Calibration of the protoDUNE Cosmic Ray Tagger

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Abstract: Cosmic rays that are incident on Earth's atmosphere have the potential to produce energetic muons which can act as a source of interference in high-energy particle physics experiments. As an example, neutrino experiments using Liquid Argon Time Projection Chambers (LArTPC) such as the upcoming Deep Underground Neutrino Experiment (DUNE) and Micro Booster Neutrino Experiment (MicroBooNE) are affected by these cosmic ray muons due to the possibility that a high-energy muon may pass through the LArTPC and be incorrectly associated with a neutrino interaction. In order to account for this interference, a Cosmic Ray Tagger (CRT) is employed to reconstruct the path of the muons as well as their timing relative to the neutrino detector. The CRT utilizes layers of scintillation modules to track and time the crossing of the muons through the CRT in order to reduce the cosmic ray background present in the neutrino detector. In this paper, I will detail the process of adapting calibration code from the Double Chooz outer veto to fit the characteristics of the CRT used in protoDUNE, a prototype of DUNE's far detector.

I. INTRODUCTION

The upcoming long-baseline neutrino physics experiment DUNE seeks to understand the nature of neutrinos and may potentially answer profound questions relating to the abundance of matter in the universe, unification of forces, and black hole formation [2]. DUNE will explore the phenomenon of neutrino flavor oscillation, or, in other words, the fact that neutrinos oscillate in flavor after traversing some distance. Through this exploration, DUNE also seeks to test charge-parity (CP) violation in the leptonic sector as well as determine neutrino mass ordering. In particular, the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ will be measured precisely, including measurements of δ_{cp} and θ_{23}. The mixing angle θ_{23} describes the mixing between neutrino flavor and mass eigenstates where as the CP violating phase δ_{cp} may constitute a CP violation in the leptonic sector if it is found to be different from 0 or π [3].

DUNE will consist of a near detector located at Fermilab and far detector located at Sanford Underground Research Facility, separated by a distance of 1,300 km. The far detector will implement a Liquid Argon Time Projection Chamber (LArTPC) divided into four modules, each with a volume of 17 kilotonnes and located approximately 1.5 km beneath the surface of the Earth [3]. At the near detector, a high-resolution neutrino detector and muon monitoring system will be implemented to exploit the full statistical capabilities of the far detector and characterize the megawatt neutrino beam. Although DUNE is not yet completed, an experimental program to test the functionality and design of DUNE's far detector, called protoDUNE, is currently operational. A diagram of the planned DUNE design is given in Figure 1.

DUNE's far detector will consist of both a horizontal and vertical drift TPC. The basis of operation of a LArTPC is shown in Figure 2 on the next page. An energetic charged particle enters into the chamber where it ionizes argon atoms along its path. The drift electrons that are produced experience an electric field that directs them towards a set of wire planes. In total, there are two drift volumes through which the electrons move, each volume on either side of a central cathode plane. Two anode planes are also placed on either side of the cathode plane to establish an electric field between the planes. The anode planes each contain three Anode Plane Assemblies (APAs), where each APA contains three parallel planes of wires on both faces which are placed at differing angles with respect to one another in order to aid in 3D reconstruction [7]. Although it is not shown in Figure 2, protoDUNE's design also includes photon detectors, built into the APAs, for the detection of scintillation light produced by the liquid argon using bar-shaped light guides to transmit the scintillation light to silicon photomultipliers. These photon detectors are instrumental for timing information and trigger capabilities [8].

Using a LArTPC, information about a particle's trajectory and interactions within the chamber can be reconstructed. A typical source of interference in this design comes in the form of cosmic rays striking Earth's atmosphere. When a cosmic ray is incident on a molecule in Earth's atmosphere, a shower of particles results. Among

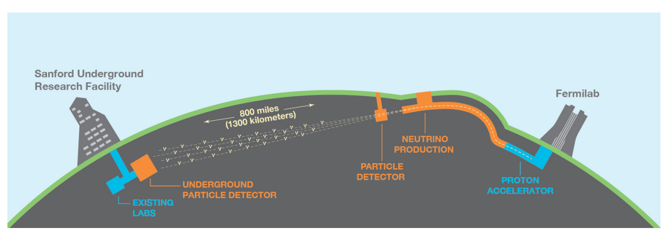

FIG. 1 A diagram of the planned experimental set-up of DUNE. DUNE will feature both a near detector and far detector separated by a distance of 1300 km in order to measure characteristics of neutrino oscillations. Photo Credit [2].

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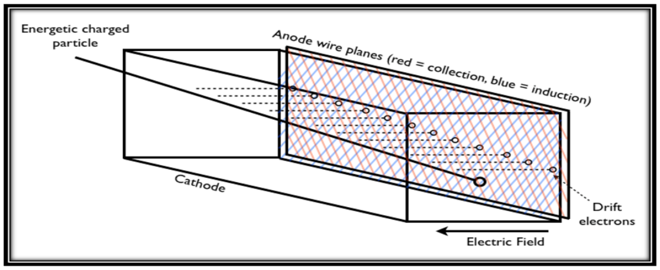


FIG. 2 A schematic of the operation of an LArTPC. An energetic charged particle passes through the chamber, ionizing argon atoms as it travels. The electrons that result from this ionization experience an electric field which directs them towards wire planes, after which information about the particles trajectory can be determined. Photo credit [5].

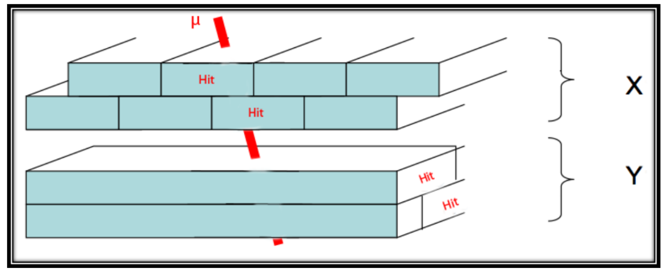


FIG. 3 A representation of a muon passing through the CRT system. The scintillating strips are grouped into either X or Y modules, indicating that they are oriented perpendicular to one another. As a muon passes through the scintillating strips, the scintillation light is directed to a PMT using a wave-length shifting fiber. Photo credit [1].

these particles are charged particles known as muons. Therefore, if a muon happens to cross the LArTPC, it could potentially be mistaken for a neutrino interaction.

A method of combating this interference due to cosmic muons is to introduce a Cosmic Ray Tagging (CRT) system. A CRT allows for the tracking and timing of energetic muons that pass within the system. As a result of the capability of tracking the muons, it becomes possible to distinguish when an interaction within the LArTPC is due to a muon. The introduction of a CRT allows for cosmogenic activity to be removed from neutrino related data sets as well as aiding in calibration using tagged muons and refining the statistical significance of measurements [4]. The principle of operation of the CRT discussed here is through the use of scintillators, which are materials that are capable of emitting light when an energetic particle passes through them.

II. DESCRIPTION OF THE CRT SYSTEM AND ITS IMPLEMENTATION AT PROTODUNE

The CRT for protoDUNE consists of rectangular scintillating strips that are labeled together as either an 'X' or 'Y' module, where an X module is oriented perpendicular to a Y module, for the purpose of providing tracking information of a muon through the CRT. Each module will consist of 64 scintillating strips, further grouped into bi-layers with 32 strips on each row [6]. In order to aid in identifying geometrically overlapping hits, the rows of a bi-layer are offset by a length equal to half the strip width. Also, each strip within the CRT is connected to a Hamamatsu M64 multi-anode photo-multiplier tube (PMT) via a wave-length shifting (WLS) fiber. Four modules (two X and Y) together form a super module, and, for protoDUNE's single-phase LArTPC, there are four super modules on the upstream and downstream sides of the TPC, for a total of eight super modules. An example diagram of a muon passing through a CRT is given in Figure 3.

An important detail of the CRT system is how it determines whether a hit in a module is truly due to a muon and not some form of radiation. The method by which muonic hits are found is carried out by a series of cuts. One such cut is the ADC to photo-electron (ADC2PE) value for each PMT. The Hamamatsu M64 PMTs contain a reflective coating on the surface. It is possible that this coating can produce photo-electron(s) that activates a channel on the face of the PMT. The ADC2PE value for that channel is then the peak ADC that is produced from this photoelectric process. Typically, ADC2PE values are small and are considered to be insignificant [1]. Therefore, a cut that can be made to the data includes checking whether the ADC value at a particular channel is greater than some integer or fractional multiple of the ADC2PE value, which would disqualify it as being due to a muon. This cut is primarily useful for reducing the noise generated from optical crosstalk (the fact that a signal in one channel may trigger a signal in a neighboring channel).

Another cut is made when finding four-fold hits. Before describing four-fold hits, it is necessary to understand bi-layer hits. A bi-layer hit is found when there are hits in geometrically overlapping strips in a module. Generally, this is done by searching the top layer of the module to find the maximum ADC value that was generated from a hit. Once the maximum ADC value on the top layer as well as its location in the module have been recorded, the next step is to then search the bottom layer and find the maximum ADC value. If these two strips overlap, a bi-layer hit has been found, and, if not, the hit is not considered a bi-layer hit. This method assumes that a muonic hit produces the maximum ADC value in the strip layers, which is usually a good assumption [1]. A four-fold hit can then be defined as bi-layer hits in overlapping modules. four-fold hits are, statistically speaking, very likely to be due to muons as opposed to background radiation. The reason for this is that incident radiation has the potential to trigger a signal in a strip through Compton scattering. While the probability to Compton scatter once may be non-trivial, the probability to Compton Scatter more than once, and thus mimic a hit due to a muon, becomes much less.

The overall purpose of calibrating the CRT is to pro-

```
// create new ntuple with coincidence hits.
if(max_adc) {

//cout << "max adc!\n";

  module_coinc->Fill(strip_bot_m,strip_top_m,adc_bot_m,adc_top_m,stime_sec_high_m ,stime_sec_low_m,stime_16ns_high_m,stime_16ns_low_m,smodule_m);
  time_in_s = (int) (stime_sec_high_m*65536.+stime_sec_low_m);
  maptimes.insert(make_pair(time_in_s,index));
  //maptimes.insert(time_in_s,index);
  index++;
}
```

(a) The Double Chooz calibration code uses a map data structure to store bi-layer hits. The initial if-statement checks whether a bi-layer hit was found. Then, an ntuple is filled with the hit information and inserted into a map.

```
//Reading in channels
string channelfile = "test_316v2.txt";
int num_pmt = get_num_pmt(channelfile.c_str());
int num_implemented_channels = get_num_implemented_channels(channelfile.c_str());
//Grab a vector of a vector of the channels
vector<vector<int>> channels_in = get_channels_on_pmt(channelfile.c_str(), num_pmt, num_implemented_channels);
```

(b) This code represents the generalized input that was implemented for the calibration program. A text file is inputted and parsed to obtain the number of PMTs being used, number of channels being used on each PMT, and a list of the specific channels being used.

FIG. 4 (a) The storage of bi-layer hits in a map data structure. (b) The code used to generalize the input to the calibration code.

duce a set of gain constants. Because each channel on each PMT may be fundamentally different, identical inputs to the channels may not necessarily produce identical outputs. The process consists of isolating signals due to muons from background radiation for each channel. After this, an average peak ADC value over all the channels on a PMT can be obtained. The final step is to calculate a set of constants, the gain constants, to multiply each ADC peak in each channel to shift it towards a targeted value. This process of applying and re-applying the gain constants can be repeated a number of times to calibrate the CRT. Since the CRT system for protoDUNE is adapted from the outer veto used in the Double Chooz Experiment, the Double Chooz calibration code needs only to be fit to the specific characteristics of protoDUNE, with no major changes necessary to the code.

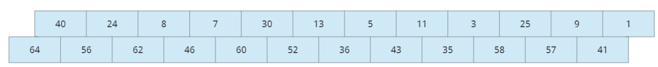


FIG. 5 A diagram of the channel to strip mapping that was used. The number on each scintillating strip corresponds to a channel number on the face of the PMT.

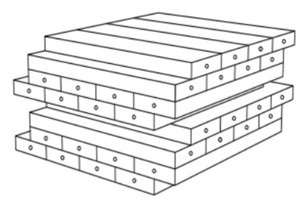


FIG. 6 A diagram of the CRT setup that was used to test the modified Double Chooz outer veto calibration code.

III. DOUBLE CHOOZ OUTER VETO CALIBRATION CODE

The calibration code for the Double Chooz outer veto contained most of the necessary logic to calibrate the protoDUNE CRT with the exception of requiring some additional functions. Primarily, the code needed to be able to calculate PMT timing offsets, map each strip in the CRT to a corresponding channel, be capable of establishing a MySQL server connection for the storage and retrieval of gain constants, and an alteration of the four-fold algorithm was required. The four-fold algorithm, as it was in the Double Chooz calibration code, finds four-fold hits between two modules and does not include corrections for PMT offsets. In the CRT system we were attempting to calibrate, a total of four modules were used with no clock-sync signal, so the calculation of offsets were required. The calculation of timing offsets between PMTs becomes necessary when there is no clock-sync signal to ensure that each PMT reads the same starting time at the beginning of data collection. The offsets between the PMTs becomes crucial for finding four-fold hits, since a four-fold hit will span two modules. Four-fold hits are found through a process that requires timing information of the hits; therefore, the initial time that each PMT reads is important and offsets are then needed to accurately compare the timing of bi-layer hits in overlapping modules in order to find four-fold hits. As for the channel to strip mapping, see Figure 5 for the mapping scheme that was used. The channel to strip mapping is particularly important for the purpose of identifying geometrically overlapping strips when finding bi-layer hits.

The way in which the four-fold algorithm is done in the Double Chooz calibration code consists of creating a map data structure. A single element in the map contains a pair of the timing information of a bi-layer hit in a module along with an index number (see Figure 4a on the previous page). The advantage of creating this map allows for a reduction in the number of bi-layer hits that must be iterated over in order to find a four-fold by first checking whether the hits are within one second of each other. Only hits that are within a second of each other are then checked to see if they are within four clock cycles of one another.

IV. RESULTS

In the particular CRT setup we were using, there were four PMTs and thus four modules, two X and two Y, that were oriented in a stack, and all modules were completely overlapping one another as shown in Figure 6 on the preceding page. Each module consisted of 24 scintillator strips, therefore 40 of the channels on the PMT face were unimplemented. Firstly, the calibration code was generalized in terms of the number of PMTs being used and the number of channels being used per PMT. A program was written to read in a text file that contains information of the number of PMTs, the number of channels being used on each PMT, and the index of the channels being used for each PMT (see Figure 4b on the previous page).

Once the calibration code was generalized and fitted to the specific channel and strip mapping, the offset code was implemented. In total, there are six pairs of offsets that must be calculated for our use of four PMTs, where an offset must be calculated between each possible pair of PMTs. The code used to find the offsets is shown in Figure 7a on the following page along with an example offsets histogram in Figure 8b on page 6.

The Double Chooz code dealt with only two modules in total. As a result, the calculation of bi-layer hits had to be extended to include two more modules, which was relatively simple after incorporating the channel to strip mapping. The final changes to be made involved the four-fold algorithm, a picture of the modified four-fold algorithm is given in Figure 7b on the following page. The four-fold algorithm was modified to include offsets corrections. While it is not shown in Figure 7b, the four-fold algorithm was also extended to include the use of four modules. A histogram of gain constants that were produced after making the changes to the code is shown in Figure 8a on page 6. Also, ADC distributions for the mean ADC values across active channels in the CRT both before and after applying gain constants are given in Figures 8c and 8d, respectively, using a target ADC value of 300.

With regards to the gain constants, a MySQL server connection was established in order to both store and update the gain constants for each run. The gain constants themselves have limited variation, with the lowest value being 10 and the highest being 27. This is in order to avoid non-linearity issues. The smallest possible adjustment is 1/16, which gives an intrinsic resolution of approximately 6.5%.

V. CONCLUSION

The implementation of CRT systems allows for the reduction of background noise in particle experiments due to muons resulting from cosmic rays incident on Earth's atmosphere. One such class of particle detector that is affected by these cosmic ray muons is the LArTPC. By introducing a CRT system, these cosmic ray muons can be tracked and timed and aid in the reduction of interference due to these muons within the LArTPC. Here in this paper, we have successfully adapted the Double Chooz outer veto calibration code to include timing offset calculations and channel to strip mapping, as well as modification of the four-fold algorithm to include more modules along with timing offset corrections. After introducing these changes, we were successful in generating a set of gain constants to calibrate the CRT. Further work to be done on the calibration code includes making corrections due to fiber attenuation as well as characterizing the code according to the protoDUNE CRT geometry. The protoDUNE geometry will not have all modules fully overlapping as we had here, but instead one X module will overlap with two Y modules. Nonetheless, these changes are necessary for the eventual integration of the CRT system into protoDUNE's single-phase TPC.

VI. ACKNOWLEDGMENTS

I would like to thank Dr. Mariani for mentoring me this summer and giving me the opportunity to participate in the Neutrino Physics REU program here at Virginia Tech. I would also like to thank Matt Murphy and Axel Campos for all their help regarding this work. Thank you, as well, to Betty Wilkins for her guidance throughout the program. I acknowledge the outstanding support from the National Science Foundation, the Virginia Tech Physics department, and the Virginia Tech Center for Neutrino Physics. This work was made possible by the National Science Foundations under grant No. PHY-2149165.

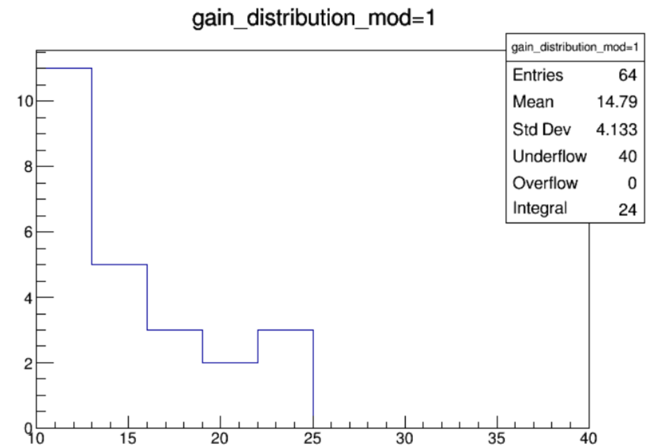
```
if(check == 1){ //Only doing this loop every 10k entries
int counter = 0; //for counting which pair we're looking at

for(int first_pmt=0; first_pmt<3; first_pmt++){
  int first_size = p_mod[first_pmt].size();  //Number of time packets for the first pmt in the pair (2,1,7)
  for(int second_pmt = first_pmt+1; second_pmt<4; second_pmt++){
    int second_size = p_mod[second_pmt].size(); //Number of time packets for the second pmt in the pair (1 7 3, 7 3, 3)

    for(int ii = 0; ii<first_size; ii++){
      for(int jj = 0; jj<second_size; jj++){ //Looping over all pairs of timing packets
   if(p_mod[first_pmt][ii].size() == p_mod[second_pmt][jj].size()){ //i.e. if both packets have all 4 entries
    if(p_mod[first_pmt][ii].at(0) == p_mod[second_pmt][jj].at(0) && p_mod[first_pmt][ii].at(1) == p_mod[second_pmt][jj].at(1)){
      //i.e. if the stime_sec_low and stime_sec_high are the same
      h_off[counter]->Fill(p_mod[first_pmt][ii].at(2)-p_mod[second_pmt][jj].at(2));
      //h_off_high[counter]->Fill(p_mod[first_pmt][ii].at(3)-p_mod[second_pmt][jj].at(3)); //for testing
    }
   }
      }
    }

  counter++;
  }
}
```

(a) A portion of the code used to find timing offsets between the PMTs. First, a vector (p_mod) of hit timing information is filled with ten thousand events. Then, a loop is initiated over all pairs of PMTs. If the events in the pair of PMTs being looped over occurred within the same second, an off-set histogram is filled with the difference between the 16-bit low times of each hit.

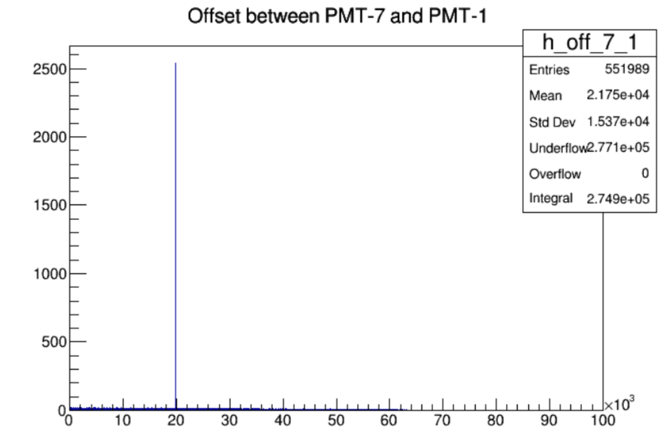
```
cout << "looping over module 1 ntuple..."<<endl;

for (int j=0; j<module_coinc2->GetEntries();j++){

  module_coinc2->GetEntry(j);
  time_in_s = (int)(stime_sec_high_m2*65536.+stime_sec_low_m2);

  typedef mymap_t::const_iterator I;
  for (int time=-1;time<=1;time++){
    std::pair<I,I> b = maptimes.equal_range(time_in_s+time);

    for (I i=b.first; i!=b.second; ++i){          //loop through all entries which match in seconds (+/-1)
    module_coinc->GetEntry((*i).second);
    //stime_16ns_low_m -= offsets[0]; //subtract the offset from the top module
    if ((stime_16ns_high_m2*65536.+stime_16ns_low_m2)<(stime_16ns_high_m*65536.+stime_16ns_low_m)){
      timediff = ((stime_16ns_high_m2*65536.+stime_16ns_low_m2-stime_16ns_high_m*65536.-stime_16ns_low_m));

    while( timediff < 0 ) timediff += 65536;

    timediff -= offsets[0];

      //cout << "timediff = " << timediff << endl;

      if(timediff<=4){
       if ( fabs(time_offset) > timediff ){
         time_offset = timediff;
         bot_adc = adc_bot_m; //module 7
         top_adc = adc_top_m; //module 7

         bot_adc2 = adc_bot_m2; //module 9
         top_adc2 = adc_top_m2; //module 9

         topstrip = (int)strip_top_m;
         botstrip = (int)strip_bot_m;

         topstrip2 = (int)strip_top_m2;
         botstrip2 = (int)strip_bot_m2;

       }
      }
```

(b) A portion of the code which was used to find four-fold hits. First, a bi-layer hit is retrieved, along with its timing information. Next, this bi-layer hit is checked to see if it is within plus or minus a second of bi-layer hits in an overlapping module. If it is within this range, the bi-layer hit is further checked to see whether it occurred within four clock cycles. If this is again true, it is considered a four-fold hit.

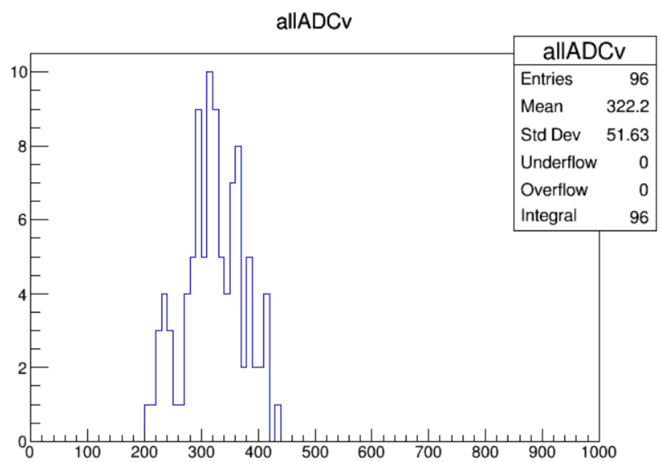
FIG. 7 (a) The offsets code. (b) The modified four-fold algorithm.



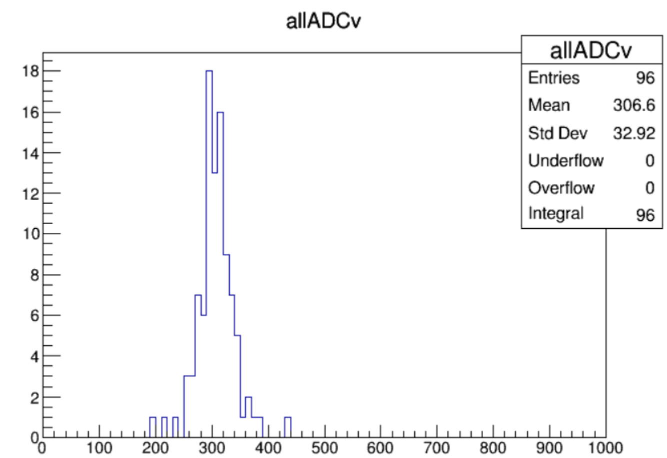
(a) A histogram of the gain constant distribution across all channels on a PMT. The calculation of the gain constants is the crux of the CRT calibration, where each gain constant multiplies the peak ADC distribution of each channel to shift it towards some specified ADC value.



(b) An example offset histogram produced from the offsets algorithm that was implemented in the Double Chooz calibration code.



(c) Histogram of the mean ADC values across all channels over all four PMTs produced after running the program with no applied gain constants.



(d) Histogram of the mean ADC values across all channels over all four PMTs after applying gain constants from a previous run. Notice that the peak of the ADC distribution has shifted toward approximately 300 ADC and has a higher resolution than before the application of the gain constants.

FIG. 8 (a) Distribution of gain constants for a PMT in the CRT system we used. (b) An example offsets histogram. (c) ADC distribution for mean ADC value of active channels on each PMT before calibration. (d) ADC distribution for mean ADC value of active channels on each PMT after calibration.

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