PRECISION VALIDATION OF THE PERFORMANCE OF THE OTMB SYSTEM FOR THE CMS MUON SYSTEM

An Undergraduate Research Scholars Thesis

by

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Major: Physics

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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Precision Validation of the Performance of the OTMB System for the CMS Muon System

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The Large Hadron Collider (LHC) is the world's highest energy particle accelerator designed to produce collisions of proton beams to study the fundamental properties of matter. The Compact Muon Solenoid (CMS) is one of the large general-purpose detectors at the LHC. Physicists analyze data collected from CMS to identify interesting physics events and compare the experimental results with theoretical predictions. It is built to identify and reconstruct parameters of particles produced in proton-proton collisions and uses a system of sub-detectors such as the tracking detectors, calorimeters, and the muon detectors. The large amount of data per collision from each sub-detector and the high rate of collisions make it unrealistic to save data for every proton-proton collision. The trigger system in CMS is designed to make fast decisions for each collision event and identify them as interesting physics or as background with high effectiveness.

The CMS Muon system is designed to identify and reconstruct properties of muons, elementary particles that often signify a potentially interesting collision, and it is important to ensure that the muon trigger decisions are efficient and reliable. The CMS muon trigger test stand at Texas

A&M is used for validating the performance of the muon trigger algorithm. This test is done by transmitting realistic collision data to the Optical Trigger Mother Board (OTMB) through a muon detector emulator board in a controlled way. The software that controls the test stand injects event data from full CMS detector software simulations and verifies that the trigger OTMB decisions in the real hardware match with the trigger decision predictions in simulation. Using the test stand, tools for precise OTMB measurements were developed and tested to verify the trigger algorithm and to validate the performance of the CMS muon trigger system.

DEDICATION

To my parents, loved ones, and mentors who have always pushed me to be better.

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NOMENCLATURE

CERN	European Council for Nuclear Research
SM	Standard Model
BSM	Beyond the Standard Model
LHC	Large Hadron Collider
CMS	Compact Muon Solenoid
HL-LHC	High Luminosity Large Hadron Collider
ECAL	Electromagnetic Calorimeter
HCAL	Hadronic Calorimeter
p_T	Transverse Momentum - A particle's momentum that is perpendicular to the beam direction.
CSC	Cathode Strip Chamber
DT	Drift Tube
LCT	Local Charged Track
CLCT	Cathode Local Charged Track
ALCT	Anode Local Charged Track
GEM	Gas Electron Multiplier
Trigger	The process to selectively keep the most important data from events
OTMB	Optical Trigger Motherboard
FPGA	Field Programmable Gate Array
BX	Bunch Crossing
CC Code	Comparator Code
GUI	Graphical User Interface

1. INTRODUCTION

Physicists have been able to explain three of the four fundamental forces of the universe using methods of Quantum Field Theory. This knowledge is encompassed in the Standard Model (SM) of particle physics [1], which explains how particles interact with each other. Standard Model predictions have received a strong confirmation with the discovery of the Higgs Boson by CMS and ATLAS, another detector at the LHC, in 2012. Unfortunately, the SM does not explain certain phenomena, such as gravity and dark matter, so theoretical extensions of the SM are proposed in attempts to explain the unexplained phenomena [2]. Besides looking for physics that exist Beyond the Standard Model (BSM), particle physicists continue to analyze the predictions of the SM by conducting precision analyses using data that is collected from high energy particle colliders such as the LHC operating at CERN in Switzerland.

1.1 Detector Overview

Proton collisions at the LHC can convert the energy of the colliding protons into new heavy particles. These particles decay through cascades giving rise to potentially hundreds of particles per collision. The bunch crossings (BX) at the LHC occur every 25 ns with approximately 10^{11} protons in each bunch, producing an average of 40 proton-proton collisions per BX [3].

The High Luminosity-LHC (HL-LHC) is an upgrade to the current LHC to increase the intensity of the proton beams. This upgrade will dramatically increase the size of the dataset containing potentially interesting high energy collisions. When this upgrade happens, the detectors in place need to operate with enough efficiency to keep up with the new demand.

CMS is one of the large general-purpose experiments at the LHC and is composed of several layers of sub-detectors. It performs precision measurements to identify interesting physics events and compares the experimental results with theoretical predictions. There are several sub-detectors within CMS, as seen in Fig. 1, including the Pixel tracking detector, the Silicon tracker detector, the Electromagnetic Calorimeter (ECAL), Hadronic Calorimeter (HCAL) and the Muon system.

Figure 2 demonstrates how different types of particles interact with the different sub-detectors: the tracker identifies the charged particle tracks; the calorimeters measure the energies of particles; the 3.8 Tesla magnetic field from the superconducting solenoid magnet bends the trajectories of charged particles from the collision point; the muon system detects muons. The work that is presented in this thesis focuses on the muon system which is found at the very outermost layer of CMS.

Muons are charged particles with properties similar to those of an electron but with about 200 times more mass. The extra mass means they interact more weakly with matter which allows them to pass through more material than an electron, such as several meters of rock or iron. Placing a muon detector system at the outer layer of CMS is ideal as the massive core of CMS stops other types of particles while allowing the muons to pass through.

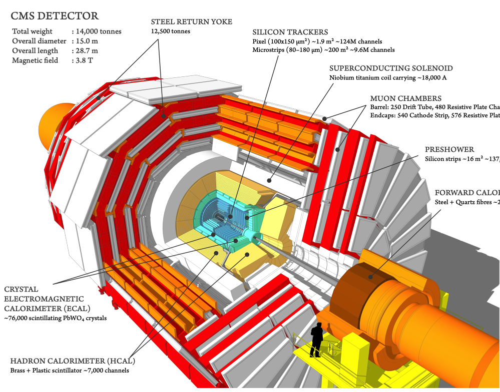

Figure 1: Layers of CMS about the central interaction point (IP) [4].

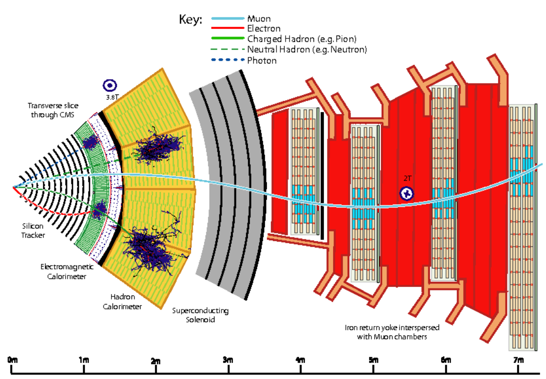

Figure 2: The layers of the sub-detectors in CMS and the types of particles that each layer measures [5].

1.2 Muon System Overview

The muon system is an intricate detector with a purpose of detecting muons and measuring their trajectory and momentum. Many interesting physics processes contain muons in decay channels making them a good tool to identify potentially interesting events [6]. The muon system is located directly outside the 3.8 Tesla solenoid primary magnet of CMS [7]. This design is intentional for the purpose of measuring the transverse momentum of muons (p_T), the muon's momentum perpendicular to the beam direction, as they travel through the different sections of the system. Because the curvature of a charged particle passing through a magnetic field is inversely proportional to its momentum, a particle with greater momentum creates a straighter path. Conversely, if a particle has less p_T, its path is more curved. This is an important characteristic that the detector uses to measure the muon's momentum as it passes through the detectors.

The muon system has two main parts, the barrel and the endcaps, which contain several different types of sub-detectors. The barrel is on the cylindrical section of CMS, where the Drift Tube (DT) muon detectors are located [6]. The Cathode Strip Chambers (CSCs) and Gas Electron Multipliers (GEMs) are the muon detectors located in the vertical endcaps of CMS where the particle flux rate is higher. DTs, CSCs, and GEMs are intended for spatial measurements to reconstruct the muon's path and determine its momentum. The Drift Tubes are a system of long metal tubes that are filled with a gas mixture, and each tube has an anode wire in the center [6]. A muon passing through the gas ionizes the gas molecules. Then, the free electrons produce additional ionization in the gas as they accelerate toward the wire by the strong electric field. The resulting avalanche of charge arrives on the wire and creates a pulse that is registered by the detector electronics. The operation of CSCs are similar in principle, with large flat planes instead of tubes, and CSCs detect the charge deposits on its cathode strips as well as on the anode wires. GEMs are discussed in detail in Section 1.2.2. The CMS Muon system also has a detector system called Resistive Plate Chambers (RPC), which is not discussed here in detail.

1.2.1 Cathode Strip Chamber

Each CSC consists of six layers, where each layer has cathode strips and anode wires that are placed perpendicularly to each other. When a charged particle passes through a CSC, gas molecules are ionized and the charges that are released create a pulse on the anode wires and the cathode strips. Figure 3 shows the cross-section of a layer in a CSC which demonstrates a muon passing through and creating an avalanche.

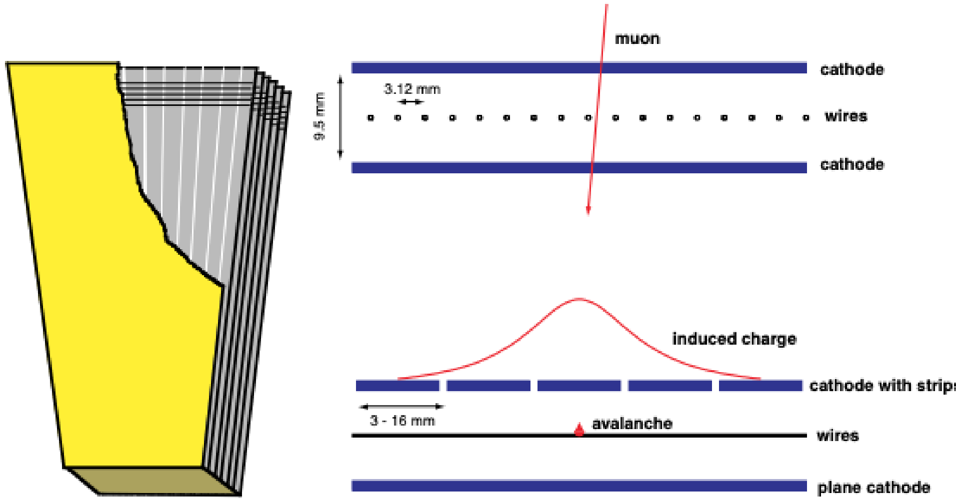

Figure 3: Gas molecules ionized by a passing particle lead to a charge avalanche on the anode wire and a corresponding pulse on the cathode strips [8].

All of the CSC chambers consist of 80 strips with the exception of the innermost CSC chambers identified as "ME1/1" which have 112 strips per layer. The ME1/1 type is a special chamber because of its location close to the beam results in high particle flux rates. With simple measurements on each strip, CSCs can achieve half-strip precision using electronic comparator circuits. Once the strip with the highest charge is identified, determining which neighbor strip (to the left or right of it) has more charge indicates which half of the peak strip is closer to the muon's path. CSCs use this method to define the "half-strip" as the fundamental unit of measure for the muon position in the cathode plane. Figure 4 can illustrate the locations of the aforementioned chambers in CMS.

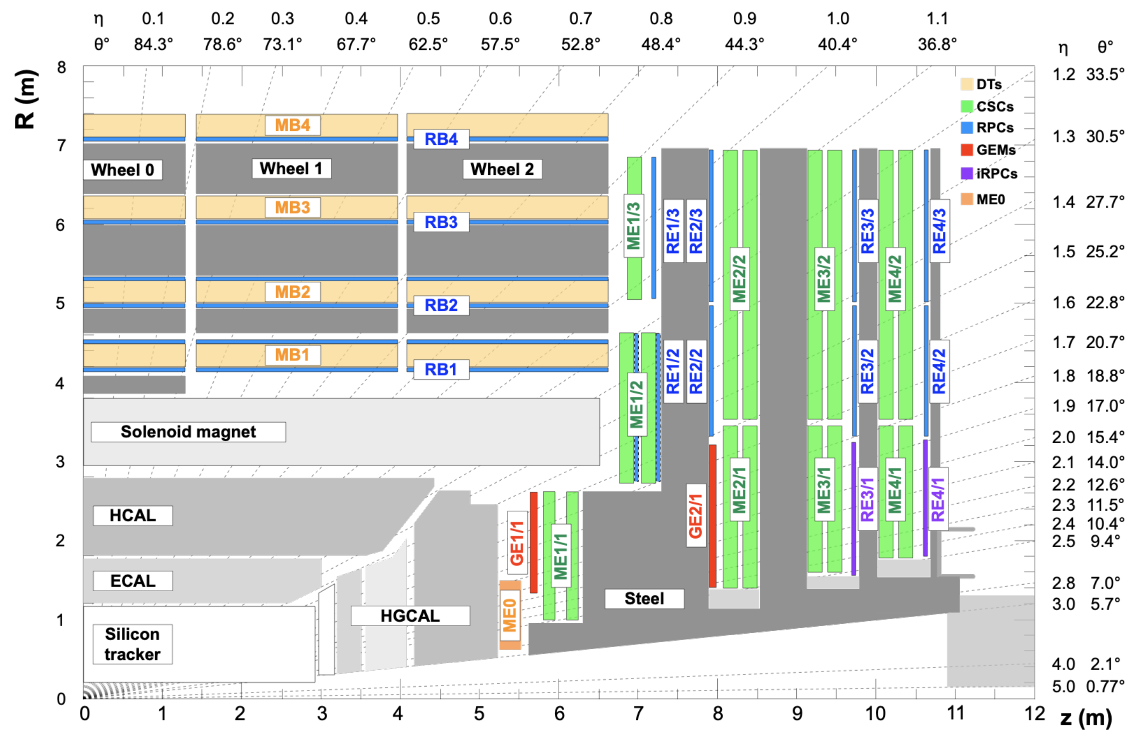

Figure 4: $R - z$ cross-sectional view of a quadrant of CMS. In the bottom left corner, $(0, 0)$, is the collision point. Located in orange, and labeled MB (muon barrel) are the drift tubes. The CSCs are in red labeled ME (muon endcap) [9].

1.2.2 Gas Electron Multiplier

The Gas Electron Multiplier sub-detector is based on a newer technology that has been designed to add redundancy to the muon system in the region with the highest particle flux. Similar to CSCs, GEMs are capable of operating at high particle flux rates. Placing GEMs next to the CSC sub-detectors improve the location and angle measurements of the muon path. The first GEM sub-detector, GE1/1, is installed in front of the CSC sub-detector ME1/1, as shown in Fig. 4. The second GEM sub-detector, GE2/1, is to be installed next to the CSCs in ME2/1 during 2024-2025.

Each GEM chamber consists of three layers of GEM foils and is filled with a gas mixture (Ar/CO_2 70:30) [10]. There is a high voltage that is applied between the top and bottom layers of a GEM foil and the foils themselves have regular holes that the ionization electrons can pass through. The gas is ionized as a muon passes through, and the free electrons are directed toward the holes in the foil where they undergo high acceleration creating further ionization and forming an avalanche. This effect gets amplified as the process repeats when the charged particles pass through the three foils as shown in Fig. 5. This amplified signal produces a signal on the strips. To provide adequate redundancy and high operational efficiency, two GEM chambers are stacked on top of each other to form a superchamber. The GE1/1 station consists of 36 superchambers on each endcap [11].

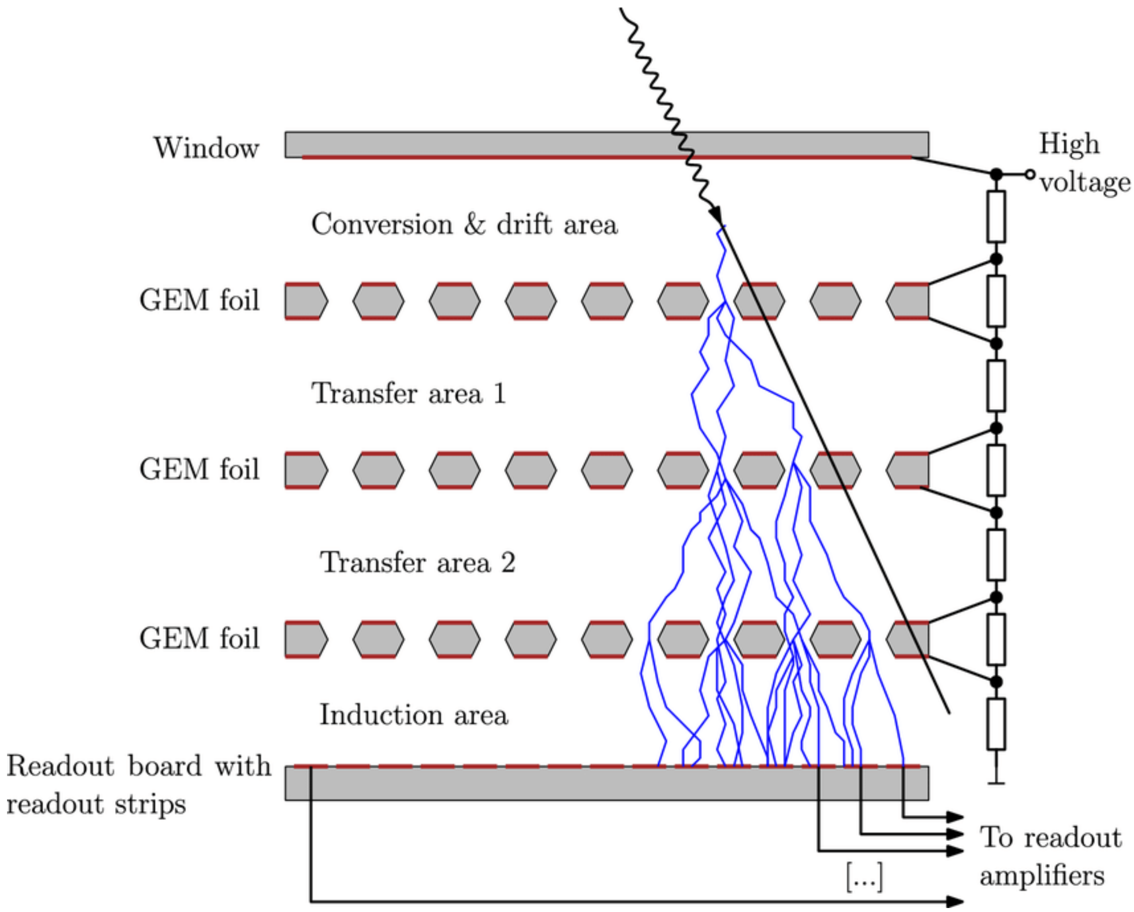

Figure 5: Charge amplification in a GEM detector leads to electronic pulses on the readout strips that indicate the location where a particle passes through [12].

1.3 CSC Trigger System

Since the data coming from the sub-detectors are so large and the rate of collisions is so high, it is impossible to save data for every collision. Instead, only the most interesting events are identified for analyses. The trigger system in CMS is designed to make fast decisions for each collision event and identify them as interesting physics or as a background with high effectiveness [8]. For example, an interesting event to save is one where a Higgs boson decays to four muons. While a Higgs boson cannot be directly detected, the muons from the Higgs decay can be detected, and that event can be triggered on in order to preserve the data for future analyses.

The first step in the trigger process is identified as the Level 1 Trigger (L1), as illustrated in Fig. 6. For triggering on muons, fast algorithms are used to identify muon candidates using the timing and coordinate data that is read out from the muon detectors [11].

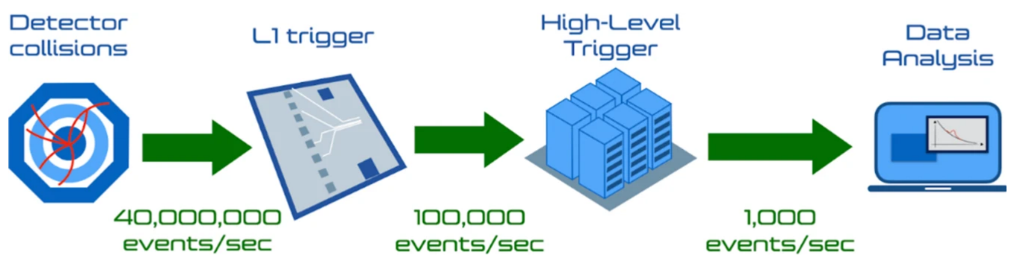

Figure 6: The trigger processing levels in CMS.

To achieve high background rejection, a muon candidate in the CSC trigger system is required to have hits on at least four of six layers. If enough charge deposition is registered on a halfstrip to surpass a specific threshold, the electronics are activated to record the location of the hit for each layer.

Muon trigger candidates are saved as Local Charged Tracks (LCTs) which are comprised of Cathode Local Charged Tracks (CLCTs) and Anode Local Charged Tracks (ALCTs). While the CLCT and ALCT are both used to record information about the deposited charge, they have different precision. CLCTs precisely record spatial dimensions while ALCTs precisely record timing information. For each CSC chamber and in every bunch crossing, the algorithm that is currently used allows for up to two CLCTs to be preserved as CLCT0 and CLCT1 and up to two ALCTs to be preserved as ALCT0 and ALCT1. They are designed to record the two best muons in the chamber for each bunch crossing. The trigger processing logic stores the CLCT and ALCT data as LCTs and sends it upstream to another module in the trigger process.

1.3.1 GEM-CSC Triggering Process

Level-1 trigger algorithms are designed to make fast decisions with limited information which usually leads to most events that are selected from the L1 trigger decision being discarded at later stages. This is because those trigger decisions do not truly contain energetic muons. Adding GEM sub-detectors to the muon trigger process introduces several key benefits including an improved p_T resolution which allows for improving the purity of the events selected by the Level-1 trigger. This improved purity enables the trigger algorithms to offset an otherwise unavoidable increase in the trigger rate with the large increase in particle flux associated with the HL-LHC upgrade.

Figure 7 demonstrates the achievable improvement if the trigger algorithm has access to both CSC and GEM information. In blue, the trigger rates for the current system are shown as a function of a potential threshold on a muon candidate transverse momentum. By comparison, in purple, the same simulations are made but the trigger process includes data that is provided by GEM detectors. The reduction shown is sufficient to fit within the available bandwidth of the CMS readout system which allows for continued efficient muon triggering in the HL-LHC regime.

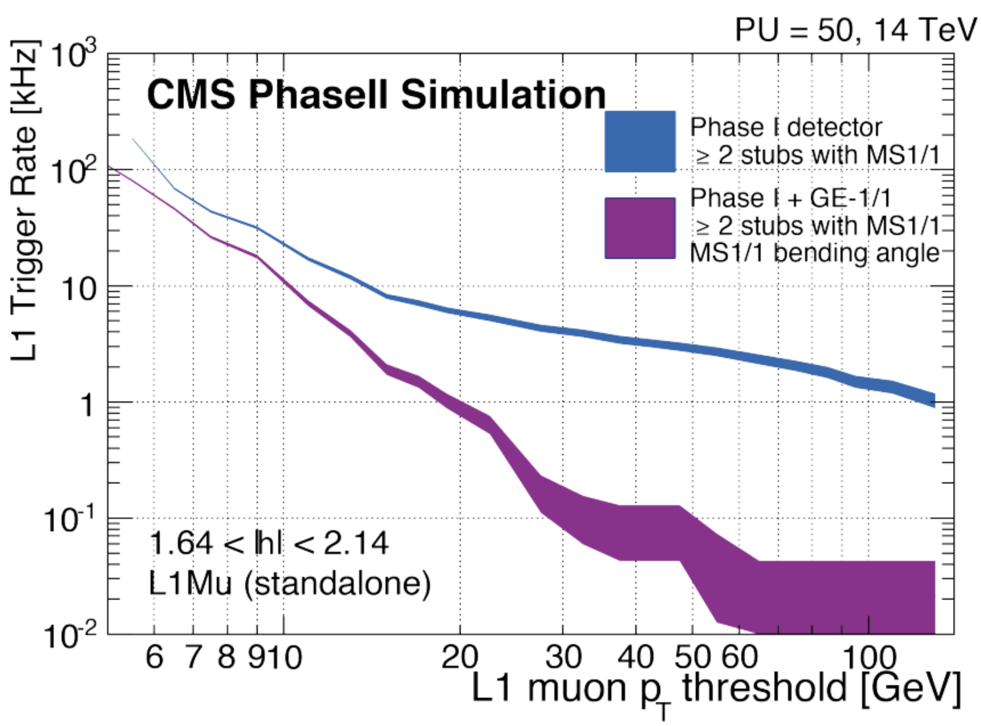

Figure 7: The potential improvement in trigger rates by providing GEM data in addition to CSC data due to the increased location and bend angle precision [13].

1.3.2 *Optical Trigger Mother Board*

The Optical Trigger Mother Board (OTMB) is the key element of the trigger system responsible for reconstructing muon candidates in a given CSC chamber, shown in Fig. 8. The OTMB algorithm is implemented in a logic chip that is located at the center called a Field Programmable Gate Array (FPGA). The FPGA is programmed to make decisions utilizing over 200 thousand programmable logic gates after receiving hit information from a CSC and a GEM detector. It builds CLCTs and matches them to ALCTs, then identifies matching hits in the GEM detector to optimize the bending angle measurements for the LCT. Once the trigger decisions are made for this section of the detector, the two best LCTs are identified and are sent upstream to the global trigger system where information from all muon detectors is brought together to make a global trigger decision.

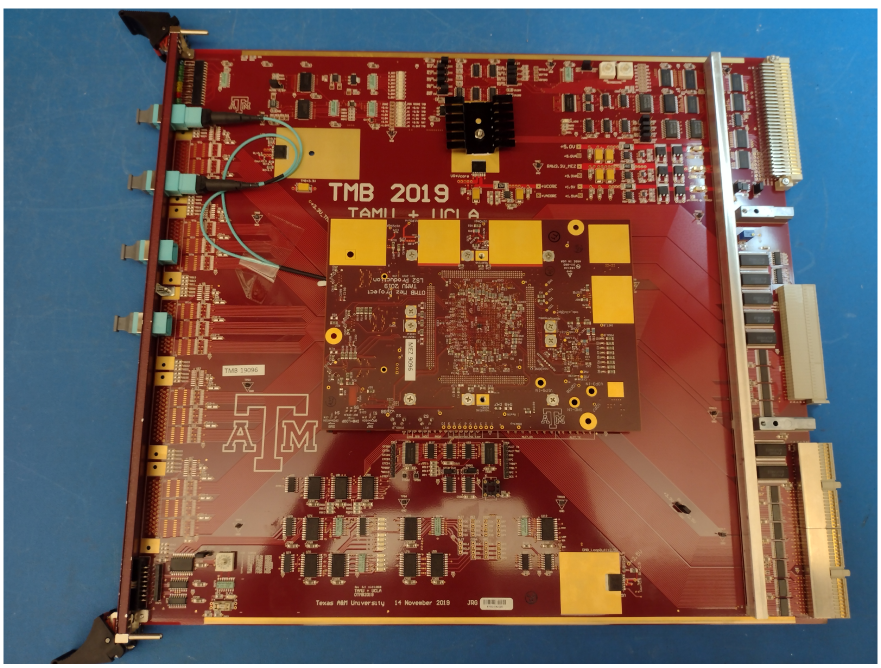

Figure 8: OTMB that is used to perform trigger decisions.

1.3.3 *CLCT Data Format*

The format that is used for conveying hit information from each layer of the CSC to the OTMB uses so-called "triads" where all the necessary information is carried as a series of three binary digits. When a strip has a signal above the threshold in the detector electronics, the system senses that a hit has been detected and sends three bits to identify the location of the hit. These three bits are sent to the OTMB over a time span of three BXs. When the first bit arrives, it identifies that a pair of strips have registered a hit. The second bit arrives one BX later and indicates which strip out of the pair is hit by the passing particle. Then, the third bit arrives and identifies which halfstrip is nearest to the particle.

When the OTMB receives the triads, it unpacks them for all layers and strips in the CSC chamber. Once all the hit halfstrips have been identified, the OTMB logic searches for straight-line paths through all six layers that provide a signature of a passing muon. The best of these have hits on at least four layers and become candidates for building CLCTs.

1.3.4 CLCT Position Precision

A CLCT is built from hits on up to six layers, where each layer has halfstrip precision. Combining the hit location information from all six layers produces a result with one-eighth-strip precision for the CLCT. The descriptor that carries the full hit information for the CLCT is called the comparator code (CC Code). The CC Code is used in the OTMB trigger logic to increase the location precision. It is also recorded as part of the CLCT trigger result.

The format of CC Code is set using binary encoding to identify the location of hits in the six layers of the CSC. There are two digits for every layer which correspond to the location of the hit relative to the key halfstrip. It is intuitive with 00 corresponding to no hits. 01, 10, and 11 correspond to the right halfstrip, the center halfstrip, and the left halfstrip hits respectively. Figure 9 shows which binary code represents which halfstrip that is registered to have a hit. With six layers, the CC code in binary is twelve bits long. When reading from left to right, the bit pairs indicate the hits starting with the top layer and working down to the bottom.

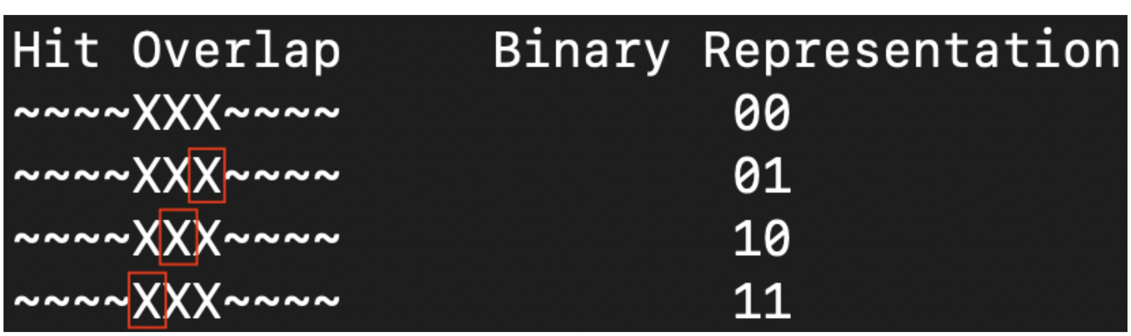

Figure 9: CC Code Binary Conversion

For example, the CC code 975 is 001111001111 in binary. Figure 10 illustrates the conversion between binary to hit locations. Reading the consecutive pair of digits, the path of the muon when it hit each layer is illustrated. Going through the bits layer-by-layer, there are no hits on the top layer (=00); there is a hit on the furthest left halfstrip (=11); there is a hit on the furthest left halfstrip(=11); there are no hits on the next layer (=00); there is a hit on the furthest left halfstrip (=11); there is a hit on the furthest left halfstrip (=11). In this way, the example in Fig. 10 represents a four-layer muon stub in the detector.

Figure 10: CC Code 975 and corresponding layers hit

Using the CC Code to improve the CSC position precision brings it to the scale that is comparable to the GEM detector which allows for a precise measurement of the slope (bending angle) of the muon trajectory by combining the CSC and GEM data. Since the slope is directly related to the transverse momentum, these combined improvements lead to better momentum resolution. This, in turn, is critical for achieving the improved trigger performance illustrated in Fig. 7.

2. METHODS

The CMS muon trigger test stand at Texas A&M is used for validating the performance of the muon trigger algorithm. The current firmware that is implemented in the OTMB is not at its final version which is why the tools that are developed in this project are useful. The validation tests are conducted by transmitting simulated pseudo-data that closely resembles the true LHC collision data to the OTMB board through a muon detector emulator board in a controlled way. The software that controls the test stand injects the simulated event data and verifies that the trigger OTMB decisions in the real hardware match with the trigger decisions that are predicted in simulation. This process is illustrated in Fig. 11.

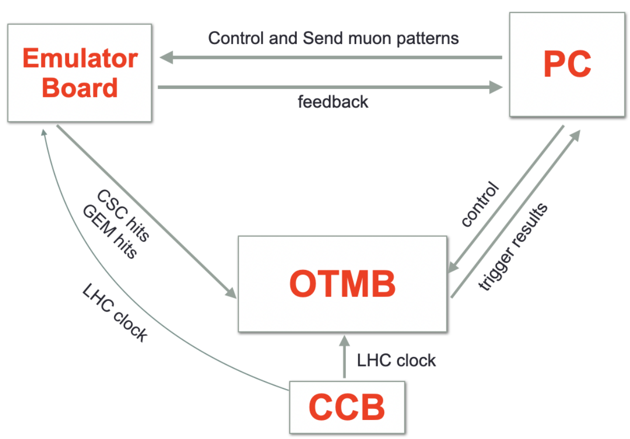

Figure 11: Visual representation of the communication and control between components in the Muon Trigger Test Stand.

All four test stand components (PC, emulator board, OTMB, and CCB) play important roles in the trigger test stand. However, the function of the emulator board is central to the operation of the test stand. The fiber links from the emulator board to the OTMB transmit the CSC trigger data with the same data format and data rate as the real collision conditions at CMS.

The software that is running on the PC has been developed to control the entire test process. It controls all test functions, collects the trigger decision for each test, and validates the results. For each test, the PC communicates with the emulator board and loads it with the simulated events to be injected into the OTMB. After each event is sent, the software communicates with the OTMB to get the trigger results and compares that with the expectation from simulation.

The CCB provides clocks and control signals such as resync and reset. The CCB communicates with the emulator board and the OTMB simultaneously so that everything operates on the same clock, just like it does in all CMS systems. The testing software on the PC configures the CCB and has access to the control functions, so commands such as reset can be issued as needed.

2.1 Injecting Simulated Muon Data into the OTMB

The muon data that are used in the TAMU trigger test stand come from precise software simulations of the CMS detector, where the muon response in the CSC is based on realistic performance in LHC conditions. The muon data for the simulated events are saved in a text file that can be accessed by the test stand control software. This data includes the hit information on each layer where the muon has deposited charge, as well as the trigger simulation results for the event.

Each simulation file contains hundreds or thousands of events and each event contains muon trigger information in a common format. Every event has an event ID that can be used for debugging purposes. Within each event, every hit is recorded with information about the BX, layer, and halfstrip hit. Finally, each event contains result information from the muon trigger simulation, which include the trigger decision for the location where the muon passes through the detector, the number of CSC layers hit, the CC Code, the left or right bend of a muon, the slope of that bend, and the pattern ID of the muon's path. These variables are fully defined in later sections.

To control the communications between the emulator board and the PC, the test stand control software utilizes a Graphical User Interface (GUI). A tool in the GUI software that has been developed for this project is an added feature that allows a user to select an event simulation file to use for the test, as shown in Fig. 12. By selecting the appropriate button, the user can tell the software to read just one event and load it into the emulator board, or to process the entire file.

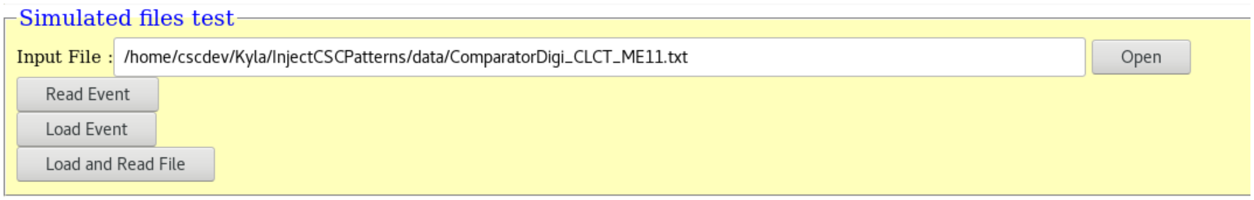

Figure 12: A screenshot of the GUI that controls simulated muon data injection to the emulator board and OTMB.

As the test stand control software reads a simulation file, the program first looks for the beginning of an event which is identified by the string "Run 1 CSCChamber with Comparatordigi (end,station,ring,chamber)". The hit information for every layer follows after this, where each hit begins with the string "Comparatordigi". When all of the hits for the event has been read, the test stand control software translates the hit information into the standard triad format and loads it into the emulator board. The final entry for each event in the simulation file is the simulated trigger result, which is recognized by the software control system with the string "CSC CLCT", and the test stand control software uses this to validate the OTMB trigger results for the event.

Once the event information has been loaded into the emulator board, the next step is to initiate the dump function that injects the data from the emulator board into the OTMB through the fiber links. Within a microsecond of receiving this data, the OTMB has already made a trigger decision and the result is available in a register accessible to the software. The test stand control software reads the trigger results from the OTMB and compares them with the expected trigger results that are stored in the simulation files. When the comparison is completed, the trigger results are printed on the PC screen and are saved to a file. In the case of an event with a failed trigger comparison, those results are saved in a separate file for further analysis.

2.2 Verification of the OTMB Trigger Results

The event processing and test procedure that is described in the previous section is implemented using an automated process that verifies the OTMB trigger results against the prediction from trigger simulation before processing the next event. The test stand control software runs this automated process in a `do-while` loop to make the code more concise. The entire process that is defined in Section 2.1 is performed within a `do-while` loop until the end of the file has been reached.

During the automated program operation, the results of the trigger and the comparison are printed on the screen while the program is running to allow monitoring. The output of the software shows the eight variables that are computed by the OTMB trigger algorithm and are compared to the prediction. Figure 13 shows an example of the printout of the program for an event where the computed and predicted values match perfectly. An example of an event, in which the two do not match is illustrated in Fig. 14.

```
CLCT0 RESULTS:
SIMULATION RUN-2 PATTERN ID (10) MATCHES TRIGGER RUN0-2 PATTERN ID (10)
SIMULATION QUALITY (4) MATCHES TRIGGER QUALITY (4)
SIMULATION CC CODE (1020) MATCHES TRIGGER CC CODE (1020)
SIMULATION BEND SIMULATION (1) MATCHES BEND (1)
SIMULATION SLOPE (0) MATCHES TRIGGER SLOPE (0)
SIMULATION KEY HALFSTRIP (191) MATCHES TRIGGER KEY HALFSTRIP (191)
SIMULATION KEY QUARTER STRIP (382) MATCHESS TRIGGER KEY QUARTER STRIP (382)
SIMULATION KEY EIGHTH STRIP (765) MATCHES TRIGGER KEY EIGHTH STRIP (765)
```

Figure 13: Example of a standard trigger result where the results are perfect in comparison.

```
CLCT0 Information:
SIMULATION RUN-2 PATTERN (10) MATCHES TRIGGER RUN-2 PATTERN (10)
SIMULATION QUALITY (6) MATCHES TRIGGER QUALITY (6)
SIMULATION CC CODE (4095) DOES NOT MATCH TRIGGER CC CODE (3055)
SIMULATION BEND (1) DOES NOT MATCH TRIGGER BEND (0)
SIMULATION SLOPE (0) MATCHES TRIGGER SLOPE (0)
SIMULATION KEY HALF STRIP (53) MATCHES TRIGGER KEY HALF STRIP (53)
SIMULATION KEY QUARTER STRIP (106) MATCHES TRIGGER KEY QUARTER STRIP(106)
SIMULATION KEY EIGHTH STRIP (213) DOES NOT MATCH TRIGGER KEY EIGHTH STRIP (212)
```

Figure 14: Example of trigger results not entirely matching simulation results.

2.3 Accessing Trigger Test Results

Analysis of the data for this project requires the development of a data format for saving the results in a file that is easy to analyze and visualize. The text that is printed on the screen is also saved in a .txt file but in parallel, a .csv file is created to save numeric information for each of the eight variables that are produced in the trigger result, which is a feature that has been added for this project.

A separate Python script is used to read the numeric data from the .csv files and is used to make plots. This script makes plots for the eight variables by utilizing a histogram function. The histograms compare the CLCT0 and CLCT1 results of the OTMB trigger decisions and simulated trigger predictions.

3. RESULTS

There are eight different variables to compare between OTMB trigger results and simulated trigger results which are the slope, key halfstrip, key quarter strip, key eighth strip, quality, pattern ID, bend, and CC Code. All of these variables are significant in the trigger result because they identify properties of muons that determine the ultimate trigger decision. The goal of this project is to provide tools for precision validation of the firmware algorithm that has been implemented in the OTMB board. The feature that allows the test stand control software to identify and isolate events, in which the electronics output and the expectation do not match, provides the firmware designers with the information necessary for debugging and implementing corrections to the firmware. Once the firmware is debugged, analysis and visualization features of the program allow for a quantitative assessment of the performance of the hardware and the accuracy with which simulation describes the performance of the actual system.

The following is an illustration of the actual use of the test stand and the analysis software to compare the actual and predicted simulation trigger decision (output) of the OTMB algorithm on the example of the most current development version of the OTMB firmware algorithm that is being prepared for future deployment in CMS.

3.1 Comparison of the OTMB and Simulated Trigger Outputs

Figures 15- 22 each contain two plots of related trigger information. The top plot in each figure shows the histogram of the trigger performance. The bottom plot in each figure shows the percent error of the OTMB's trigger performance with respect to the expectation from trigger simulation. It should be noted in the histograms that every event has a CLCT0 but most events do not have a second muon so the statistics in CLCT1 are much lower.

3.1.1 Slope

Slope is used to indicate how much curve a candidate muon's path has. A lower slope value indicates a straighter path, which means a more energetic (i.e. high p_T) muon. Higher p_T

muons are typically more interesting to trigger on as they could indicate a hard collision producing heavier particles that decay into muons. Slope values are independent of the direction of bend. A different variable, Bend, determines if a muon's slope leans left or right, and indicates a muon electric charge. Slope determines how much of a curve is present.

Figure 15 shows the comparison of the predicted and actual values of the slope that are computed by the OTMB for the events analyzed. The tools that have been developed in this project provide a quick comparison of the triggered and expected OTMB decisions which benefit the designers of the firmware to improve the performance of the muon trigger test stand when future tests are conducted. Now, the firmware developers can conveniently determine the accuracy of the test stand which helps them find the errors in the firmware.

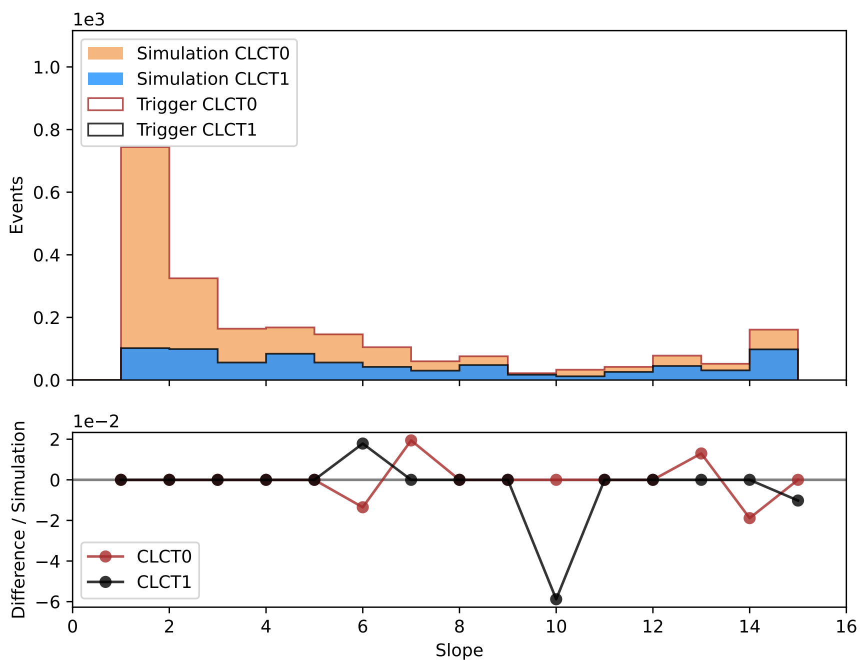

Figure 15: The slope of a muon in approximately 6,000 events identified. The subplot illustrates the percent error between real trigger results and expected trigger results, which will benefit future firmware developers.

3.1.2 Key Halfstrip

As addressed in the *Introduction*, the key halfstrip is the primary unit to measure a muon's position in the cathode plane of a CSC. Figure 16 shows the trigger decision results and the percent error of the trigger test stand to be compared to the simulated events for CLCT0 and CLCT1 for the key halfstrip. This information can be fully visualized due to the tools that have been developed to benefit firmware developers when future tests are conducted.

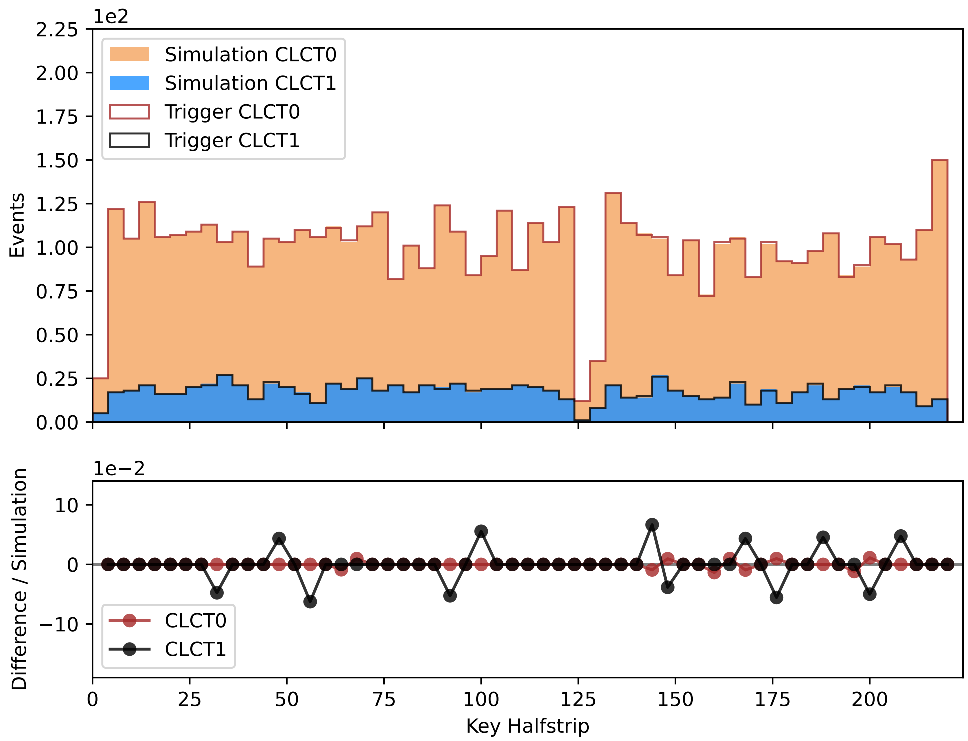

Figure 16: The key halfstrip of a muon in approximately 6,000 events identified. The subplot illustrates the percent error between real trigger results and expected trigger results which will benefit future firmware developers.

One interesting bin is around key halfstrip 127. CLCT0 and CLCT1 identify almost no hits on that halfstrip. This is because of how the halfstrips are identified on a CSC. The numbering of halfstrips on a CSC is split between the top half of the CSC and the bottom half of the CSC where key halfstrip 127 is found at the very furthest right, near the edge of the CSC. Those halfstrips are least likely to receive a hit. It is sensible to expect a large drop in that bin for both CLCT0 and CLCT1.

3.1.3 Key Quarter Strip

Similar to key halfstrip, key quarter strips are useful for identifying the location where a muon passes through the CSC with improved precision. A half of a halfstrip is a quarter strip.

Taking the halfstrips that have been previously defined, the quarter strips identify a more specific location on the halfstrips where the charge depositions occur, and consequently where a muon passes through. Looking at Fig. 17, the figure is the same as the key halfstrip figure (Fig. 16) because of how key halfstrip and key quarter strips are defined.

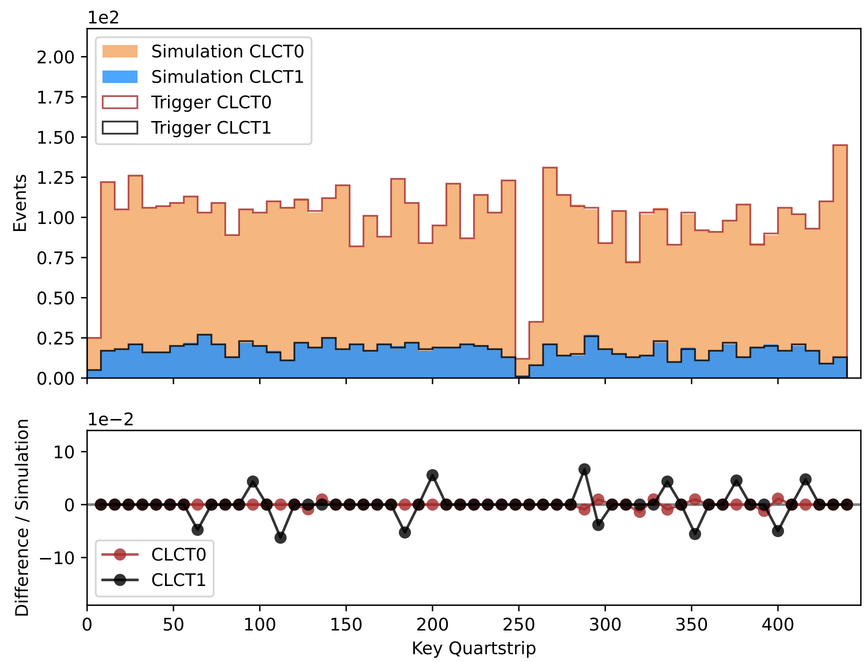

Figure 17: The location of where a trigger occurred in over 6,000 events identified based on the Key Quarterstrip. The subplot illustrates the percent error between real trigger results and expected trigger results, which will benefit future firmware developers.

3.1.4 Key Eighth Strip

Key eighth strips provide an improved precision for the location where a muon passes through the CSC. Analogous to key halfstrips and key quarter strips, key eighth strips are halves of the key quarter strips. After identifying which strip is hit, the key halfstrip identifies which half is hit. The key quarter strip identifies which half of the halfstrip was hit. The key eighth strip identifies which half of the quarter strip is hit. Figure 18 conveys the same information as what is presented in Fig. 17 and Fig. 16.

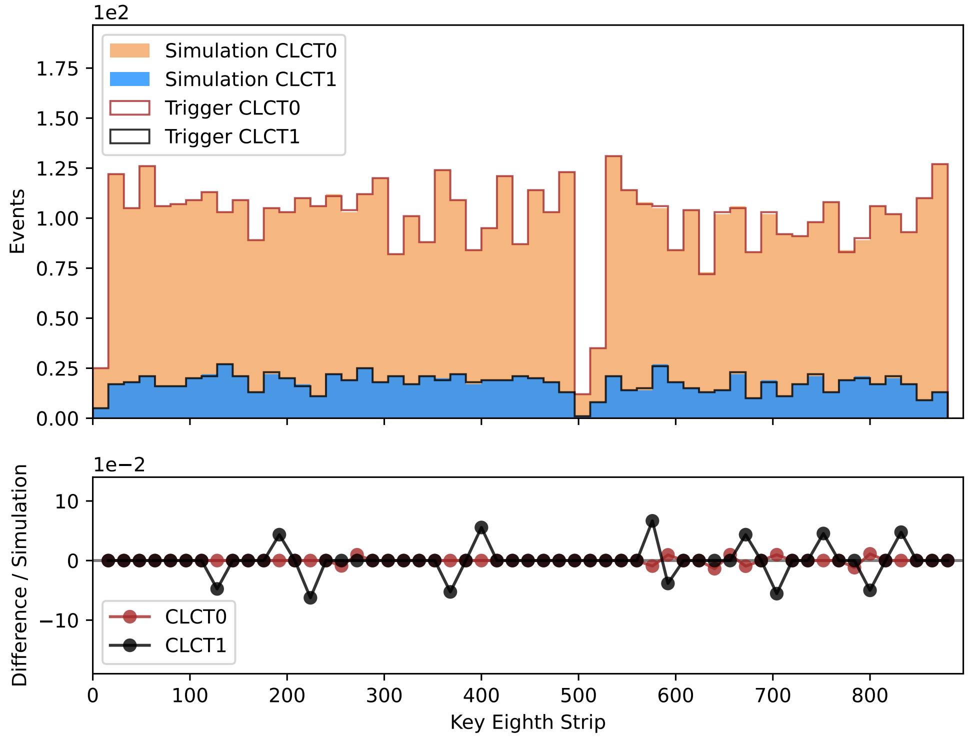

Figure 18: The location of where a trigger occurred in over 6,000 events identified based on the Key Eighth Strip. The subplot illustrates the error between real trigger results and expected trigger results, which will benefit future firmware developers.

3.1.5 Quality

Another important variable is the number of layers hit. In order for an event to trigger, at least four out of the six layers in a CSC must register a hit. Furthermore, the simulated event files do not create an event that has three or fewer layers hit because the simulation does not trigger. Figure 19 is a product of the tools that are developed in this project in order to help firmware developers efficiently improve the performance of the test stand.

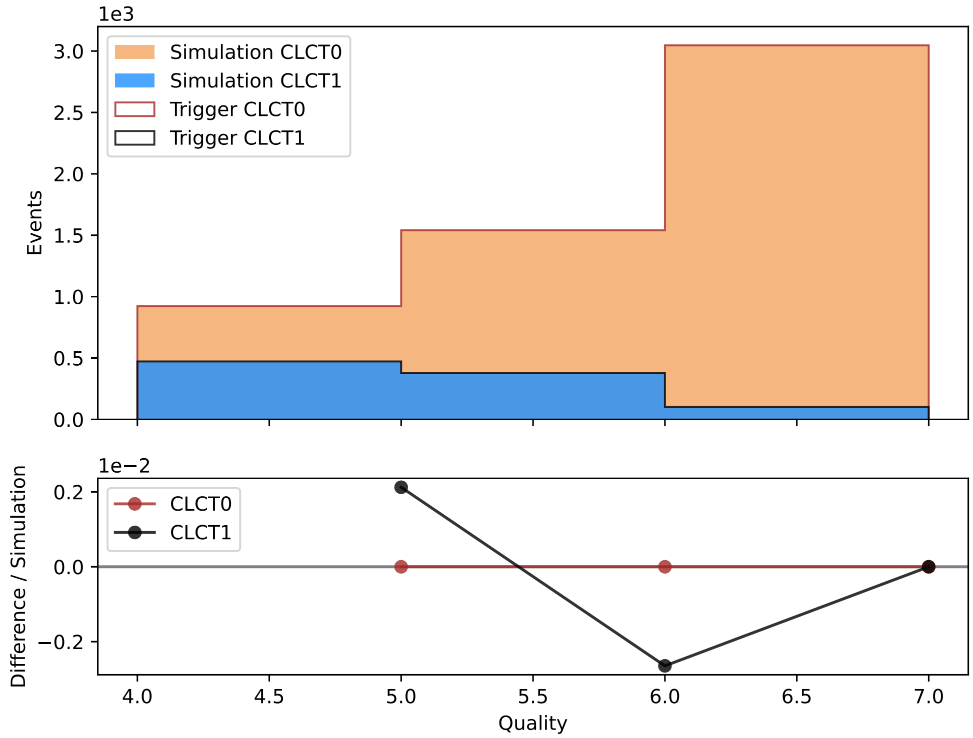

Figure 19: The number of layers hit in over 6,000 events. The subplot illustrates the percent error between real trigger results and expected trigger results which will benefit future firmware developers.

3.1.6 Pattern ID

Pattern ID is used to identify the paths of muons when they pass through a CSC. A straighter muon path has a greater p_T which is important to identify reliably. Pattern 10 identifies the straightest path a muon can take and pattern 2 identifies a very curved path. The tools that are developed in this project result in Fig. 20 which can be used when the OTMB firmware needs verification. It is also useful to recognize that Fig. 20 can also illustrate if CLCT0, CLCT1, or both may need firmware debugging.

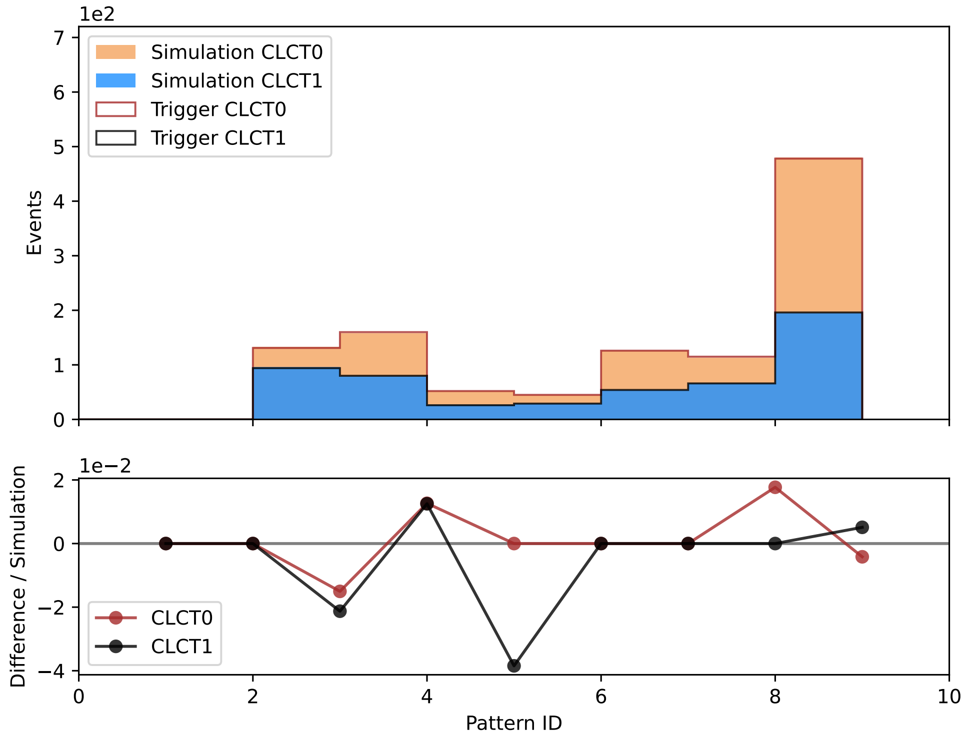

Figure 20: Pattern ID real trigger data and expected trigger data for over 6,000 events. The subplot illustrates the error between real trigger results and expected trigger results, which will benefit future firmware developers.

3.1.7 Bend

The bend of a muon identifies if the particle has curved left or right. This information is provided in a single binary bit. A bit that is sent as a 0 indicates a left bend and a bit that is sent as a 1 indicates a right bend. However, events without a trigger also send a bit value of 0, as this is the default value. This means that the first step to analyzing the bend of the simulated events requires excluding the events without a trigger. This can be done by verifying the event is "valid" from the OTMB. With each simulated event that is sent, the OTMB decides if that event has an interesting muon to trigger on. If it does, then the bit that represents the validity of the event is 1. If not, then a bit value of 0 is sent instead. This information is used only to analyze the events that the OTMB triggered on for the bend. Figure 21 has been produced by the tools that have been created in this project and can benefit firmware developers when verifying the muon trigger test stand.

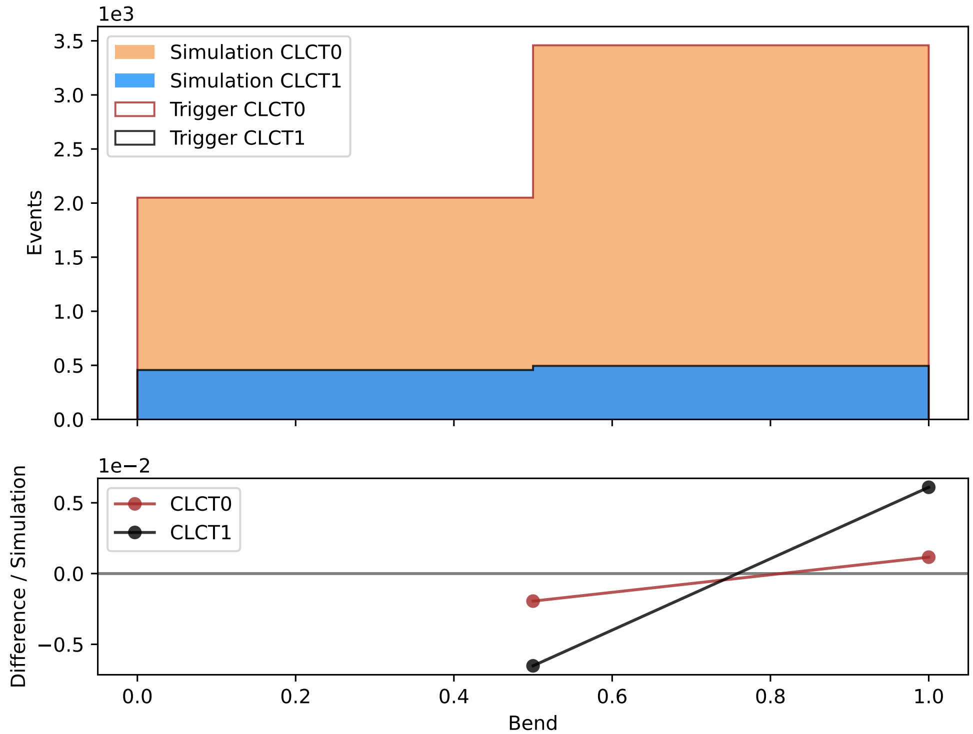

Figure 21: The bend for over 6,000 events while removing the non-triggering events. The subplot shows the percent error between real trigger results and expected trigger results, which will benefit future firmware developers.

3.1.8 Comparator Code

As addressed in the *Introduction* chapter, the CC Code is necessary for improving the position precision of a muon. Due to its importance, it is also crucial to recognize if the trigger test stand makes correct decisions regarding the CC code of muons. Reliability in correctly identifying the comparator code is important because it is critical to measure the path of the muon with the highest possible precision. Therefore, Fig. 22 can be a helpful tool for firmware developers to verify that the firmware makes accurate trigger decisions.

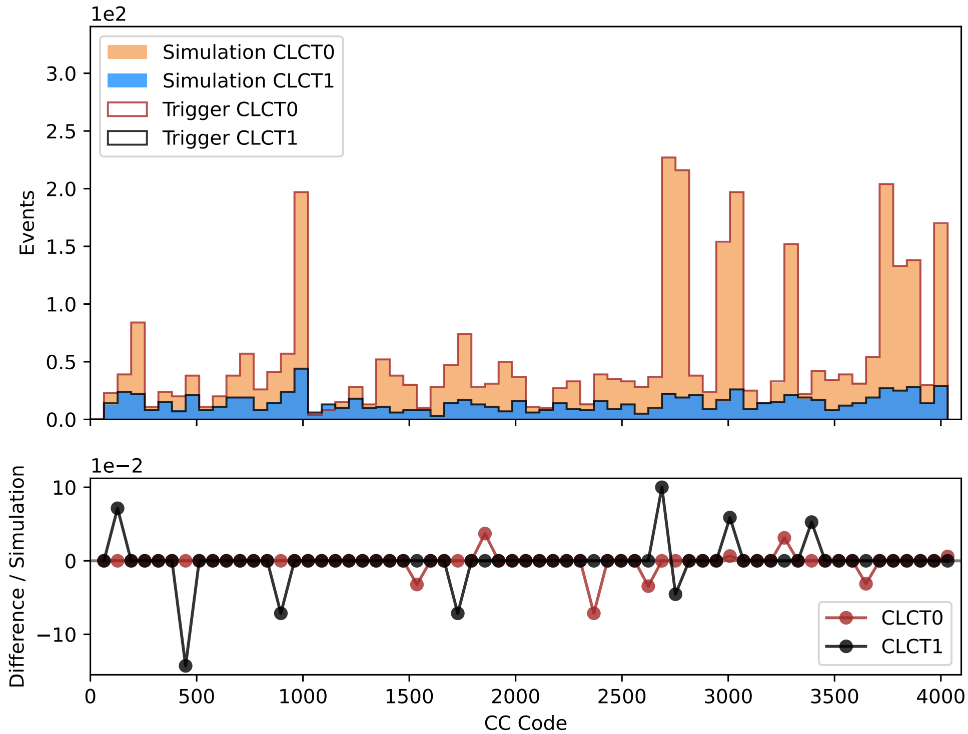

Figure 22: The CC Code for over 6,000 events identified. The subplot illustrates the error between real trigger results and expected trigger results, which will benefit future firmware developers.

4. CONCLUSION

The tools that were developed and utilized on the muon trigger test stand at TAMU performed a precision comparison of the expected and actual results of computations by the OTMB board using realistic simulated collision data. The plots produced had illustrated the comparisons between the simulated event trigger decisions and the actual OTMB trigger decisions. This tool allows convenient visualization of information and allows developers to implement corrections to the OTMB firmware. The same tool can be used to evaluate the accuracy of the actual system for the purposes of systematic uncertainty assessment in later physics data analyses.

The tools produced from this project will be helpful in the future development of the test stand and testing of additional firmware features that will be added. One important future development of the tools will include a comparison of the expected and actual hardware computations for the algorithm that will include both CSC and GEM data. The corresponding firmware development is already ongoing and the extended tool will allow a precision validation of the new firmware.

Future uses of the tools that resulted from this project will provide significant benefit to firmware developers in their pursuit of verifying the accuracy of the muon trigger test stand at TAMU. The HL-LHC upgrade demonstrates the importance of developing new tools for future operations. The new tools created for such operations require new algorithms and implementation of these new algorithms. The tools produced by this project can perform the validation of such algorithms.

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APPENDIX: PLOTS

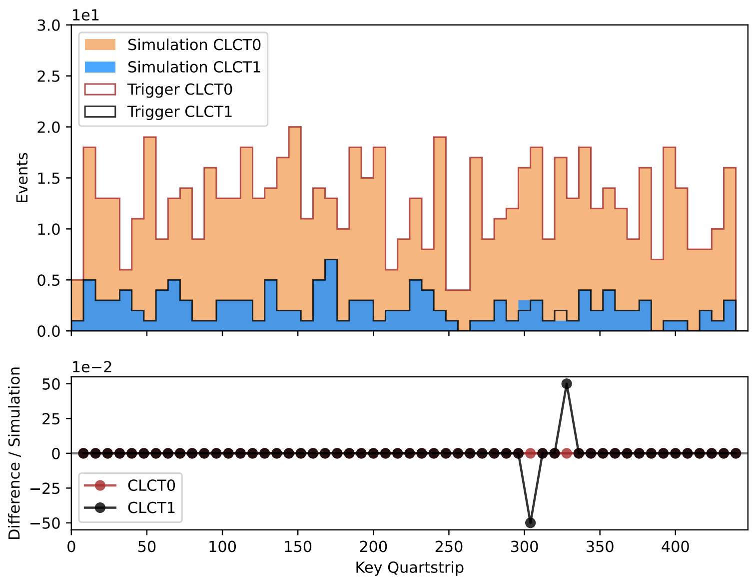

Figure A.1: The location of where a trigger occurred in over 800 events identified based on the key quarter strip. The subplot illustrates the error between real trigger results and expected trigger results for CLCT0 and CLCT1 which will benefit future firmware developers.

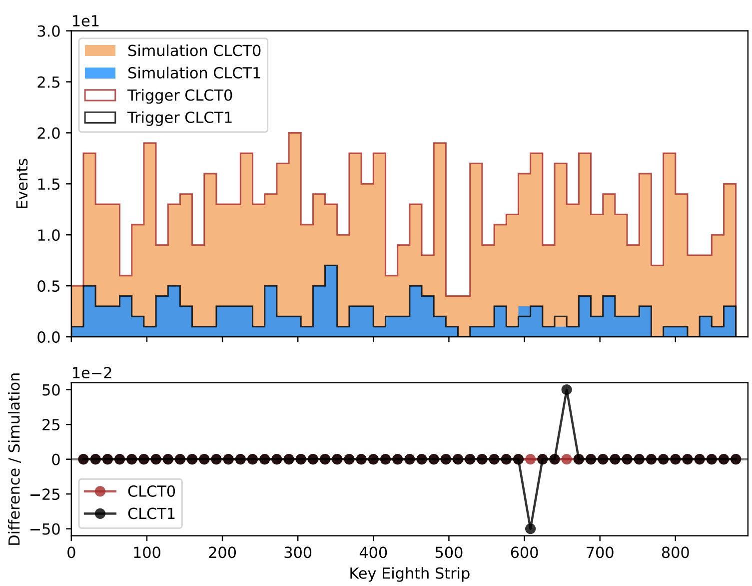

Figure A.2: The location of where a trigger occurred in over 800 events identified based on the key eighth strip. The subplot illustrates the percent error between real trigger results and expected trigger results, which will benefit future firmware developers.

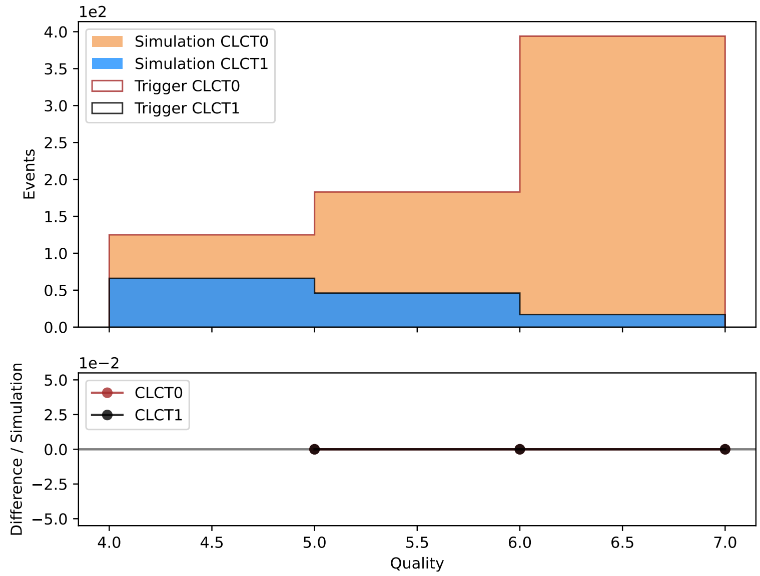

Figure A.3: The top plot shows number of layers hit in a CSC (quality) for over 800 events. The subplot shows the percent error between real trigger results and expected trigger results which will benefit future firmware developers.

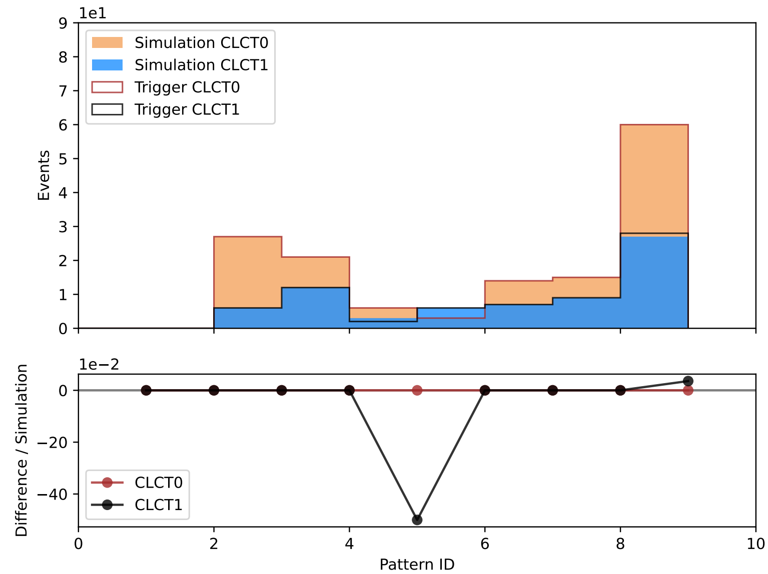

Figure A.4: The top plot shows pattern ID for over 800 events. The subplot shows the percent error between real trigger results and expected trigger results which will benefit future firmware developers.

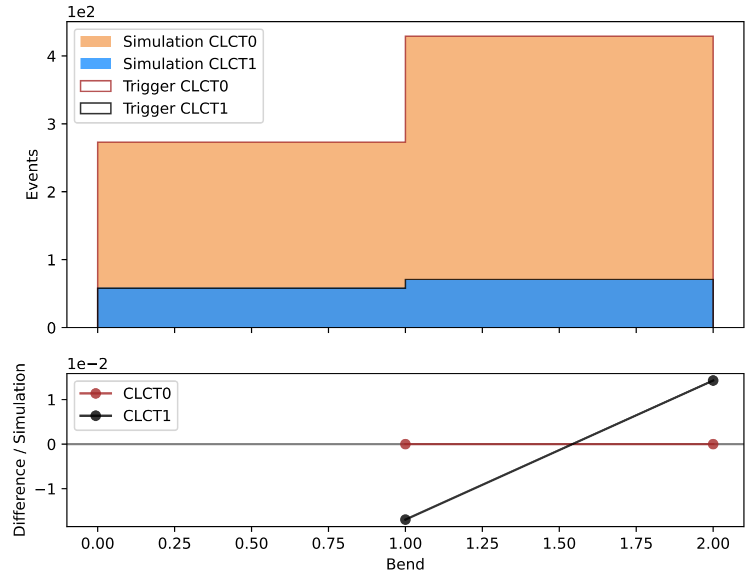

Figure A.5: The bend for over 800 events with the events without a bend removed. The bottom subplot shows the percent error between real trigger results and expected trigger results which will benefit future firmware developers.

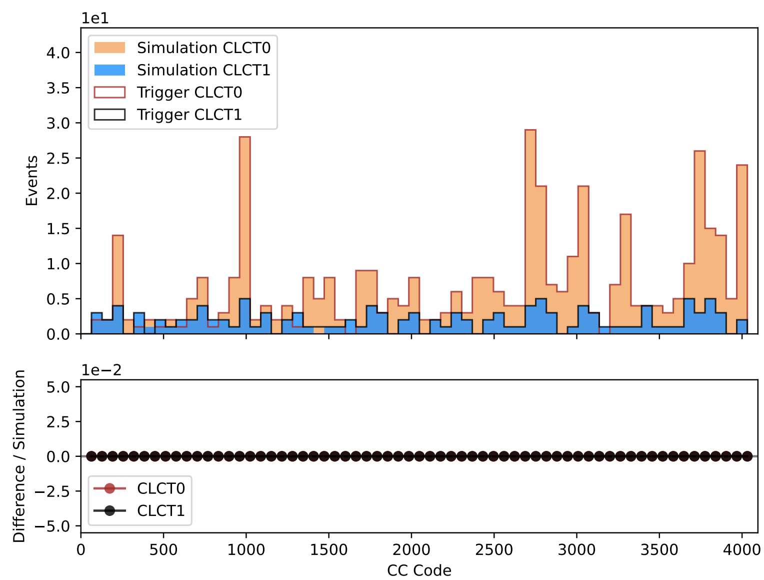

Figure A.6: The top plot shows the CC Code for over 800 events identified. The subplot illustrates the percent error between real trigger results and expected trigger results which will benefit future firmware developers.