutrinos are known to have tiny masses, only the differences between these masses have been measured so far. The situation is further complicated by quantum mechanics, as the mass states of neutrinos do not align with their flavor states. This discrepancy means that when neutrinos interact, they do so in their flavor states, not their mass states, making it essential to use precise detectors to study them.

One such detector is ICARUS, which stands for "Imaging Cosmic And Rare Underground Signals." ICARUS is a Time Projection Chamber (TPC) detector that uses a uniform electric field to drift charged particles produced in neutrino interactions, creating a 3D image of their tracks. The detector is filled with liquid argon, chosen for its high density, effective scintillation properties, and stability. Liquid argon not only stops charged particles efficiently but also produces light when these particles pass through it, providing additional data on their trajectories.

ICARUS is particularly well-suited for neutrino research, as it can accurately reconstruct the paths of charged particles resulting from neutrino interactions with matter. However, ICARUS is not limited to neutrino detection; it also captures a wealth of data from cosmic rays, which are essential for understanding the detector's behavior and refining its performance.

1. Method overview

To address simulation uncertainty in Liquid Argon Time Projection Chambers (LArTPCs), we employ a method that involves modifying the waveforms of detected signals. The process begins with the digitization of waveforms from each wire, which are then divided into regions containing signals and signal-free regions. Each signal region is represented by one or more Gaussian functions characterized by peak position, integrated charge (Q), and width ().

These Gaussian functions are modified based on the properties of the simulated energy deposits matched to them. The discrepancies between observed data and simulations are quantified using data-to-simulation ratios for Q and . These ratios are applied to adjust the Gaussian functions, aligning the simulated waveforms more closely with the observed data.

Several factors are considered during these modifications, including the diffusion of the charge cloud, the attenuation of electrons by impurities, and electric field distortions caused by non-responsive or cross-connected wires. Additionally, the angular orientation of particle trajectories relative to the wire planes is taken into account, as it affects the accuracy of signal modeling.

Post-deconvolution wire waveforms are characterized by Gaussian fits, referred to as "hits," which measure the integrated charge (Q) and width () of the waveform. These hits serve as the basis for modifying the underlying waveforms to better reflect the observed data.

This method is designed to be independent of the downstream reconstruction and analysis chain, as well as the upstream detector simulation model. By considering variations in the detector's response related to different physical and geometric factors, it addresses systematic uncertainties effectively. The result is a reduction in discrepancies between simulated and actual data, leading to more accurate simulations with reduced computational requirements.

II. OUTCOME

Initial comparisons between the detector data, simulation, and the modified simulation indicated that the modification inadvertently increased the discrepancy between the simulation and the observed data. This issue was traced back to a bug in one of the C++ modules responsible for calculating the scaling ratio. As shown in Figure 2, there is a noticeable peak in hits around a hit width of 3.333 and 6. The modification overcompensated for the peak at 3.333 while under compensating for the peak at 6. Despite these specific discrepancies, the modification did seem to better align with the overall shape of the data. However, the chi-squared value for the unmodified simulation was 437.960221, whereas the value for the modified simulation increased to 504.922767. This suggests that the modification, contrary to its intended purpose, made the simulation less consistent with the actual data.

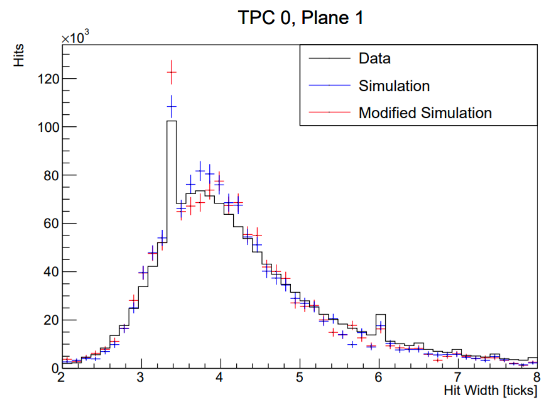

FIG. 2. A plot of sample data from East side SBN detector's first TPC's second wire plane (ref figure 1 for plane), simulated data of the same event, and the modifed simulation (ref legend for colors).

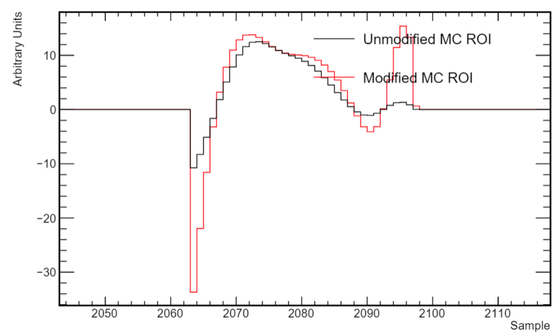

FIG. 3. A plot of sample data from East side SBN detector's first TPC's second wire plane (ref figure 1 for plane), simulated data of the same event, and the modifed simulation (ref legend for colors).

III. FUTURE WORKS

As discussed in Section II, further refinement of the modification algorithm is necessary. Figure 3 presents a simulated signal on a representative TPC wire, where the modified signal exhibits excessive amplitude near the extremities, while appearing more accurate in the central region. This issue is currently being addressed by resolving the error identified in Section II. Following these corrections, additional datasets and simulations will be utilized to re-calibrate the modification ratios. The anticipated outcome is an enhanced modification algorithm that will significantly improve the alignment between simulation and observed data and reduce modeling uncertainty.

IV. ACKNOWLEDGEMENTS

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V. APPENDIXES

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