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Performance Study of the SND@LHC

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Summary

SND@LHC is a triggerless detector aiming to measure high energy neutrino cross section. The experiment has superior nuclear emulsions, allowing for detailed measurement of of neutrino interactions in an unexplored pseudo-rapidity region. My project focused on event building from raw data sets and testing the parameters of employed event building strategies to further our understanding of neutrino interactions.

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1 Introduction

1.1 Overview and Goals

The Scattering and Neutrino Detector at the Large Hadron Collider (SND@LHC) experiment at CERN focuses on studying high energy neutrinos, a type of particle created through collisions of protons within the LHC, and their probability of interacting with the material they pass through. This experiment is special because it studies neutrinos at energies never measured before (around 1 trillion electron volts) in a specific region of space that larger detectors cannot access. Located about 480m from where these collisions occur, the SND@LHC experiment is shielded by over 100m of solid rock to ensure that only neutrinos (and muons, a closely related particle) can reach the detector. This specific setup allows researchers to exclusively observe neutrino interactions without any other unwanted particles. Since neutrinos are extremely small and light particles, the SND@LHC target is made up of 800kg of the very dense material of tungsten to increase the probability of particle interactions. This tungsten is interleaved with many tiny detectors called nuclear emulsions that have exceptional spatial resolution which allows them to accurately capture the details of neutrino interactions. In particular the resolution allows researchers to clearly identify the interactions of a specific type of neutrino called the tau neutrino, due to the distinct features of the particle that the tau neutrino decays into.

The goal of my project was to optimize the way data is analyzed from the detector in a process called event building and to further test currently employed event building strategies. This is to ensure that all of the relevant physics such as neutrino interactions that the detector is looking for is present and not accidentally left or cut out.

1.2 Experimental Setup

The detector was developed to identify three neutrino flavors and search for feebly interacting particles as a potential dark matter candidate. Figure 1 is composed of a target region where the particles enter that is followed downstream by a hadronic calorimeter and muon identification system. The detector is made up of four systems: The veto planes, the Scintillating Fibre (SciFi) planes, the Upstream (US) planes and the Downstream (DS) planes. The veto system rejects charged particles to reduce excessive noise and therefore allow neutrino interactions to be more easily observed. The SciFi system provide the timestamp of the events within the detector and provide an energy measurement of electromagnetic showers. The US system is similar to the veto system, and the DS system plays a large role in the muon identification system. [1]

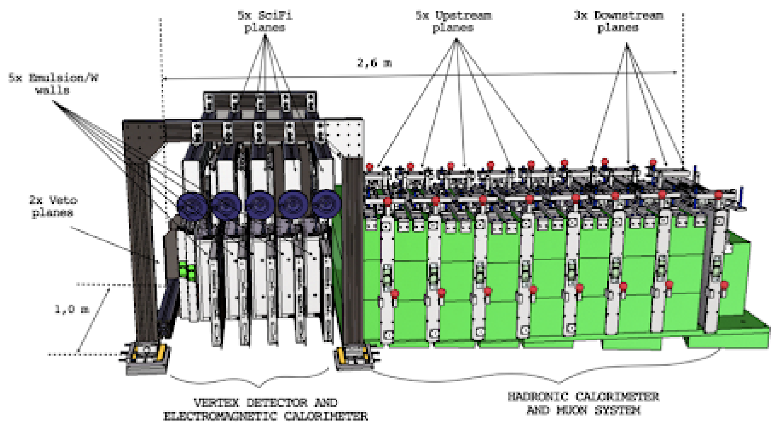


Figure 1: Experimental Setup of SND@LHC. [1]

2 Event Building

2.1 Event Building Process

Event building is the process collecting, combining and organizing raw data from the detector into useful and understandable data that represents a particle interaction. The process of event building can be seen in Figure 2.

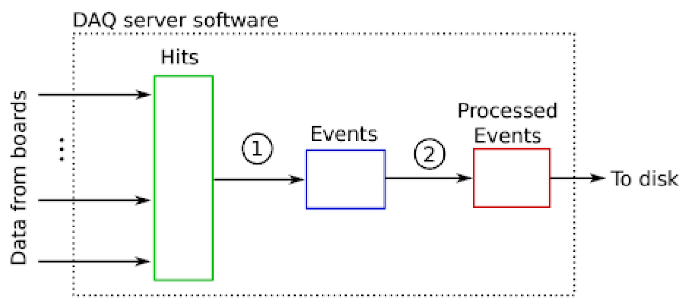
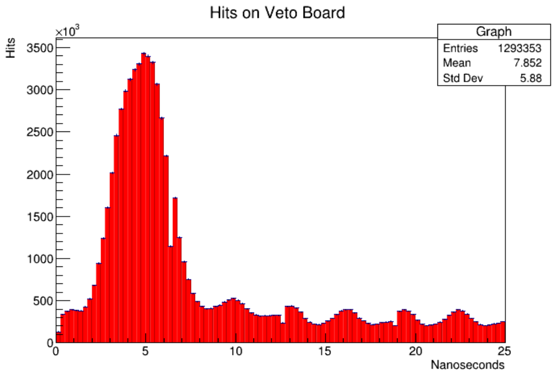


Figure 2: Event building process. [1]

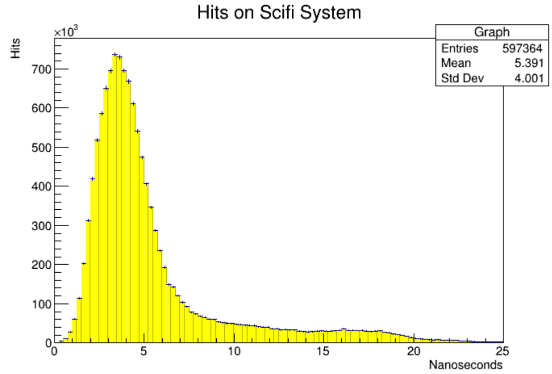
First, the detector receives information from a particle interaction and stores its data, generally referred to as a “hit”. The information within in a hit is as follows: The TOFPET chip that recorded the hit, the channel that recorded the hit, the Time-To-Analogue converter used for the calibration of the hit, the coarse and fine timestamp of the hit, and the coarse and fine value of the hit. [2] The relevant information of a hit for my research is the coarse and fine timestamp of the hit, further explained in Section 3.1. All of the hits on all of the systems are then grouped together in intervals of 25ns, (this time period being determined by the clock cycle of both the LHC and SND), and these are called “events”. These events are then filtered and processed online, with many possible setting configurations but always including noise filtering. Finally, the events are written to a disk. [1]

2.2 Event Building for Each System

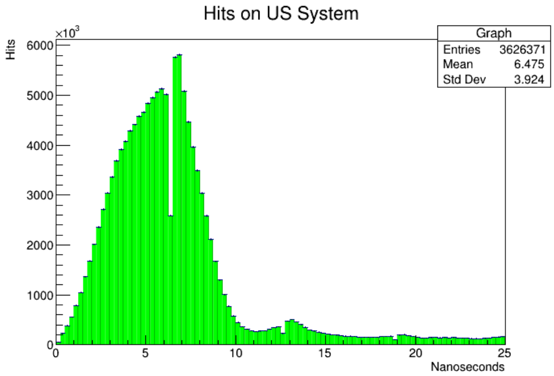
The first event building I completed was with the raw data from the LHC's 2022 proton run. I created 1D histograms for each individual system by plotting the amount of hits on the system over 25ns.



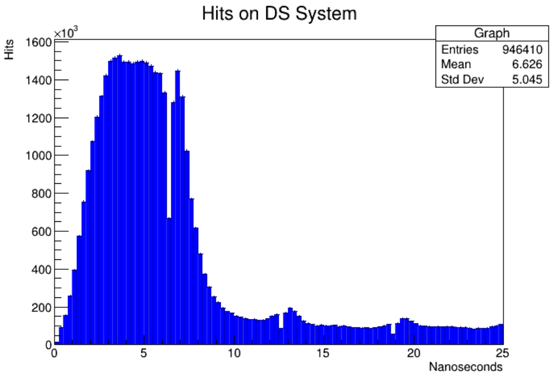
(a) One event of the veto system with a peak around 7.5ns.



(b) One event of the SciFi system with a peak around 4.75ns.



(c) One event of the US system with a peak around 6ns.



(d) One event of the DS system with a peak around 3-5ns.

Figure 3: Event building for each of SND's systems for the 2022 proton run.

These plots were created by first loading in the raw data from the 2022 proton run and creating a board ID map that assigned each constituent board to their corresponding system, allowing event building graphs for each system. I then looped over all of the hits in the event and assigned an index to each hit that corresponded to their respective board ID. I then checked which system the hits were in, and after finding the hits on the desired system, filled the histogram with each of the hits and their associated event timestamp.

The most striking part of these graphs are where there are small columns of missing data, most apparent in the US and DS systems. These "dips" in data are likely due to the difference in synchronization of the LHC's and SND's internal clock. The dips can be seen at regular intervals of 6.25ns. Correspondingly, the LHC's clock runs at 40Mhz (25ns), while SND's clock ticks exactly four times faster than that at 160Mhz (6.25ns). The data was likely "pushed over" from just after each 6.25ns interval, creating the small and artificial peaks that are easily seen in Figure 3a, 3c, and 3d just after the dip in data.

Finally, I plotted a 2D histogram that shows the the event building for each system compared to one another.

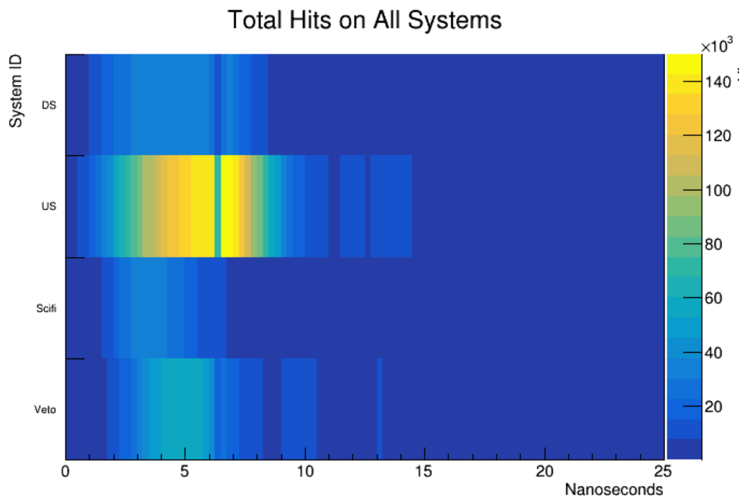
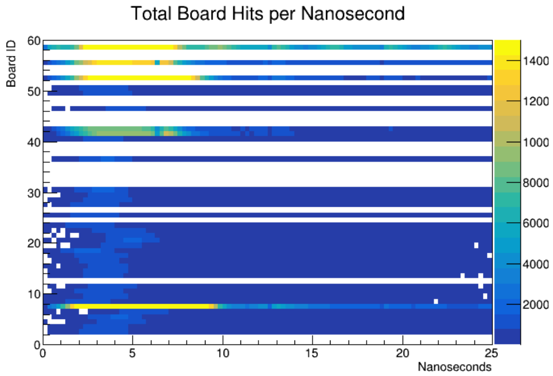


Figure 4: Hits on all systems for one event.

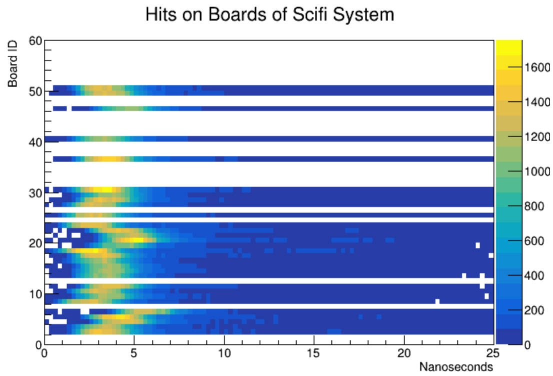
The y-axis on the left side are each of the four systems, the y-axis on the right side are the number of hits, while the x-axis is the timescale. The US system is hit much more than other systems over a slightly longer period of time because it has the largest surface area, followed by the veto system, then finally the SciFi and DS systems. Once again it is possible to see the dip in data most starkly at 6.25ns as there is a consistent change in color (amount of hits) across the systems. This graph was created very similarly to Figures 3a - 3d; the large difference being assigning each hit to each system at once (instead of only one system) and plotting all of the data on one canvas.

2.3 Event Building for Boards of Each System

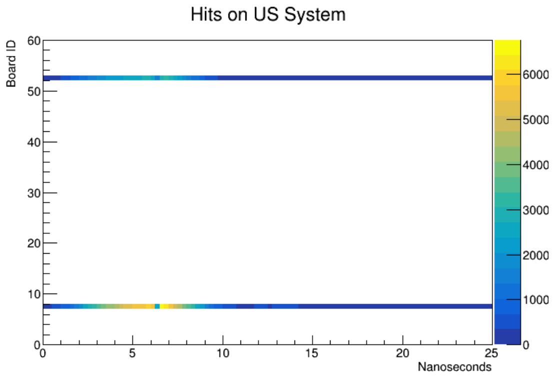
Each system of SND is made up of boards with individual ID numbers. The veto system has only one board and is the smallest system, and the SciFi system has the most boards with 30. Knowing which boards of each system are being hit relative to each other in an event is important alongside the event building for the entire system. The following graphs show a deeper insight by breaking up Figure 3a - 3d into their individual board components. (The veto system is not included in these plots since it only contains one board, therefore Figure 3a would plot the same data with only a visual difference.)



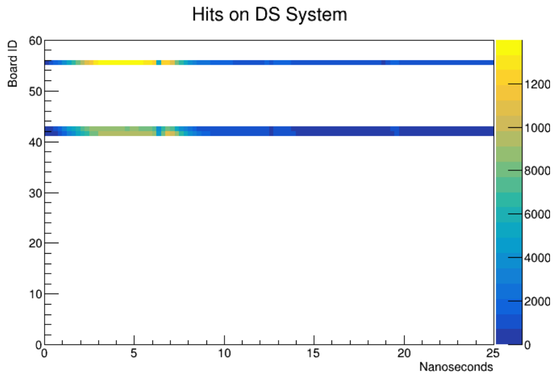
(a) Hits on all boards where boards 7, 55, 58, 60 are hit most frequently.



(b) Hits on SciFi boards where every board is consistently hit with similar peaks at similar times.



(c) Hits on US boards where board 7 is hit most frequently.



(d) Hits on DS boards where board 55 is hit most frequently.

Figure 5: Hits on individual boards for each system of SND.

These are 2D histograms where the left y-axis is the specific board ID, the right y-axis is the number of hits, and the x-axis is the time of one event. The disparity in the amount of boards allocated to each system is easily apparent with SciFi containing the large majority, necessary to provide high spatial resolution of the particles as they traverse the detector and to provide extremely accurate timestamps.

These plots were again created similarly to Figures 3a - 3d, but instead of the hits being assigned to their larger respective system, they were assigned to the exact board ID within the system that they hit. It is useful to know that all of the boards are being hit at a similar time across all systems, because it means that the systems are properly synchronized with one another. In 2022, the veto system was out of sync with the other systems due to the physical implementation of boards, and this created many problems for the detector.

3 Investigation of Timestamps of Hits

3.1 Definition of Timestamps

To further investigate the dips in data first seen in Figure 3a - 3d, it was necessary to learn more about how the timestamps of hits are calculated. The timestamp of a hit is calculated using both the coarse and fine timestamp. The coarse timestamp is a rough estimate of when the hit occurred. It is expressed in integer values of the SND clock cycle. The fine timestamp is a more precise measurement of when the hit occurred, and contains the raw value of the charge that is digitized by the Time-To-Digital Converters, often defined within the interval of the coarse timestamp. Together, both timestamps define the time in which a hit occurred by first defining in which clock cycle the hit occurs (coarse timestamp) and then specifically when in that clock cycle the hit occurs (fine timestamp). The following equation is the mathematical definition to find the timestamp of a hit. [2]

$$\text{timestamp} = tc + f_{\text{TDC}}(\text{tf}, a, b, c, d) \tag{1}$$

where f_{TDC} is defined as:

$$f_{\text{TDC}}(x, a, b, c, d) = \frac{-b - \sqrt{b^2 - 4a(c - x)}}{2a} \tag{2}$$

The parameters a, b, c, and d depend on the previously mentioned TOFPET ID, channel, Time-To-Analogue Converter and Time-To-Digital Converter. These parameters are given and are calculated before data taking. [2]

3.2 Plotting of Coarse and Event Timestamps

My goal was to investigate if the synchronization of event timestamps, made up of the coarse and fine timestamps, were causing the dips in data in the event building. To do so I overlaid two normalized event building graphs of the US system over one another, Figure 3c and a graph of the event using only coarse timestamps instead of event timestamps.

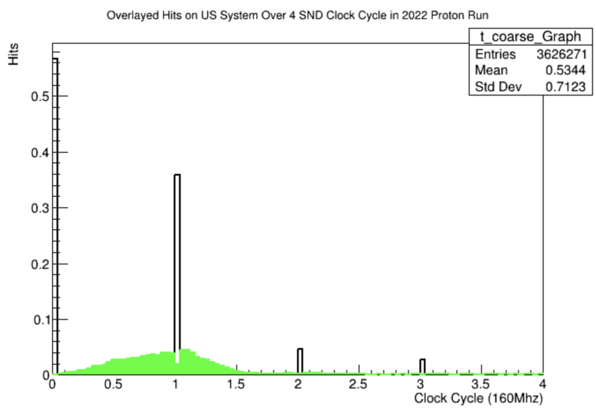


Figure 6: Overlaid normalized event building graphs using event timestamp in green and coarse timestamp in black.

This graph contains the SND clock cycle on the x-axis (still over an entire length of 25ns as previously done as each clock cycle is 6.25ns), and the hits on the y-axis. One will notice the y-axis has fractional hits which isn't physically possible. This is because graph has been normalized in an effort to better compare the data between event timestamp and coarse timestamp.

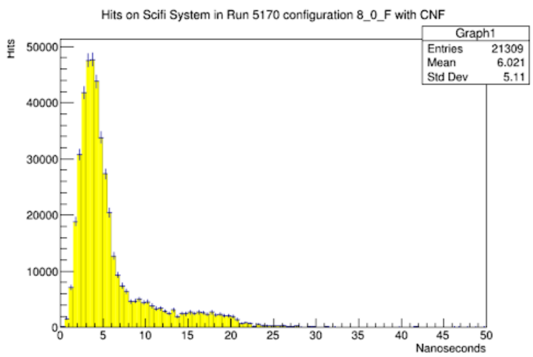
It is clearly shown that the coarse timestamps appear at every SND clock cycle where the original dips in data occurred. This could possibly indicate synchronization issues between different parts of the detector. Fixing these possible issues is beyond the scope of this research, but it was important to discover.

4 Testing Efficiency of Existing Event Building Script

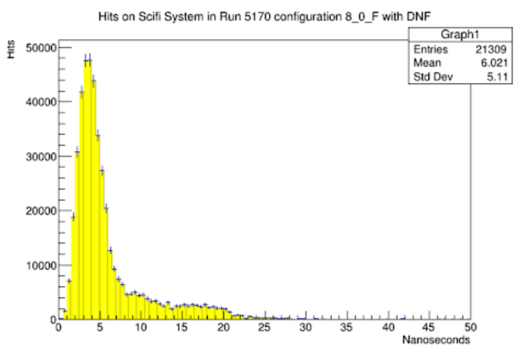
4.1 Testing Event Building Script's Noise Filters

The final part of my research was testing the parameters of already employed event building techniques. To begin, I had to install the necessary software, compilers and modules to be able to successfully run the DAQ server and then the following event building script. The script is useful because it can loop over many possible runs with many specific predetermined parameters including the noise filters, max event duration, hit gap, and clock alignment.

The first part of this project was to test the different possible noise filter configurations. This is very important because noise filters are essential in clearing out useless data so that the useful physics we are searching for is visible. The script had two types of noise filters: a different noise filter that was comprised of a fast noise filter and an advanced noise filter, and a combined noise filter that joined the fast and advanced filters together. I ran the script under the exact same parameters and changed only which noise filter was used for each run, and found the data to be perfectly equal.



(a) One event in the SciFi system using the script and combined noise filter (CNF).

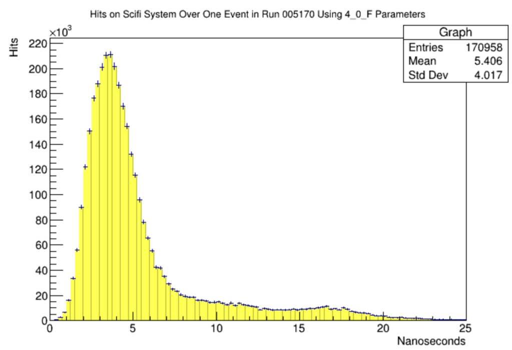


(b) One event of the SciFi system using the script and the different noise filter (DNF).

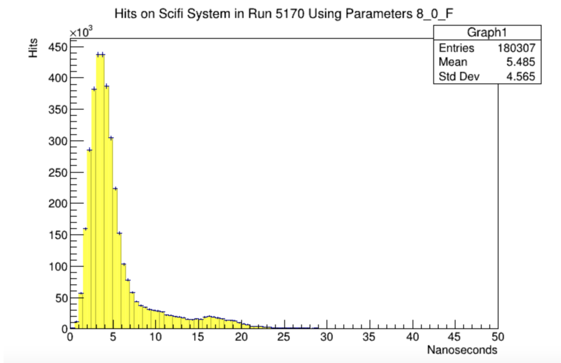
As seen in the titles, the parameters 8_0_F relating to the max event duration, hit gap and align with clock are unchanged in both graphs, while only the respective noise filters are different between the two. These graphs are exactly identical as seen in the data boxes in the top right, confirming that the noise filters are accurate.

4.2 Testing Parameters of Event Building Script

The next step of the script was to test the parameters in an attempt to further investigate the raw data and then see if there is any noticeable inefficiency in the event building. The most important parameter to change was the max event duration. I therefore ran the script with this value at 4 and 8, corresponding to 4 and 8 SND clock cycles. This was then compared to the initial event building I did previously in Figures 3a - 3d to check that there no drastic changes in the raw data. As there are many graphs for this comparison, I will only compare the SciFi graphs and total graphs for both parameters.

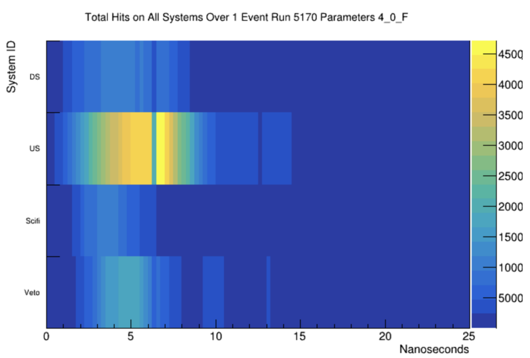


(a) One event in the SciFi system over 4 SND clock cycles.

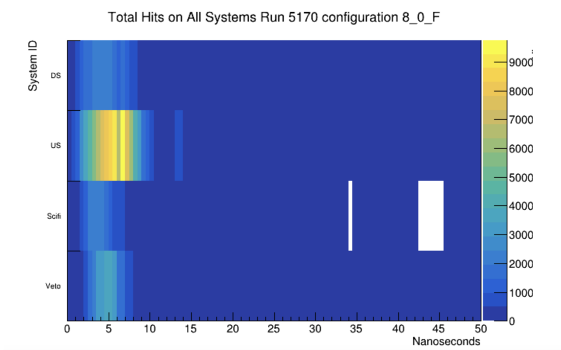


(b) One event in the SciFi system using 8 SND clock cycles.

These plots are very similar, as seen both visually and by the mean value in the data box in the top right. Notice that there are more hits on the graph with 8 SND clock cycles because the event is twice as long. This is the expected and desired result. This means that there are no drastic changes on the raw data level even though we increase the event duration, a necessary data point to verify. The next graphs shown will be a 2D plot of all systems plotted against one another with the different event durations.



(a) One event in all systems over 4 SND clock cycles.



(b) One event in all systems using 8 SND clock cycles.

Once again these are the expected plots as they show similar trends of when the hits are detected, and there are more total hits in the event that is twice as long. Two interesting notes for more analysis are that in the event with 8 SND clock cycles, there are very little hits past the 4th clock cycle and there are exactly no hits for a period of time in the SciFi system. The next steps in this research will be to see if there is a difference in efficiency, specifically in either tracking or veto inefficiency. I began this process by plotting the QDC (Charge to Digital Converter) values for both event duration settings. By analyzing the QDC values one can assess how efficiently the detector detects and records signals for different energies.

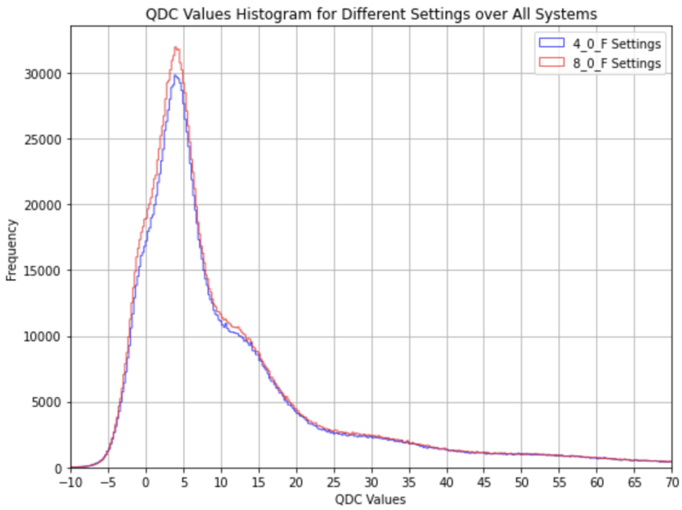


Figure 10: QDC Values for 4 and 8 SND clock cycles from event building script overlaid.

The interesting part of this graph that requires more analysis is the small shoulder that exists around 10-15 QDC values. The expected amount of charge received by the QDCs should be smooth increase and decrease with an obvious peak. Overall, this part of the research reached good conclusions by verifying necessary information but requires necessary further analysis that will be performed over the summer of 2024.

5 Conclusion

My research was completing event building and testing parameters of current event building strategies for SND@LHC to further understand neutrino physics. I discovered that there were possible synchronization issues in how the event timestamps were calculated in the detector, and tested the noise filters and different event length parameters of current event building scripts. This was all possible because of my mentor Simona Illieva who graciously helped teach and guide me through all of my work, and because of Tiziano Camporesi who organized the entire opportunity.

References

[1] LHC Collaboration. Snd@lhc: The scattering and neutrino detector at the lhc, 2023.

[2] Ettore Zaffaroni. SND-SciFi Software Wiki: Raw Data Format. https://gitlab.cern.ch/snd-scifi/software/-/wikis/Raw-data-format, 2024. Accessed: 2024-07-04.