CMS Level-1 Calorimeter Trigger Detailed Simulation

S. Dasu, W. Badgett, M. Jaworski, J. Lackey and W. H. Smith

Department of Physics, University of Wisconsin, Madison WI 53706

Abstract

CMS level-1 calorimeter trigger simulation results are discussed. The simulation results are obtained using CMSIM version 111 program based on the GEANT simulation of the detector. These CMSIM results compare favorably to the results from our fast simulation program used in earlier studies. Both these results indicate that the rate requirements of the data acquisition system can be met with a reasonable safety factor of three while providing high efficiencies for high $E_T$ physics processes of interest to CMS.
1 Introduction

The CMS [1] level-1 calorimeter trigger algorithms [2] and the conceptual design [3] are based on a fast simulation program [4, 5, 6, 7]. Some aspects of these results have been verified using detailed simulation [8]. A proposal to use the fine granularity of the CMS ECAL to further refine the electron/photon trigger algorithm [9] was verified with fast simulation [10, 11]. However, a more detailed simulation is needed to understand the intricacies of the shower development in the ECAL for fine-grain algorithm verification and the energy losses in the ECAL/HCAL interface for missing transverse energy resolution. In this note we provide a comprehensive study of the trigger system using a detailed GEANT-based simulation of the CMS calorimeter performance.

2 Overview of conceptual design

An overview of conceptual design is provided here for completeness, but a reading of [3, 12] may be necessary to follow the details of the algorithms. The CMS barrel and endcap calorimeter trigger system is implemented in 18 crates, illustrated in Figure 1, each handling 256 trigger towers covering $0.087\phi \times 0.087\eta$ apiece, arranged in $8\phi \times 26\eta$ regions. The very forward calorimeter trigger will be implemented in a separate 19th crate and is not discussed here. The mapping of the barrel and endcap calorimeter towers onto trigger crates is shown in Figure 2. This figure shows the full granularity trigger implemented out to $\eta = 2.6$. However, sufficient channels are provided to extend the full granularity trigger to $\eta = 3$. Continuous coverage for energy sums and jets is provided out to $\eta = 3$ in the barrel and endcap crates with the coverage extended to the very forward calorimeter
Figure 2: Mapping of barrel and endcap calorimeter towers in the range $0 \leq \phi \leq 2\pi$ and $-3 \leq \eta \leq 3$ onto trigger crates. Only $|\eta| \leq 2.6$ is used in the current design of ECAL.
by the 19th crate.

Data from ECAL and HCAL trigger towers arrives on copper cable in serial form at 1.2 GBaud to the back side of the 8 Receiver cards plugged into the rear of the crate. Each receiver card covers $4\phi \times 8\eta$ towers or an area of $0.35\phi \times 0.7\eta$ as shown in Figure 2. After the serial-to-parallel conversion and checking of error bits the data are transferred through the card to the front side of the Receiver cards. Data are synchronized and passed through look-up tables to separately linearize the energies into the number of bits needed for electron and energy triggers. Data in parallel form is shared with the neighboring crates after synchronization of the data at 40 MHz. The entire system operates in lock-step after this stage at 160 MHz. The energies are then summed to $4 \times 4$ trigger tower regions using custom Adder ASICs on Receiver card. The heart of the crate is a central “backplane” which provides data sharing at 160 MHz. Data for the electron identification logic which includes both the data received on the input serial links and that received on intercrate cables are transferred to the Electron Identification cards plugged into the front-side of the “backplane”. The $4 \times 4$ sums are transferred to Jet/Summary card plugged into the center of backplane on the front-side of the crate.

The Electron Identification card implements its algorithm in a custom integrated circuit. The two highest $E_T$ candidates from each of the eight electron identification cards are passed to the Jet/Summary card. The Jet/Summary card sorts the electron and jet candidates in the crate to output the top four ranking isolated and non-isolated electron candidates, and the top four $E_T$ jets on a cable to the global trigger. The global trigger cards further sort or sum their input to obtain the final output of the calorimeter trigger which is used together with the muon trigger data to provide the final trigger decision.

3 Simulation

Simulation for the results reported here is carried out in multiple phases. At the outset PYTHIA version 5.720 or ISAJET version V7.22 programs are run to produce minimum bias, QCD jet, Top, Standard Model Higgs, MSSM Higgs or SUSY particle event n-tuples. The saved stable particle n-tuples are then run through both CMSIM version 111 and our FASTSIM programs to obtain calorimeter data. The same calorimeter trigger simulation program is run separately on both the CMSIM and FASTSIM data to obtain trigger rate and efficiency results presented here.

CMSIM version 111 is run with the default detailed geometry (circa 1996) and simulation for the calorimeter, and a simplified geometry and no hit simulation for the tracker. The ECAL crystal size is $0.0145\phi \times 0.0145\eta$, with matching of groups of $6 \times 6$ crystals with HCAL tower boundaries, in this version of the CMSIM geometry. The latest design of ECAL with larger crystals is not available in the CMSIM version 111 program. The preshower, the very forward calorimeter and the muon systems are not simulated. The selected CMSIM parameters are:

```
GEOM 'CMSE' 3 'ECAL' 3 'HCAL' 3 'TRAK' 1 'ESBX' 0 'ESFX' 0 'VCAL' 0 'MUON' 0
SETS 'CMSE' 0 'ECAL' 1 'HCAL' 1
```

The GEANT shower particle cutoffs, CUTGAM, CUTELE etc., are chosen to be 10 MeV. The default calorimeter hit generation in the CMSIM version 111 is used. The GEANT hits are summed using the JTRG package, to save ECAL crystal and HCAL tower energies for each event.

Our FASTSIM program [4, 5, 6, 7, 10] is setup with calorimeter geometry similar to that in CMSIM. The tracker is represented by a cylindrical uniform medium 6m in length and 1.37 m in diameter with 1 radiation length material. A preshower with 3 radiation lengths material is also included in both barrel and the endcap regions. The ECAL crystal and HCAL tower geometry in both CMSIM and FASTSIM are identical. However, there are no support structures implemented for both ECAL and HCAL. The gap between the ECAL and HCAL is left empty. The fast simulation program involves stepping the particles through a uniform magnetic field of 4 Tesla, while allowing for electron bremsstrahlung, photon conversions and meson decays until they reach the preshower or calorimeter. The energy loss in the calorimeter is then calculated using parameterizations of the longitudinal and transverse shapes of the the showers for each ECAL crystal and HCAL tower before saving to disk in an identical format to the CMSIM data.

The QCD jet events and the various signal events are run through both CMSIM and FASTSIM data. However, the minimum bias data (100000 events) are only run through the FASTSIM to save time. The trigger simulation
program reads in an event at a time from the CMSIM or FASTSIM QCD jet and signal calorimeter energies, and adds in the calorimeter energies from a sample of minimum bias FASTSIM data based on the selected luminosity for the run. Note that the time development of calorimeter pulses, additional pileup effects due to minimum bias events in the neighboring beam crossings and the complications due to the filtering algorithms are not included in this simulation. However, we expect that the inclusion of time integrated energies from each of the several Poisson distributed events separately will include the most significant minimum bias background. Additional normally distributed electronics noise hits are added to each event. The ECAL and HCAL tower data are then used to form trigger primitives described below. The trigger simulation is done using integer scales with appropriate bit resolutions and dynamic range implemented in the hardware [12]. N-Tuples generated from this trigger simulation of the QCD jet events are used to make integrated trigger rate plots versus the $E_T$ values for various trigger channels and combinations. The signal event data n-tuples and the Pythia input n-tuples are used together to obtain the trigger efficiencies as a function of generated trigger particle momenta.

4 Trigger primitives

The CMS calorimeter front-end electronics provides 8-bit non-linear scale sums of transverse energies in trigger towers of size $0.085\phi \times 0.087\eta$ for both ECAL and HCAL separately. The ECAL and HCAL towers are aligned so that trigger algorithms can exploit this longitudinal division of the shower profile. In addition to this $E_T$ value, the calorimeter front-end electronics also provides a single bit summary of the fine-grain shower profile within the trigger tower.

The fine-grain EM ID bit is determined by applying the algorithm illustrated in the Figure 3 the $6 \times 6$ ECAL crystals that make up the trigger tower in the barrel region. The first step involves summing the energies in each strip of the six crystals in the $\phi$ direction - the direction in which the showers spread because of being immersed in the 4 Tesla magnetic field. Then pairs of adjacent $\eta$ strips are added to recover any leakage along $\eta$ within the trigger tower. Any leakage of energy outside of the trigger tower is ignored in the determination of this fine-grain EM ID bit. The maximum of the five strip pair sums is compared to the total energy in the trigger tower to obtain the fine-grain EM ID bit. A cut of 0.9 is chosen to determine the EM ID bit based on the results for single electron and pion simulation data for this ratio shown in the Figure 4. The FASTSIM program is not expected to provide reliable simulation of the transverse shower shape, particularly for charged pions. Note that the new technical design report version of the barrel ECAL has $5 \times 5$ crystals per trigger tower modifying this algorithm somewhat. The effect of larger crystals in the endcap is expected to be even larger. Further, the change in the organization of calorimeter front-end electronics to be partly based in the electronics house away from the detector, and resulted in a redesign of the trigger primitives generation. It may now be feasible to design an algorithm better suited to the new crystal to trigger tower mapping.

5 Electron/Photon trigger

An overview of the electron isolation algorithm is shown in Figure 3. This algorithm involving only the eight nearest neighbors around the central trigger tower is applied sliding over the entire $\eta - \phi$ plane. Each $4 \times 4$ trigger tower region in this plane is allowed to report an electron/photon candidate before ranking and sorting, on the basis of shower profile and isolation cuts shown in the Figure 3, to find the top four ranking isolated and non-isolated candidates for the event separately.

The trigger primitives received by the regional trigger system include the fine-grain characterization bit and the 8-bit total $E_T$ (nonlinear scale) within the trigger tower. The Receiver card linearizes the $E_T$ and passes a 7-bit value with the best resolution and saturation value attainable, e.g., 0.5 GeV with 63.5 GeV limit. Although, the current design of the Receiver card only passes $E_T$ in the ECAL, this simulation uses the sum of ECAL and HCAL $E_T$ values because this is expected to help in the design of a potential $\tau$ trigger algorithm to be implemented in the Jet/Summary card. The Receiver card also ORs the 16 fine-grain EM ID bits within each $4 \times 4$ trigger tower regions and directly passes a single bit to the Jet/Summary card. The sum of the 7-bit $E_T$ in the central trigger tower and the maximum of the four edge neighbors, i.e., the leakage tower, is treated as the total energy of the electron/photon candidate. Two shower profile and two neighbor isolation cuts are calculated. The fine-grain shower profile cut already ORd for the $4 \times 4$ region is available for forming the rank on the Jet/Summary card. The HCAL Veto bit for each tower is determined using a lookup table, e.g., programmed to pass only $H/E_\gamma \geq 5\%$ when $E_\gamma \geq 1$ GeV. The second shower profile cut requires the passing of the HCAL Veto bit for the central tower. The first isolation cut requires the passing HCAL Veto bit for all the eight neighbors. The second isolation cut requires that at least one
Sliding window centered on all ECAL/HCAL trigger tower pairs

Tower count = 72φ x 54η x 2 = 7776

Shower Profile Cuts:
Fine-grain feature
Compare max Et η-stripe pair out of 5 pairs versus total Et in trigger tower, e.g., require 80% energy in a pair.

HAC Veto
Compare HCAL versus ECAL Et in Memory Lookup to veto non-EM deposits, e.g., H/E<5% when E is significant.

Candidate Energy:
Max Et of 4 Neighbors
Hit + Max Et > Threshold

Summary:
Regional
Pick highest energy candidate in 4x4 trigger tower region.

Global
Sort to find top-4 isolated and non-isolated candidates separately.

Figure 3: The electron/photon trigger algorithm showing various sub-algorithms based on fine-grain data and isolation cuts. Note that an older ECAL geometry, with 6 × 6 crystals for each trigger tower, is simulated and shown here.
Figure 4: The fine-grain algorithm energy ratio, i.e., the ratio of energy in the maximum of five strip pairs to the total energy in the trigger tower is shown for single electron (left plot) and pion (right plot) events for both CMSIM and FASTSIM. The arrows indicate the selected cut value.

Figure 5: The ratio of the HCAL and ECAL transverse energies for the central trigger tower is shown for single photon (left) and pion (right) events for both CMSIM and FASTSIM. The arrows indicate the selected cut value.
Figure 6: The ratio of the HCAL and ECAL transverse energies for the eight neighbor trigger towers is shown for single photon (left) and pion (right) events for both CMSIM and FASTSIM. The arrows indicate the selected cut value.

Figure 7: The ECAL energy in the lowest five neighbor trigger towers (in units of 0.5 GeV) is shown for single photon (left) and pion (right) events for both CMSIM and FASTSIM. The arrows indicate the selected cut value.
Figure 8: The electron/photon algorithm cut quantity distributions are shown for CMSIM and FASTSIM simulation of top events which decay into an electron. The histograms are only filled for the central ECAL trigger towers with transverse energy greater than 5 GeV to suppress the noise.
The electron/photon algorithm efficiency is plotted versus the $p_T$ of the top decay electron for various cuts. CMSIM (left) and FASTSIM (right) results are shown. The $E_T$ cutoff is at 25 GeV.

of the four corners has all five towers quiet, e.g., $E_T < 1.5$ GeV. Only a corner is required because the side/corner with leakage is not expected to pass this tight isolation cut.

The CMSIM and FASTSIM ratios of the HCAL and ECAL energies which play a crucial role in identifying the electrons/photons are shown for single photon and pion events in the Figure 5 for center towers and in the Figure 6 for the 8 neighbor towers centered around each ECAL trigger tower with energy greater than 5 GeV. Note that the distribution is truncated at $H/E=1$ suppressing a preponderance of events with very large hadronic fraction. All the single particle events have a flat distributions with the ranges $5 \leq E_T \leq 100$ GeV, $0 \leq \phi \leq 2\pi$ and $-2.5 \leq \eta \leq 2.5$. Single photon events are picked rather than the single electron events because some electrons bend at just the correct angle to pass through the ECAL crystal support structures leaving little energy in the crystal. A cut of 0.05 is used to select the electrons with high efficiency while rejecting the hadrons. However, notice that the integral number of events below the cut of 0.05 in the charged pion plot is much smaller for FASTSIM than CMSIM. There is also a significant shape difference between the distributions over the $H/E$ range shown.

The isolation of the electrons/photons from other particles is also used to further suppress the jet background. To accomplish this while considering only the nearest neighbors, requires that at least one of the four five ECAL trigger tower corners are quiet, i.e., their energy is below a tunable cut, picked to be 1.5 GeV based on the single photon and pion data shown in Figure 7.

Although the FASTSIM and the CMSIM hadronic shower simulations are in poor agreement, the electromagnetic showers are in reasonable agreement. Therefore, we can not select the cuts based on equal rejection power of the charged pions. However, we were able to select the cuts requiring similar efficiencies for electron/photon triggering. Further, the agreement in the cut parameter distributions is such that we have used the same cut values for both the CMSIM and the FASTSIM simulation data.

The Figure 8 compares the various cut parameters used in the electron/photon algorithm obtained from top events as simulated by CMSIM and FASTSIM. This more representative sample of interesting events shows that the agreement between CMSIM and FASTSIM is quite reasonable. Note that these histograms are only filled for central towers with $E_T > 5$ GeV for the top events selecting out only the electromagnetic showers and the sample of hadronic showers which started within the ECAL. The distributions are also weighted by the particle production in a real high $P_T$ event.

Figure 9 shows the electron/photon algorithm efficiency for top to electron decay events as a function of the generated momentum of the electron for CMSIM and FASTSIM. The efficiency is shown for the full algorithm and for the various sub-algorithms separately. The asymptotic efficiency, for the selected cuts, of 91% and 92% for CMSIM and FASTSIM respectively, is the same within the uncertainties of the simulations, requiring no separate tuning of the cuts. This plot includes the minimum bias data appropriate for the high luminosity LHC.
Figure 10: The electron/photon integrated trigger rate is shown as a function of the trigger $E_T$ cutoff before and after trigger cuts for FASTSIM and CMSIM cases.

i.e., $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Figure 10 shows the integrated trigger rate above trigger $E_T$ cutoff versus the cutoff before and after the electron algorithm cuts for both CMSIM and FASTSIM. Although the rates before the cuts are in good agreement, as is expected, because they are both determined using the same set of generated events, the rates after the cuts are different by a factor of 2.25. In order to investigate the reason for this discrepancy, the rate is plotted after each of the four sub-algorithms in the Figure 11. It is seen that the fine-grain and quiet neighbor cuts are simulated equally well in both CMSIM and FASTSIM. However, there is a significant difference in the rates after the HCAL energy based cuts. The HAC veto and neighbor HAC isolation algorithms seem to be much less effective in the case of CMSIM generated data. Comparisons of the reconstructed single pion energy within and outside 5x5 trigger towers and within the calorimeter with the generated transverse energy, ranging from 5 to 100 GeV, is shown for CMSIM and FASTSIM in Figure 12. The pion energy loss in the CMSIM is substantially more than the FASTSIM. There is reasonable agreement in H/E ratio within 5x5 trigger tower region. However, the cuts based on H/E ratio, at individual trigger tower level, do result in significantly different rates as seen in Figure 11. This seems to indicate that the shower fluctuations may be responsible for the rate differences after H/E cuts. Although this is a plausible explanation, further studies are needed to resolve this discrepancy fully.
Figure 11: The electron/photon trigger integrated CMSIM and FASTSIM rates are shown for each of the four electron algorithm cuts.
Figure 12: The reconstructed single pion energy distributions, i.e., energy within 5x5 trigger towers centered on pion energy peak (top left), energy outside 5x5 trigger towers (bottom left), total energy in the calorimeter (top right) and H/E ratio for energy within the 5x5 region, all scaled to the generated pion momentum, are shown.
5.1 Jet trigger

The jet trigger algorithms are based on sums of non-overlapping $4 \times 4$ trigger tower transverse energy sums in the $\eta \times \phi$-space shown in Figure 13. Although, the coverage of the $\eta \times \phi$-space is expected to span the entire HCAL, i.e., $|\eta| = 3$, this simulation is restricted to $|\eta| = 2.6$. The small jet cone radius of 0.348 in this space ensures that the trigger is based on the core energy of the jet and the multijet events are counted reliably [6]. The single, double, triple and quadruple jet trigger integrated rates are shown as a function of the $E_T$ cutoffs for CMSIM and FASTSIM in the Figure 14. There is reasonable agreement between CMSIM and FASTSIM data, and any difference can be attributed to the decreased HCAL energy deposition in CMSIM. The CMSIM and FASTSIM jet trigger efficiencies are plotted versus the $p_T$ of the jets reconstructed using LUCLUS algorithm from the PYTHIA hadrons in the events in the Figure 15. Somewhat higher efficiency, i.e., sharper turn-on, seen for the FASTSIM case is due to the acceptance of the slightly higher rate as seen in the Figure 14.

6 Missing and total $E_T$ trigger

The missing transverse energy for the events is calculated using the same $4 \times 4$ trigger tower transverse energy sums used for the jet algorithm and converting them to $E_x$ and $E_y$ with memory lookup tables. The data is added up over the full $\eta - \phi$-space, i.e., $\eta < 2.6$ in this simulation, to obtain the missing $E_T$. The $E_T$ values over the full space are also added to obtain the total $E_T$. The integrated rates for missing and total transverse energy are plotted in the Figure 16 for both CMSIM and FASTSIM data. The FASTSIM rates are somewhat higher than the CMSIM rates and are most probably due to the decreased HCAL energy deposition in CMSIM. The missing $E_T$ trigger efficiency is plotted versus the missing $p_T$, calculated at the particle level within the trigger acceptance, $|\eta| < 2.6$, in the Figure 17, for SUSY sparticle events at both high and low luminosities. With the trigger cutoff at 80 GeV, the high luminosity efficiency turnon does not quite saturate for this set of SUSY events selected. Therefore, we also show the low luminosity turn-on curve with a trigger cutoff of 40 GeV. The missing transverse energy resolution is quite poor as seen in the FASTSIM results earlier [5] and reconfirmed here. However, note that this SUSY event missing $E_T$ efficiency is supplemented by the multi-jet triggers discussed earlier.

7 Physics performance

In order to study the physics performance of the calorimeter trigger we follow our earlier procedure [7] of selecting a representative $E_T$ cutoffs for various sub-triggers satisfying the target total rate of 15 kHz. We then explore the efficiencies of triggering on various high $p_T$ physics processes. The CMS data acquisition system is expected to handle 100 kHz input rate. However, the calculated baseline trigger rates are potentially uncertain by an unknown amount due to the poorly measured gluon distribution in proton which contributes significantly to the QCD background that dominates the CMS calorimeter triggers. In order to provide a safety factor we require that the total calculated CMS trigger rate be limited to 30 kHz and the calorimeter portion of it to 15 kHz. For efficiency studies, we only select the physics processes amongst those considered in the CMS Technical Proposal [1] that place most stringent requirements on the trigger system, i.e., the lowest masses of interest to CMS and channels involving least number of trigger particles. When evaluating efficiencies, we do not include any effects of offline reconstruction inefficiencies or cuts. Therefore, these results are conservative. We perform these studies at two levels of luminosity, $\mathcal{L} = 10^{34}$ (high) and $10^{33}$ (low) cm$^{-2}$ s$^{-1}$.

The trigger rate breakdown and the selected $E_T$ cutoffs for various sub-triggers, at high and low luminosities, are shown in the Tables 1 and 2 respectively. The $E_T$ cutoff selection is, of course, arbitrary, but we select these specific values to emphasize the electron/photon triggers that enable the exploration of high $p_T$ physics with the best signal to noise ratio. At low luminosity we prioritize the total and missing $E_T$ and jet+electron triggers over the jet triggers. These $E_T$ cutoffs were selected in an earlier FASTSIM based study [7], with rates totalling 15 kHz. That run of the FASTSIM used different set of PYTHIA events and an older version of the electron/photon trigger algorithm. We do not retune the $E_T$ cutoffs to obtain the 15 kHz target rate. These rates are all consistent within the uncertainties of the simulation. The differences in the hadronic energy responses between CMSIM and FASTSIM account for the lower electron and dielectron rates in the FASTSIM case.

For the efficiency studies several physics processes are selected. The generic Standard model physics processes of importance are

- $t \rightarrow e + X$ (sets the most stringent requirement on the single electron trigger)
- $W \rightarrow e + X$
Figure 13: The jet and missing $E_T$ trigger algorithms.
Figure 14: The single, double, triple and quadruple jet trigger integrated rates are shown as a function of the trigger $E_T$ cutoffs for FASTSIM and CMSIM cases.
QCD jet efficiency - 4x4 algorithm

Figure 15: The jet trigger efficiencies are plotted versus the $p_T$ of the jets reconstructed from the PYTHIA hadrons in the event for CMSIM (left) and FASTSIM (right). The trigger $E_T$ cutoffs are 100, 60, 30 and 20 for single, double, triple and quadruple jets.

Missing $E_T$ trigger rates

Total $E_T$ trigger rates

Figure 16: The missing and total $E_T$ trigger integrated rates are shown as a function of the trigger $E_T$ cutoffs for FASTSIM and CMSIM cases.
Figure 17: The missing $E_T$ trigger efficiency for CMSIM and FASTSIM are compared versus the generator hadron level $p_T$ for at low (left) and high (right) luminosities. The arrows indicate the trigger cutoffs at 40 and 80 GeV for low and high luminosities respectively.

<table>
<thead>
<tr>
<th>Trigger Channel Type</th>
<th>Trigger $E_T$ Cutoff (GeV)</th>
<th>Rate (kHz)</th>
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<tr>
<td></td>
<td></td>
<td>CMSIM</td>
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<tr>
<td>Sum $E_T$</td>
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<td>0.3</td>
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<tr>
<td>Missing $E_T$</td>
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<td>11.4</td>
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<td>Dielectron</td>
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<td>2.1</td>
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<tr>
<td>Single jet</td>
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<td>1.5</td>
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<tr>
<td>Dijet</td>
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<td>1.2</td>
</tr>
<tr>
<td>Trijet</td>
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<td>2.3</td>
</tr>
<tr>
<td>Quadjet</td>
<td>20</td>
<td>2.6</td>
</tr>
<tr>
<td>Jet+Electron</td>
<td>50&amp;12</td>
<td>1.3</td>
</tr>
<tr>
<td>Cumulative rate</td>
<td>16.7</td>
<td></td>
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</tbody>
</table>

Table 1: High luminosity background rates for a representative set of trigger $E_T$ cutoffs.

<table>
<thead>
<tr>
<th>Trigger Channel Type</th>
<th>Trigger $E_T$ Cutoff (GeV)</th>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CMSIM</td>
</tr>
<tr>
<td>Sum $E_T$</td>
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<td>1.0</td>
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<tr>
<td>Missing $E_T$</td>
<td>40</td>
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<tr>
<td>Electron</td>
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<td>11.4</td>
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<td>Dielectron</td>
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<td>1.2</td>
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<tr>
<td>Single jet</td>
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<tr>
<td>Dijet</td>
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<tr>
<td>Trijet</td>
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<td>Quadjet</td>
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<td>0.6</td>
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<tr>
<td>Jet+Electron</td>
<td>15&amp;9</td>
<td>11.2</td>
</tr>
<tr>
<td>Cumulative rate</td>
<td>17.8</td>
<td>11.8</td>
</tr>
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</table>

Table 2: Low luminosity background rates for a representative set of trigger $E_T$ cutoffs.
The Standard Model Higgs processes selected are

- \( H(80 \text{ GeV}) \rightarrow \gamma \gamma \)
- \( H(120 \text{ GeV}) \rightarrow ZZ^* \rightarrow ee\mu\mu \)
- \( H(200 \text{ GeV}) \rightarrow ZZ \rightarrow eeqq \)

For the Minimal Supersymmetric Standard Model we include the following processes,

- \( H, A(M = 100 - 400 \text{ GeV}, \tan \beta = 10 - 30) \rightarrow \tau\tau \)
- \( pp \rightarrow tt \rightarrow H^+X; H^+ \rightarrow \tau\nu \) (uses top to electron trigger)

The SUSY sparticle production studies are more difficult to select due to a very large parameter space. We restrict our study to minimal SUGRA model considered in the CMS Technical Proposal Scenario A with mass of LSP at 45 GeV and other sparticle masses in the 300 GeV range.

The efficiencies for the above physics channels studied at the appropriate high or low luminosity LHC running are listed in the Tables 3 and 4. The selected trigger \( E_T \) cutoffs yield high efficiency for these representative physics processes while satisfying the bandwidth requirement.

## 8 Summary

A detailed simulation of the CMS calorimeter level-1 trigger system performance confirms the earlier conclusions based on the fast parameterized simulations. The trigger rates and the efficiency turn-on curves obtained from the two simulations are compatible. Any differences between the two programs is attributable to the simulation of hadronic showers which are notoriously difficult to parameterize well. Further studies are needed to understand this minor discrepancy. Nevertheless, both programs indicate that the high \( p_T \) physics goals of the CMS experiment can be met within the data acquisition bandwidth with a considerable safety factor and high efficiency for a representative set of physics processes.

## References


