# Calibration of the protoDUNE Cosmic Ray Tagger


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## Introduction

In particle physics experiments where it becomes necessary to track or reconstruct events of particle interactions, it is important to identify and reduce sources of background interference. In the case of DUNE and other such experiments relying on Liquid Argon Time Projection Chambers (LArTPCs), highly-energetic muons can potentially become a source of such interference. These muons are generated when cosmic rays strike Earth's atmosphere, resulting in a shower of particles, shown in Figure 1. As a result, approximately 10,000 muons per square meter per minute reach the surface of the Earth[1].

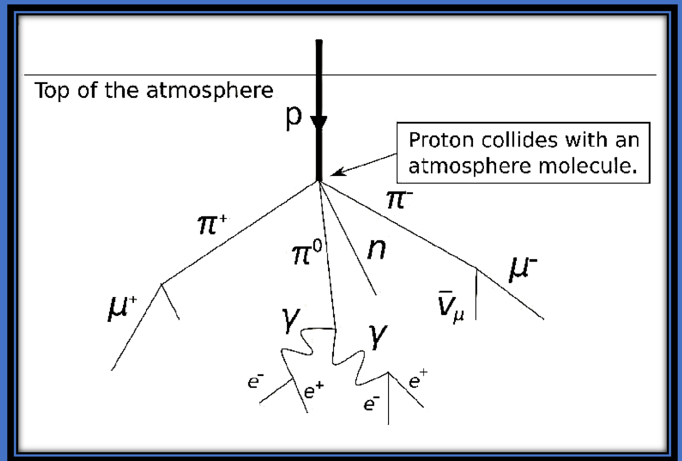


Figure 1: A cosmic ray striking Earth's atmosphere resulting in a shower of particles. Among these particles, muons ($\mu$) are generated.

## The Deep Underground Neutrino Experiment (DUNE)

DUNE is a planned experiment in long-baseline neutrino oscillation physics which seeks to understand the nature of neutrinos and has the potential to answer questions such as[4]:

- ➡ Why does matter currently dominate our universe, as opposed to anti-matter?
- ➡ Does a proton undergo decay?
- ➡ Do neutrinos and anti-neutrinos oscillate differently?

Currently, DUNE is not scheduled for completion until the early 2030s. However, protoDUNE, a prototype of DUNE's far detector meant to test the design, is operational. As mentioned, DUNE will operate using a LArTPC, which is a kind of particle detector. The LArTPC can detect when an energetic charged particle passes within, because the charged particle will ionize argon atoms within the chamber. The drift electrons, produced from this ionization, then experience an electric field which directs them to wire planes, as seen in Figure 2.

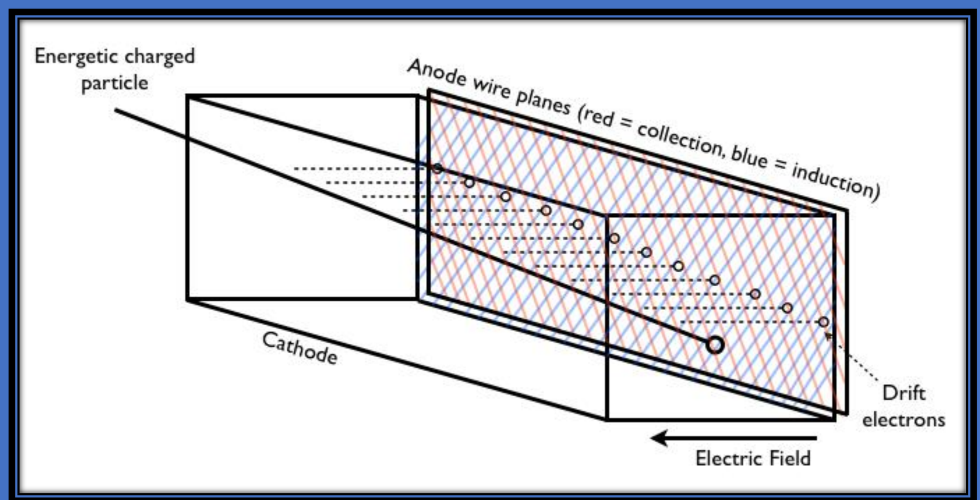


Figure 2: A simplified diagram of how a Liquid Argon Time Projection Chamber (LArTPC) operates. Argon is chosen for its low electronegativity and inexpensiveness[2].

The potential for cosmic muons to create interference is then clear by the principles of the LArTPC's operation, since cosmic muons are both energetic and charged. This interference can create ambiguity between events due to neutrino interactions and events due to muons. Therefore, it is vital to reduce this ambiguity, which can be done using a system known as a Cosmic Ray Tagger.

## Cosmic Ray Taggers (CRTs)

For the CRT discussed here, scintillating strips form bi-layers (a scintillator is a material that can absorb energy from incident particles and re-emit the energy in the form of light). These bi-layers, composed of two rows of scintillator strips each, are labeled either an 'X' module or a 'Y' module, signifying the fact that, between the two modules, the strips are orthogonal. The bars are also placed in such a way that there is an overhang on either end of a bi-layer. Hits in the scintillating strips can then be used to reconstruct the path of the muon through the CRT using the orthogonality of the bi-layers (see Figure 3). The primary purpose of the CRT is to track and time the crossing of muons in order to mitigate any background noise in the LArTPC.

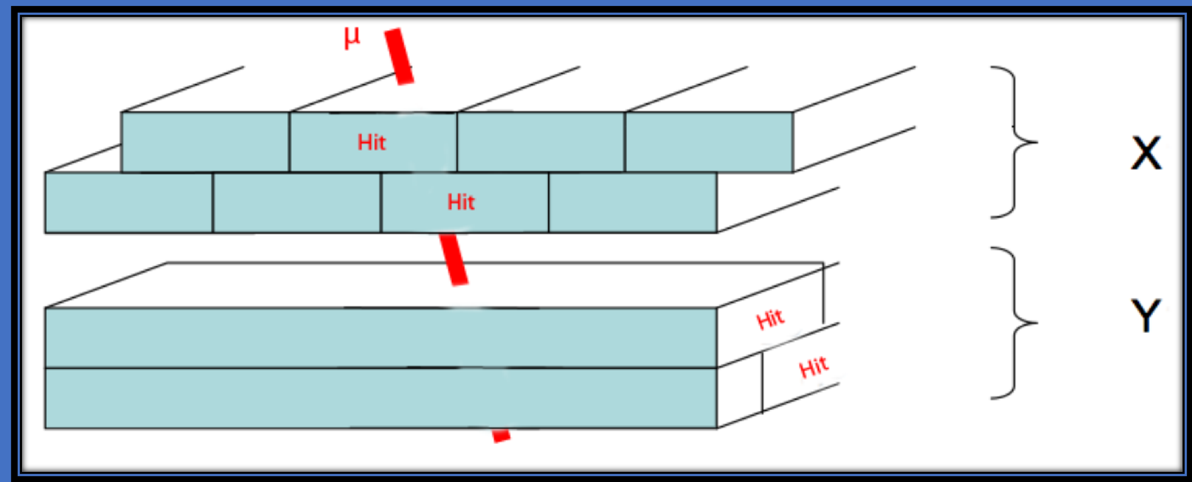


Figure 3: A schematic of a muon passing through the CRT. One bi-layer, labeled 'X', is oriented perpendicular to another bi-layer, labeled 'Y'. This orthogonality between layers allows for determination of the muons track through the CRT[3].

Each strip in the CRT is connected to a multi-anode photo-multiplier tube (PMT) via a wave-length shifting (WLS) fiber, with each PMT having a total of 64 channels. The peak absorption wavelength of the WLS fiber should ideally match the peak emission of the scintillating material, allowing for the scintillation light to be transferred to the PMT, where the signal is then amplified.

When a scintillating strip is hit by an incoming particle, the scintillation light will travel through the fiber and to the face of the PMT. Thereafter, the signal can be processed using a computer, yielding information of the ADC value of each channel on the PMT, the PMT the signal originated in, and more. Ideally, all the channels on the PMT face would produce identical signals for identical inputs, however this is not the case. The purpose of the calibration of the CRT is then to produce a set of so-called gain constants that correct for this phenomenon. These gain constants act to shift the peak ADC distribution for each channel of each PMT to a pre-specified value.

## The Calibration Code

The foremost goal of this project was to take existing code for the calibration of the Double Chooz experiment Outer Veto (Double Chooz being a previous neutrino experiment) and modify it in order to fit the characteristics of the protoDUNE CRT. Since protoDUNE is reusing the same cosmic ray outer veto from the Double Chooz experiment, the overall logic of the code did not have to be appreciably changed. There were three primary modifications to the code:

- ➡ Add the calculation of timing offsets for the PMTs
- ➡ Create channel to strip mapping
- ➡ Alter the four-fold algorithm

In general, because a CRT may not have instrumentation to ensure that all PMTs read the same starting time when data is taken, the calculation of timing offsets allows for each PMT to have the same "starting point". The channel to strip mapping assigns each channel on each PMT to a scintillator strip within the CRT. Finally, the contribution that I personally made was with regards to the four-fold analysis.

A bi-layer hit in a CRT module occurs whenever there are two geometrically overlapping hits. Two bi-layer hits are referred to as "four-fold", as shown in Figure 3. One method of identifying when a four-fold hit occurs is to observe the timing information of the hits. Since muons move at relativistic speeds, the time between hits in two overlapping modules is expected to be small. Specifically, we require that the hits be within a few clock-cycles of each other. In this case, a 16-nanosecond clock-cycle is used. Four-fold hits are particularly useful since, statistically speaking, a four-fold hit is most likely due to a muon rather than background radiation[3].

## The Four-Fold Algorithm

The method by which four-fold hits are found in the Double Chooz calibration code is based on a comparison of timing information. Initially, two bi-layer hits in overlapping modules are checked to see If they occurred within 1 second of each other. Once the hits that are within 1 second of each other are found, they are checked to see if they occurred within 4 clock cycles of each other. An example of the ADC distribution in all active channels before and after applying gain constants is shown in Figures 4 and 5 respectively and the modified four-fold algorithm is shown in Figure 7 along with an example gain constants histogram shown in Figure 6.

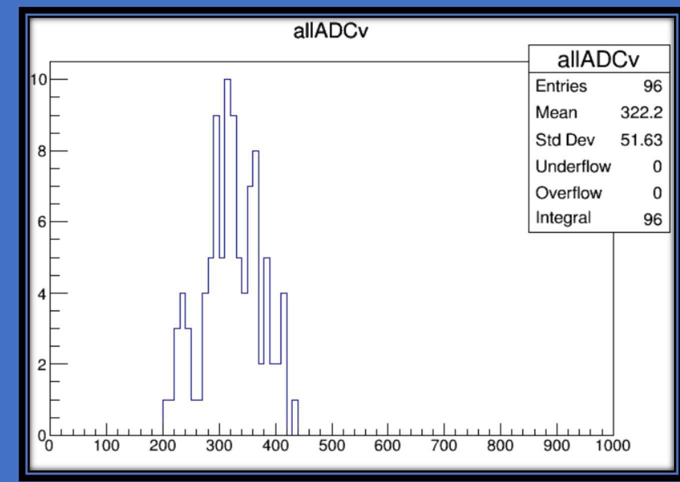


Figure 4: ADC distribution of mean ADC values for each active channel in the CRT before calibration.

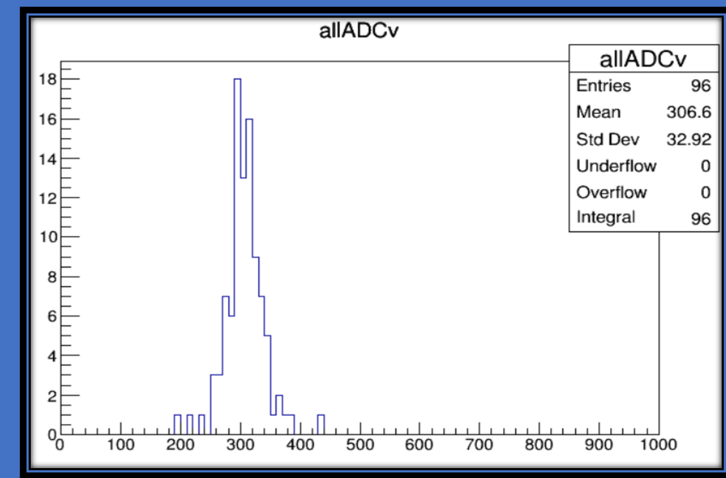


Figure 5: ADC distribution of mean ADC values for each active channel in the CRT after calibration

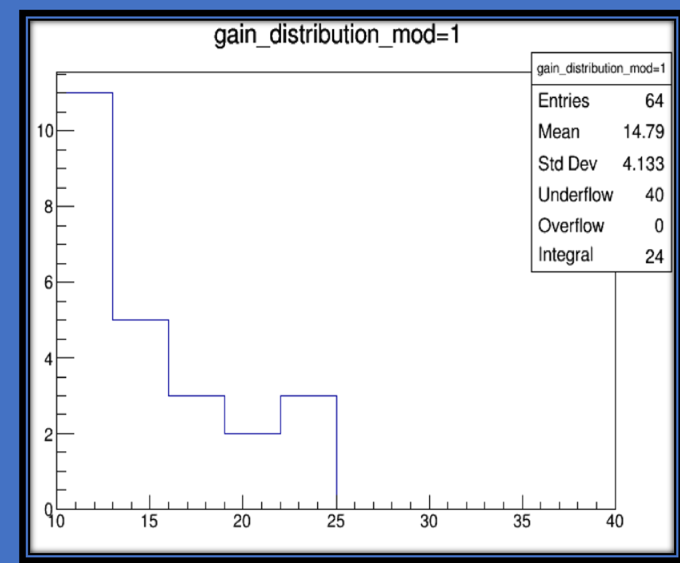


Figure 6: A histogram of the gain constants produced for each channel for a PMT in the CRT system. The peak ADC values for each channel are then multiplied by these gain constants in order to shift them to a specified value.

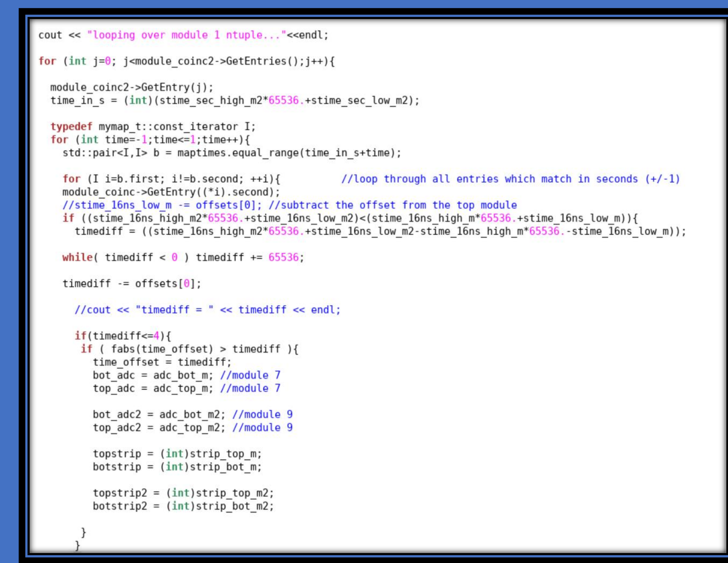

Figure 7: The modified four-fold algorithm. The key differences with regards to the original include the addition of offset information and extension of the algorithm to handle more modules.

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## References


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