COMPARISON OF TWO DIFFERENT TRIGGERING METHODS FOR THE DEEPLY VIRTUAL COMPTON SCATTERING CALORIMETER AT JEFFERSON LAB

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Chapter 1: Introduction

In order to investigate the characteristics of subatomic particles, particle physicists employ a number of tools. Because the particles are too small to be observed by conventional methods such as optical or electron microscopy, observations are made in the form of scattering experiments at particle accelerators. At Jefferson Lab[1], one method which is currently being used to learn more information about the internal structure of the nucleons is the analysis of Deeply Virtual Compton Scattering (DVCS).

DVCS, like any other accelerator experiment, requires a variety of detectors in order to identify the properties of interest. Perhaps the most important step in acquiring data from the detectors is the application of a hardware trigger.[2] The trigger's job is to check whether the signal is worth taking time to store for later analysis. This discrimination step is a first step in separating the rare DVCS events from the many other types of interactions that can happen. Most importantly, it helps prevent the "dead time" in which the system is being tied up storing data from unwanted processes.

The end goal of the analysis in this project is to explore an alternative main triggering system to be used as a backup should the current method have future technical difficulties, and to find out which method is better for removing as much background as possible without removing the DVCS photon data along with it.

Chapter 2 contains a brief background discussion of the DVCS process and the detectors used at Jefferson Lab to monitor it. It also contains a more in depth discussion of the DVCS trigger system, and its proposed alternative.

Chapter 3 gives additional information about the detector setup for the 2010 experiment, and discusses challenges posed by the instruments involved.

Chapter 4 describes the steps taken to normalize the background for both triggers, and where these backgrounds come from.

Chapter 5 outlines the process of simulating the two different triggers individually. The thresholds are then compared side by side.

Chapter 6 recounts the results of the tests, makes clear which method is the superior triggering system, then explains why these results agree with intuition.

Chapter 2: Motivation

Of the reactions which can provide information about the inner workings of nucleons, Deeply Virtual Compton Scattering (DVCS) is of specific interest due to the wealth of information it can provide about the structure of nucleons. The DVCS process itself ($\gamma*q \rightarrow \gamma q$) is an interaction between a photon, and quark inside a nucleon. This reaction can be measured (along with many others) as a result of ep $\rightarrow$ epγ reactions. The rate at which the reaction occurs is valuable in learning about the transverse spatial and longitudinal momentum distribution of the quarks inside the proton. Specifically, DVCS can be used to create simultaneous spatial and momentum maps of the quarks in the nucleon. These maps work like a tomography, providing many images of the spatial distribution of quarks at different momenta.

The DVCS reaction is currently being employed in multiple experiments at Jefferson Lab. The detectors in Jefferson Lab's Experimental Hall A are designed to accurately identify both the scattered electron, and produced photon from the DVCS process. Combining the information from the photon and electron provides information about the proton which is not directly observed. In order to retrieve data, the setup employs a high resolution spectrometer to detect the electron, a segmented calorimeter to detect the photon, and a trigger system which ensures coincidence between the data recorded on both systems. The layout of these detectors is shown in Figure 1.
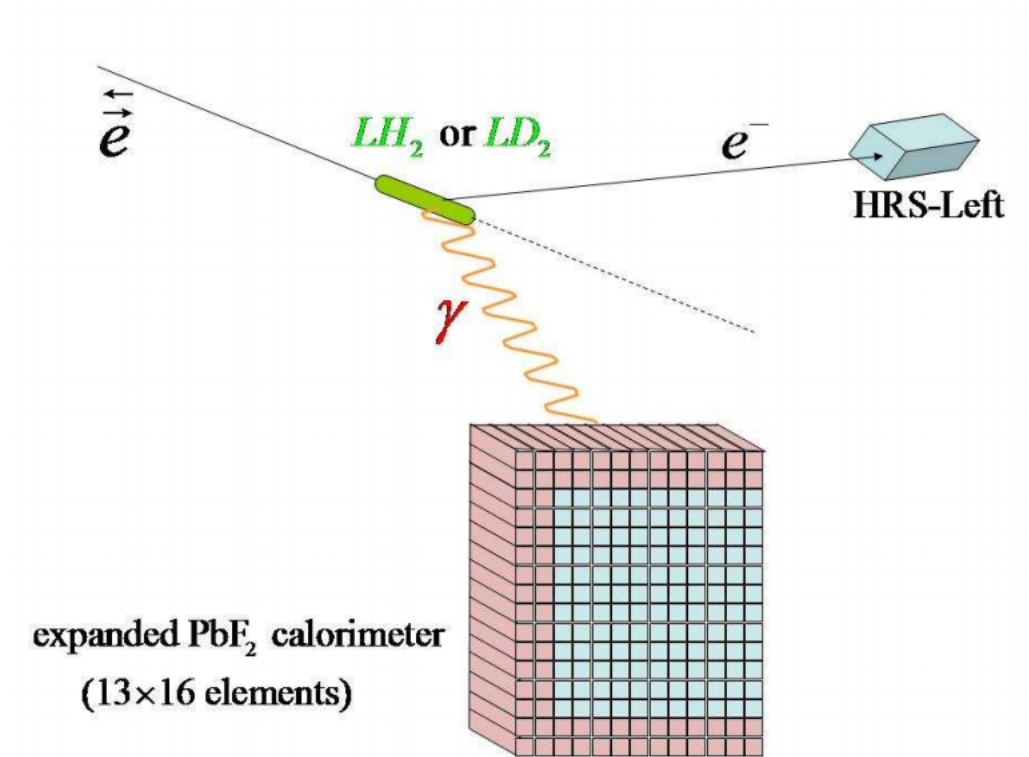
Figure 1: Experimental setup used for the DVCS experiment in Hall A. The scattered electron is detected in the left High Resolution Spectrometer (HRS). The produced photon is detected in a highly segmented calorimeter.[2]

The calorimeter is a 13x16 array of 208 lead fluoride glass blocks, each of which is attached to its own photomultiplier tube. It is designed to catch the photons which are produced by the interaction of electrons with the target. The dense blocks force the photons to fully shed their energy. Thanks to the grid layout, the calorimeter can provide the energy of the particle to within 5% precision, and the location at which photons enter it to within 2 mm.

The triggering system portion of the calorimeter used for the DVCS experiment takes advantage of the segmentation, measuring energy shed into 2x2 block groups, called towers. This method is used in order to account for the fact that multiple high energy

photons could shed their energy across multiple blocks at nearly the same time. By using the 4 block towers, the trigger can monitor energy shed across multiple blocks without needing to look at signal from all 208 blocks in tandem. Data from the towers as opposed to blocks also provides a more accurate indication of a single particle's shed energy. The segmentation allows the trigger to make a more accurate decision whether or not to store an event, based on both the photon's direction, and its energy. This more accurate selection method helps reduce the dead time the detectors experience whenever data must be stored to memory.

The DVCS trigger immediately converts each block's signal into a digital value. These digital values are then summed into towers and sent to field programmable gate arrays (FPGA),[3] which only allow the data to be stored if a tower's value has exceeded a given threshold. This method is illustrated in Figure 2.

While this trigger method worked well in experiments in 2005, it is natural to ask whether another method could be used in its place. At no time is this question more apparent than when the trigger experiences technical difficulties, as it was at the time of this project in 2014. One of the simplest alternatives to the tower trigger method is to apply a trigger to the sum of the signal from all 208 blocks. In this case, the photon sum trigger adds all 208 block's analog signals before applying a threshold to the amplitude of their combined ARS wave. This method is illustrated in Figure 3.
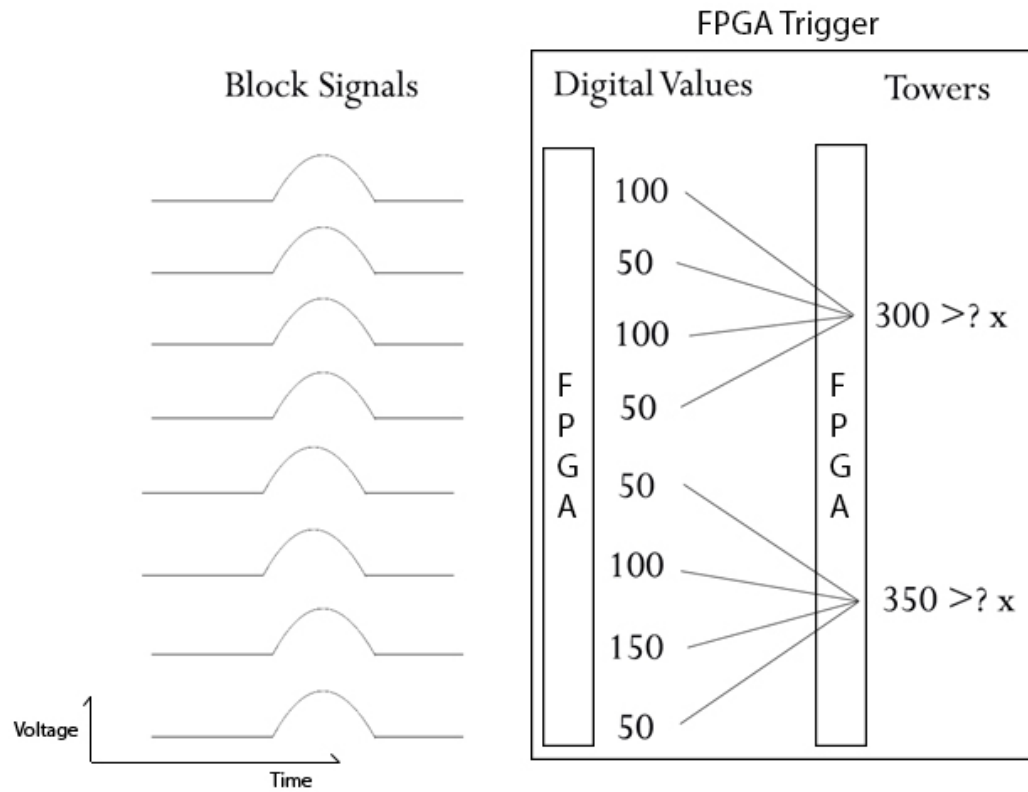
Figure 2: Diagram of the main DVCS trigger. FPGA's are used to work with the digital values for energy deposited into each block. In this example, 8 blocks' digital values are read before being summed as groups of 4. Each group of 4 creates a tower which can then be compared to a threshold value.
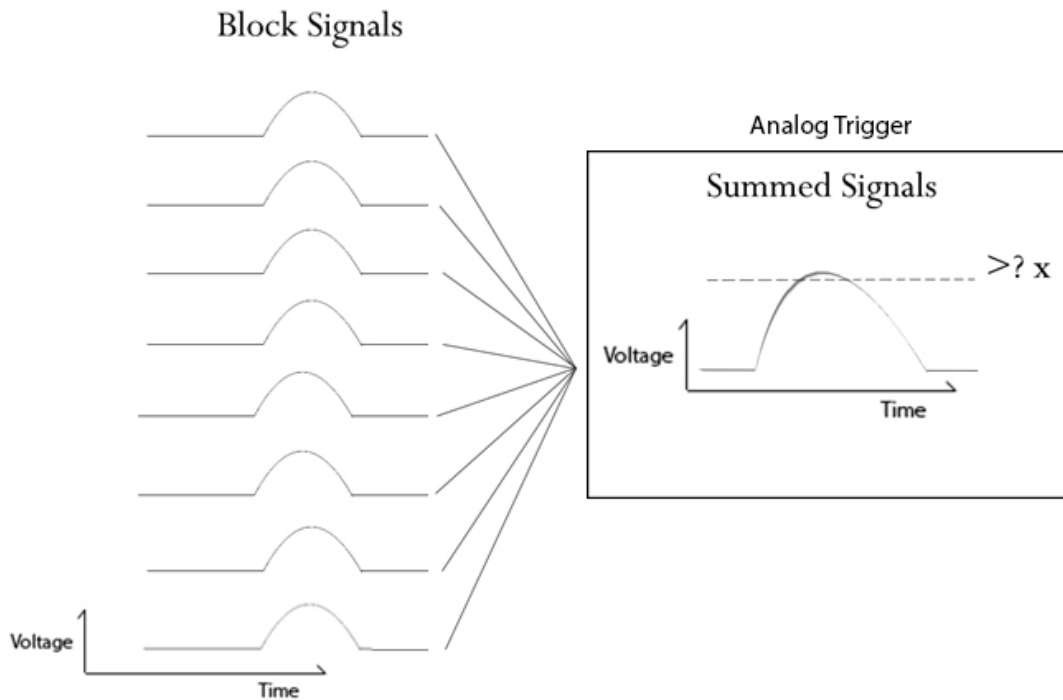
Figure 3: Diagram of the alternative analog trigger studied in this project. All blocks signals are summed into a single voltage to which a threshold is applied.

In order to compare the two competing trigger methods, equivalent thresholds were applied to the total energy entering all 208 blocks at each nanosecond, and the greatest summed tower signal. These two triggering methods were used to simulate the effects of triggers when they were applied to data that were taken without a physical trigger system during the 2010 experiment. This study is discussed in depth in this document.

Chapter 3: Experimental Setup

Data for this experiment were taken in Jefferson Lab's experimental Hall A. A polarized electron beam was aimed at a 15 centimeter liquid Hydrogen or deuterium target. A High Resolution Spectrometer (HRS) was positioned at the angle which electrons would be cast off from Deeply Virtual Compton Scattering (DVCS) interactions. The DVCS calorimeter was placed at an angle intended to capture photons from the same process.

The calorimeter is an array of 208 lead fluoride glass blocks. Each block is attached to its own photomultiplier tube, whose signal is sent to an Analog Ring Sampler (ARS, shown in Figure 4)[4] and digitizer to await a corresponding signal from the spectrometer.
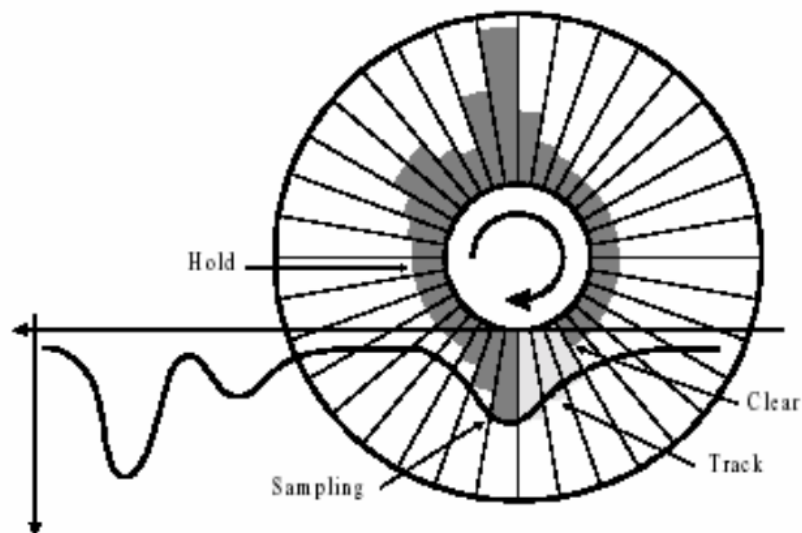

Figure 4: Diagram showing how the circularly oriented capacitors of the analog ring sampler produce a sample voltage difference vs time graph.[4]

Each block in the calorimeter sends its signal to its own ARS, which continuously samples at 1 GHz. When the energy deposited in the block is plotted vs elapsed time, a useful plot is obtained, known as an ARS wave. If an electron of interest was detected in the spectrometer, the calorimeter signal was digitized, saving the past 128 ns of energy information stored on the capacitors of the Analog Ring Sampler. If no signal from the spectrometer arrived, the capacitors were automatically overwritten with new energy information. By waiting for the signal from the sensitive spectrometer before saving any information, a large amount of events can be rejected before any data is actually stored.

Saving the time dependent ARS wave gives information that can become relevant when the data are processed at a later time. Time dependent waves can be used to resolve pile ups, when multiple events are caught in the same 120 ns window. A sample ARS wave containing pile ups is shown in Figure 5. Unfortunately, storing data in this form also requires a lot more memory. The 208 ARS produce 40 kB of data per event.[5] With data-taking periods containing hundreds of thousands of events, this further increases the necessity of only taking the time to store the right data. Figure 6 shows the dead time introduced at different points in the triggering process. It is important to note that actually storing data takes nearly 1000 times longer than checking for detector coincidence.
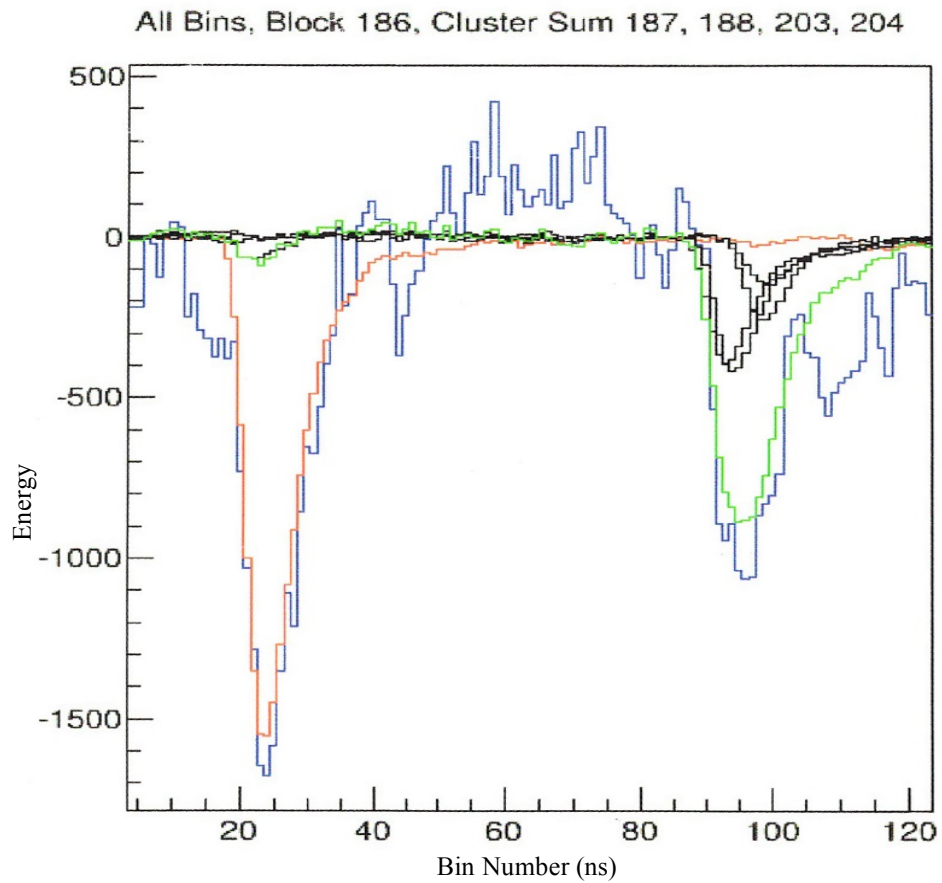
Figure 5: Sample Analog Ring Sampler (ARS) signal showing pile up. One photon is detected around 25 ns, while the second is detected around 95 ns. The blue line is the total signal, where the other color lines are single block signals.
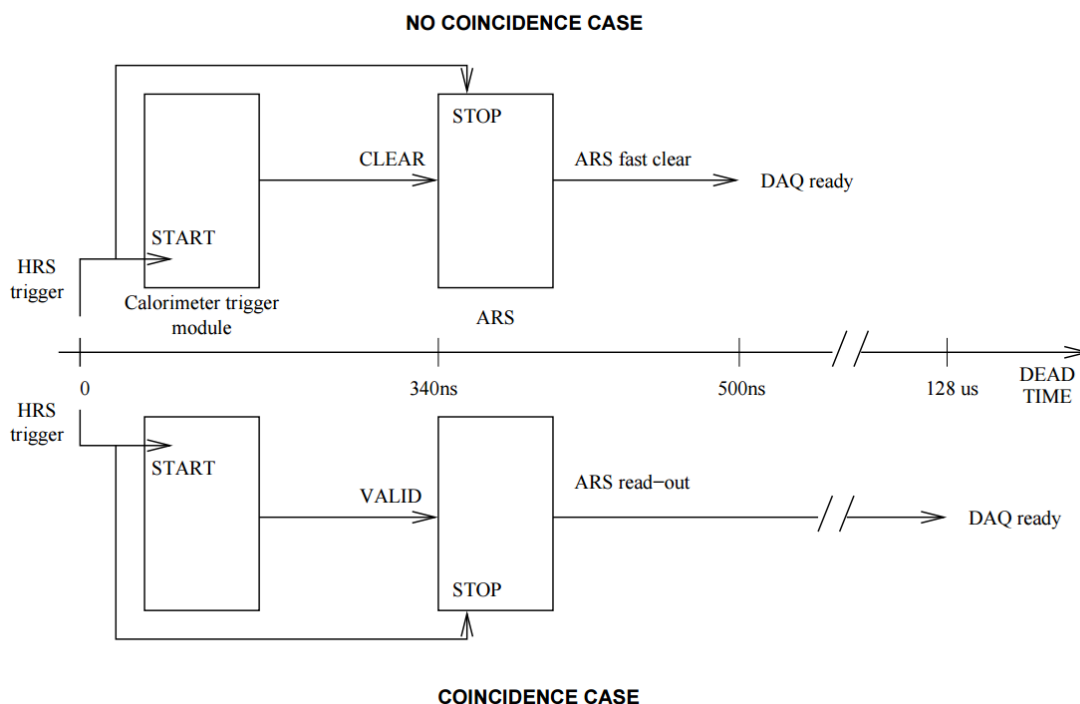
NO COINCIDENCE CASE

Figure 6: Approximate times associated with different parts of the triggering process. In the case of coincidence, it takes 128 μs to find a coincidence between the HRS and the calorimeter, and to save the corresponding signal. When no coincidence is found the ARS is cleared, and is ready to investigate a new event after only 500 ns.[5]

For this study, a total of eight separate data taking periods were tested. Run 9211 was studied in the most depth due to the lack of any noted issues during its collection. The data was taken on Friday December 3, 2010 with a liquid hydrogen target. The electron beam energy was 5.5 GeV with a current of 2.9 μA. The calorimeter was positioned 1.1 m from the target at a 14.78 degree angle with respect to the beam line. The spectrometer detected electrons at 21.49 degrees with respect to the beam line with momentum of 2.591 GeV/c.

The stored data were accessed, and run through software filters programmed in ROOT-cern[6] in order to simulate the effects of different triggering methods that could be implemented physically.

Chapter 4: Data Analysis

In order to properly calibrate the calorimeter, a number of background subtraction steps were taken. During data taking, each individual block's photomultiplier tube had been given a different potential in order to create a uniform sensitivity across the slight variations in electronics. Due to these adjustments, each of the 208 block's signals needed to be adjusted to a common zero in what is called a pedestal correction. In order to find the most accurate average, a set of data was chosen in which the electron beam was turned off. This reduces the number of high energy particles that enter the detector to a minimum. Figures 7 and 8 show an early simulation of the digital energy values of the towers-based summing method before and after the pedestal correction for run 9211. In Figure 8, there is a noticeable background which makes the towers on the right side of the graph have much higher energy. This is due to their closer proximity to the beam dump (see Figure 1), and is one of the major reasons why the trigger system must be implemented.
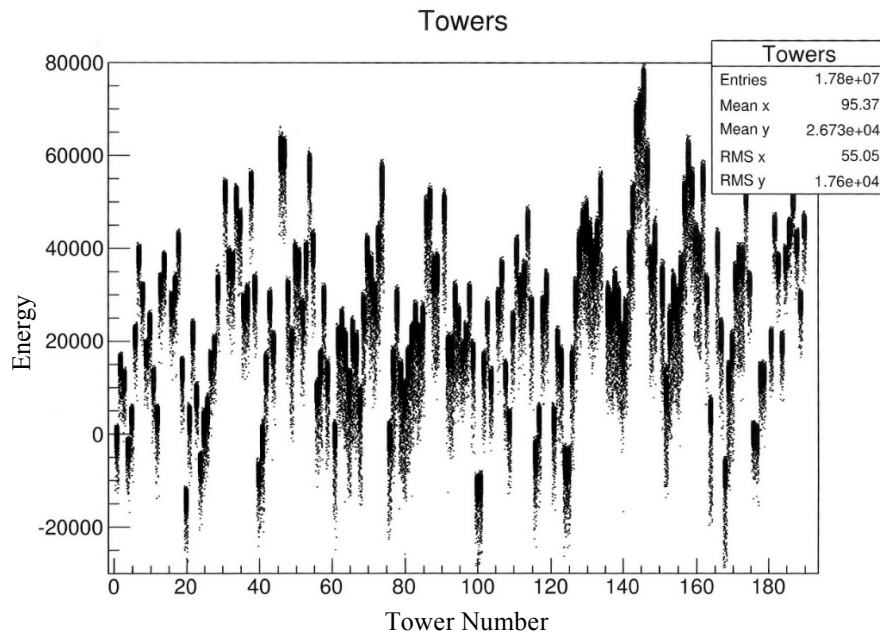
Figure 7: Total integrated charge in each tower cluster for run number 9211 with 18 million entries, before any calibration.
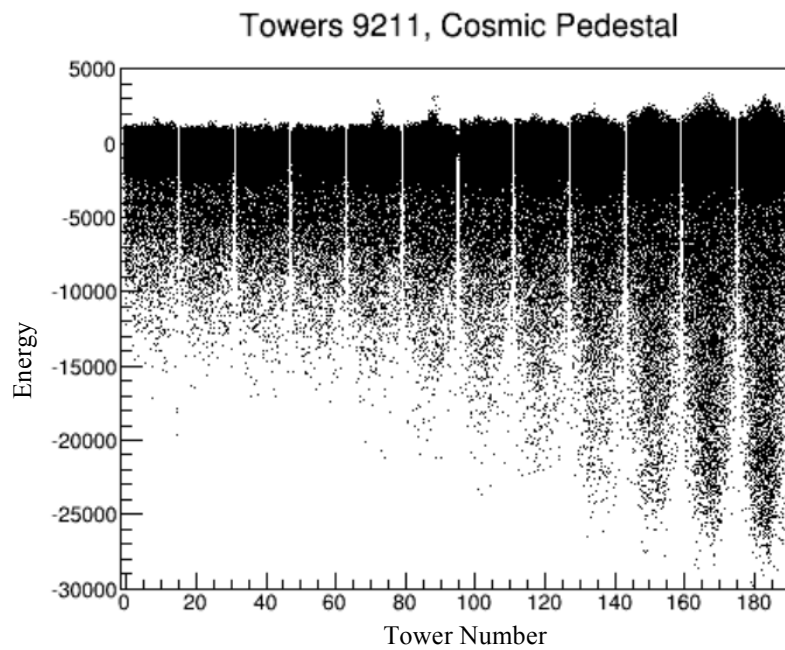

Figure 8: Total integrated charge in each tower cluster for a run number 9211 with 18 million entries, after beam off pedestal correction and proper block number order.

For simulating the analog photon summing method, an additional step of calibration was needed. Since signals from each block had been stored on capacitors before being written to data, a small amount of charge decay had occurred throughout the 120 ns sampling window. However, when all 208 blocks signals were summed, the decay compounded and the amount of energy loss was great enough to overwhelm the incoming particle signals. In order to address this, the average decay in charge was calculated for every nanosecond in every block's signal by finding how far each bin tended to vary from zero. This correlated to a correction of the charge decay of every capacitor individually. Figures 9 and 10 show an example of analog summing before and after these calibrations.
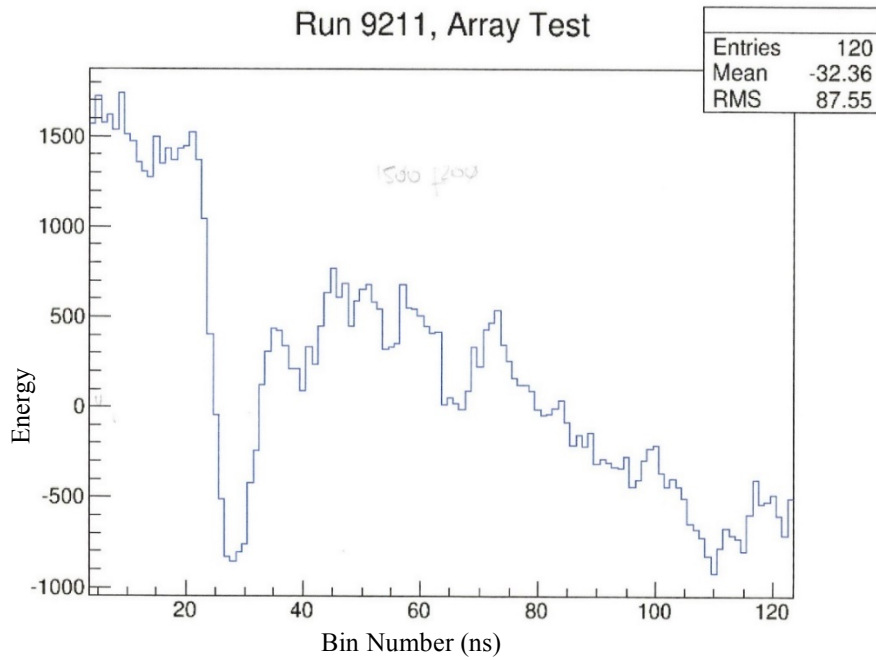
Figure 9: Summed 208 block signal over time for one entry in run number 9211, without bin by bin averaging.
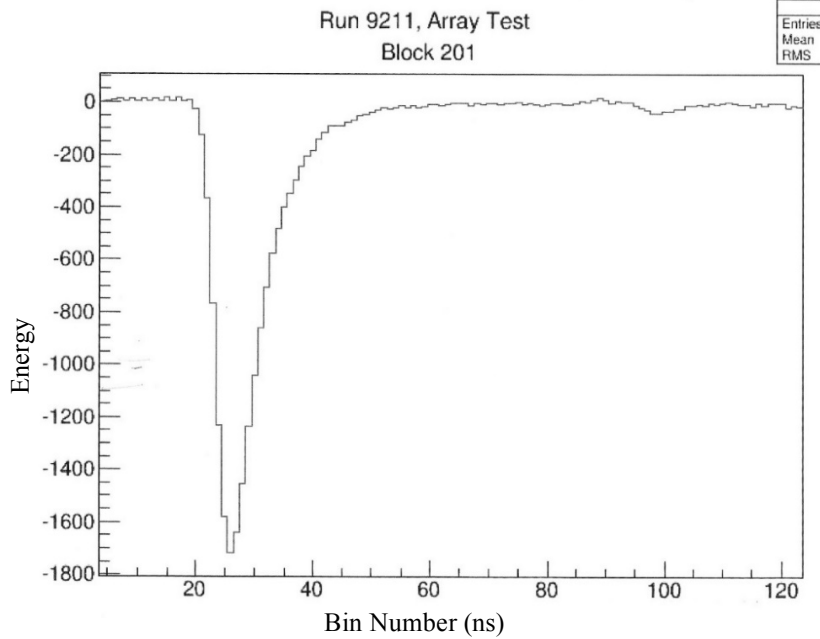

Figure 10: Single block's signal for the same time period in run number 9211, corrected for charge decay bin by bin.

Chapter 5: Threshold Simulations

To fully simulate the tower sum method, the pedestal and charge decay-corrected signal of each block was integrated over the 120 ns window recorded. The blocks' total energies were then summed as sets of four to create the aforementioned towers. The tower with the largest summed energy was identified. A threshold could then be applied by the FPGA trigger to only select entries which have at least one tower over a certain energy. Figure 11 shows the distribution of block energies for an event that would pass a tower threshold.
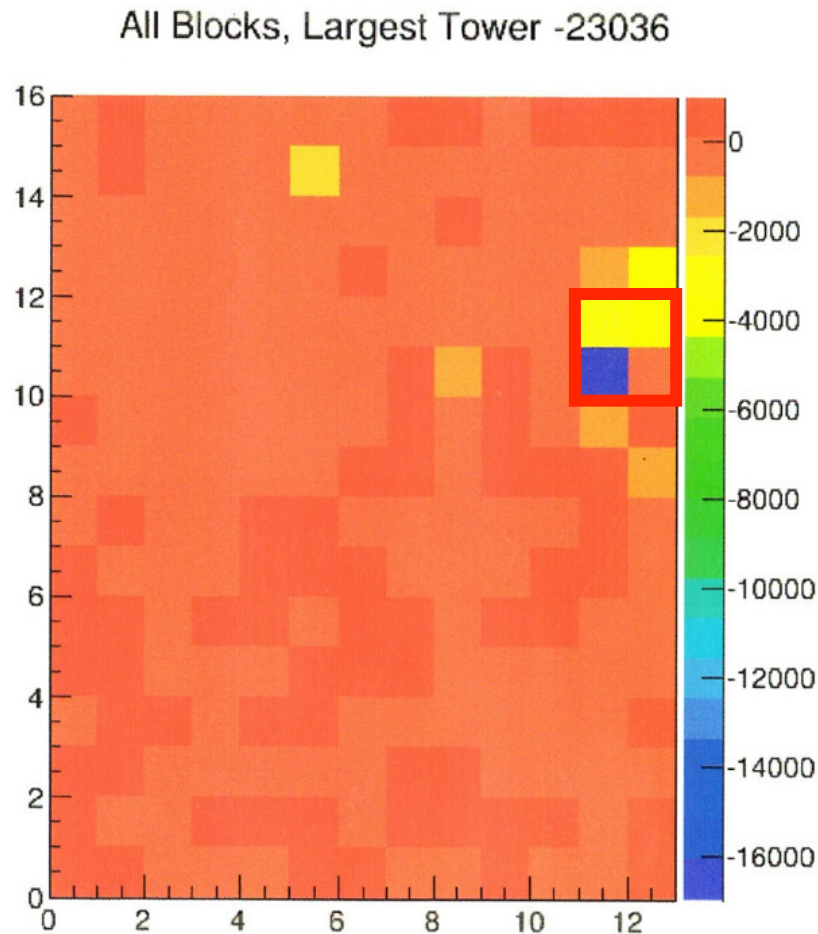
Figure 11: A block by block display of energies collected during an event. Although there is clearly more than one particle interacting with the detector in this time frame, the red box highlights the largest energy tower (2x2 block group) which would be used to identify this event.

The analog sum method used the ARS energy output more directly. After pedestal and decay corrections, all of the blocks were summed together bin by bin, resulting in a single 120 ns wave. In this method, a threshold was applied to the maximum bin value, rather than an integrated total energy. This is the equivalent of applying a minimum amplitude on the graph produced by the ARS output. Like the tower method, events can then be identified by the value of their maximum ARS wave

amplitude. Figure 12 shows an ARS wave with a large enough amplitude to pass the threshold.
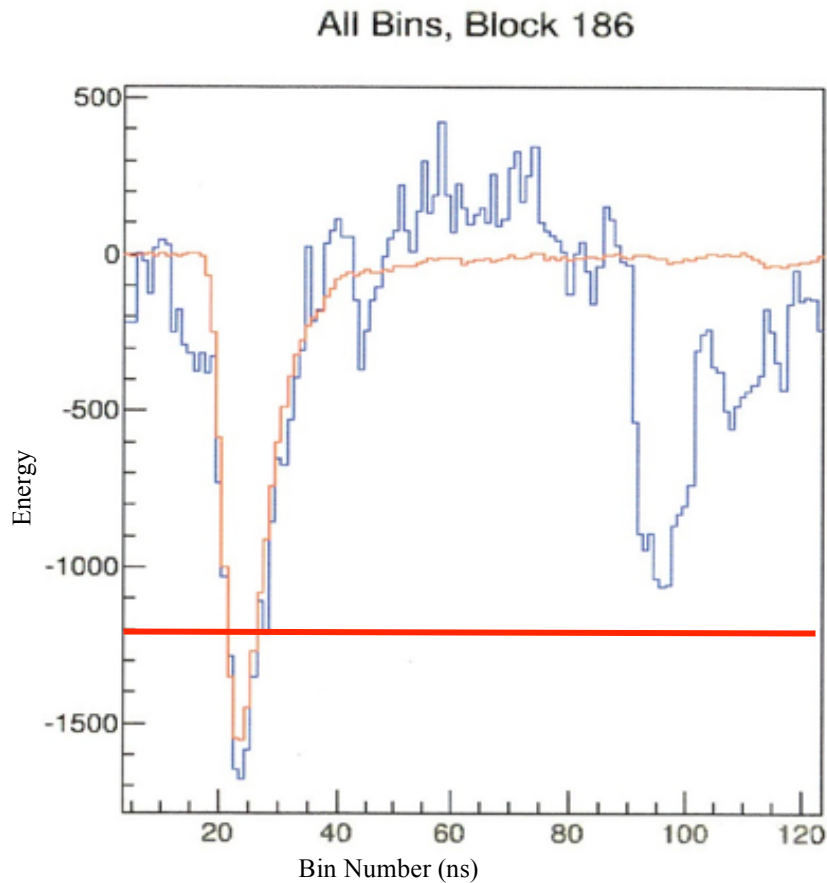
All Bins, Block 186

Figure 12: Summed analog ring sampler wave for an event with a high amplitude. The red bar indicates where a threshold could be placed.

By graphing all of the entries' maximum amplitudes as a function of their largest tower energy, one can see both thresholds on the same plot. Figure 13[7] uses this method, applying both trigger methods to the same data, and showing where a 1 GeV threshold would remove values. A Monte Carlo simulation performed for an earlier experiment provided the expected energies of photons created by DVCS interactions. The energy distribution is shown in Figure 14.[1] A 1 GeV threshold was chosen in

order to ensure that a majority of the photons in this energy distribution would pass the
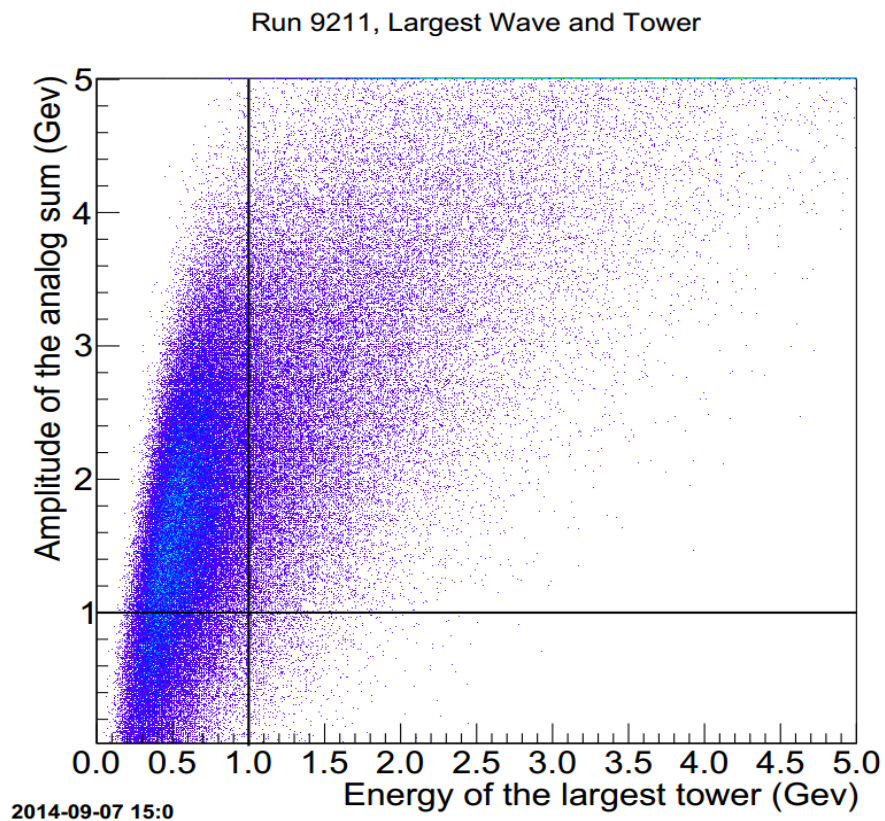
thresholds.

Figure 14: All entries in run number 9211 with their largest amplitude values as a function of their largest tower values. 1 GeV thresholds are marked for both axis.[6]
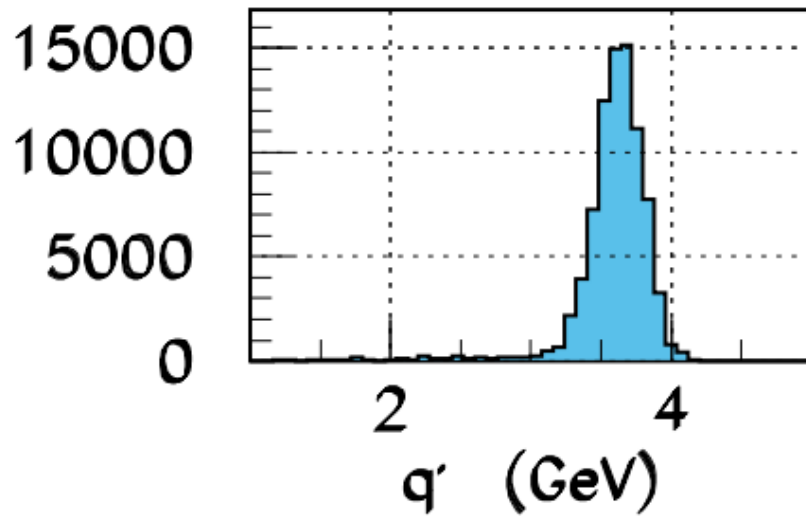
Figure 13: Expected energies of photons (q') created by DVCS interactions from a 6 GeV electron beam.[1]

With both simulated thresholds applied to the data, every entry was then sorted into one of four categories:

1. Entry passed neither threshold.

2. Entry passed only the tower threshold.

3. Entry passed only the amplitude threshold.

4. Entry passed both thresholds.

100,000 entries from run number 9211 were sorted into these four categories with a 1 GeV threshold, and the result of this sort is displayed in Figure 15.
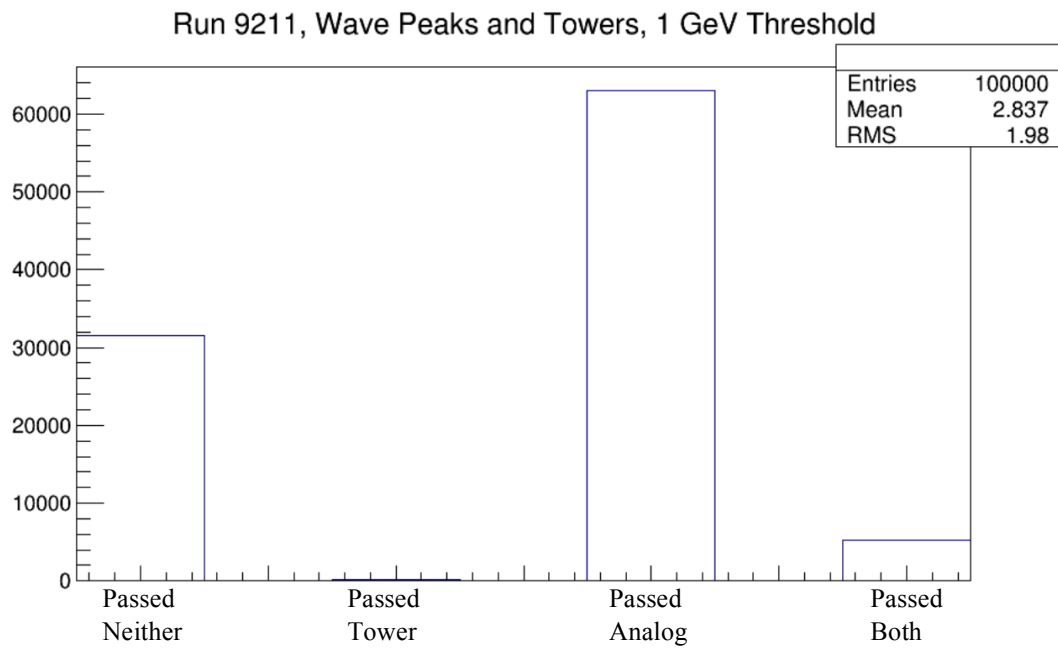
Figure 15: 100,000 entries in run 9211 sorted by which thresholds they would pass at 1 Gev.

Chapter 6: Conclusion

After proper background subtraction and analysis, both methods of applying thresholds to filter data have been shown to be capable of removing lower energy events. However, after choosing a 1 GeV threshold for both methods in order to reproduce the trigger of DVCS photons for a 6 GeV electron beam, the entry sorting shows a clear difference in the amount of entries that are removed in the filtration processes. The tower filtration method removed far more entries than the analog sum filter, making it the superior method to reject events which do not contain high energy photons. This result agrees with intuition, as the analog sum trigger must account for background generated by all 208 blocks, whereas the DVCS trigger need only account for 4 at a time. The background for the summed 208 blocks became so large that it became difficult to detect when photons entered the detector above the noise. Despite being outperformed by the DVCS trigger, the analog trigger can still be used as a backup in case of a failure in the current DVCS trigger system.

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