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Comparing CRT and Pandora Tagged Tracks in ICARUS

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Abstract

The ICARUS Liquid Argon Time Projection Chamber (LArTPC) is used to investigate short-baseline neutrino oscillations and the possible existence of sterile neutrinos. To aid in identifying and rejecting cosmic ray backgrounds, the system is outfitted with external Cosmic Ray Taggers (CRTs). The CRT is able to measure more tracks and at a wider range of angles, useful in further detailing future calibrations. This project compared the most probable values (MPVs) of charge deposition between CRT tagged and TPC tagged tracks. The Y-Z maps of charge scale for both datasets show a strong correlation, not just in their overall structure, but also in how they reflect known detector effects. Both reconstruction paths showed similar structures in their charge distribution, such as less effective wire section or mechanical support, confirming that CRT-tagged tracks, despite being external, respond to the same calibration landscape as Pandora tracks, validating previous Pandora reconstructions and values. Overall, the analysis supports the idea that the CRT tags are a useful addition to ICARUS calibration efforts. Their broad angular range and independence from Pandora reconstruction make them a helpful secondary tool and a potential asset in extending calibration across the detector volume.

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1 Introduction

1.1 Understanding the ICARUS Detector

ICARUS is a liquid argon time projection chamber (LArTPC) designed to investigate short-baseline neutrino oscillations and the possible existence of sterile neutrinos. Originally constructed at the Gran Sasso Laboratory in Italy, the detector was later transported to Fermilab, where it now serves as the far detector in the Short-Baseline Neutrino (SBN) program. Positioned 500 meters downstream of the near detector SBND, ICARUS receives neutrino beams from two neutrino beams: the Booster Neutrino Beam (BNB), which ICARUS is on-axis to, and the Neutrinos at the Main Injector (NuMI) beam, which ICARUS is 5.7° off-axis to.

The detector itself is made up of two adjacent cryostats, each holding two LArTPCs. When a neutrino interacts within the liquid argon, it produces charged particles that ionize the argon atoms along their trajectories. An electric field, generated between a central cathode and the anode planes on the sides, causes the freed ionization electrons to drift toward the anode. Each TPC has three wire planes spaced 3 mm apart, with individual wires also spaced 3 mm from one another: a front induction plane, a middle induction plane, and a collection plane. The front induction plane wires lie along the horizontal, with the middle induction and collection plane wires ±60° to the horizontal, depending on the TPC. As electrons pass by or hit these wires, they induce signals that are recorded and later used to reconstruct the original particle trajectories and energies.

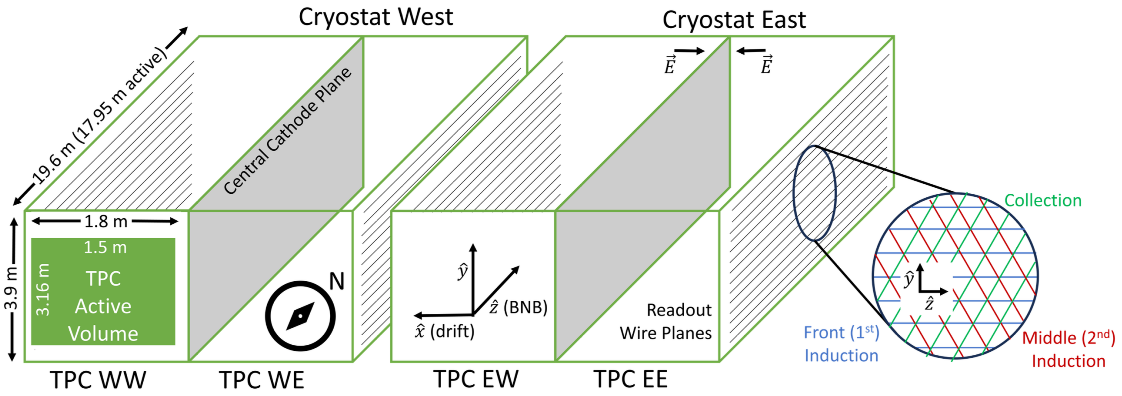


Figure 1: A diagram of the TPC structure of ICARUS, including wire planes, axes, and electric field information [2]

Surface-level detectors like ICARUS receive a significant background of cosmic rays, which interfere with beam neutrino interaction measurements. To aid in identifying and rejecting cosmic ray backgrounds, the system is outfitted with external Cosmic Ray Taggers (CRTs). While the CRT system has some small coverage gaps, these are well-characterized and accounted for during data reconstruction. Cosmic muons passing through the CRT panels produce scintillation light, which is detected by silicon photomultipliers. This provides precise timing and position information, which is then matched to TPC signals. The correlation between CRT and TPC data allows for improved event reconstruction and calibration, a topic explored in more detail in the analysis section of this report.

1.2 Calibrations

Accurate calibration is critical to extracting meaningful physics from the ICARUS Liquid Argon Time Projection Chamber (LArTPC). Calibrations correct for both electronic and physical non-uniformities in the detector response, ensuring consistency across all four TPCs. Without these corrections, various distortions can degrade the reconstruction of particle tracks and their energies. This section summarizes the calibration improvements applied to Run 2 data (taken from December 20th, 2022 to July 14th, 2023) in order to address these challenges in past and future data.

One key calibration involved correcting the electronics response, which varies across the readout system and among groups of 64-channel cables. This was done through test pulse runs, where known charge pulses were injected into each wire channel. By comparing the injected signal to the recorded output, the gain and shape of each channel's response were measured. These measurements allowed the raw signals to be normalized during reconstruction, making signals comparable across all wires. In addition, the slightly varying baseline voltages of each channel were measured in empty runs and then subtracted from the raw waveforms to find the true ionization signal.

Another crucial improvement involved 2-D signal deconvolution, which corrected for distortions in both time and space. Charge deposited by a particle can spread across adjacent wires and time, especially due to drift effects or induction between wires. While previous calibrations only involved temporal deconvolution, the 2-D deconvolution mathematically removed both these effects, recovering the original shape of the ionization signal and improving both temporal and spatial resolution [1].

Every calibration adjusts the reconstructions found from ICARUS, drawing the measured data closer and closer to its true ionization signal. Precise analyses are imperative to advancing the world of physics, so experimental methods must keep advancing.

1.3 Motivation

It is necessary to constantly improve and add to calibrations for any detector, especially one with many non-uniformities like ICARUS. In this pursuit, including the CRT as well as the TPCs in tagging tracks serves two purposes. First, comparing the MPV values of two independent systems in the same detector effectively tests the accuracy of the previous calibrations, such as those discussed previously for the TPC. Additionally, the CRT adds the ability to measure more tracks and at a wider range of angles, useful in further detailing future calibrations.

The broad focus in this project was to create maps of the MPVs of the Y-Z plane of the detector through both Pandora and CRT tagged tracks, where Pandora is the reconstruction software used for the TPC. Utilizing the data from run 2, we attempted demonstrate the calibration potential of comparing these two tracks. This project requires an extensive view of various characteristics, patterns, and differences between values measured in the experiment. Differences in structure or bias can greatly affect the results and are important to analyze for an accurate construction.

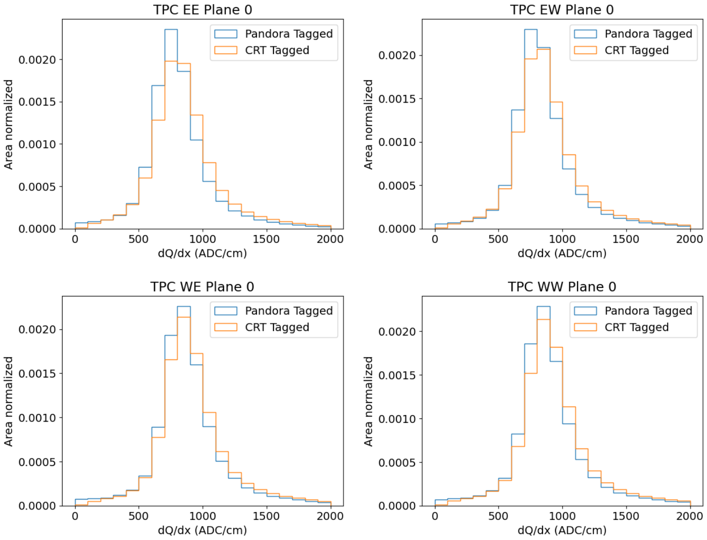
2 Data Analysis

Several aspects of the analysis process need to be clarified to better understand the results that follow. In this section, Planes 0, 1, and 2 refer to the front induction plane, middle induction plane, and collection plane, respectively. The TPCs in ICARUS are labeled EE, EW, WE, and WW, which designate the east or west cryostat and the east or west TPC within it [1]. Throughout this section, the graphs compare the normalized charge area (rather than total hit counts) of CRT and Pandora tagged tracks. This normalization makes it easier to observe structural similarities and differences in how charge is collected.

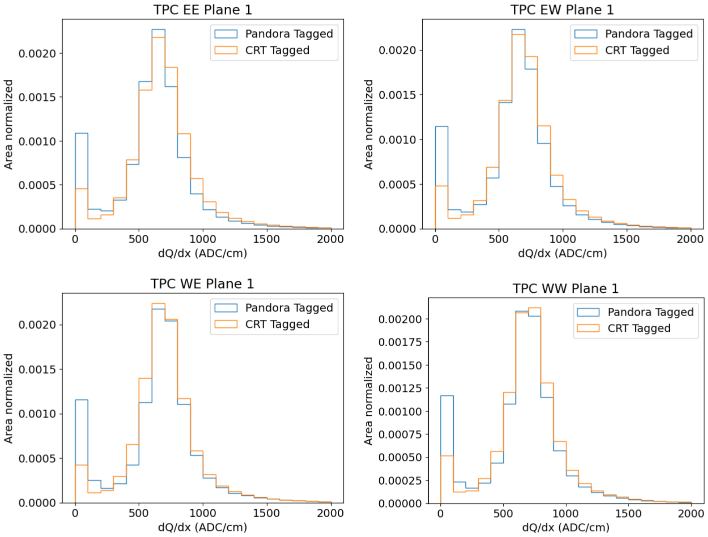
Both the CRT and TPC systems have differing geometric and operational biases that appear clearly in the distributions. The CRT, a largely horizontal array, prefer to record more vertical cosmic muons perpendicular to its plane, while the TPCs are more sensitive to horizontal tracks perpendicular to the cathode. These preferences show up across many observables and must be considered when interpreting the charge maps and distributions.

2.1 Distributions

(a) Front Induction Plane



(b) Middle Induction Plane



(c) Collection Plane

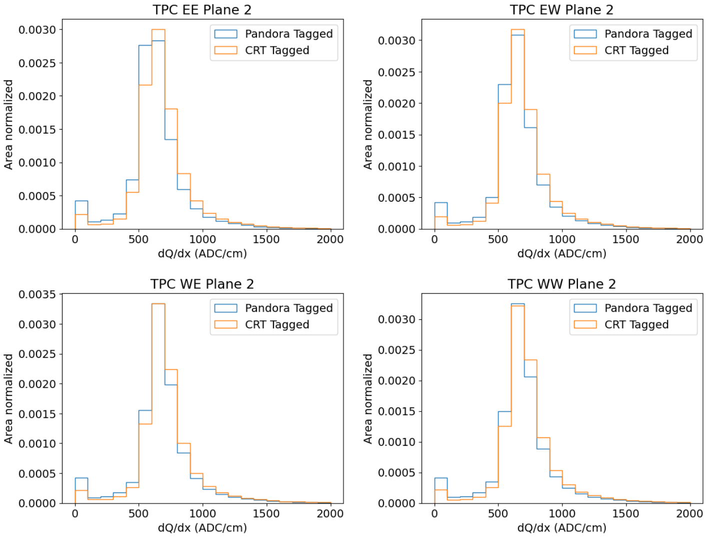
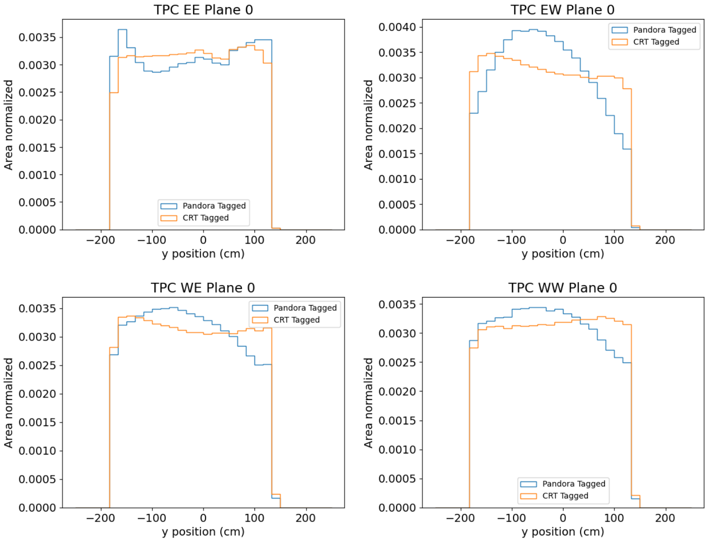
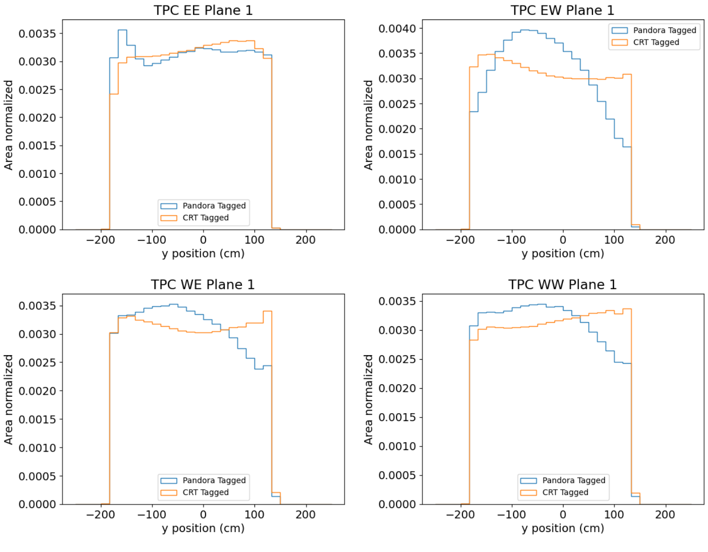


Figure 2: Normalized CRT and Pandora dQ/dx distributions

(a) Front Induction Plane



(b) Middle Induction Plane



(c) Collection Plane

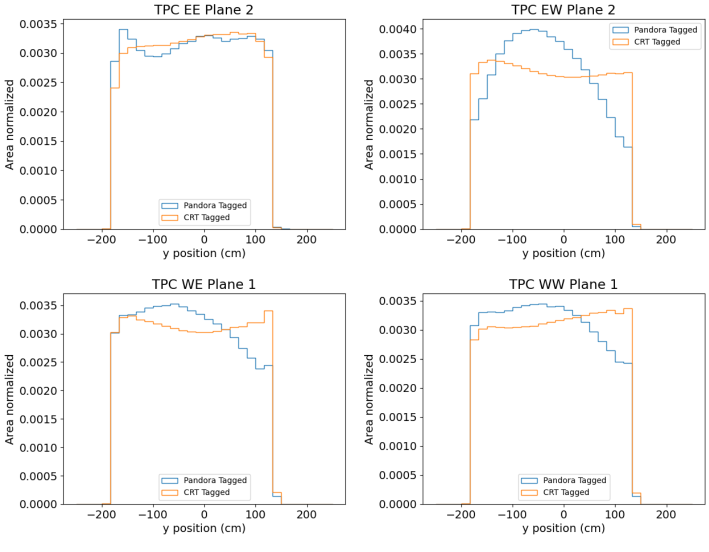
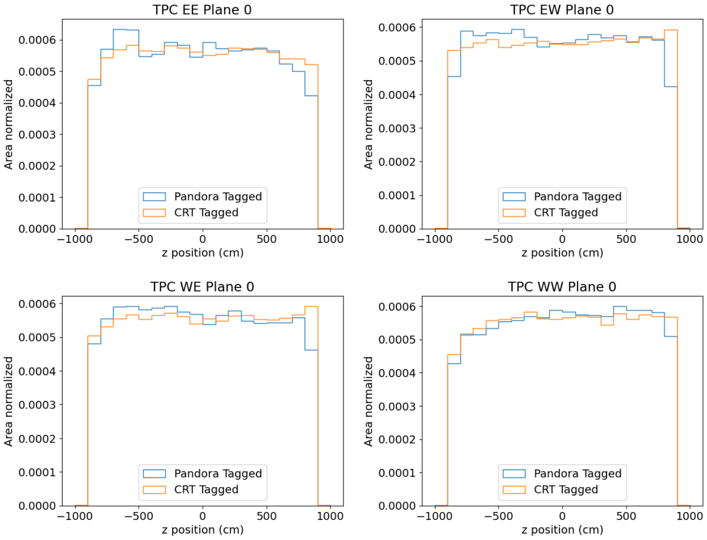
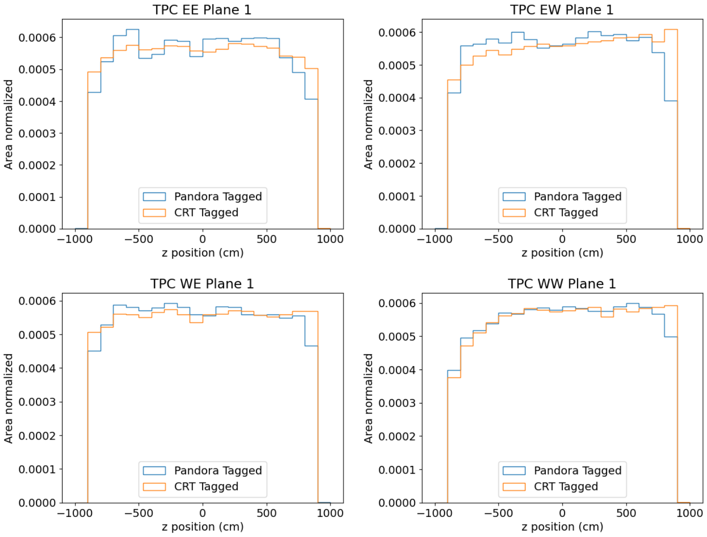


Figure 3: Normalized CRT and Pandora y position distributions

(a) Front Induction Plane



(b) Middle Induction Plane



(c) Collection Plane

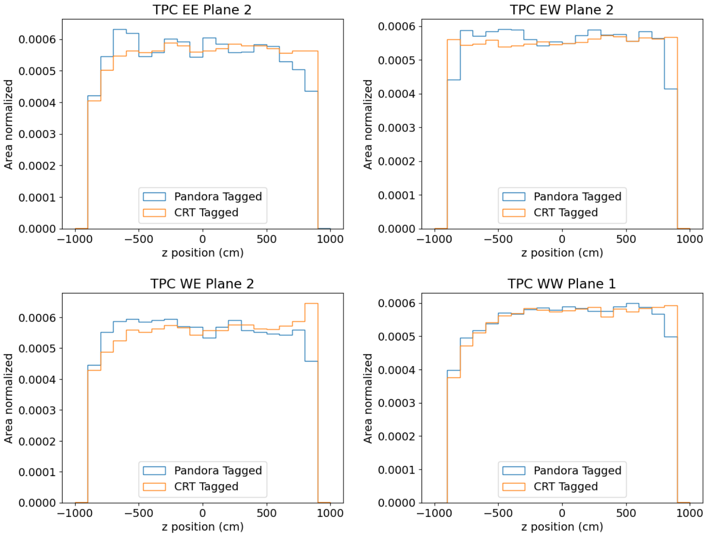


Figure 4: Normalized CRT and Pandora z position distributions

This project analyzed several properties of particle tracks across all TPCs and planes, including dQ/dx, spatial position (x, y, z), and directional components. Due to the large number of resulting distribution plots, only the most relevant to the construction of Y-Z maps are included here. The dQ/dx distributions show how the basic charge deposition behavior within the detector, while the y and z position plots help identify where in the detector these deposits are most common.

By comparing distributions from CRT tagged and Pandora tagged tracks, we were able to examine how well the systems align and whether observed differences are physical or systematic. Notably, many small-scale non-uniformities are caused by detector structure or electronics rather than true differences in the datasets.

Figure 2 shows the distribution of dQ/dx (in ADC/cm), a measure of ionization per unit drift length (in ICARUS, the x direction). The CRT and Pandora data show strong agreement in structure, with small magnitude differences reflecting angle-dependent biases. There are a few notable differences between planes. For example, the spikes near 0 ADC/cm are due to differing hit thresholds across planes, with the lowest threshold in the middle induction plane and highest in the front. The broader peak in the front induction plane is likely due to worse charge resolution, which spreads the signal more.

In Figure 3, we see the y position distribution of hits. Both CRT and Pandora tracks show very similar shapes, but Pandora hits are noticeably peaked around y = 0. This aligns with the TPC bias toward horizontal tracks, which pass closer to the detector's middle.

Figure 4 represents the distribution of the z positions of particles measured by the detector. The z detector's large range of positional data seems to be fairly consistent along the plane, as well as mostly consistent between the CRT and Pandora data.

2.2 Y-Z Maps

The Y-Z maps are essential for revealing both the detector's charge response and how well the CRT and Pandora systems align. To construct these maps, we first calculated the dQ/dx Most Probable Value (MPV) in each Y-Z bin using a Landau-Gaussian fit. Then, we normalized the MPVs by dividing them by the average MPV across the detector, resulting in a relative charge scale map. This highlights variations in charge deposition across the planes and makes spatial irregularities stand out clearly.

Mapped over these charge distributions are physical features of the detector that may impact the response, such as mechanical supports and the boundaries between wire flange sections in the induction and collection planes. These structures are important because they can introduce small but consistent effects to the signal readout.

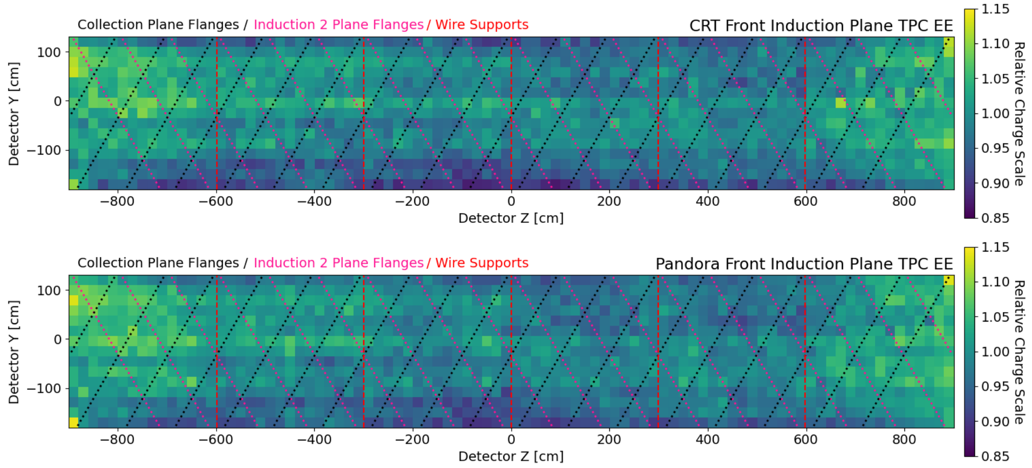
The relative charge maps for CRT and Pandora-tagged tracks show a strong correlation, not just in their overall structure, but also in how they reflect known detector effects. Both tagging methods highlight the same regions of increased or decreased response, especially around detector edges or transitions between wire groups. This agreement between two completely independent systems suggests that the underlying calibration is working very well, and that real detector features are being consistently measured. It also shows that CRT tagged tracks can be a viable tool for calibration, validating previous Pandora reconstructions and values.

2.3 Outlier Positions

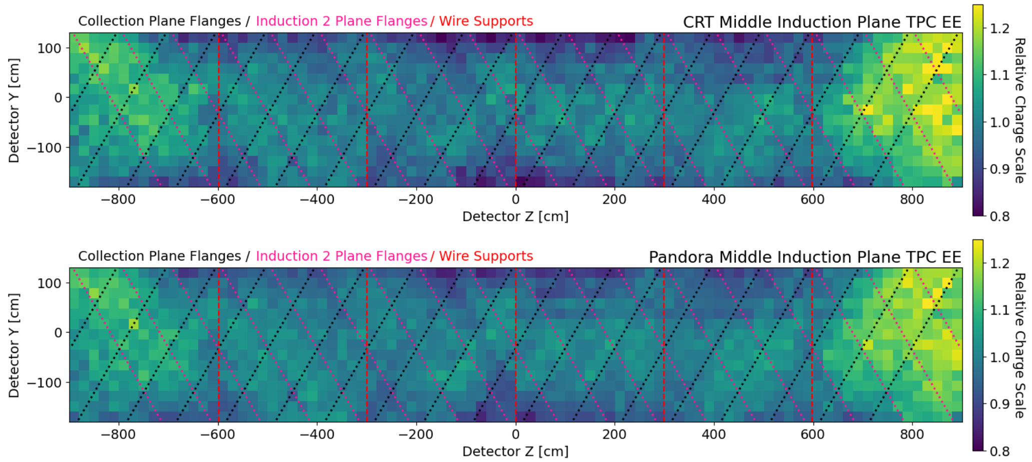
While the MPV maps from CRT and Pandora are highly correlated, we identified several outlier bins where the agreement broke down. To find them, we created a scatter plot comparing the relative charge scales of CRT and Pandora across all bins. Points that deviated significantly from the general grouping of points (determined by visual observation and adjustment) were flagged as outliers and plotted in red, as shown in Figure 9.

After finding the position and bins of the outlier points on the charge scale graphs, plotting them in the Y-Z plane helped visualize the potentially problematic points of the detector. Figure 10 shows these positions as a scatter plot, with outliers weighted by the number of hits at that

(a) TPC EE - Front Induction Plane



(b) TPC EE - Middle Induction Plane



(c) TPC EE - Collection Plane

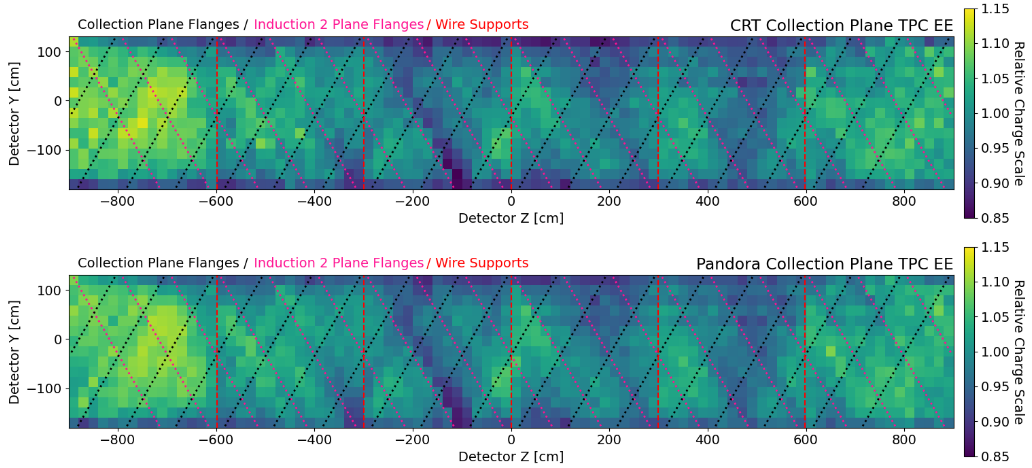
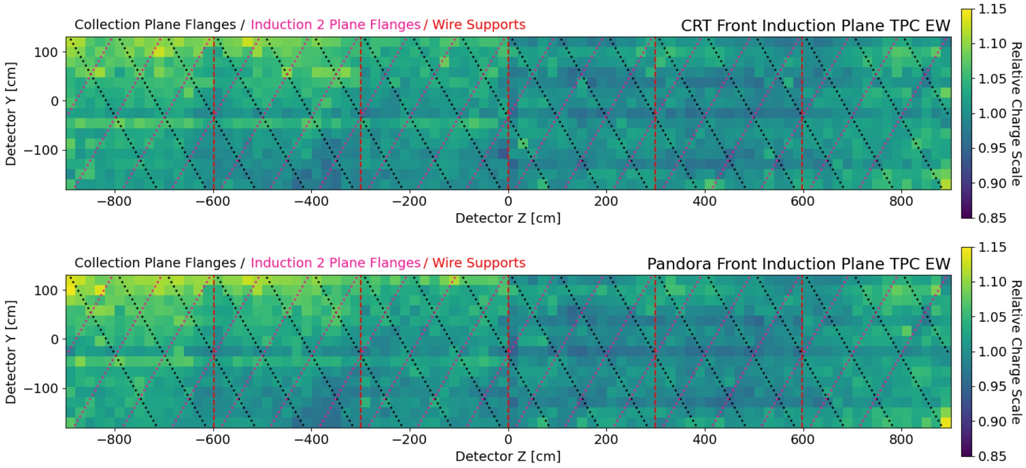
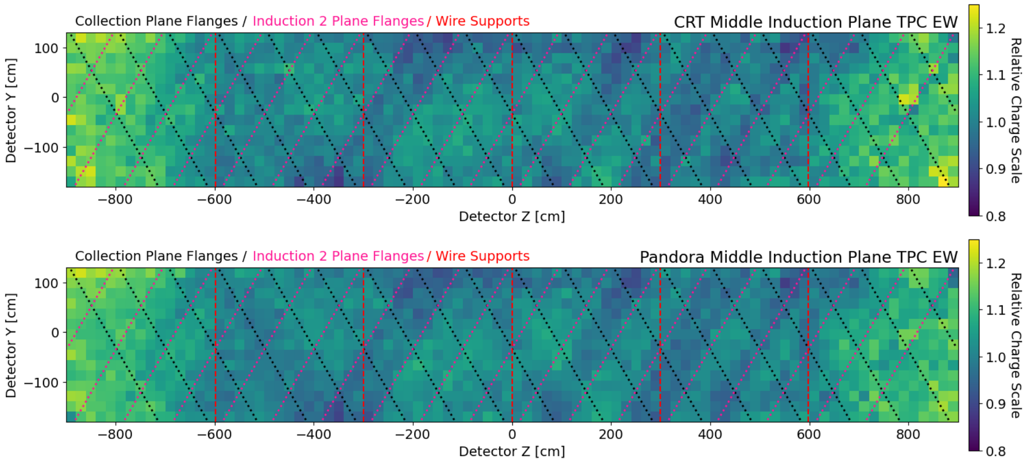


Figure 5: Comparison of the coarse-grained dQ/dx MPV values for CRT and Pandora tagged tracks in each plane of the EE TPC from the dataset of Run 2. Shown also are the vertical mechanical supports and wire flange borders of the induction and collection planes

(a) TPC EW - Front Induction Plane



(b) TPC EW - Middle Induction Plane



(c) TPC EW - Collection Plane

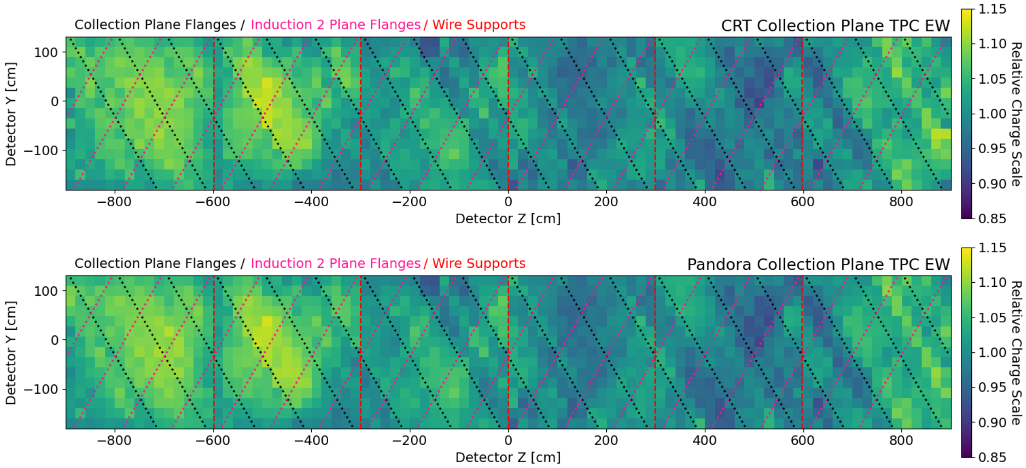
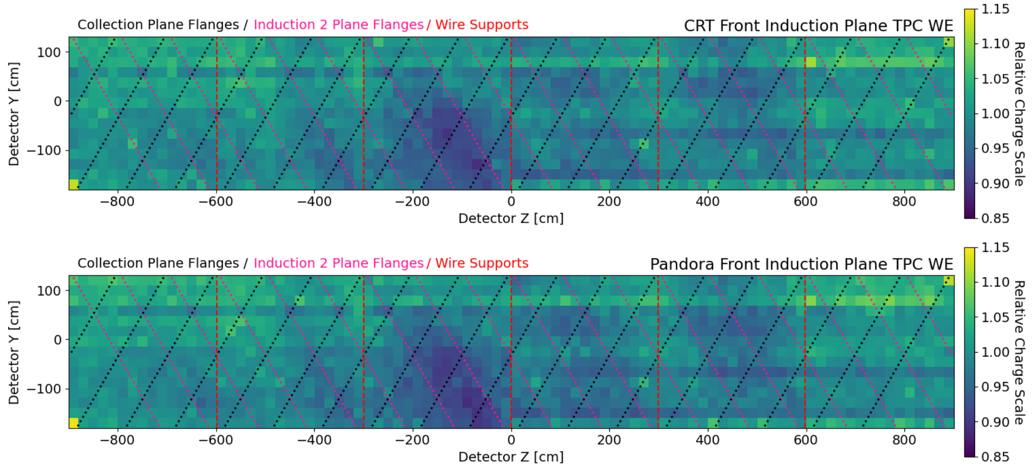
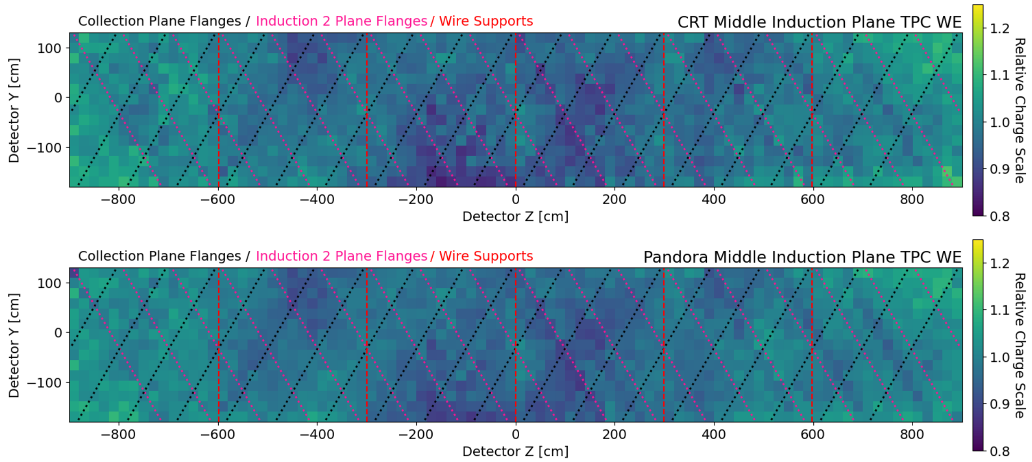


Figure 6: Comparison of the coarse-grained dQ/dx MPV values for CRT and Pandora tagged tracks in each plane of the EW TPC from the dataset of Run 2. Shown also are the vertical mechanical supports and wire flange borders of the induction and collection planes

(a) TPC WE - Front Induction Plane



(b) TPC WE - Middle Induction Plane



(c) TPC WE - Collection Plane

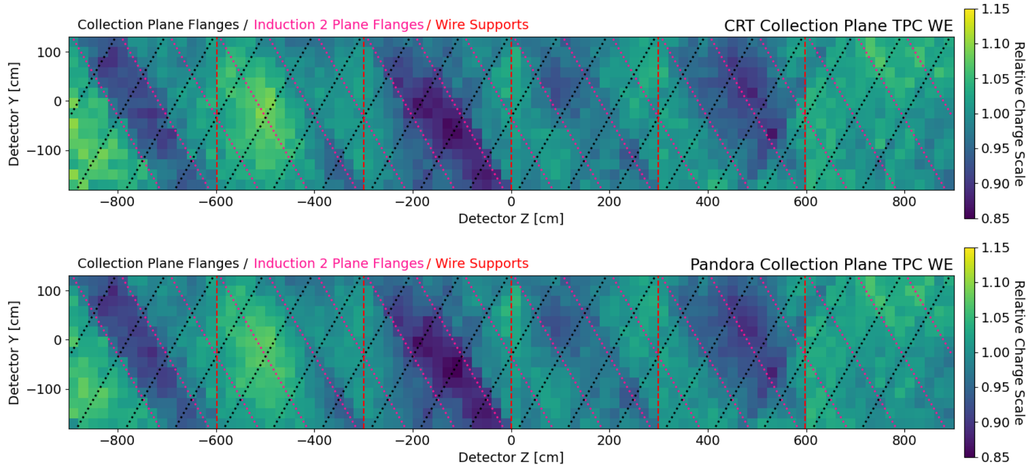
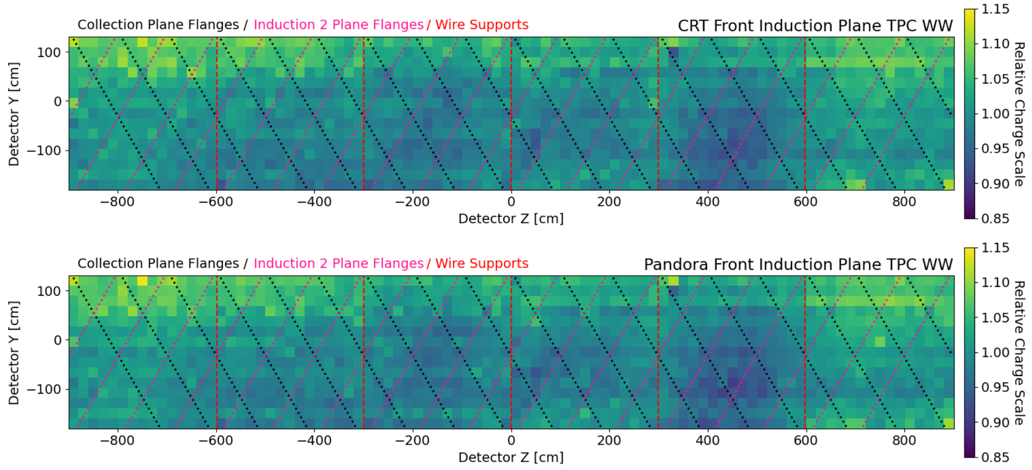
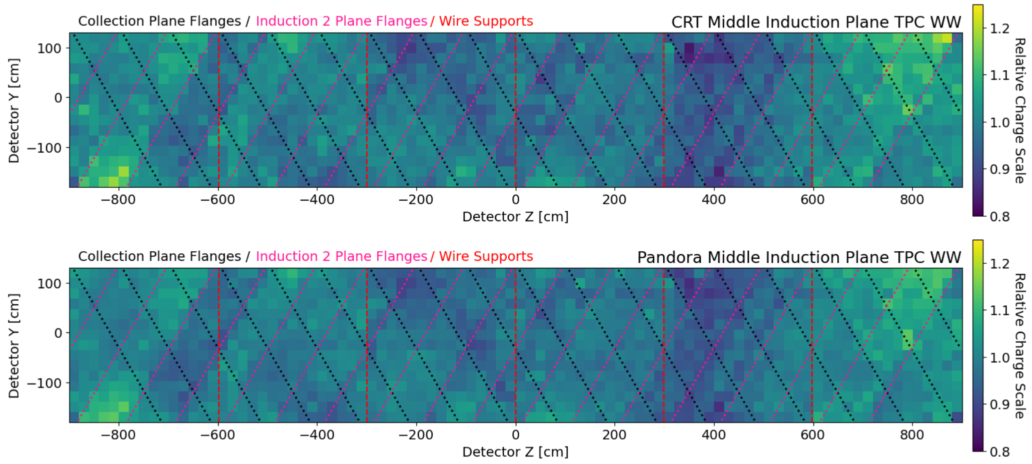


Figure 7: Comparison of the coarse-grained dQ/dx MPV values for CRT and Pandora tagged tracks in each plane of the WE TPC from the dataset of Run 2. Shown also are the vertical mechanical supports and wire flange borders of the induction and collection planes

(a) TPC WW - Front Induction Plane



(b) TPC WW - Middle Induction Plane



(c) TPC WW - Collection Plane

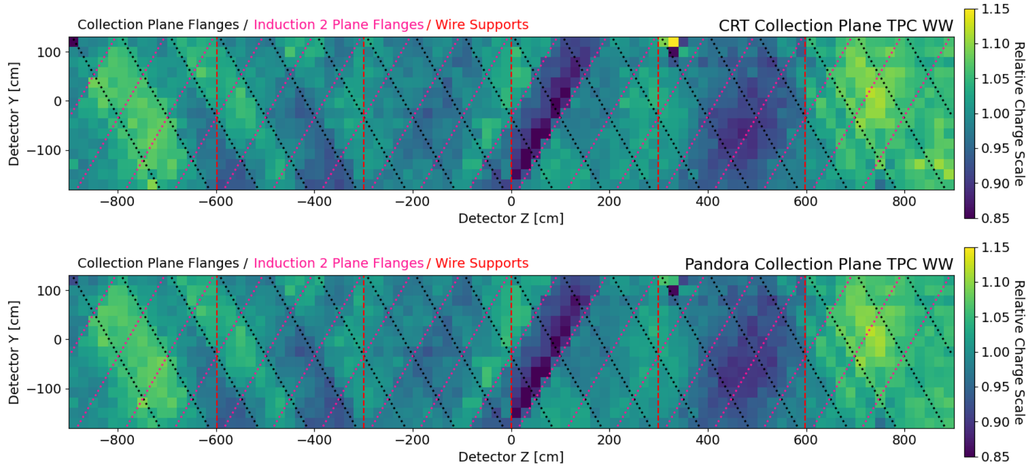


Figure 8: Comparison of the coarse-grained dQ/dx MPV values for CRT and Pandora tagged tracks in each plane of the WW TPC from the dataset of Run 2. Shown also are the vertical mechanical supports and wire flange borders of the induction and collection planes

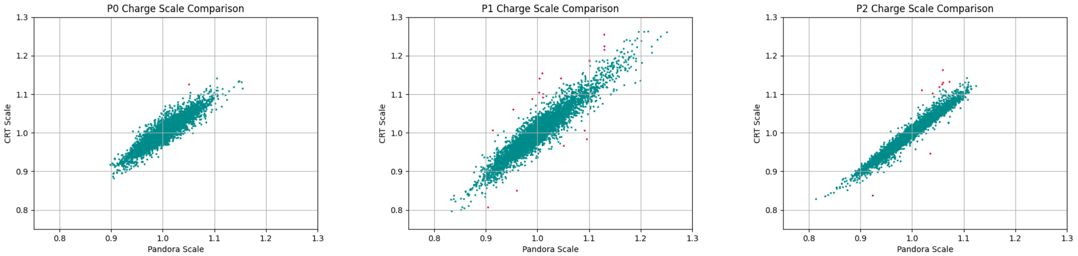


Figure 9: Scatter plots of CRT vs. Pandora charge scale, highlighting outlier points (large MPV difference) in red

point. Finding the average position in each Y and Z bin allows each data point to be plotted in a scatter plot. These outliers apply to all the TPCs.

After finding the bins of the outlier data points, we looked at their locations in the Y-Z plane to see if there was a spatial pattern, using an averaged y and z position from the bin to create a scatter plot representing the detector. Figure 10 shows the positions of these outliers, where each point is weighted by the number of hits in that bin.

The vast majority of these outliers are located near the outer edges of the detector planes. The exterior regions of the detector are more likely to experience edge effects, mechanical inconsistencies, or lower signal-to-noise ratios due to proximity to physical boundaries and supports. The fact that outliers mostly appear there suggests that the central regions of the detector are uniform and well-calibrated.

3 Conclusion

This project explored the spatial charge response of the ICARUS TPC by comparing most probable values (MPVs) of charge deposition between Pandora and CRT tagged tracks. By creating 2-D Y-Z maps of charge scale for both datasets, we were able to visually and quantitatively assess the consistency of the two methods and their sensitivity to detector features.

Both reconstruction paths showed similar structures in their charge distribution, such as less effective wire sections or mechanical supports, confirming that CRT-tagged tracks, despite being external, respond to the same calibration landscape as Pandora tracks.

The outliers in the correlation plots tended to cluster near the physical edges of the Y-Z planes. This coincided with regions of lower track density and potential mechanical interference, such as detector support structures and wire flange boundaries. Including these maps helped connect spatial non-uniformities in the charge scale with known physical components inside the TPC.

Overall, the analysis supports the idea that CRT tagged tracks are a useful addition to ICARUS calibration efforts. Their broad angular range and independence from Pandora reconstruction make them a helpful secondary tool and a potential asset in extending calibration across the detector volume.

4 Acknowledgements

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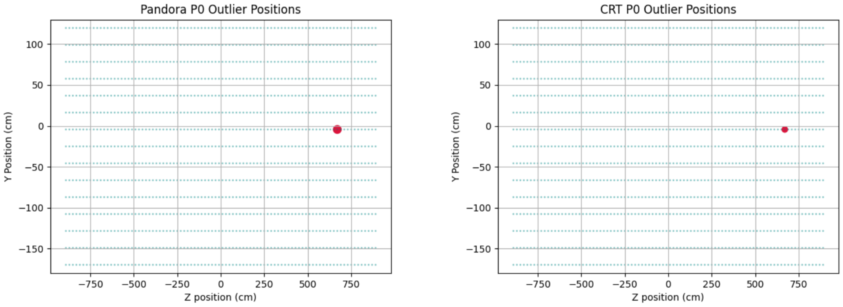
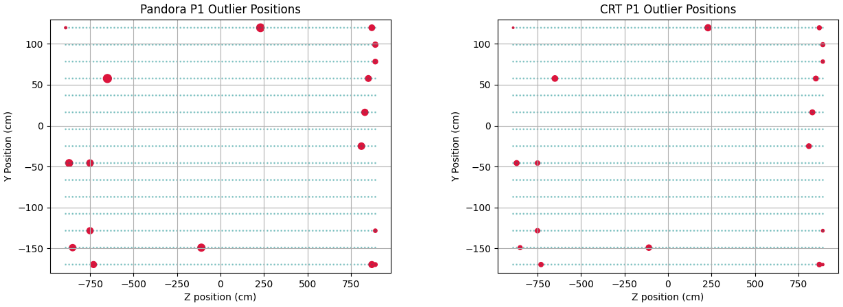
(a) Front Induction Plane


Pandora P0 Outlier Positions

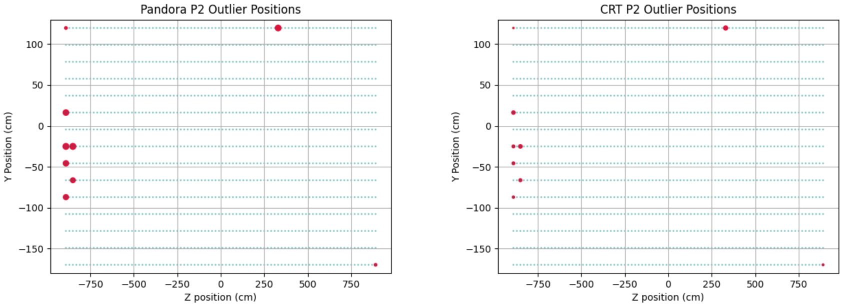
CRT P0 Outlier Positions

(b) Middle Induction Plane


Pandora P1 Outlier Positions

CRT P1 Outlier Positions

(c) Collection Plane


Pandora P2 Outlier Positions

CRT P2 Outlier Positions

Figure 10: Position of outliers on the Y-Z plane, determined by a large difference in MPV. Outlier points are weighted by the amount of hits in that position

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