The CMS Calorimeter Trigger for LHC Run II

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Abstract. The Compact Muon Solenoid (CMS) experiment has implemented a sophisticated two-level online selection system that achieves a rejection factor of nearly $10^5$. During Run II, the LHC has increased its centre-of-mass energy up to 13 TeV and will progressively reach an instantaneous luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. In order to guarantee a successful and ambitious physics programme under this intense environment, the CMS Trigger and Data acquisition (DAQ) system has been upgraded. A novel concept for the L1 calorimeter trigger is introduced: the Time Multiplexed Trigger (TMT). In this design, which is similar to the CMS DAQ or High Level Trigger (HLT) architecture, nine main processors each receive all of the calorimeter data from an entire event via 18 pre-processors. The advantage of the TMT architecture is that a global view and full granularity of the calorimeters can be exploited by complex algorithms. The goal is to maintain the current thresholds for calorimeter objects and improve the performance for their selection. The introduction of new triggers based on the combination of calorimeter objects is also foreseen.

1. Introduction

During Run II at the Large Hadron Collider at CERN, proton beams are collided with a centre-of-mass energy of 13 TeV at a bunch crossing rate of 40 MHz. The CMS experiment [1] is a general purpose detector built to perform precision measurements of Standard Model processes and searches for new physics at the high energy frontier. The high rate of collisions and large amounts of data produced by each of the sub-detectors require a sophisticated hardware trigger system to rapidly select which events may contain interesting physics processes and should be saved for offline analysis. The CMS Level 1 trigger must reduce the event rate from 40 MHz to 100 kHz within a timeframe of 3.2 µs, passing events to the software-based High Level Trigger, which further reduces the rate to 1 kHz for recording to disk.

Run II provides a substantial increase in instantaneous luminosity, resulting in a challenging environment in which the trigger must quickly identify physics objects using trigger primitives constructed from the detector readout and generate a trigger decision. A significant increase in the number of pileup vertices makes it difficult to maintain the low energy thresholds required to measure electroweak scale physics whilst also providing necessary trigger bandwidth for new physics searches. The Run I trigger would produce a factor of six increase in trigger rates in the beam conditions of Run II. To maintain both low trigger thresholds and a Level 1 rate of 100 kHz, the trigger was completely replaced with a new system with a novel architecture and greater logic resources, allowing more complex identification algorithms introducing online pileup subtraction at Level 1 and improving object selection performance.

1 On behalf of the CMS Collaboration
2. The CMS Calorimeter Trigger

The upgraded CMS calorimeter trigger has adopted a novel time-multiplexed architecture consisting of two layers, with higher granularity calorimeter data for the full detector being processed in a single main processor (MP), providing extra latency for more sophisticated algorithms (Figure 1). Layer 1 consists of 18 CTP7 pre-processor cards that receive trigger primitives optically from regions of ECAL and HCAL, sum the transverse energies and further format the data ready for processing at Layer 2, which consists of 10 MP7 cards that perform the object identification and compute global energy sums. Both cards are built around high performance Xilinx Virtex 7 FPGAs, which provide the large IO and logic resources that are required [3]. The main processors receive data on 72 links, each link containing 2 out of 72 $\phi$ segments with alternate links carrying data from the top and bottom $\eta$ halves of the calorimeters. Input data are pipelined in $\eta$ such that processing can commence once a minimum amount of data is received. A Molex Flexplane patch panel provides the interface between Layer 1 and Layer 2, fanning out data from the pre-processor cards for all detector regions to each main processor. The time required for a given MP to receive full detector information is around 7 bunch crossings, therefore at least 8 MPs are required. However, 9 MPs are used such that any given bunch crossing in an orbit will be sent to the same MP.

The data protocol used between Layer 1 and Layer 2 is a 16-bit word comprising the sum of ECAL and HCAL transverse energies, their ratio, and various feature flags, thus allowing the separate calorimeter energies to be utilized. Each link carries two of these words, with the full 32-bit word computed at a clock frequency of 240 MHz. The MP identifies up to twelve jets, $e/\gamma$, and tau candidates, and calculates the total transverse energy, total jet energy, along with their $x$ and $y$ components, both with and without the forward hadronic calorimeter data. The transverse momenta and $\eta-\phi$ co-ordinates of the particle candidates and the energies of the sums are sent from each MP over 6 links to the demux board (also an MP7), which calculates the vector sums and forwards data to the global trigger.

![Figure 1. CMS calorimeter trigger architecture.](image-url)
3. Algorithms

3.1. Jet and energy sums algorithms
Jet candidates are identified starting with a seed tower, which must have an energy above a programmable threshold of around a few GeV. A jet is then constructed by taking a $9 \times 9$ sliding window centred on the local maxima. The window size is chosen to correspond with the cone radius of 0.4 used in the offline jet reconstruction algorithm. An inequality mask is applied comparing seed tower energy with the rest of the tower energies within the window to avoid double counting of jets. The jet candidate is then defined as the sum of all tower energies within the $9 \times 9$ window. Comparisons between firmware algorithm output and software anti-kt jet finder algorithm used in offline reconstruction show excellent agreement [4].

Dynamic pile-up subtraction is applied to each jet, operating on an event-by-event basis and estimating the local energy density to provide an appropriate response to fluctuating pileup conditions. The “chunky donut” algorithm sums the tower energies in four $3 \times 9$ strips on each edge of the $9 \times 9$ window, and subtracts the sum of the lowest three energy strips from the total jet energy. Studies have shown a strong correlation between the chunky donut estimate of the pileup energy density and number of interactions [4].

Total transverse energy is calculated by summing the energies of all towers in the event, with the $x$ and $y$ components also calculated and used as input to a cordic function to produce the missing transverse energy. The scalar sum of all jet energies, $H_T$, is also calculated, along with its corresponding vector sum, $H_T^{\text{miss}}$.

3.2. $e/\gamma$ algorithm
$e/\gamma$ candidates are identified by first forming clusters seeded by a local energy maxima above a programmable threshold. As much as possible of the $e/\gamma$ candidate energy is included whilst minimising the effect of pile-up by limiting the maximum size of clusters to 8 trigger towers. Due to the magnetic field, electron and photon showers spread mostly in the $\phi$ direction, and thus better containment of the shower is achieved by extending the region in $\phi$. The improved calorimeter resolution now available allows the candidate position to be calculated as an energy-weighted average centred on the seed tower, which provides a factor of four improvement with respect to the legacy algorithm. Shape vetoes are utilized with dynamic clustering to improve background rejection by discriminating against jet clusters and reducing the fake rate, whilst maintaining high efficiency. Isolation criteria can be applied to significantly reduce $e/\gamma$ rates for a small loss in efficiency.

3.3. $\tau$ algorithm
$\tau$ candidates that decay hadronically are identified using the same dynamic clustering implementation used for $e/\gamma$. Several clusters may be produced from the $\tau$ decay products that are spatially separated along $\phi$ due to the magnetic field, and these can be merged. Isolation can also be applied in a similar way to $e/\gamma$ candidates. The footprint of the $\tau$ candidate is subtracted from the isolation energy, which is compared to an $\eta$ dependent threshold. Background rejection is improved by utilising a shape veto LUT to remove background-like clusters.

The algorithms described above are also implemented in a C++ bit-level emulator. This provides a cross-check of the algorithm performance that can be used online for data quality monitoring. Figure 2 shows a comparison between firmware and emulator outputs produced using a sample of $t\bar{t}$ Monte Carlo events. Excellent agreement is observed, demonstrating that the firmware algorithms are well understood.
Figure 2. Excellent agreement for transverse energies between firmware and emulator for (a) jets and (b) $e/\gamma$ candidates.

4. Performance

The upgraded Level-1 jet algorithm with pile-up subtraction provides significantly improved performance. Figure 3 shows rate vs. efficiency curves comparing the expected performance of the Run I and Run II triggers. Simulated $t\bar{t}$ events were used to estimate efficiency, and minimum bias MC was used to estimate the rate. Efficiency is computed with respect to events fulfilling a corresponding generator-level requirement, and the curves produced by varying the Level 1 transverse momenta threshold. The upgraded jet algorithm maintains high performance in efficiency whilst providing a significant reduction in rate of multi-jet triggers. Similar levels of improvement in performance are achieved for energy sums and $\tau$ leptons [5]. The improved performance of the $e/\gamma$ algorithms is discussed in [6].

Figure 3. Rate vs. efficiency curves comparing the expected performance of the Run 1 and Run II (upgrade) Level-1 jet trigger using simulated $t\bar{t}$ events.

References
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