Analyzing Potential Tracking Algorithms for the Upgrade to the Silicon Tracker of the Compact Muon Solenoid

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Abstract

The research performed revolves around creating tracking algorithms for the proposed ten-year upgrade to the silicon tracker for the Compact Muon Solenoid (CMS), one of two main detectors for the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The proposed upgrade to the silicon tracker for CMS will use high-speed electronics to trace particle trajectories so that they can be used immediately in a trigger system. The additional information will be combined with other sub-detectors in CMS to distinguish interesting events from background, enabling the good events to be read-out by the detector. The algorithms would be implemented directly into the Level-1 trigger, i.e. the first trigger in a two-trigger system, to be used in real time. Specifically, by analyzing computer generated stable particles over various ranges of transverse momentum and the various tracks they produce, we created and tested various simulated trigger algorithms that would be hopefully used in hardware. As one algorithm has proved very effective, the next step is to test this algorithm against simulated events with an environment equivalent to SLHC luminosities.
1 Introduction: The LHC Machine

In Geneva, Switzerland, home to the European Council for Nuclear Research (CERN), is the world’s most powerful man-made particle accelerator. Located an average 100 meters below the surface, the Large Hadron Collider (LHC) accelerates protons and heavy ions in a 27-kilometer ring for collision. The LHC looks to answer some of the most fundamental questions concerning the nature of the universe. The Standard Model of Particle Physics is currently acknowledged as the most complete description of particle interactions between the electromagnetic, weak, and strong forces. However, under certain symmetries, the electromagnetic and weak forces can be unified under one electroweak force, but only if the particles mediating the weak force have no mass. Yet, the W and Z bosons are observed to have mass, and so something must be added to the theory. One explanation is the Higgs boson, which continues to remain elusive. Finding the Higgs boson is one of the main reasons behind the construction of the LHC and its detectors. In addition to solving the electroweak symmetry breaking, the LHC looks to answer questions concerning the nature of dark matter, dark energy, supersymmetry, and extra dimensions. All these questions seek to test physics beyond the Standard Model.

At design specifications, the LHC reaches a maximum of 14 TeV center of mass energy for proton-proton collisions. Each proton beam has an average energy of 7 TeV, which corresponds to approximately 7500 times the rest mass energy of a proton. Due to initial setbacks, the LHC is currently operating at only half of this energy. The current peak luminosity, or the number of particles per unit area per unit time, of the proton beam collisions is on the order of $1.25 \times 10^{33} cm^{-2}/s$ [2]. Design specifications have bunch crossings occur every 25 ns, or 40 MHz, resulting in 2808 bunches in the entire LHC [1].

2 The CMS Detector

The Compact Muon Solenoid is the detector for one of two major particle physics experiments being performed at the LHC, the other being ATLAS. CMS gets its name from being small relative to ATLAS, from the solenoid inside of it which produces a 3.8T magnetic field, and from the muon detectors which sit outside the solenoid and make up a large percentage of the overall volume. CMS is designed for both flexibility in studying various results of particle collisions and especially for efficiency and accuracy in detecting muons. CMS has 4 layers, each consisting of a barrel and an endcap. See Figure 2 below for schematic layout. The layers are the silicon tracking layer, the electromagnetic calorimeter, the hadron calorimeter, and the muon detector when they are listed from innermost to outermost. The
A superconducting solenoid is directly between the hadron calorimetry layer and the muon system. The barrel of each layer is optimized to detect events which are close to perpendicular from the beam line (low $\eta$, or pseudorapidity), while the endcap tends to be oriented perpendicular to the barrel and is optimized for higher $\eta$ events. $\eta$ is a measure of how close a particle is to being parallel with the beam. $\eta=0$ corresponds with a perpendicular, while $\eta=\infty$ describes a line parallel with the beam. $\eta=1.2$, the cutoff for most of the barrel detectors, is an angle 33.5° off the beam line.

![Diagram of CMS detectors](image)

**Figure 1:** Inside of CMS. Picture Ref: CMS TDR [1]

### 2.1 Detectors in CMS

#### 2.1.1 The Muon Detector

The outer shell of CMS is the muon detector. It is a detector array consisting of 3 different types of muon detectors: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. For the details of the workings of these detectors, please see the section 3.1 of the CMS TDR [1].
2.1.2 The Solenoid

Directly inside of the muon layer is the super conducting solenoid. This produces a 3.8T magnetic field inside of it for the purpose of bending particles in order to investigate their momenta. The uniform magnetic field inside of this detector provides a method of converting a curvature of a particle into a momentum, which can then be translated to energy once the identity of the particle is known. The inner radius of this solenoid is about 3m, so the HCAL, ECAL, and the silicon tracking make up only about 15% by volume of CMS.

2.1.3 The Hadron Calorimeter

The HCAL lies inside of the solenoid and is used for finding the energies of hadrons resulting from different particle events. The HCAL barrel portion achieves this with layers of metal (mostly brass) plates sandwiching scintillating crystals. The HCAL also includes an outer hadron calorimeter; it is a thin layer of scintillating crystals placed just outside the solenoid. This outer layer is used to measure how much of the hadron shower is missed [1]. The hadron endcap contains similar detectors oriented in a direction consistent with capping the cylinder. The hadron detector layer is unique in its inclusion of a forward detector to cover angles even less perpendicular to the beam line than the typical endcaps (3.0 < \eta < 5.0 instead of 1.2 < \eta < 3.0). muons will deposit very little energy in this layer and can therefore be tracked and measured in the outer muon layer.

2.1.4 The Electromagnetic Calorimeter

Below the HCAL is the electromagnetic calorimeter (ECAL), which is used to measure the energies of photons and electron resulting from events. The ECAL consists of many lead tungstate crystals that emit light with a short distance of interaction and in a short amount of time, but fail to produce much light per energy of incident particle. The light is therefore amplified and readout with 15 bits of precision (over a dynamic range) [1]. The endcaps of the ECAL are made of the same material. Both heavy hadrons and muons will deposit minimal energy in this layer, so that accurate readings can be taken as they move to the outer layers.

2.1.5 The Silicon Tracker

Closest to the beam line is the silicon tracking layer, which is a series of cylinders made from silicon strip detectors and, in the case of the innermost layers, silicon pixel detectors. This set of detectors extends to a radius of approximately 1.2m. Silicon detectors are strips of metal placed on top of two layers of alternately doped silicon making what is essentially a
very large diode this allows them to detect the current of charged particles passing through them, and this can be read out directly. The spatial resolution is limited by how small the metal plates can be created, as a voltage change only allows for the information that the particle hit somewhere on the plate. This can be improved somewhat if the particle goes in between two plates and leaves some charge on each, as then the charges can be shared to determine where in between the plates the particle passed. The silicon pixel detectors have three layers with radii 4.4cm, 7.3cm, and 10.2cm away from the beam line, and provide accurate 3 dimensional location data for charged particles passing through them. Between 20cm and 55cm are silicon strip detectors, which sacrifice one dimension of resolution in space for a large savings in readout electronics, and out wide of this range are still larger silicon strip detectors, for a total of ten layers. The problem of spatial resolution in strip detectors can be somewhat resolved if 2 layers are positioned closely together with the strips in an slightly off parallel and one event fired relatively few strips; this is performed by using the data in both layers to pinpoint the exact 3D location where the particle must have been if it went through both strips.

Despite being thick, which can cause a particle to change trajectory, silicon detectors can accurately measure positions of particles that pass through them. This high precision in position leads to another well-defined measurement: transverse momentum \( p_T \). Due to the solenoid's magnetic field being parallel to the beam, from electromagnetism, a charged particle will bend while moving in the transverse, or perpendicular, direction of the beam. A particle’s radius of curvature can be determined based only on 2 points, and \( p_T \) can be directly found from magnetic strength and radius of curvature. Precisely, if CMS is in a cylindrical coordinate system with the beam line as the z axis, \( \phi \) being the angle, and r the radius, then it is in the r direction (\( \phi \) cross z). Since the transverse momentum is always oriented away from the middle of the detector, the sign of the momentum is used to indicate the charge of the particle (and therefore which direction it will curve in the magnetic field). It is possible to measure the total momentum, given the angle between the transverse plane and the particle. By measuring a component of the momentum, it is possible to obtain the full vector quantity of the momentum. These determinations can only be made if the particle’s initial position is directly on the beam line, as the most energetic particles will be.

2.2 CMS: Triggering

At design specifications events occur in the center of the detector at a rate of 40MHz. Each event produces approximately 1 MB of detector data, which corresponds to a data rate of 40 TB/s. It is not feasible to write data out at this rate, much less store it. Therefore there
is a system of triggers which quickly identifies which events are interesting, and thus which events to store. These triggers are adjusted based on what kind of physics is being studied at a given time, but they eventually reduce this data to write rate to 100 Hz. As a quick note, currently write rate at CMS is 300 Hz. This reduction is done in two stages: the Level-1 (L1) trigger and the Higher Level Trigger (HLT). The L1 trigger brings the data rate down to 100kHz, but can only do so much, as it must make decisions at the full detector rate and is limited by processing time. In order to react this fast this trigger must be implemented in custom hardware, which limits the complexity of the algorithm, as complexity scales price and size of the component quickly. Triggered events are then passed to the HLT which is implemented in software, and so can run with more complexity at the slower rate. As an example, the L1 muon trigger takes data from all of the detectors in the muon layer and decides if a muon is likely, if so, the event is passed to the HLT, which then uses the data in the muon layer and the silicon tracking layer to reconstruct the muon track and determine its momentum and energy [1]. The HLT can implement different types of tracking algorithms on the data; many start first from the calorimetry layers and muon systems to reconstruct objects, creating partial tracks. If these hits are not rejected by the trigger, this information can then be combined with information from the tracking layer in order to get the exact path of the particle. This is a process known as tracking. Currently, the L1 trigger does not implement any form of tracking but leaves that process to the HLT. The reasons for not including a track trigger before the HLT are historical. When CMS was first envisioned back in the late 1980’s, lower level triggers with track reconstruction were seen as ineffective. CMS also made a large gamble in only using two triggers, whereas almost all detectors use three. CMS projected the developments in computing would be ready to handle the large computational demands present for processing the high rates of events to the HLT by the time the LHC turned on. With an already robust calorimetry and muon system, and low amounts of interactions per bunch crossing, there was no immediate need to include another trigger or any sort of lower level tracking.

### 2.3 CMS: Tracking

By using all of the information on all of the layers together, CMS can identify tracks. Since this is done with the HLT, the algorithm can be relatively involved and, indeed, is a 5 step process. By first starting with the clusters of hits from the pixel and strip detectors, seeds, or two closely spaced hits, are generated from the innermost layer. By projecting the trajectory of the seed outwards, the tracker moves through a pattern recognition phase. After sorting out fake and duplicate tracks with combined data from the other layers, the tracker
finally assigns a fit to the track. The pattern recognition requires that a variety of possible paths through the hits be processed. The possible paths can be computed because the solenoid maintains an almost constant, well known magnetic field over the tracker volume. This whole process is effective, but its complexity necessitates that it be implemented in the HLT. For more information on the tracking process, see section 6.4 of the CMS TDR 2006 (p.240) [1].

3 LHC Upgrade in 2020: SLHC

After an extended period of continual operation, the LHC will be shutdown in order to upgrade the machine and its detectors. From 2010 to 2020, known as Phase 1, the LHC will work towards achieving design energy and luminosity. Two long shutdowns will occur in 2013 and 2017 to prepare the machine to reach full 14TeV energy and $2 \times 10^{34} cm^{-2}/s$ luminosity. A more substantial upgrade to the machine and detectors will come around 2020, termed Phase 2, in which the machine will have another long shutdown to prepare the LHC and its detectors for a factor of 10 increase in luminosity. [2]

This upgrade in 2020 will move the LHC to the SuperLHC (SLHC). The upgrade will seek to increase luminosity from $10^{34} cm^{-2}/s$ to $10^{35} cm^{-2}/s$. This will significantly increase the number of particle collisions per bunch crossing, mainly by increasing the number of protons per bunch. Currently, CMS is operating at around 8 interactions per bunch crossing. At SLHC luminosities, there will be on average 200 interactions per bunch crossing, assuming bunch crossings will occur every 25 ns. CMS is not currently outfitted to handle such high collision rates. The L1 trigger rate as it is now at CMS flattens out with $p_T$ threshold, due to a poor momentum measurement in the current L1 muon system. The detector components are not robust enough to distinguish so many particles at such high occupancy. At luminosities around $10^{35} cm^{-2}/s$, the current trigger fires at a rate well over 20 kHz for muons, which is hoped to be reduced by a factor of 100 [3].

After ten years of operation, the inner components of the detector, specifically the pixel detector and the silicon tracker, will have to be replaced anyway. At this time, these components will have been so significantly radiation bombarded that most of the electronics will no longer be fully operational. This is in part due to the fact that the radiation from the collisions will destroy the crystal lattice of the silicon, and thereby fry some of the electronics permanently. The shutdown will provide an excellent opportunity to replace the tracking layers.

As stated previously, the current trigger at CMS uses a two level triggering system, but the new tracking detector will require a new trigger. With SLHC luminosities, the L1
trigger would trigger on muons much more often, thus overloading the HLT in its ability to select the important events in which to save. To reduce the load placed on the HLT, there is significant interest in implementing track reconstruction in the L1 trigger for the upgrade. This presents a significant challenge, as the hardware necessary would have to be incredibly precise and fast to process the extremely high occupancies in the silicon trackers created by such large amounts of pileup, or additional interactions created per crossing.

Hardware is significantly faster than software in analyzing and computing transverse momentum given a set of hits, which gives a motivation for providing tracking information to the L1 Trigger. Once a collection of hits from each event is found, this information can be immediately passed to the L1 trigger composed of high-speed electronics. Through the use of field programmable gate arrays (FPGAs), the hardware could quickly sort out matched tracks from fake or incomplete tracks. FPGAs consist of an integrated circuit whose logic can be configured after production and any time after implementation. Depending on the physics that is being investigated, certain cuts can be placed on the trigger, in which many events can be rejected based on acceptance in $p_T$ and location in $\phi$ and $\eta$ of the actual hits by changing the logic in the FPGA.

4 CMS Upgrade Geometry

For the purpose of the upgrade, different geometries are being investigated for the silicon tracker than the one currently in place at CMS. The silicon tracker geometry that was investigated for this study was long barrel straw-man. [3] The long barrel extends the full length in the beam direction. In order to cover a complete circle around the beam, the cylinder is divided into alternating sliced layers. The full geometry is shown below.

In this geometry, there are no forward end caps. In order to catch near parallel tracks, four other forward barrel stack layers are added at 180cm in the z direction. The stacks are spaced radially at 32cm, 35cm, 48cm, 52cm, 98cm, 102cm, and with the forward barrel stacks at 64cm, 68cm, 80cm, 84cm. The tracker extends to 275cm in the z direction. Each layer in the above diagrams has two sides of sensors, together that layer makes a stack. A pair of connected hits in a stack is known as a stub. In the upgrade to CMS, there will not be silicon strip detectors, as all layers will use only silicon pixel detectors. The sensors to be used are silicon pixels that are 100$\mu$m by 1mm.
4.1 Path Computation

Using software release CMSSW_3_3_6, Monte Carlo simulation studies done in Fast Simulation were first performed as to how well this geometry could match actual hits with simulation truth information. This was first performed with single track events without pileup. For the sake of simplifying the study, $\eta$ was restricted to 1.2 to exclude the forward barrels. The efficiency of finding all the stubs created for single track 5 GeV/c muons was very close to one hundred percent. Charged pions and electrons at 5 GeV/c were fairly similar to each other, staying around 97 to 93 percent per stub layer. Upon moving to real events, such as high $p_T$ QCD events and Higgs to four lepton events, the efficiency remained exceptionally high. After this initial testing was completed, confirming the usefulness of the new geometry, a new algorithm was developed based on intersecting concentric circles. Charged particles in the detector are assumed to travel in perfect circles in the transverse direction due to the magnetic field of the solenoid. Due to the symmetry of the cylinders, it is possible to reconstruct the path of the particle in $\phi$ given a hit in any layer. For the purposes of this algorithm, it was assumed that tracks that were worth saving made it all the way to the furthest layer in radius, at 102cm, shown in the figure as $r_6$, and high $\eta$ events that left stubs in the forward barrel were ignored. From this, a position in $\phi$ is calculated per layer by projecting the track back to the vertex. See Figure 4 and Equations 1 and 2 for an example.
This equation allows calculation of track position on a lower layer given only the position of the outer stub and R, the radius of curvature (or \( p_t \)). X and Y can then be converted into a detector \( \phi \) position.

\[
x = r_1 \cos(\phi - \cos^{-1}\left(\frac{r_6}{2R}\right) + \cos^{-1}\left(\frac{r_1}{2R}\right))
\]
\[
y = r_1 \cos(\phi - \sin^{-1}\left(\frac{r_6}{2R}\right) + \cos^{-1}\left(\frac{r_1}{2R}\right))
\]

\( p_T = \frac{(0.3)(3.8)\frac{r}{\sin(\Phi_0 - \Phi)}}{\sin(\Phi_0 - \Phi)} \) (3)

.3 is the value of the physical constants in front of that equation. 3.8 is the strength of the magnetic field in Tesla, while the other variables are defined as in the picture.

4.2 Stub \( p_T \)

Stub \( p_T \) is measured by taking the two closely spaced hits in a given stub, and by projecting a circular curve back to the vertex, the curvature from the magnetic field gives a transverse momentum. At higher momentum, tracks bend less, and the angle between the hits on a stub becomes significantly smaller, reducing the precision in the momentum measurement. At momenta above 50 GeV/c, the difference between angles becomes so small, the sign of the curvature actually becomes ambiguous, as positive and negative curvatures can no longer be accurately determined. Figure 5 shows how stub \( p_T \) is visualized.

As shown in Figure 6 (See online for color), momentum resolution quickly falls off towards higher momentum tracks, around 5 GeV/c, often considered the cutoff for high momentum. If cuts were to be placed on tracks, it is guaranteed that true 2 GeV/c tracks
will not be measured above 5 GeV/c, and true 5 GeV/c tracks will not be measured below 2 GeV/c. For the purposes of designing a tracking algorithm, using stub $p_T$ measurement as a cut can greatly reduce both the possibilities of stubs for building tracks and thus reducing the chances of finding fake tracks. Additionally, although not shown, tracks that are 100 GeV/c, will never be measured lower than 10 GeV/c, which can be useful in placing cuts on tracks associated with high momentum used for track finding to reduce fake tracks.

![Measured Stub $p_T$ of Single Track Muons (5000 events)](image)

Figure 6: Range of stub measurements of $p_T$ for different incident muon energies.

5 CMS Upgrade Tracking

Due to the increased luminosity (both instantaneous and absolute), the triggering system needs to improved to handle the increase in detector occupation. The method which was investigated for this is an upgrade to the L1 triggering system which incorporates tracking, and, through this, $p_T$ estimation. By incorporating track information into the L1 trigger, the rejection rate for the L1 trigger can be increased significantly, which would allow the amount of data being sent to the HLT to remain constant with the increased event rate entering the L1 trigger.
5.1 First attempt: Stub $p_T$ Matching

The first method of track finding we attempted was matching stub $p_T$s from the sixth layer based on a computed uncertainty function in the measurement. For the purposes of this investigation, we are focusing only on the barrel portion of the long barrel, and so the sixth layer refers to the outermost layer. This attempt was not successful, as the momentum uncertainty was very large (and asymmetric) when measured, and so many of the stubs contained overlapping momenta. The uncertainty was so large because the layers forming the stubs are so close together, and so there is little ability to see the effects of the curvature of the particle in a magnetic field. This resulted in the algorithm being overwhelmed by the number of matches, and therefore producing little to no interesting information. The number of matches can be decreased substantially by requiring that the stubs lie, with some degree of uncertainty, on a straight line from where they were produced. This is a straight line in the r-z plane, and starts at a z value between -10cm and 10cm, narrowing to a point at the sixth layer. The SLHC interaction point is expected to have an error of 5cm in z.

5.2 Final Approach: Curvature Bins

Even using this z cut, matching stub measured $p_T$ was unsuccessful in singling out tracks, so we decided to ignore the reported $p_T$ at first and only use the location of the stubs for information. So instead we started from the assumption that any stub in the sixth layer was formed by a particle starting at the center which passed through all six layers and left stubs. We then set out to investigate what $p_T$ it might have had. This was done by creating ranges in $p_T$ which, when converted to their corresponding curvature and intersected with the lower layers, corresponded to specific ranges in $\phi$. These ranges in $\phi$ are referred to as $\phi$ bins. The cut in the z axis was left in, as it still is an effective way to shrink the stub space. We started by creating 100 bins spaced in momentum such that they subtended equal $\phi$ ranges. This caused the momentum resolution to decrease as momentum increased, but this was not unexpected, as particles tend to take paths that approach a straight line as momentum tends toward infinity. When these bins were implemented with no overlap, the efficiency vs $p_T$ plot contained oscillations due to the fact that some particles with a momentum near the bin boundaries would fail to have all hits in one bin or the other, and so there would not be a hit on each layer in the bin. To fix this problem, we had to define overlapping bins, which was done by defining the bin centers with a given amount of slop. Slop is a quantity which scales the bin widths linearly in curvature. The lowest and highest curvature bins presented were exceptions, as 0.5 slop corresponds to bins, which completely fill momentum/curvature space, but have zero overlap, while 1.0 slop means that a bin will extend from the center of
the bin before it to the center of the bin after it. This slop value is a parameter which we adjust based on binning. Higher slop values will lead to a higher efficiency of track finding at the expense of a higher fake rate. This method of binning tended to slice the lower part of the momentum spectrum much too finely, to the point that efficiency was lost below 5 GeV/c depending on the exact parameters. If slop was increased to bring this efficiency up, then the resolution on the higher end of the $p_T$ spectrum was decreased by too large of a factor to be useful.

Our first attempt to resolve this issue was to allocate a set number of bins for different parts of the momentum spectrum (while still keeping a total of 100 bins), but this merely resulted in the spectrum being sliced too finely in two spaces instead of one. As this indicated that 100 bins was too many, we decided to merge the lower bins until a specific threshold was met, but this either did not fix the problem, or created too few bins. Another tack we took was to plateau the $p_T$ ranges of the smaller bins, or dynamically increase the slop such that these bin widths never got smaller than a given $p_T$ or $\phi$ range, but this tended to result in absurdly wide bins at low momenta (the same $\phi$ point being covered by 10+ bins). Finally we came to the conclusion that we needed to decrease the number of bins to get efficient $\phi$ coverage. We used linear $p_T$ steps (of varying size) on the low momentum end of the spectrum and switch over to the equal curvature slicing starting at 10 GeV/c.

In the final iteration of this custom binning, there was one bin from 0.1 GeV/c to 2 GeV/c, followed by linear steps of size 0.2 GeV/c from 2 GeV/c to 4 GeV/c, then linear steps from 4 GeV/c to 6 GeV/c of size 0.5 GeV/c. After this, the 100 bin equal curvature function from 2.0 GeV/c to 300 GeV/c is called for the last 33 bins (there are 33 bin between 6 and 300 GeV/c in that binning, which gives an estimation of how finely sliced the low $p_T$ bins were before the linear step sizes). The final bin is from 300 GeV/c to -300 GeV/c. The very high momentum tracks all move straight through the detector, and so tracing continuously through $\phi$ space is equivalent to tracing through infinite momentum and coming back from negative infinite momentum. As such, the mid-
dle bin contains very positive and very negative momenta. The bins are symmetric and there are a total of 48 bins on each side and 1 in the middle making 97 bins in total.

At first we used a slop of 1.2 to get a reasonable efficiency plot, but then we realized that we were using a magnet strength of 4.0T when we should have been using a strength of 3.8T. This caused errors in the proper \( p_T \) binning. We were then able to decrease the slop to 0.8 without a significant negative impact to the efficiency plot. One final upgrade to our algorithm was to remove all of the stubs which reports less than 2 GeV/c for their momentum. The current binning scheme is seen here in Figure 7.

6 Efficiencies and Fake Rates

In order to test the efficiency of our tracking algorithms we first tested them on a spectrum of single muon tracks. These tracks should be the easiest to find, as muons are one of the most penetrating particles through the detector material as evidenced by the enormous volume of the detector devoted to detecting only them.

Muons also have a small chance of interacting and being deflected, and their large mass means they radiate less, which makes their tracks very close to perfect circles and don’t produce additional tracks due to radiation. The muon efficiency plot from 2 GeV/c to 1 TeV is seen in Figure 8. Note that the initial very low values for 2 GeV/c and 3 GeV/c are due to cutting out stubs which reported below 2 GeV/c. The uncertainty on the stub measurement, even at this large angle of curvature, ensures that many of these stubs will get cut and hurt the track efficiencies. The effect abates above 3 GeV/c because the uncertainty range does not reach that low for higher momentum tracks. Between 6 GeV/c and 10 GeV/c, there is a small dip due to the change of styles of momentum measurements. After 10 GeV/c, it remains flat save for 2 dips: one at about 200 GeV/c and about 400 GeV/c. These features of the efficiency plot are not well understood, but are likely due to how particles at these energies are deflected and where the bin cuts occur in curvature. Also see Figure 9 for a detail of the lower \( p_T \) range of the same plot.

As a test of how this would affect a trigger, “MinBias” events were analyzed. A minimum bias event is what we expect to constitute a pileup event. In order to get an estimate of how often this algorithm would find a nonexistent track at high \( p_T \)s, the algorithm was run on 200 thousand individual minimum bias events and the highest momentum fake for a given event (if there were any) was placed in a histogram. The overplotted histogram shows this without vetoing stubs less than 2 GeV/c versus the effect with vetoing Figure 10. Unfortunately, these fake rate do not scale linearly with detector occupancy, but this is a good starting estimate of algorithmic performance. Assuming it is possible to look at only
Figure 8: Efficiency of finding muon tracks in the range 2 GeV to 1 TeV

Figure 9: Efficiency of finding muon tracks in the range 2 GeV to 25 GeV

1 MinBias event in the detector, that these events occur with cross section 71mb, and that the LHC is operating at luminosity $10^{34} cm^{-2}/s$, then one fake on this plot corresponds to a readout rate of about 3.6kHz. This estimation needs to be taken with a grain of salt not only due to the nonlinearity of the effect, but also due to the fact that only a few counts are
obtained above 10 Gev, so the uncertainty on the rate of counts is quite high.

7 Future Investigation

The algorithm developed for the new geometry has performed well under single track events without pileup. The tuning of the algorithm presented a unique challenge; selecting the best types of $\phi$ bins, the proper amount of $\phi$ bins, and slop in $\phi$ each took time to compile and analyze. Due to the improper magnetic field constant being used in our algorithm, a significant amount of overestimation in slop was given for high momentum, resulting, initially, in very high fake rate. Further study is needed to optimize the algorithm, investigating different slop values, tuning the number of $\phi$ bins, and how to bin in $\phi$. The algorithm should also account for high $\eta$ tracks, and incorporate the forward barrels into the algorithm as well. In addition, once the optimal algorithm has been determined, single track events with pileup as well as realistic events with pileup will need to be studied. If the algorithm proves to operate well under high amounts of pileup, with high efficiency of finding real tracks and low fake rate, then this algorithm should be moved to a simulated FPGA code.
Upon successful implementation into hardware code, the algorithm should move towards actual production in hardware to be tested for integration into the new silicon detector for CMS.

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