Efficiency of the CMS Level-1 Trigger to

Selected Physics Channels

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Abstract

The efficiency of the Compact Muon Solenoid (CMS) Level-1 Muon Trigger (L1T) to select certain physics channels were calculated for three different decays: $H \rightarrow Z^0 Z^0 \rightarrow u^+ u^- u^+ u^-$, $H \rightarrow W^+ W^- \rightarrow u^+ u^-$, and $B \rightarrow J/\psi \rightarrow u^+ u^-$. Efficiencies were obtained from computer simulations of the collisions, the detector, and the trigger. The endcap is very important to the acceptance of these three physics channels. For example, approximately 80% of Higgs to 4 muon decays have at least one muon in the endcap. Of these, the L1T accepts approximately 88%.

1. Introduction

The Compact Muon Solenoid (CMS) experiment will be used to detect particles resulting from proton-proton collisions at the Large Hadron Collider (LHC). Fig. 1 shows a cutout view of the CMS. CMS is presently being constructed at the European Center for Nuclear Research (CERN). Currently, the Tevatron collider at Fermilab in Illinois is the highest energy collider in the world. The Tevatron is a proton-antiproton collider, which produces collisions at energies up to 2 trillion electron volts (2 TeV, or $3.20 \times 10^{-7}$ J. Higher energies are required to search for more massive particles. The LHC will be used to search for these particles, and of particular importance among them is the Higgs...
Boson, which is a key ingredient to the Standard Model. To search for these massive particles, the LHC will collide protons at energies of 14 TeV.

At the LHC, beams of protons will collide with each other at a rate of 40,000,000 collisions per second. It would be impossible to analyze the resulting data from every collision, so the CMS detector must use a trigger to filter out data resulting from unimportant events. A trigger is an electronic device, which, immediately after an event (collision) occurs, decides whether to reject the event as unimportant data, or accept the event for further analysis. The muon detectors of the endcap regions of CMS will use a three level trigger system. Researchers at the University of Florida have designed and built the first trigger of this system, called the Level-1 Muon Trigger (L1T). Muons are important signatures of a Higgs decay, as well as J/ψ, etc. Muons are very penetrating, and are primarily the only particles that can penetrate the materials of the CMS detector to reach the endcaps.

In order to determine whether or not an event should be allowed to move on to be analyzed further, the L1T must calculate the Transverse Momentum (Pt) of the muons generated by the event. If the L1T finds the Pt of the muons to be above a certain threshold, then the event is allowed to pass on to the next trigger; if not, the event is discarded. The L1T receives its input data from the endcap detectors. CMS will use a combination of four disks of Cathode Strip Chamber (CSC) detectors in each endcap region to measure the trajectories of incoming particles (see Fig 2(a). The CSC’s are trapezoidal in shape and overlap in azimuth to provide seamless coverage around the disk. Each CSC is a type of proportional chamber with six layers. Each layer consists of several cathode strips in the radial direction, held at ground potential. Perpendiculars to the cathode strips are several anode wires held at high voltage. These wires are held in a
special mixture of gas, which ionizes when a charged particle passes through it. The electrons from the ionization drift towards and collect on the anode wire inducing an opposite charge on the nearby cathode strips. By calculating where the difference in charge on the cathode strips is the highest, and where the electrons collected on the anode, the location of the particle on the CSC plane can be determined[1]. This location of the particle on each of the six layers of the CSC forms a track stub for that plane of CSC's. The L1T uses the track stubs for the particle in as many as all four CSC disks to reconstruct the track that the particle followed through the endcap. This track information can then be used to calculate the momentum of the particle.

2. Efficiency of the Level-1 Muon Trigger

Although beams of protons will be colliding with each other at the extremely high rate of 40,000,000 beams per second, the rate at which we expect these collisions to produce Higgs particles is relatively low. The Higgs will be created at a rate of less than one per every trillion collisions. Because Higgs production is expected to be so rare, it is important that the L1T selects as many Higgs events as possible. To select an event is to simply allow that event to move on to the next trigger level.

To decide whether or not to select an event, the L1T must first define the track of the incoming muons based on the location information through the four CSC disks, as described above. Once the L1T has defined the tracks of the muons, it uses that information to calculate the Pt of the muons. To calculate the Pt of incoming muons the L1T uses the following equation:

$$\Delta \phi = a(\theta) \times Pt^{-1}$$

(1)
Where $\Delta \phi$ is equal to the difference in the azimuth angle $\phi$ between two muon sectors. If one thinks of the beam line in CMS as the Z-axis in cylindrical coordinates, then $\phi$ would be equivalent to $\theta$. The constant $a$ depends on which two stubs are being measured and also the angle of the particles position with respect to the beam line.

Once the L1T has calculated the Pt of an incoming muon, it selects that muon depending on how the trigger is set by the experimenter. In the case of the search for the Higgs Boson, the trigger might be set so that all events that produce muons with a Pt greater than 25 GeV are selected. The efficiency of a trigger to select certain decays is given by the equation:

$$\varepsilon = \frac{N_{\text{trk}}}{N_{\text{gen}}}$$  \hspace{1cm} (2)

Where $N_{\text{gen}}$ is the number of particles that were produced by the decay, and $N_{\text{trk}}$ is the number of those particles that the detector actually detected, and found by the trigger. The efficiency for the L1T when selecting events with Higgs decays should be as high as possible, because of the very low frequency at which the Higgs particle is expected to be made.

3. Using Simulations to Generate Data

CMS is not scheduled to begin operation until the year 2006; therefore, all collisions and detector data must be simulated. Though a prototype of the L1T is already built, we used a software model of its behavior for this experiment. The following steps were used to simulate the particle collisions, detection, and Level-1 triggering.

The first step is to simulate the particles resulting from the decay of the Higgs boson or $J/\psi$ particles produced from the collision of the two protons, using an event
generator program called Pythia[2]. Given a specified collision, Pythia simulates particles produced by that collision, based on the real probabilities of producing particles established by quantum theory. Pythia also lets the user allow only specific decays to take place. For example, \( pp \) collisions can be set so that in every event they create a Higgs boson, which in turn can be set so that the Higgs always decays into two \( Z^0 \) particles. Pythia stores the information for all of the particles produced by the collision in a binary output file, to be read by the detector simulation program.

The detector simulation program used was CMSIM, which is based on the GEANT program developed at CERN. CMSIM simulates the behavior of the particles produced by Pythia as they interact with the material of the CMS experiment. For L1T research, we are concerned with the particles that interact with the CSC detectors in the endcap regions. The final simulation program used is ORCA. ORCA simulates the response of the detectors when they interact with the particles, and also simulates the behavior of the L1T in response to the digitized data from the detectors. ORCA stores the information about the particles produced by the collision, the generated data, as well as the results as interpreted by the L1T, the tracked data, all in a binary file. This binary file can then be analyzed using the graphical analysis program ROOT[3].

4. Calculating the Efficiency for Select Physics Channels

Using the simulated \( pp \) collisions, detection, and triggering for three different physics channels. The efficiency of the L1T to select these events was calculated based on the L1T tracking muons from the event for three different Pt thresholds; these were \( Pt > 0 \) GeV/c, \( Pt > 10 \) GeV/c, and \( Pt > 25 \) GeV/c.

4.1 \( H \rightarrow Z^0 Z^0 \rightarrow u^+ u^- u^+ u^- \)
Pythia was first set so that the **pp** collision produced the Higgs Boson, which was set to decay into two \( Z^0 \) particles, which then decayed into a maximum of four muons (see Fig 3), some of which might go into the endcap region. The procedure was repeated for six different possible Higgs masses. They were: 125, 150, 175, 200, 225, and 250 GeV/c. 1000 events were simulated for each of these six masses. The efficiency of the L1T to select Higgs events was then calculated for three different types of events: events which generated one muon in the endcap, events which generated two muons in the endcap, and events which generated three muons in the endcap.

The following equation was used to calculate the efficiency of the L1T when one muon was generated in the endcap:

\[
\varepsilon = \frac{N_{\text{trk}(1+2)}}{N_{\text{gen}(1)}}
\]  

(3)

where \( N_{\text{gen}(1)} \) is equal to the number of events which generated one muon in the endcap, and \( N_{\text{trk}(1+2)} \) is equal to the number of events that the L1T tracked as having either one or two muons in the endcap. I used a similar equation to calculate the efficiency of the L1T when two muons were generated in the endcap:

\[
\varepsilon = \frac{N_{\text{trk}(2+3)}}{N_{\text{gen}(2)}}
\]  

(4)

where \( N_{\text{gen}(2)} \) is equal to the number of events which generated two muons in the endcap, and \( N_{\text{trk}(1+2)} \) is equal to the number of events that the L1T tracked as having either two or three muons in the endcap. The equation for the efficiency of three muon events was simply:

\[
\varepsilon = \frac{N_{\text{trk}(3)}}{N_{\text{gen}(3)}}
\]  

(5)
which gives the number of events tracked as having generated three muons divided by the actual number of generated three muon events. I did not add the number of tracked four muon events to the numerator because that number was typically zero.

Fig. 4 is a summary of the results of the efficiency calculations as a function of the Higgs mass. In the case of one, two, and three muons events, the efficiencies for the three different Pt ranges at the lowest Higgs mass cover a wide range, having a value as low as approximately 25% for three muon events at Pt > 0 GeV/c, to as high as 90% for one muon events in Pt range greater than 25 GeV/c. As the Higgs mass rises, so does the efficiency. For example, for Pt > 0 GeV/c, the efficiency for one muon events is about 90%, for two muon events it is about 80%, and for three muon events it is about 70%. Fig. 4 is shown with error bars for the efficiency. The error for each efficiency was calculated using the following equation:

$$\sigma = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}}$$  \hspace{1cm} (6)

4.2 \(H \rightarrow W^+ W^- \rightarrow u^+ u^-\)

The calculations explained above were also done for the \(H \rightarrow pp \rightarrow W^+ W^- \rightarrow u^+ + u^-\) decay. The calculations were identical except that no three muons in the endcap events were calculated, because \(H \rightarrow W^+ W^- \rightarrow u^+ u^-\) produces a maximum of only two muons. The results of these calculations are similar and can be seen in Fig. 5.

4.3 \(B \rightarrow J/\psi \rightarrow u^+ u^-\)

I also simulated \(B \rightarrow J/\psi \rightarrow u^+ u^-\) for minimum bias pp collisions(see Fig. 6). Fig. 7 shows the number of events the L1T tracked as having between one and four muons in the endcap, under the condition that the actual number of muons generated per event in
the endcap was either one or two. This condition, the number of generated particles, is shown as ngen. Table I summarizes the efficiency’s for the J/Psi decay, which I calculated the same way that I calculated the efficiencies for the previous two Higgs decays.

TABLE I

<table>
<thead>
<tr>
<th>Efficiency to select J/Psi decaying to 2 mu for different Pt ranges and number of particles generated in endcap</th>
<th>Pt &gt;= 0</th>
<th>Pt &gt;= 10</th>
<th>Pt &gt;= 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mu in endcap</td>
<td>.844 +/- .011</td>
<td>.232 +/- .013</td>
<td>.035 +/- .006</td>
</tr>
<tr>
<td>2 mu in endcap</td>
<td>.689 +/- .015</td>
<td>.067 +/- .008</td>
<td>0.00</td>
</tr>
</tbody>
</table>

4.4 Probability of Muons going into the Endcaps

The probability of muons going into the endcap is a measure of the importance of having a high efficiency in that region. Figs. 8 and 9 show the probability of generating one or more, two or more, and three or more muons in the endcap for the three different Pt ranges. The probability is equal to \( \text{N}_{\text{gen}(1+)} / 1000 \), simply the number of events generating one or more events in the endcap divided by 1000 (the total number of events). For probability of two or more and three or more, \( \text{N}_{\text{gen}(1+)} \) would be replaced by \( \text{N}_{\text{gen}(2+)} \) or \( \text{N}_{\text{gen}(3+)} \), the number of events generating two or more or three or more events in the endcap. Table 2 shows the probability of generating muons in the endcap for \( B \to J/\psi \to u^+ u^- \), which was calculated using the same method as for the Higgs decays.

TABLE II

<table>
<thead>
<tr>
<th>Probability of J/Psi generating one or two more muons in the endcap</th>
<th>Pt &gt;= 3</th>
<th>Pt &gt;= 10</th>
<th>Pt &gt;= 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 or more mu's</td>
<td>.27 +/- .014</td>
<td>.015 +/- .004</td>
<td>0.00</td>
</tr>
</tbody>
</table>
During this experiment, 1000 event simulations of three different physics channels were made: \( H \rightarrow Z^0 Z^0 \rightarrow u^+ u^- u^+ u^- \), \( H \rightarrow W^+ W^- \rightarrow u^+ u^- \), and \( pp \rightarrow B \rightarrow J/\psi \rightarrow u^+ u^- \). The efficiency of the Level-1 Trigger to select the Higgs decay channels by detecting one, two, and three or more muons was calculated for three different \( Pt \) thresholds: \( Pt > 0 \), \( Pt > 10 \), and \( Pt > 25 \) GeV/c. The efficiency was found to be significantly lower for events generating three muons in the endcap than for events generating one or two, for both Higgs decays (see Figs 4 and 5). The range in which the efficiency distributions fell was also found to narrow as Higgs mass increased. The efficiency of the Trigger to select \( J/\psi \) events for one or more muons generated in the endcap was found to be around 23% for \( Pt > 10 \) GeV/c muons, and 4% for \( Pt > 25 \) GeV/c muons. This is in part because the Higgs is heavier than the \( J/\psi \), and therefore easier to detect at higher \( Pt \)’s.

The probability of one, two, or three or more muons going into the endcap was calculated for \( H \rightarrow Z^0 Z^0 \rightarrow u^+ u^- u^+ u^- \) and found to be in the range of 50% to 90% for one or more muon events, 10% to 50% for two or more muon events, and 0 to 20% for three or more muon events(see Figs. 8 and 9). Of all Higgs decaying to four muon events, at least 50% were found to generate one or more muons in the endcap regions. For the \( B \rightarrow J/\psi \) decay, only 27% of events were found to generate 1 or more muons in the endcap, for \( Pt \)’s greater than 3 GeV. These probabilities give an indication of the relative importance of the L1T to select different Higgs decays.

| in endcap | 0.05 +/- 0.007 | 0.00 | 0.00 |

5. Conclusion
Future research might involve doing similar efficiency calculations for the Level-2 and Level-3 triggers, and a final analysis of the efficiency of the CMS Trigger system. Attempts could also be made to calculate the mass of the Higgs particle using data obtained from the L1T.

Acknowledgements

I would like to thank the National Science Foundation for funding the REU program, and Darin Acosta for helping me with this project.
References


above FIGURE 2(b): The layers of four CSC’s are arranged side by side in a circular pattern in the endcap region of CMS.

above left FIGURE 2(a): The four muon chambers as part of the endcap. In reality, they are much further apart from each other.
FIGURE 3: A Feynman diagram for Higgs decaying into ZZ decaying into four muons
FIGURE 4: Efficiency of the Level-1 Muon Trigger to detect events with one muon (upper left), two muons (upper right), or three muons (lower left) in the CMS endcap from $H \rightarrow Z^0 Z^0 \rightarrow u^- u^+ u^- u^-$ events as a function of the Higgs mass. Three different trigger thresholds are shown: $P_T \geq 0$ GeV (black), $P_T \geq 10$ GeV (red), and $P_T \geq 25$ GeV (blue).
FIGURE 5: Efficiency of the Level-1 Muon Trigger to detect events with one muon (upper left), two muons (upper right), in the CMS endcap from $H \rightarrow W^+W^- \rightarrow u^+u^-$ events as a function of the Higgs mass. Three different trigger thresholds are shown: $Pt \geq 0$ GeV (black), $Pt \geq 10$ GeV (red), and $Pt \geq 25$ GeV (blue).
FIGURE 6: A Feynman diagram of pp collision decaying into J/Psi decaying into 2 muons
FIGURE 7: top left; number of tracked muons found in endcap with $Pt > 0$, and number generated in endcap equal to 1
top mid; number of tracked muons found in endcap with $Pt > 10$, and number generated in endcap equal to 1
top right; number of tracked muons found in endcap with $Pt > 25$, and number generated in endcap equal to 1
bottom left; number of tracked muons found in endcap with $Pt > 0$, and number generated in endcap equal to 2
bottom mid; number of tracked muons found in endcap with $Pt > 10$, and number generated in endcap equal to 2
bottom right; number of tracked muons found in endcap with $Pt > 25$, and number generated in endcap equal to 2
FIGURE 8: Probability of generating one or more (upper left), two or more (upper right), or three or more (lower left) in the CMS endcap region from $H \rightarrow Z^0 Z^0 \rightarrow u^+ u^- u^+ u^-$ events as a function of the Higgs mass. Three different trigger thresholds are shown: $Pt \geq 0$ GeV (black), $Pt \geq 10$ GeV (red), and $Pt \geq 25$ GeV (blue).
FIGURE 9: Probability of generating one or more (upper left), or two or more (upper right), in the CMS endcap region from $H \rightarrow W^+ W^- \rightarrow \mu^+ \mu^-$ events as a function of the Higgs mass. Three different trigger thresholds are shown: $Pt \geq 0$ GeV (black), $Pt \geq 10$ GeV (red), and $Pt \geq 25$ GeV (blue).