Examining ICARUS Cosmic Muon Signal Shapes

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In the search for new physics, such as sterile neutrinos, we must compare our experimental data to the null hypothesis, which is provided by simulations. However, our detectors and simulations are not perfect, so we need to be able to differentiate imperfections in our simulations, detector effects, and unknown unknowns from new physics. Thus, we need to quantify ICARUS detector systematic uncertainties. To calculate this uncertainty, we study the signals, or waveforms, produced in ICARUS by cosmic muons. Ideally, we want to fit these waveforms as Gaussians and compare the fits from experimental data to fits from simulations to calculate the uncertainties, but first, we need to know how accurately these curves can be described by Gaussians. We examined the peak and the full width at half maximum (FWHM) of signals from simulations, and we produced plots of the distribution of peaks and FWHMs for these signals. We further studied how the peaks and FWHMs varied depending on where the signal came from in the detector. Ultimately, by comparing the actual distribution of peaks and FWHMs to the distribution predicted by the Gaussian fits, we hope to determine how accurately Gaussians can represent these waveforms.

I. INTRODUCTION

In the search for new physics, such as the existence of sterile neutrinos, physicists must compare experimental data to the null hypothesis, which is typically provided by simulations. However, it can be challenging to determine whether differences between experiments and simulations are due to new physics or other effects. These simulations are not perfectly accurate, and detector effects contribute to the results from experiments. Physicists need to be able to differentiate imperfections in our simulations, detector effects, and unknown unknowns from new physics, and thus, when studying the results produced by the ICARUS detector, they need to quantify the detector systematic uncertainties.

Since neutrinos may follow unknown physics, we hope to quantify ICARUS detector systematics by studying cosmic muons, which are muons produced in the atmosphere by cosmic rays. Since these muons are very well understood, we know that they do not follow any new physics, so any difference we see between experimental data and simulations for cosmic muons must be due to the detector systematics. From the simulation side, we use Monte Carlo simulations, or simulations that rely on random sampling, to model how cosmic muons are detected by ICARUS and determine the distribution of subsequent signals they produce.

II. COSMIC MUON WAVEFORMS

ICARUS is composed of four liquid argon time projection chambers (LArTPCs), referred to West West, West East, East West, and East East (WW, WE, EW, EE). These chambers are constantly showered with cosmic muons. When a muon passes through the detector, it ionizes the liquid argon, sending out a flurry of electrons. Due a static electric field, the freed electrons all drift to one side of the chamber, where they pass through three parallel planes of wires. As the electrons move past these wires, they induce a current, and each of these planes of wires is oriented at an angle such that, combined with time measurements, the signals produced in the wires can be used to reconstruct the location of the muon's interaction and its energy loss. Since the muon continuously frees electrons as it moves through the LArTPC, this procedure can be used to fully reconstruct the muon's trajectory and energy loss as it moves through the detector.

The signals produced in the wires by the passage of the electrons are called waveforms. To illustrate the basic ideas behind how ICARUS functions, Fig. 1 shows a model of the MicroBooNE detector and how wire waveforms are created; ICARUS produces waveforms using the same principles, but it has four LArTPCs instead of

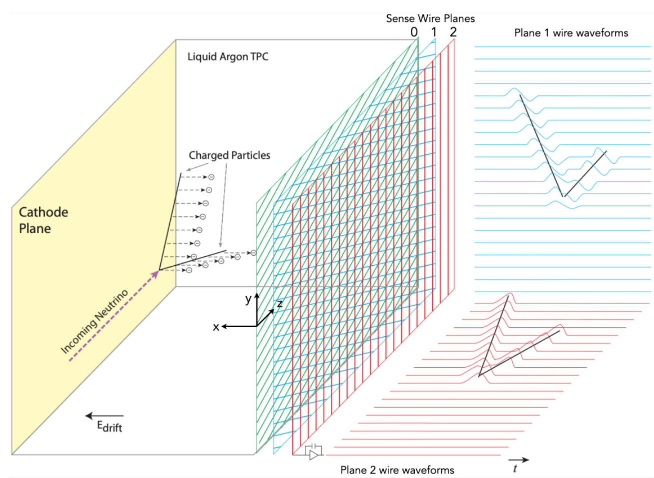

FIG. 1. Model of MicroBooNE detector and how wire waveforms are produced [1]. ICARUS detector functions in a similar fashion, but with four of these LArTPCs instead of one.

one. Another important note is the existence of cathode and anode planes. To be able to reconstruct the x position of a muon, the total time taken by the muon's trajectory must be known, so since at least one measurement of the muon's x position and time is necessary, the muon must cross either the cathode or anode plane for its x position to be reconstructed. Some examples of muon trajectories, or tracks, that successfully cross an anode or a cathode plane are shown in Fig. 2.

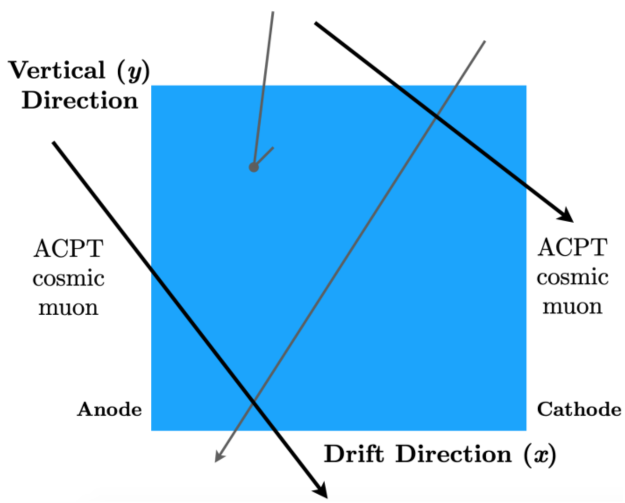

FIG. 2. Image of tracks that pierce the anode or cathode (in black) or tracks that pierce neither (in gray) [1].

III. WAVEFORM SHAPE DISTRIBUTIONS

To calculate the systematic uncertainties for the ICARUS detector, we planned to compare cosmic muon waveforms from experimental data to those from Monte Carlo simulations. However, first we needed to determine the best way to fit and compare these waveforms. As explained in [1], the MicroBooNE collaboration developed a novel approach for evaluating detector systematics. The members of this collaboration began by looking at the deconvoluted waveforms produced by cosmic muons that had anode/cathode piercing tracks (ACPTs). They fit both the data and simulation waveforms as Gaussians, and they describe each Gaussian using two parameters: the standard deviation and the area under the curve, called the integrated charge.

By comparing simulation and data waveforms and taking averages of these Gaussian parameters at each point in the detector, they obtain a set of modified Gaussians. These modified Gaussians are used to scale the simulation waveforms at each point in the detector so that the simulation waveforms more closely resemble the data waveforms. The simulation waveforms are modified in this way because it is too computationally expensive to produce simulations that more accurately match the data, so modifying the simulation waveforms using experimental data is a cheaper and faster alternative that can be utilized to capture detector effects in simulations.

These modified waveforms can then be compared with another previously untouched set of cosmic muon waveforms produced by simulations. Since the physics of cosmic muons is well understood, the difference between these sets of waveforms cannot be due to new physics, and thus, it is a direct result of the detector systematics. Therefore, by comparing the modified waveforms with the nominal simulation waveforms, they can quantify the detector systematic uncertainties in MicroBooNE measurements. Once these uncertainties have been computed, they can be applied to neutrino experiments, such as in the neutrino energy reconstruction plots.

Evidently, this procedure developed by the MicroBooNE collaboration assumes that the deconvoluted waveforms can be accurately fit as Gaussians. Our project's main goal was to determine the validity of this assumption before applying this procedure to ICARUS. In other words, we attempted to determine how accurately ICARUS cosmic muon waveforms can be fit by Gaussians and what role detector geometry plays in shape of waveforms.

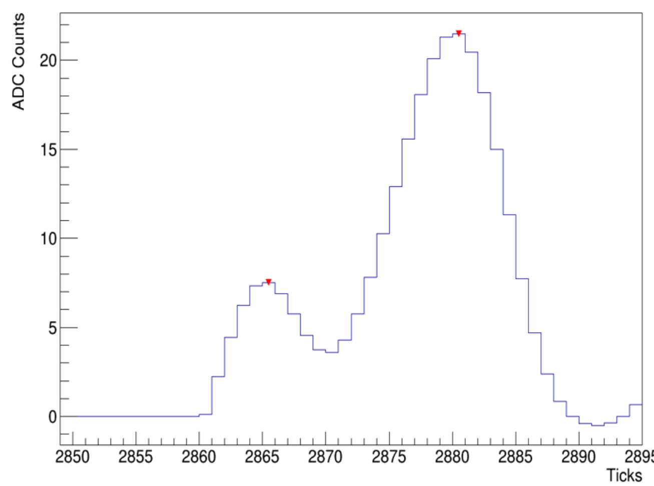

FIG. 3. Cosmic muon waveform after deconvolution, produced by Monte Carlo simulations.

To determine this, we studied waveforms produced by Monte Carlo simulations after the raw signal has been deconvoluted into a waveform depicting ADC counts, which can be thought of as a measure of the current in the wire, as a function of time. Examples of waveforms after deconvolution can be seen in Fig. 3 and 4. These waveforms could theoretically be fit with n Gaussians, where n is the number of peaks, but to start with, we chose to focus on waveforms with only a single peak, such as the ones shown in Fig. 5 and 6. For each of these waveforms, we found their peak and FWHM, and to see how these values varied, we plotted the distributions of peaks and FWHMs, as shown in Fig. 7 and 8 respectively. To determine how accurately Gaussians fit these waveforms, we must compare the distributions of peaks and FWHMs

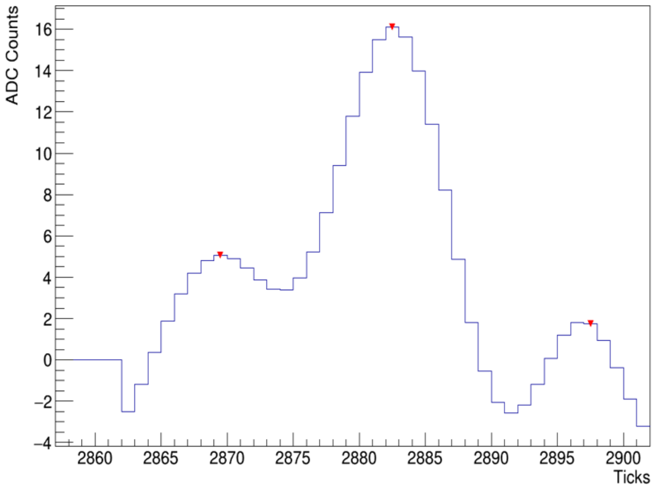

FIG. 4. Waveform with multiple peaks, produced by Monte Carlo simulations.

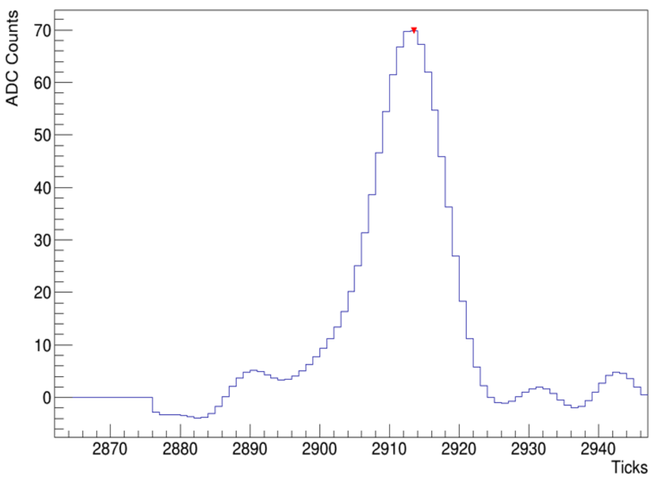

FIG. 5. Waveform with a single peak, produced by Monte Carlo simulations.

of the waveforms to the distributions of the peaks and FWHMs of the Gaussian fits, and if these waveforms actually are well described by Gaussians, then the two sets of distributions should closely match.

IV. DETECTOR GEOMETRY

Before looking at the distribution of peaks and FWHMs for the Gaussian fits, we instead chose to characterize these quantities across the detector geometry and see how the peak and FWHM of waveforms depend on the location of the hit in the detector. The goal of this project was to check how accurately Gaussians described these waveforms, but the answer might depend on the location of hit. Perhaps waveforms from certain regions of the detector look more like Gaussians than those from other regions.

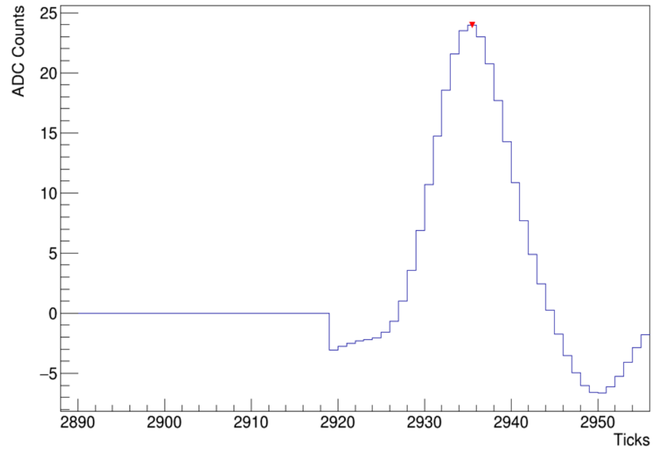

FIG. 6. Waveforms with a single peak, produced by Monte Carlo simulations.

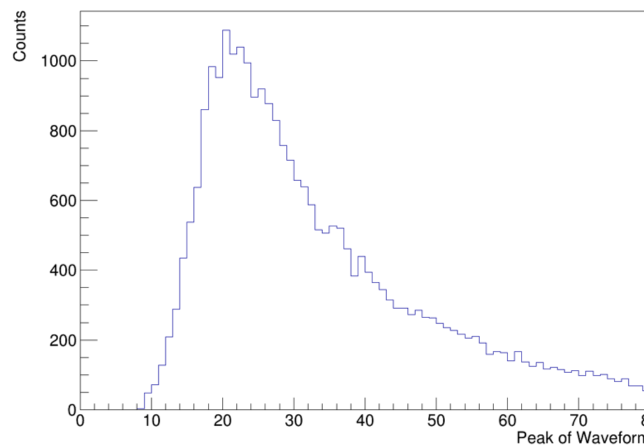

FIG. 7. Plot of peak distribution for waveforms with a single peak, where the waveforms were produced by Monte Carlo simulations.

To investigate the role that the detector geometry plays on the shape of the waveforms, we produced 2D histograms that showed how the distribution of peaks and FWHMs depended on position of the hits. For example, Fig. 9 and 10 depict how the peaks and FWHMs depend on the y position of the hits, and Fig. 11 and 12 depict how they depend on the x position of the hits. As shown in Fig. 11, we noticed that many waveforms had FWHMs around 15 and 25, but very few had FWHMs around 20. To discover why this trend is occurring, we looked at waveforms with FWHMs of 15 or 25, but we did not notice anything unique about these waveforms. Thus, we shifted our focus to ACPTs.

Previously, we had not restricted the waveforms we were studying to be from ACPTs. However, in order to reconstruct the x position of the hits from experimental data, the tracks must be ACPTs, for since the x position is a function of the total drift time, the position of the muon at a known point in time needs to be measured.

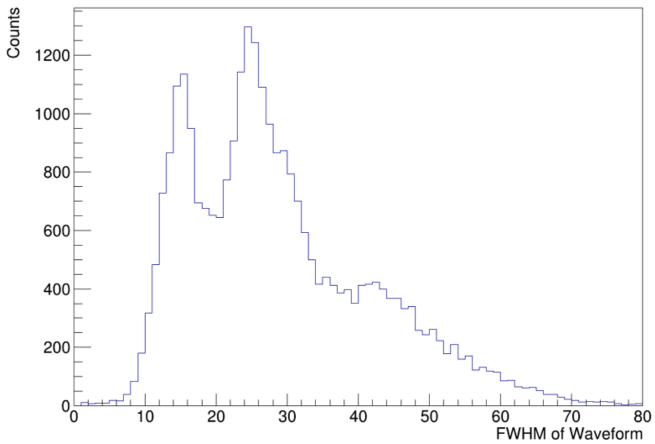

FIG. 8. Plot of FWHM distribution for waveforms with a single peak, where the waveforms were produced by Monte Carlo simulations.

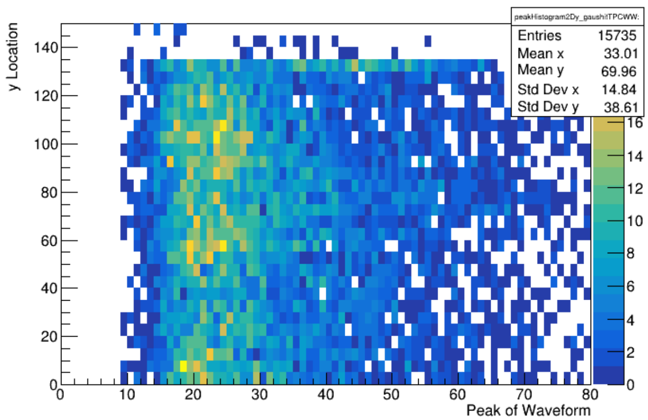

FIG. 9. Distribution of waveform peaks and y positions of the corresponding hits, for hits in the WW chamber.

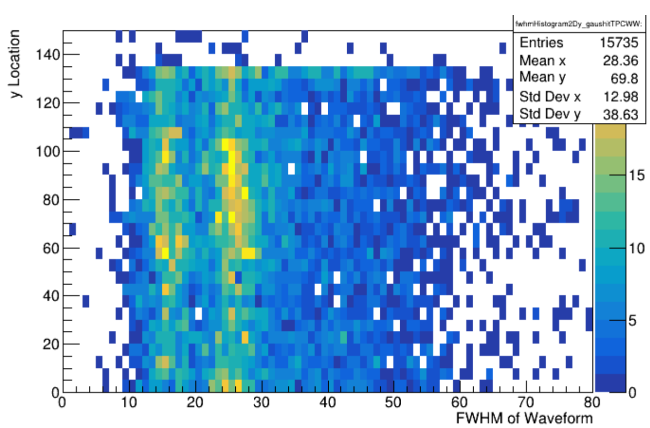

FIG. 10. Distribution of waveform FWHMs and y positions of the corresponding hits, for hits in the WW chamber.

Thus, we investigated how the x positions of hits varied for ACPTs in each of the LArTPCs, and in Fig. 13, 14,

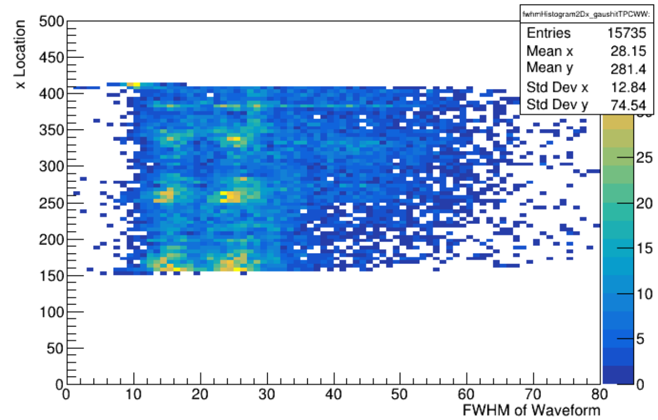

FIG. 11. Distribution of waveform peaks and x positions of the corresponding hits, for hits in the WW chamber.

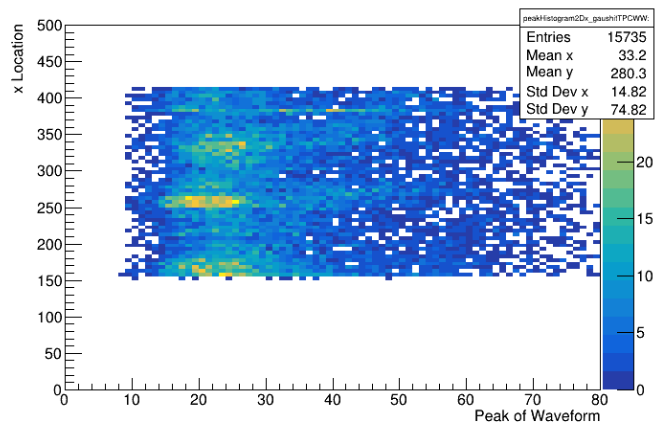

FIG. 12. Distribution of waveform FWHMs and x positions of the corresponding hits, for hits in the WW chamber.

15 & 16, we plotted the distribution of the x position of hits in ACPTs in the WW, WE, EW, & EE chambers, respectively.

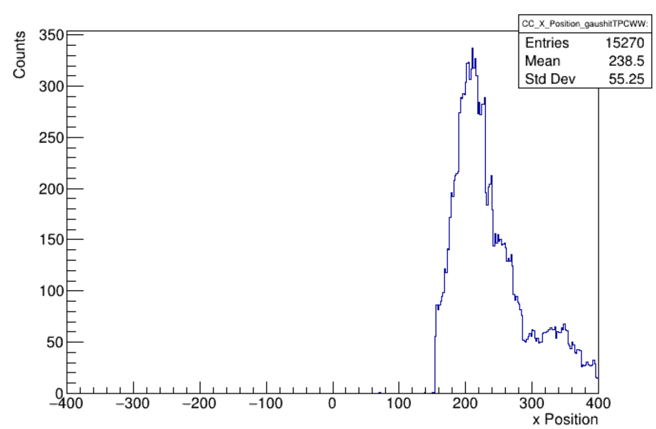

FIG. 13. Distribution of x position of hits in ACPTs in WW chamber.

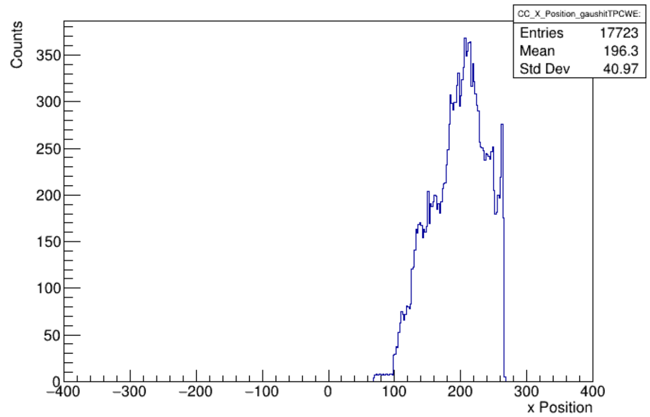

FIG. 14. Distribution of x position of hits in ACPTs in WE chamber.

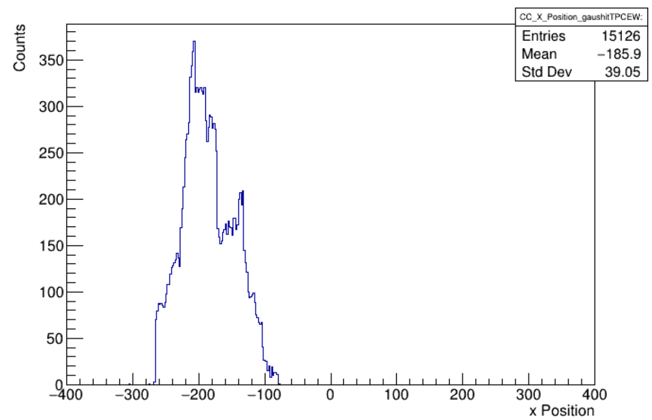

FIG. 15. Distribution of x position of hits in ACPTs in EW chamber.

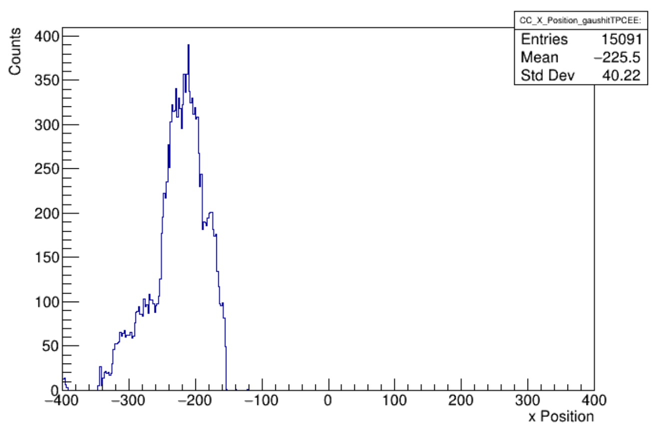

FIG. 16. Distribution of x position of hits in ACPTs in EE chamber.

V. DISCUSSION

We studied how cosmic muons interact with the ICARUS detector and produce waveforms that can be used to reconstruct their path and energy loss. Using data sets of deconvoluted waveforms produced by Monte Carlo simulations, we determined the peak and FWHM for each waveform, and we plotted the distributions of peaks and FWHMs in each LArTPC for various data sets. To better understand the detector geometry, we produced histograms that illustrated how the distributions of peaks and FWHMs depended on the location of the hits. Finally, we investigated tracks that crossed either the cathode or anode plane, and we created histograms that illustrated the distribution of the x position of hits in such tracks.

The overarching goal of this project was to determine how accurately cosmic muon waveforms can be represented by Gaussian fits, and all of this investigation into peak and FWHM distributions and the effects of detector geometry is the first step in calculating the detector systematic uncertainties. Next, we must perform this same analysis and investigation into the distributions of the Gaussian fits, and only by comparing how well, and for what regions, the distributions of the waveforms and the Gaussian fits match can we answer our guiding question.

Regardless of the outcome of this study, there is further work to be done. If the Gaussian fits do a poor job of describing the cosmic muon waveforms from simulations, then we must investigate alternative fitting functions to Gaussians, repeat this work, and discover whether other functions can represent the waveforms better than Gaussians. If the Gaussian fits do an excellent job of describing the waveforms, then we can continue following the procedure developed by the MicroBooNE collaboration in [1] to finally determine the detector uncertainties. In either case, our work has completed the first steps necessary to calculate the ICARUS detector systematic uncertainties.

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[1] Abratenko et al., "Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data," *The European Physical Journal C*, Vol. 82, No. 5, May 2022.