

Update to the CMS Muon System Level 1 Trigger

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Abstract

This project focused on preparing for upgrades to the Large Hadron Collider that are scheduled to take place in the next 3 to 8 years. These upgrades will require changes in the abilities of the Compact Muon Solenoid (CMS) Level 1 Trigger system. This project specifically dealt with upgrades in the muon detection system in the endcap area of the detector, and the hardware algorithms used to perform immediate high-speed calculations of the paths of muons passing through that region.

Introduction

The Large Hadron Collider (LHC) is a high-energy particle accelerator located outside Geneva, Switzerland. This accelerator is designed to produce collisions of protons, as well as of certain heavy ions, and does so by accelerating a particle beam consisting of discrete bunches of the particles in question [1]. Though it was originally designed to create proton collisions with a center of mass energy of 14 TeV, it is currently functioning at 7 TeV. The LHC's four largest detectors are ALICE (A Large Ion Collider Experiment), LHC-B, ATLAS (A Toroidal LHC Apparatus), and CMS (Compact Muon Solenoid).

CMS is located on the north side of the LHC. It is composed of a superconducting solenoid magnet, as well as an inner tracker, Electromagnetic Calorimeter, Hadron Calorimeter, and muon detecting system, all arranged in concentric cylinders around the particle beams [1]. These layers can be seen in Figure 1. This system allows CMS to detect many types of particles, and to sense when there is energy that is unaccounted for in the collisions, which indicates the existence of objects such as neutrinos that cannot be observed by any of the detecting layers. The inner tracker

measures the paths of charged particles through the 4 T magnetic field. A charged particle moving through a magnetic field will bend, and that bending will be proportional to the transverse momentum, so the inner tracker provides an accurate way to calculate the momenta of charged particles. The Electromagnetic Calorimeter (ECAL) is the next layer of the detector and provides data on the energies of photons and electrons. The Hadron Calorimeter (HCAL) produces values for the energies, positions, and arrival times of hadrons, which are particles composed of quarks and gluons. The solenoid magnet is between the HCAL and the muon system, the final layer of the detector [2].

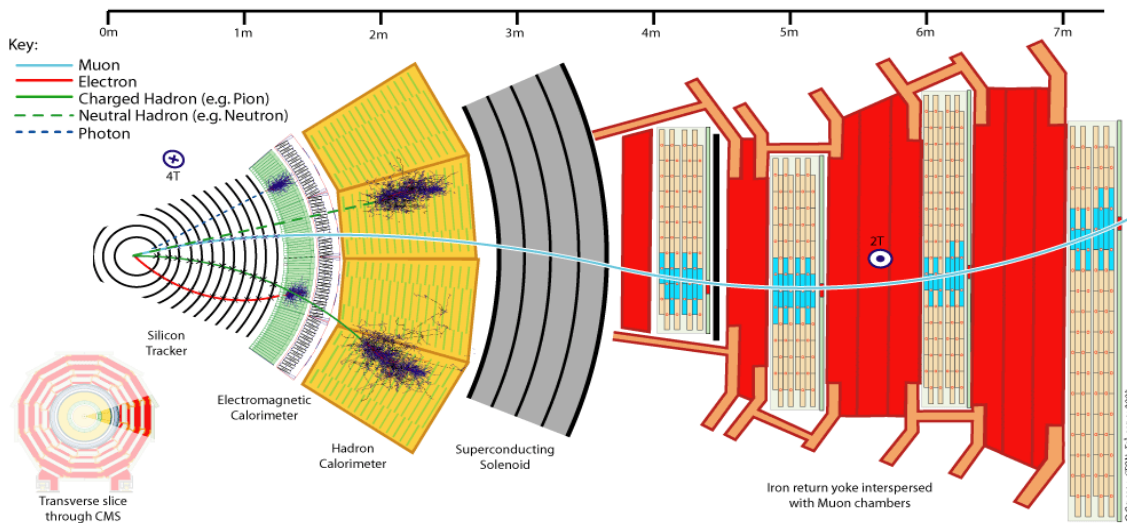


Figure 1: Slice of CMS, showing the layers of the detector [2]

In order to detect muons throughout the entire geometry of the detector, the muon system has two separate regions. The division of the muon system that exists in a cylinder around the beam axis is the barrel. The barrel detects muons using layers of drift tubes [1]. The other region of this system is the endcap region, which finds muons whose trajectories are towards the ends of the detector, and thus miss the barrel portion of the

system. If we take the coordinates x , y , and z to point towards the center of the LHC, upwards, and towards the west along the beam axis, respectively, then we can take the angle ϕ to be the angle in the x - y plane with $\phi = 0$ when pointing in the positive x direction, and θ to be the angle in the y - z axis with $\theta = 0$ when pointing in the positive z direction. We can also use the pseudorapidity, η , defined as $\eta = -\ln(\tan \theta/2)$ [1]. This angular coordinate system can be seen in Figure 2. The endcaps function in the range of $|\eta|$ between 0.9 and 2.4, though there is overlap between the endcap and the barrel drift tubes between 0.9 and 1.04 [3].

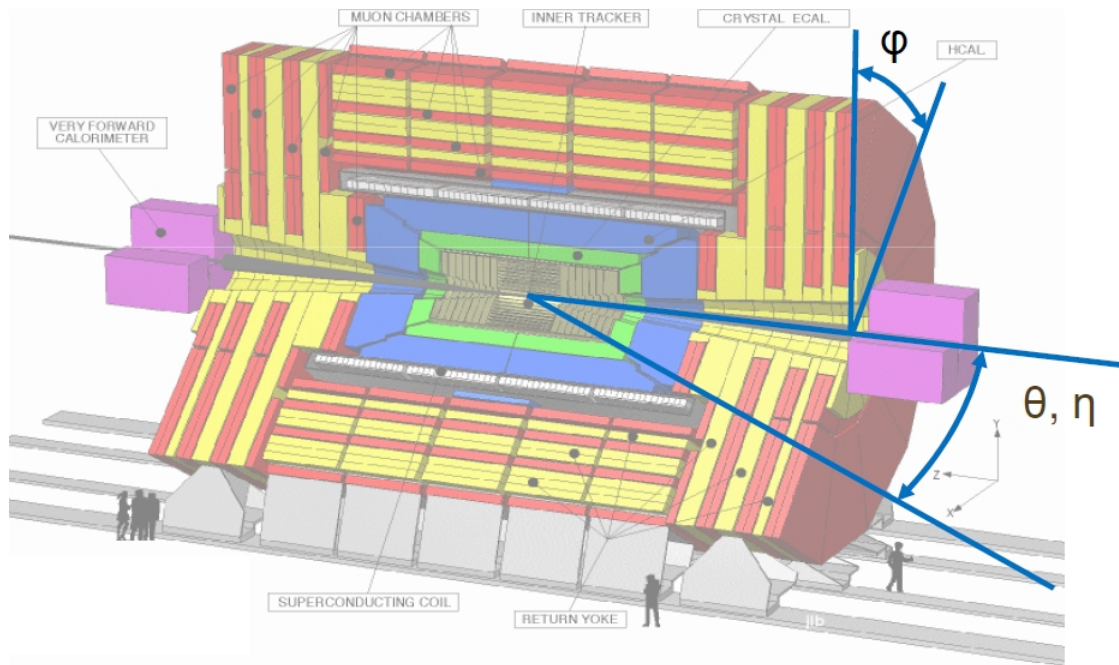


Figure 2: Angle Coordinates for CMS [4]

The muon detection in the endcaps is done with cathode strip chambers (CSCs). These chambers contain gas that is ionized by the charged particle that passes through it. CSCs have cathode strips pointing outwards from the z -axis, with anode wires that are orthogonal to the strips. When a muon passes through the CSC, the electrons from the

ionization then trigger a charge avalanche towards the anode wires, which also induces a charge in the cathode strips [1]. The charges on the anode wires and cathode strips produce information on the location of the muon in η and ϕ , respectively.

Each endcap of CMS has four CSC stations. A station is composed of six layers of the trapezoidal chambers which form a circle around the beam axis. These stations are labeled ME1-ME4 (where ME stands for muon endcap), and are layered next to each other along the z-axis, with ME1 being closest to the center of the detector [3]. Also, each endcap is divided into sectors of 60° in ϕ . This division is important in design of the muon system's trigger system, which sorts out the interesting data from less interesting data based on muon transverse momentum. Muons with high momenta usually signal interesting physics processes.

The massive amounts of data created by the LHC collisions make it impossible to record every hit sensed by CMS. As such, the detector systems require a trigger, something that can sort out what signals should be stored for later analysis, and which signals should be discarded as they are uninteresting. The Level 1 (L1) trigger acts as the first layer of filtering. The two calorimeters and the muon system participate in the L1 trigger [1]. Because of the large amount of data, the L1 trigger must be able to do this in a very short period of time (the current L1 trigger takes $3.2 \mu\text{s}$) [1]. Therefore, instead of functioning with normal software, the L1 trigger uses electronics boards to do the extremely fast calculating and sorting required.

The first set of electronics boards are used to find separate muon track segments for the anodes and cathodes of each chamber. These track segments record the number of layers of the CSC hit by the muon, its position, and the angle of its track [5]. Each

chamber can produce up to two of these segments from the anode and the cathode for every bunch crossing. These are then combined into a single Local Charged Track (LCT) that keeps track of the bunch crossing, ϕ , and η of the muon, which is used by the CSC Track Finder to reconstruct the track taken by the muon through the detector [5]. The LCT are also assigned quality (based on how many stations are used to create it) as well as measurements of position and angle [5]. These are used by hardware called the Muon Port Cards to filter out the best LCTs per station. 18 LCTs per station are sent to the Port Card, but only 3 are then sent to the Sector Processor [4, 5]. This Sector Processor then uses the LCTs to reconstruct the entire track of the muon that it is given and assigns an estimated p_T value [3].

Purpose

An upgrade to the LHC, called the Super Large Hadron Collider (sLHC), is planned to occur between 2013 and 2018 that would dramatically increase the luminosity for collisions [6]. This increase of luminosity would require an update to the endcap muon detector systems, as they are not currently designed to deal with the number of hits per chamber that the sLHC would generate. In the current design, parts of the L1 Trigger system would act as “choke points,” making it difficult for dimuon events to be allowed through to the CSC Track Finder and to the rest of the system. Because of how few signals would be let through, and the increased amount of background that would be created, the present working algorithm would block an inordinate number of these types of events [7]. In order to compensate for this, the Muon Port Card would allow all 18 LCTs through to the Sector Processor. As a result, the SP must be modified to handle the higher number of LCTs per bunch crossing, and the track finding algorithm has to be

improved to handle the increased number of LCTs. Before a prototype of the new SP hardware can be built, we must check to make sure that the update algorithm is at least as efficient and accurate at detecting and locating muons as the previous one was.

Method

The algorithms for the new and old Sector Processor have been coded into a software program for comparison and debugging purposes. This way, data generated by Monte Carlo simulations can be run through the model SP. At present, we compare the track reconstruction for a simulation in which a single muon is shot at the detector at a known η , ϕ , and p_T , either with the magnetic field on or off. This provides a baseline indicator of how well the algorithms are functioning, as they should have little difficulty in finding a track for a single muon.

We have an analyzer program that can pull event information from the simulated Sector Processor. In order to be able to effectively compare the old and new Sector Processor, each of them has had identical Monte Carlo data run through it to reconstruct tracks, so that, for each event, the tracks found should be identical between the two processors. We know what value of η , ϕ , and p_T the simulated muon was generated to have, so we can not only compare the two algorithms to each other, but we can also check and see for anomalies occurring around specific ranges of generator values. This allows us to detect any defect in the algorithm for a particular region in the detector.

To do comparisons, I created a software test environment in which to compare the two SP algorithms. This environment was written in Python, and utilized ROOT, a program developed by CERN for use in high-energy physics analysis. This test script pulled the data for the generator values and for the tracks found by each version of the SP

logic from a text file containing data from the analyzer program and used ROOT to make histograms of this data. The first histograms it created were one-dimensional histograms of the difference between the values of variables between the new and old code environments and 2D histograms plotting the new versus old values. For my program, if multiple tracks were found for an event, all combinations of new and old pairs would be added to the histograms. If the old and new track finders worked identically, the histogram of the difference would have all events in the zero bin, and the new versus old plot would be a diagonal line with a slope of one. However, as can be seen in Figure 3, which shows the differences for the transverse momentum in GeV, this is not exactly what happened.

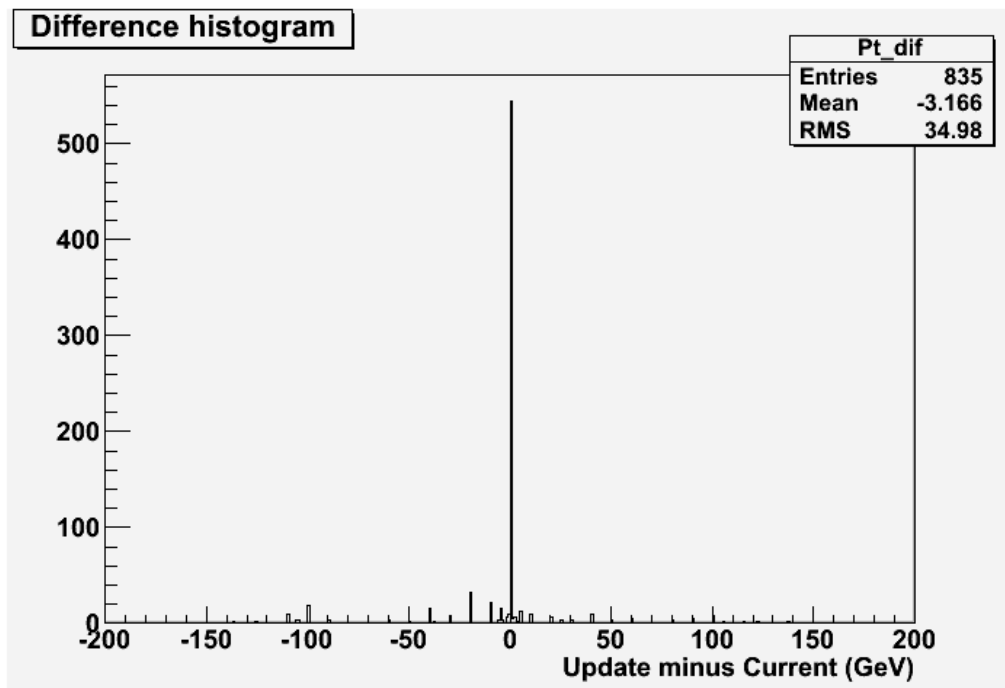


Figure 3: Value of p_T for the update minus current value of p_T

The majority of the data does end up showing now difference between what was found by the updated logic and the current logic. Only a relatively small amount of

disagreement can be seen in the rest of the histogram. It appears that most of this disagreement is from the updated algorithm underestimating the value for the transverse momentum. However, most of this difference was likely to occur in low quality tracks – those tracks created using few layers in the endcap.

In the comparison plot, we make a cut based on the quality of the track. Roughly speaking, quality refers to the number of stations used to create the track. When we plot p_T for tracks with quality greater than or equal to 2, we can see reasonable agreement between the upgrade algorithm and the current algorithm.

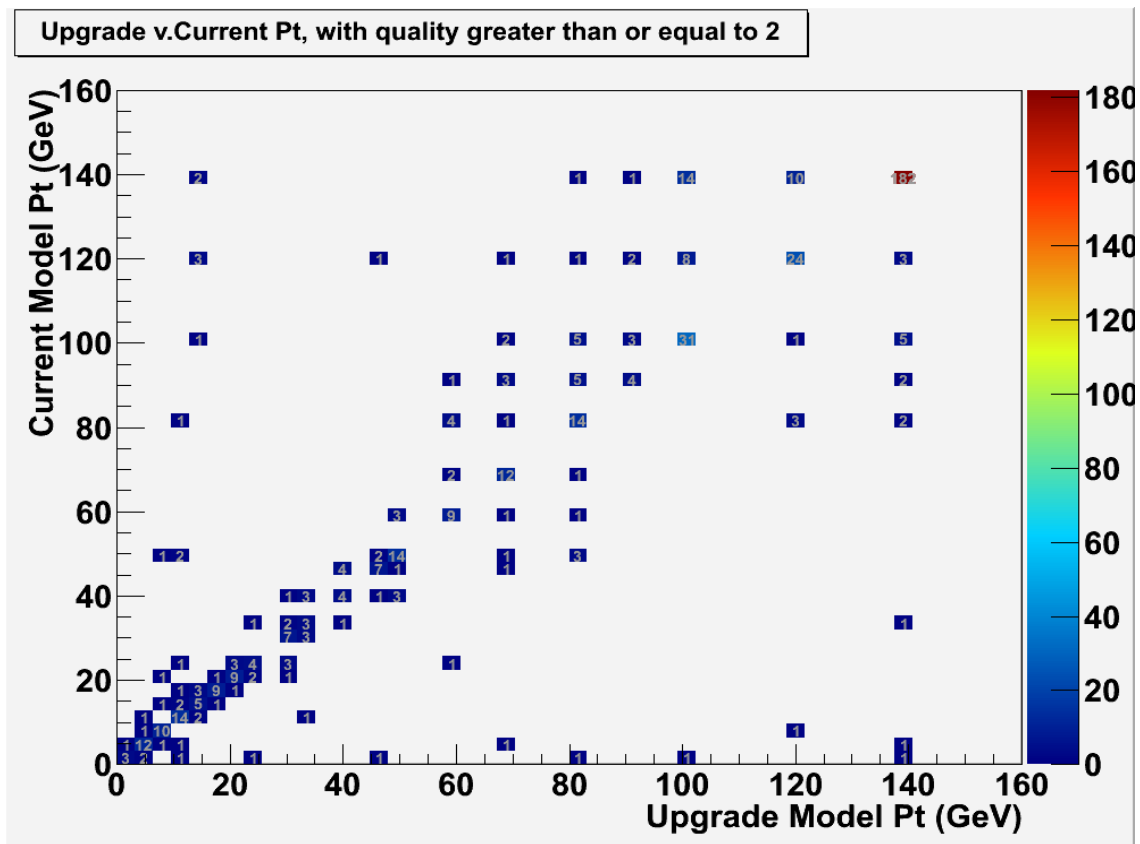


Figure 4: Update p_T v. Current p_T

There is still noise that can be seen away from the diagonal, but very little. The current and update model agreement for reconstructed eta and phi values is very reasonable,

especially for quality greater than or equal to two, as shown in Figure 5 and Figure 6 .

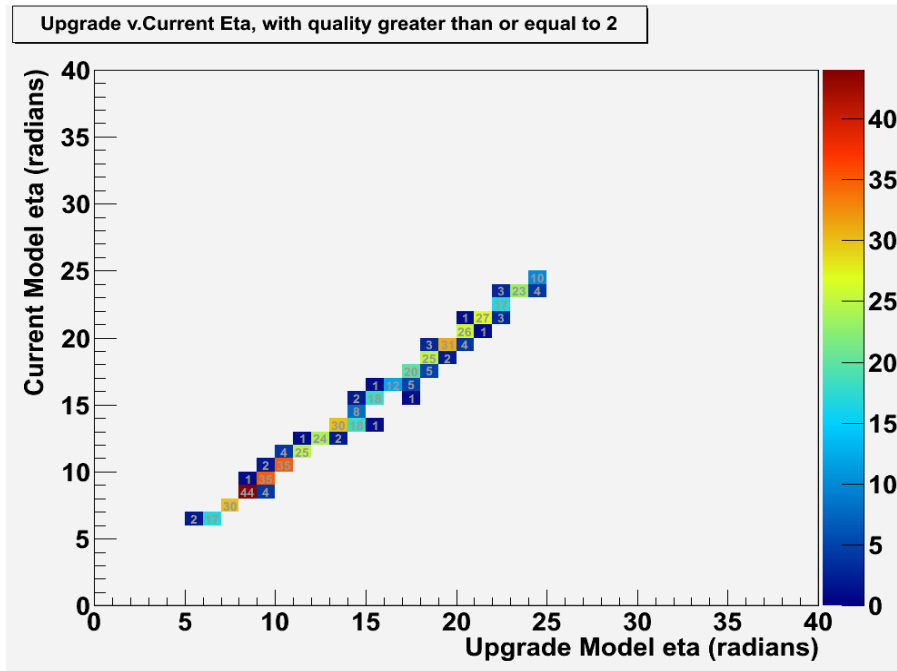


Figure 5: Upgrade η v. Current η

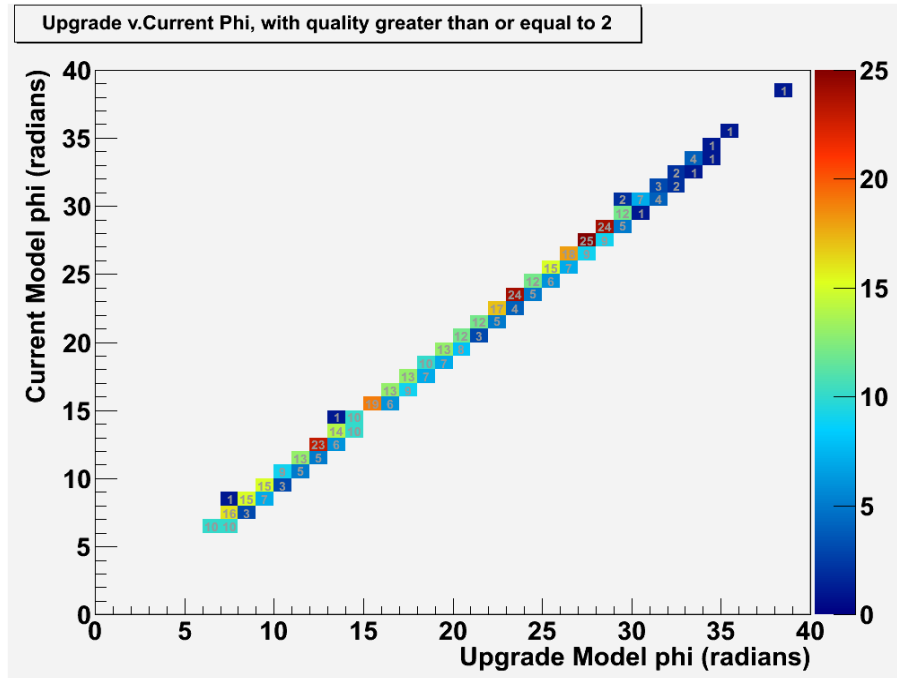


Figure 6: Upgrade ϕ v. Current ϕ

The next question that needed to be asked is whether or not the differences we did

find were related to the location at which the simulated muon struck the detector. In an attempt to determine this, I plotted the difference values of each variable against the generator value of η and ϕ . This led to interesting results. Plotting the difference in p_T against the generated ϕ value (Figure 7) shows that there is little to no ϕ dependence in the momentum calculated by the new track finder. The highly negative differences are spread across the range of ϕ .

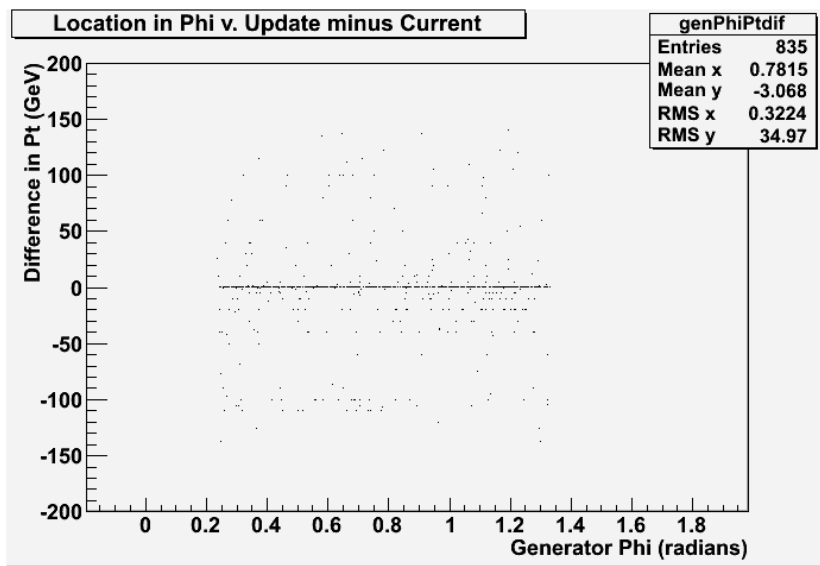


Figure 7: New minus Old p_T v. the generated value of ϕ (radians)

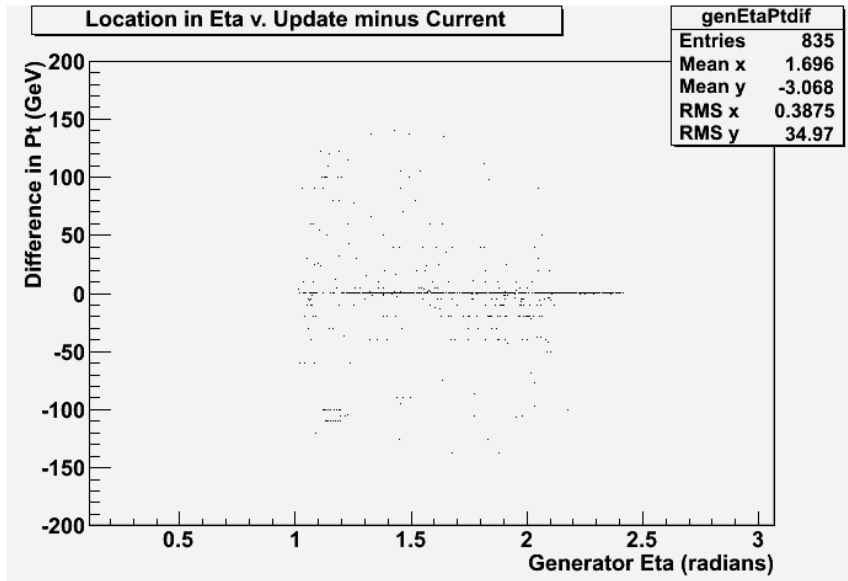


Figure 8: New minus Old p_T v. the generated value of η (radians)

However, unlike for generator ϕ , the generated value of η appears to be somewhat correlated to the large difference in p_T (Figure 8). This suggests that there is something wrong with the new Sector Processor's algorithms in those particular ranges in eta.

When a signal is detected and goes through the L1 Trigger and Track Finder, it has a piece of information connected to it that is referred to as the mode. This is a 4-bit integer that encodes information on which stations are used to make a track. When I plotted the old and new environments' values for mode against each other, there were also minor discrepancies (Figure 9). We can see that there is a gain the diagonal line that would result from identical results, but there are also a large number of events for which the new environment's location is different. Checking to see if these also were related to η , I made another difference v. generator η plot, this time for mode (Figure 10). This also shows an anomalous dependence on eta, in the range where eta is between 0.9 and

1.2. That range contains the region of overlap between the CSCs and drift tubes, so that eta dependence could be due to the fact that the upgrade model does not use DT information in track reconstruction, limiting the quality of the tracks.

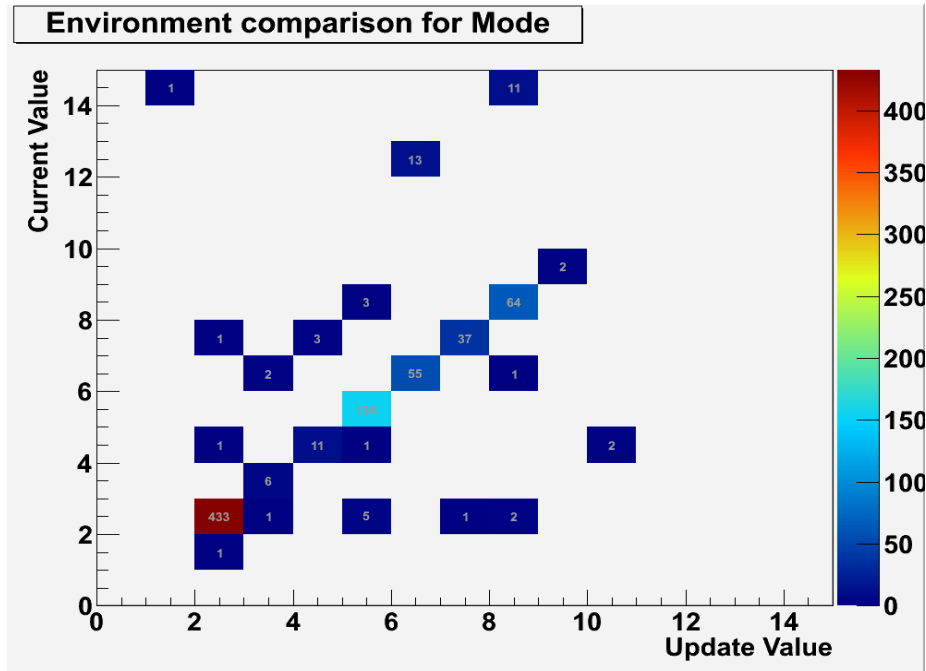


Figure 9: Current mode values v. Update mode values

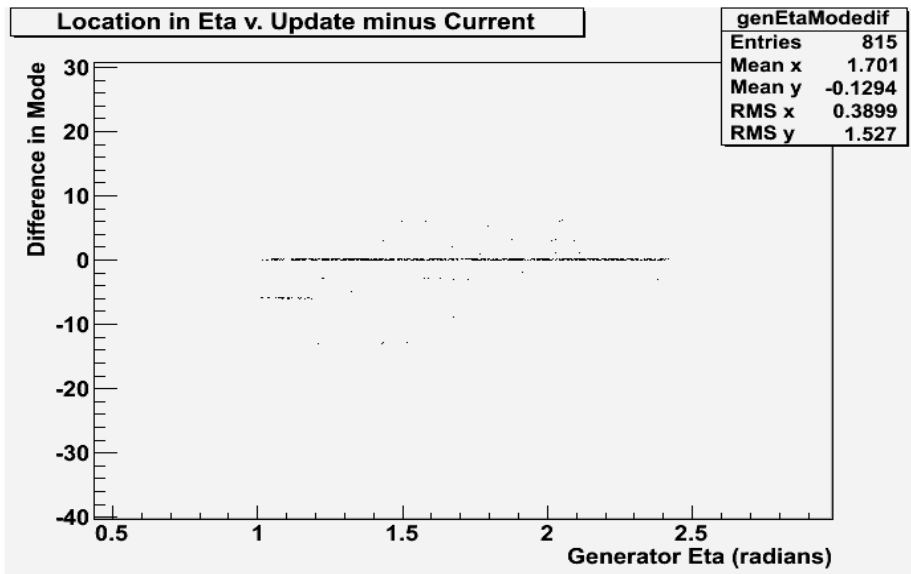


Figure 10: Update minus Current mode value v. generator value of η

Our analyzer program also generates efficiency plots, so we can compare the η and p_T efficiencies between the current and updated track-finder. These display how often the algorithm reconstructs a track when a muon is shot toward the detector with a certain value of eta. Figure 9 shows the efficiency plot for the current track finder. The lack of quality greater than 2 tracks around $\eta = 1.6$ and 1.7 are due to physical gaps in the CSC stations, and are to be expected. Comparing Figure 11 and Figure 12 shows rough agreement between the two. The lack of high-quality tracks in $\eta < 1.2$ for the updated algorithm exists because the update has not yet been designed to incorporate data from the drift tubes for the area where the CSC and DT systems overlap. The rough agreement shows that the update is close to being as efficient as the current track-finder.

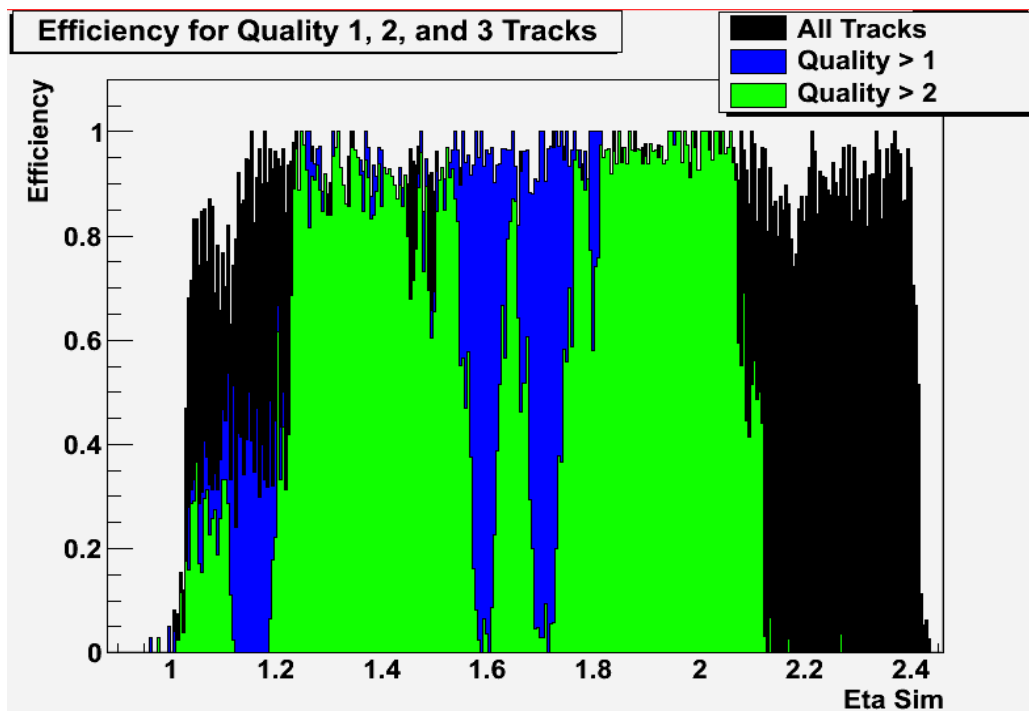


Figure 11: Current Eta Efficiencies

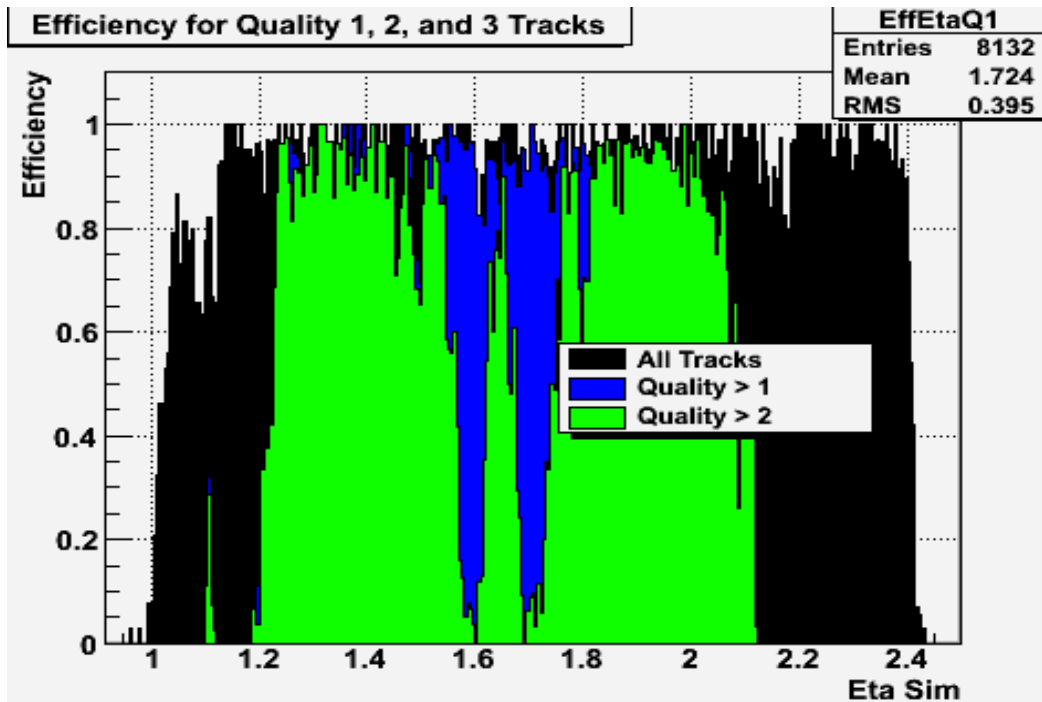


Figure 12: Update Eta Efficiencies

The p_T efficiency histogram for the current (Figure 13) and updated (Figure 14) algorithms also seem to show rough agreement. These histograms display whether, for a simulated particle with a particular p_T value, the track-finder calculates a p_T estimate greater than a particular value. We do not want the track-finder to underestimate the momentum of particles, as that would allow the L1 Trigger to filter out events that could have interesting physics, so the fact that the updated logic's p_T efficiencies are approaching those of the current logic is a good sign.

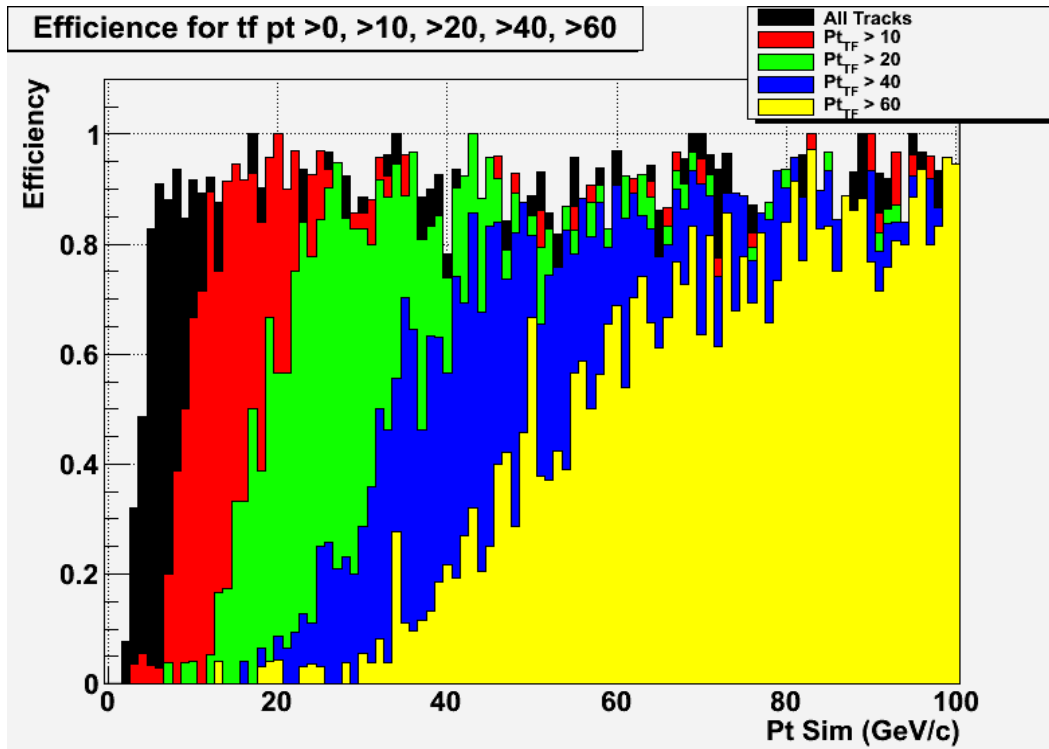


Figure 13: Current p_T efficiencies

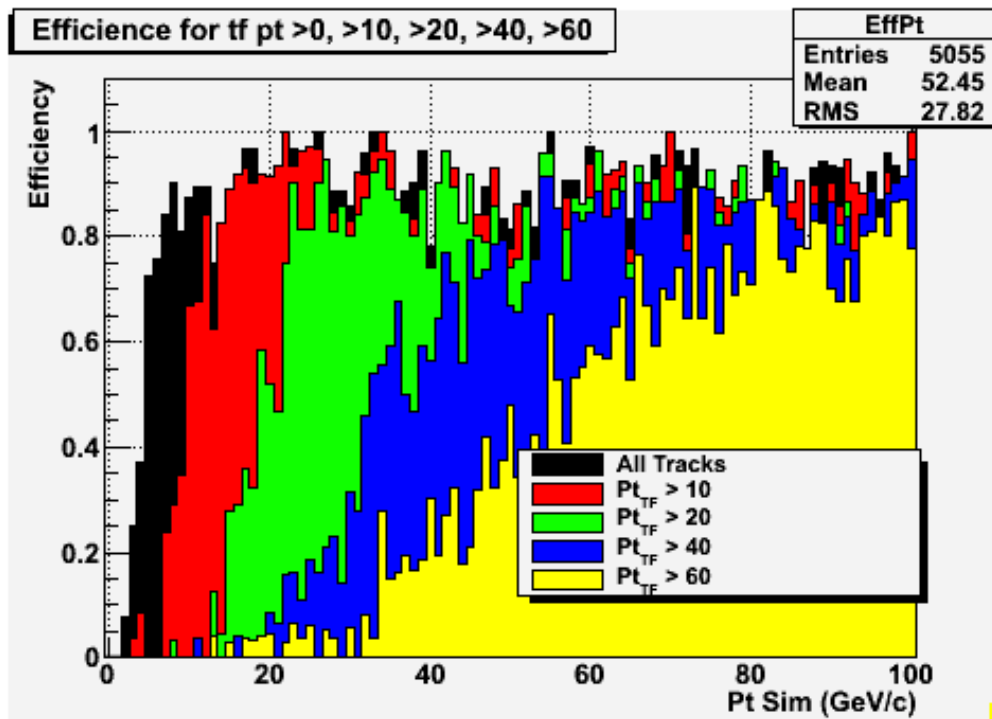


Figure 14: Update p_T efficiencies

Results

We have detected that there are some inconsistencies in the track finding capabilities between the version of the Sector Processor that is currently in use at the LHC and the upgraded version that has been modeled. These variations seem to be linked to the eta value of the muon whose path the track finder is trying to reconstruct. There are also signs that the modes involved in this reconstruction are also varying based on eta and this variation merits further inquiry. However, except for these inconsistencies, the new SP algorithm seems to be well on its way towards matching or exceeding the performance of the current algorithm.

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