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Summer 2025 SULI: Nucleus ID, TinyTPC, and Scientific Communication

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***Abstract*—This paper summarizes my work during the Summer 2025 SULI internship, which focused on two main projects and broader scientific development. The first project involved improving the particle identification (PID) of protons, deuterons, and tritons using PIDA distributions and template fitting, with the goal of modeling nuclear final-state interactions (FSI) and testing the robustness of the method against systematic uncertainties. These techniques pave the way for future application to LArTPC data from the ICARUS detector. The second project centered on the optimization and data-taking of the TinyTPC detector, a compact LArTPC used for high-resolution low-energy measurements. I adjusted gain and threshold parameters, performed hardware validation tests, and developed analysis strategies to extract meaningful physics from collected data. Throughout the summer, I also enhanced my scientific communication and mentorship skills through presentations, collaborative analysis, and peer guidance.**

I. Introduction

This summer, I had the opportunity to continue contributing to an ongoing experimental physics program centered on liquid argon time projection chambers (LArTPCs). My efforts focused on two main components: improving the identification of nuclear particles through calorimetric techniques, and optimizing the hardware configuration of a small R&D LArTPC called TinyTPC. Together, these projects support long-term goals in neutrino physics for large-scale upcoming projects like DUNE.

In addition to the technical work, this summer also provided me the chance to grow as a scientific communicator and collaborative researcher. I expanded my role compared to the previous year, not only contributing to analysis and hardware development, but also mentoring peers, presenting results, and shaping the direction of ongoing research through regular discussions and code development.

My work was organized around three primary goals:

1) Develop and refine a pipeline to identify nuclear interactions in LArTPC data via calorimetric techniques and template fits.
2) Tune and validate TinyTPC hardware parameters to enhance detector sensitivity, particularly for low-energy physics.
3) Improve scientific communication through talks and collaboration, and mentoring skills.

II. Nuclear Particle Identification via PIDA and Template Fits

A. Motivation

LArTPCs provide detailed, 3D event reconstruction with excellent calorimetric information. While protons are regularly reconstructed and identified in neutrino interactions, heavier nuclei like deuterons and tritons are often overlooked due to their rarity and overlap in energy deposition profiles. However, isolating and quantifying these particles can provide new insight into nuclear final-state interactions (FSI), which play a significant role in the interpretation of neutrino-nucleus scattering measurements. Better understanding of FSI is crucial for future oscillation experiments, including DUNE, where mis-modeling of nuclear effects could bias oscillation parameter extraction.

To address this, I used the PIDA (Proton Identification Algorithm) variable. PIDA is a calorimetric observable derived from the energy loss per unit length (dE/dx) and the residual range (RR) of a particle track.

The quantity dE/dx represents the rate at which a charged particle loses energy as it travels through the detector medium, typically measured in MeV/cm. Heavier, more ionizing particles like protons tend to have higher dE/dx values near the end of their tracks due to the Bragg peak.

The residual range (RR) is the remaining distance a particle has to travel before coming to a stop, measured from any given point along its track to the endpoint. As a particle slows down and approaches the end of its range, dE/dx tends to increase, creating a characteristic pattern that PIDA exploits for particle identification.

My aim was to use PIDA to separate and identify protons, deuterons, and tritons. By designing a set of cuts that isolate these signals and developing a template-fitting framework, I established a pipeline capable of extracting nuclear signals from mixed event samples in our MC simulated “fake data”.

B. Peak Splitting and Cut Optimization

The nucleus Monte Carlo (MC) dataset used in this study was a simple particle gun configuration with one muon and one nucleus from the set: p, D, T, ^{3}He, ^{4}He, or ^{6}Li. This allowed for a clean exploration of PIDA behavior across different nuclear species.

The PIDA variable is defined as:

$$\text{PIDA} = \text{median}\left(\frac{dE}{dx} \cdot \text{RR}^{0.44}\right) \tag{1}$$

where dE/dx is the energy deposited per unit length, and RR (residual range) is the distance from a given point to the end of the track. The exponent 0.44 reflects empirically motivated scaling to account for the Bragg peak behavior of stopping particles.

Different particles slow down and deposit energy differently as they stop. Higher PIDA values correspond to heavier stopping particles like protons, deuterons, or tritons.

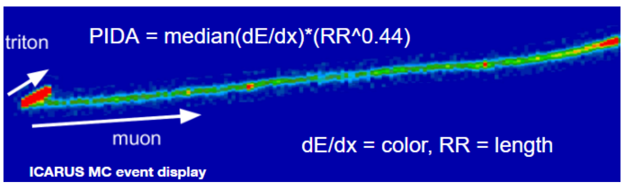

Fig. 1. Example of event display MC in ICARUS with muon and triton.

A set of preselection and optimization cuts were implemented to isolate clean nuclear tracks. These included requirements on track length (to eliminate both short noise-like tracks and long cosmic rays), hit count, pitch (the effective distance between consecutive charge depositions along the track, accounting for track angle), dE/dx extrema, and residual range behavior. The cut on "PID Power," a variable derived from the logarithmic scaling between PIDA and dE/dx, proved especially powerful in separating true nuclei from background tracks.

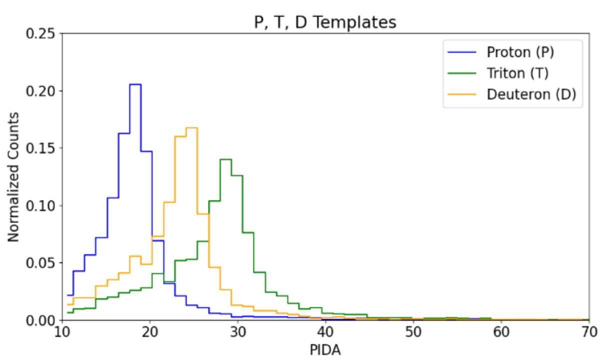

Fig. 2. PIDA distribution after all cuts, showing peak separation for protons, deuterons, and tritons.

After applying all cuts, distinct PIDA peaks corresponding to protons, deuterons, and tritons emerged. This validation step demonstrated that calorimetric separation is viable even for closely overlapping species like D and T.

C. Muon Removal for Signal Purity

A significant challenge in isolating nuclear peaks comes from muons—particularly those arising from cosmic rays in surface detectors. While these typically deposit less energy per unit length than nuclei, long tracks with low dE/dx values can still contribute to the low-end tail of the PIDA distribution, degrading separation power.

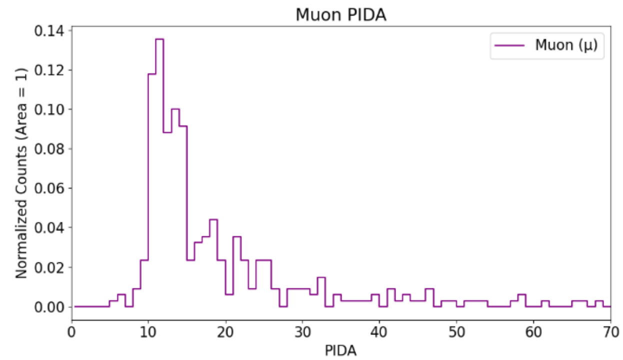

Fig. 3. PIDA distribution of muons.

To suppress this contamination, I examined 2D distributions of dE/dx vs. RR. Muons appeared as a long diagonal streak distinct from the tightly peaked nuclei distribution. By comparing labeled MC samples with and without muons, I confirmed that a cut of $dE/dx < 10\,\text{MeV/cm}$ was effective in removing most of the muon component. This filtering step increased the signal-to-noise ratio for D and T in both MC and data.

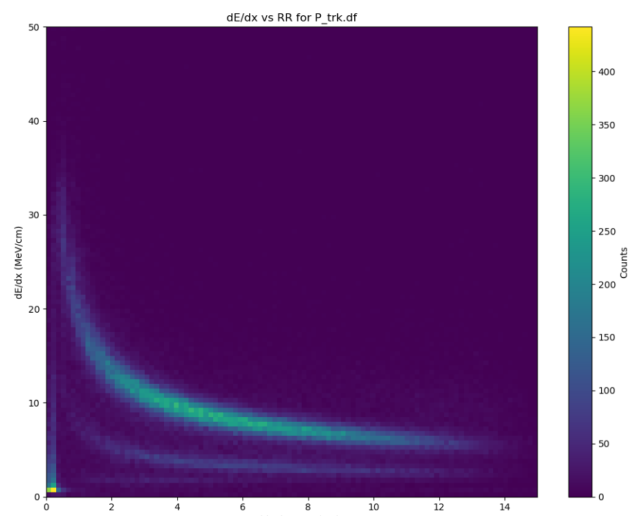

Fig. 4. dE/dx vs RR in proton template before muon removal.

D. Template Fitting and Systematic Robustness

With peaks isolated, I used a template-fitting approach to identify the nuclear species in mixed populations. Using a full neutrino interaction MC, I created normalized histograms of PIDA values for protons, deuterons, and tritons. These templates were then combined in fixed fractions to simulate "fake data," to which fits could be performed to extract the original composition.

Fake data was constructed by scaling templates to realistic exposure (via protons-on-target, POT) and introducing Poisson fluctuations to simulate statistical noise. Deuteron and triton contributions were varied to test sensitivity.

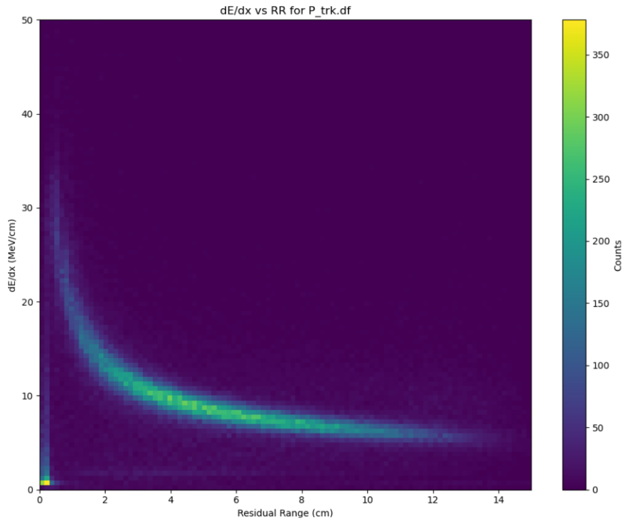

Fig. 5. dE/dx vs RR in proton template after muon removal. The muon streak disappears post-cut.

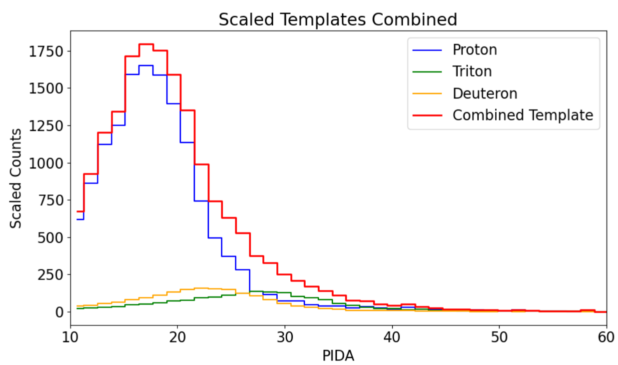

Fig. 6. Example template with 10% deuteron and triton content added to proton background.

Systematic variations were introduced in several ways:

- Gaussian smearing of dE/dx values to simulate poor resolution,
- Counting smearing of dE/dx to simulate poor reconstruction,
- Shifting the PIDA distribution of D and T to test alignment sensitivity.

The fitting procedure was stable under a wide range of smearing and remained accurate for D/T content down to $\sim$1.5% of the sample. Sensitivity degraded sharply only when shifts of ± 2 PIDA units were introduced, highlighting the importance of accurate calibration.

E. Next Steps

This approach provides a data-driven method for quantifying nuclear content in neutrino events, and we are currently preparing to apply this method to ICARUS data, where nuclear effects are expected to be important for understanding track multiplicities and energy loss profiles.

An important finding emerged when comparing different smearing strategies applied to the template and fake data.

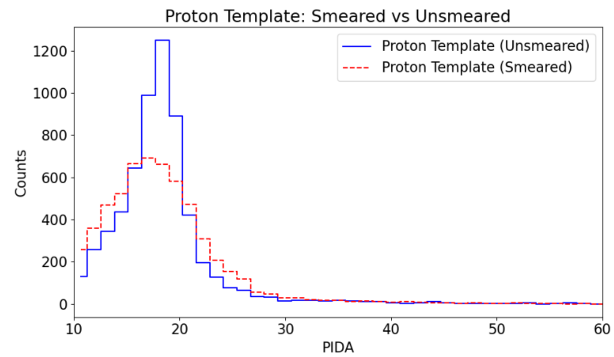

Fig. 7. Example of 50% smearing of the proton background vs no smearing.

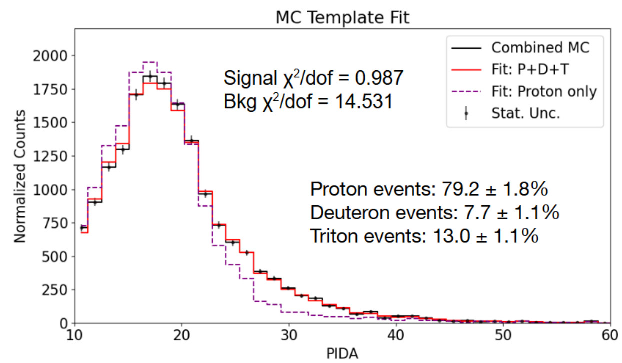

Fig. 8. Example of template fit with 10% D/T injected each, proton background vs template with signal.

When both the template and the fake data were subjected to identical levels of constant Gaussian smearing, the resulting fits were highly stable and consistent across a wide range of smearing percentages.

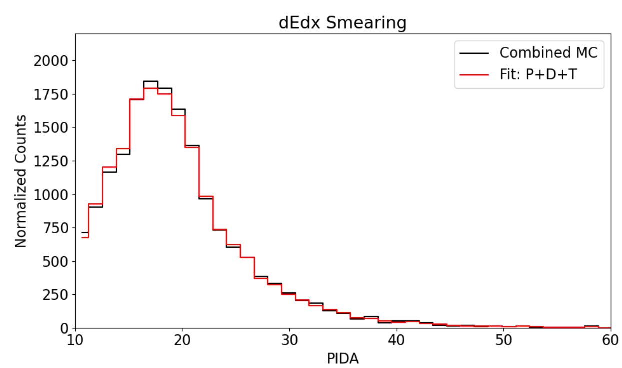

Fig. 9. Template fit result with constant Gaussian smearing applied equally to both the fake data and the template. The proton peak and the signal region are both well-modeled.

However, when the fake data was smeared using a "counting" method—where the amount of smearing varies event by event—while the template remained only constant-smeared, a systematic bias was observed. Specifically, while the fit accurately reconstructed the signal region associated with deuterons and tritons, it consistently underestimated the proton peak in the PIDA distribution.

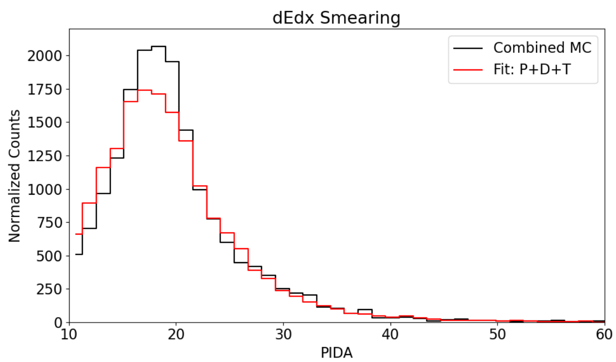

Fig. 10. Template fit result with counting smearing applied to the fake data and constant smearing applied to the template. The signal region is preserved, but the proton peak is underestimated.

This mismatch suggests a misalignment in resolution modeling between the template and data, which must be accounted for when applying the method to real detector data. Going forward, incorporating more realistic smearing into the templates, or developing correction factors, may be necessary to preserve accurate background normalization and fully exploit the power of template-based fits.

III. TinyTPC Optimization and Data Collection

A. Detector Overview

TinyTPC is a compact, pixelated LArTPC that employs the LArPix pixel plane for 3D charge readout. Unlike traditional wire-based TPCs, LArPix enables fine-grained spatial resolution and low noise, making it well suited for low-energy physics. In recent studies, TinyTPC has also served as a platform for testing the effects of dopants in liquid argon—specifically photosensitive molecules like isobutylene.

Preliminary studies using 4 ppm isobutylene in liquid argon indicated an increase in collected charge on the order of 6%, attributed to enhanced ionization via scintillation-molecule interactions. The 2025 goal was to improve detector sensitivity to these effects in the low ADC region seen in Figure 13 by optimizing gain and threshold settings for better low-energy performance.

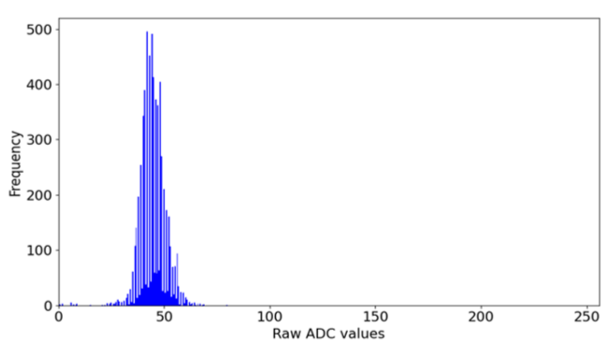

Fig. 11. Histogram of raw ADC values from pedestal subtracted hits from the 2024 run.

B. Hardware Tuning Strategy

LArPix allows for precise tuning of several analog parameters, which directly influence signal integrity:

- $\mathbf{V_{ref}}$ controls the analog front-end's voltage range,
- $\mathbf{V_{cm}}$ sets the baseline voltage,
- **Gain** determines the amplification level applied to each signal.

Thresholds are then set relative to the baseline to determine what constitutes a valid signal. Tuning involves balancing low thresholds (to capture small energy depositions) with noise suppression (to avoid spurious hits).

Bench tests were performed with injected signals and varied gain/threshold settings to map out operating regions that preserved clean signal response. The baseline configuration adopted a conservative gain of 1, with future tests planned to push to higher gains and lower thresholds once baseline stability was confirmed.

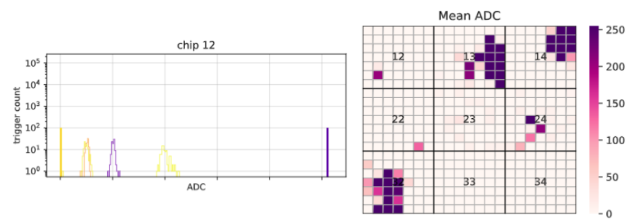

Fig. 12. 2D Heatmap of Mean ADC value and trigger event count vs ADC for Vref 219 and Vcm 77

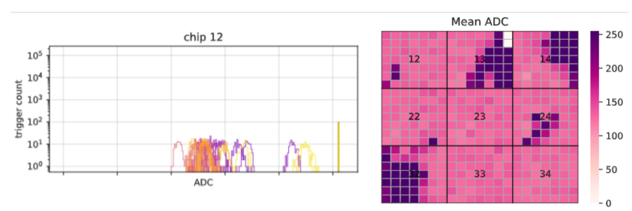

Fig. 13. 2D Heatmap of Mean ADC value and trigger event count vs ADC for Vref 80 and Vcm 27

C. Preparation for Cryogenic Deployment

Following successful bench tests, the detector was prepared for integration into the BLANCHE cryostat—a cryogenic facility that enables realistic, cold operation conditions. Running TinyTPC in liquid argon allows us to evaluate the real-world performance of the tuned electronics, study dopant effects on signal resolution, and refine our calibration strategy.

The deployed detector will undergo systematic scanning of threshold and gain settings in cold conditions, with a focus on maximizing signal-to-noise for low-energy depositions. This iterative characterization will support the long-term goal of turning TinyTPC into a high-precision low-energy calibration detector for future LArTPC programs.

IV. Scientific Communication and Mentorship Development

A. Scientific Storytelling and Presentations

Throughout the summer, I participated in multiple scientific presentation opportunities. These included both less formal collaboration updates and structured talks:

- A seminar on my analysis from the 2024 data involving lab leadership,
- A research "Ignite" talk explaining looking for evidence of FSI using PIDA to a general lab audience,
- A formal talk at the New Perspectives conference, for which I was awarded Best Talk.

Preparing these presentations helped me practice distilling complex analysis into digestible insights. I refined my slide design, developed modular visual explanations for technical processes, and practiced adapting tone depending on the audience's background. These experiences greatly strengthened my ability to communicate effectively with both experts and newcomers as well as boosted my confidence for public speaking.

B. Mentorship and Peer Collaboration

Compared to previous summers, I took on a more active mentoring and leadership role within the team. I helped other students debug hardware and software issues, guided analysis development, and introduced tools for data visualization and plotting.

By leading discussions and suggesting analysis strategies, I not only contributed to the group's progress but also learned how to communicate technical ideas clearly and foster collaborative problem-solving. These skills will be especially valuable as I move into more senior roles in future research projects.

C. Reflection on Growth

The development of communication and mentorship skills this summer proved just as critical as technical achievements. Learning how to explain a cut flow, justify fit models, or guide someone through a confusing bug helped me internalize analysis logic more deeply. I found that by helping others, I sharpened my own understanding and became more confident in my problem-solving abilities.

V. Conclusion

This summer provided an amazing research experience that combined hands-on detector work, data analysis, and professional development. I made concrete contributions to the field of nuclear calorimetry by refining a PIDA-based identification method and validating it under systematic conditions. I also helped prepare TinyTPC for high-sensitivity low-energy data-taking by tuning its electronics and conducting bench tests that will inform future cryogenic operation.

I also grew as a collaborator and scientific communicator—taking in a leadership role within the group, mentoring others, and presenting complex work clearly to varied audiences. These skills, alongside the technical expertise I developed, have prepared me for deeper research engagement in graduate school and beyond.

I leave this internship with new confidence, curiosity, and a stronger foundation for tackling the challenges of neutrino physics and detector development in the years ahead.

Acknowledgments

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