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Performance of the CMS Global Calorimeter Trigger

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Abstract

The CMS Global Calorimeter Trigger system performs a wide-variety of calorimeter data processing functions required by the CMS Level-1 trigger. It is responsible for finding and classifying jets and tau-jets, calculating total and missing transverse energy, total transverse energy identified within jets, sorting e/γ candidates, and calculating several quantities based on forward calorimetry for minimum-bias triggers. The system is based on high-speed serial optical links and large FPGAs. The system has provided CMS with calorimeter triggers during commissioning and cosmic runs throughout 2008. The performance of the system in validation tests and cosmic runs is presented here.

Key words:
High Energy Physics, Trigger, Large Hadron Collider, Compact Muon Solenoid,

1. Introduction

The CMS detector[1] is a general purpose detector at the CERN Large Hadron Collider. The central feature of the CMS apparatus is a superconducting 4-Tesla solenoid. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass scintillator hadronic calorimeter (HCAL). Muons are measured in gas chambers embedded in the iron return yoke. Besides the barrel and endcap detectors, CMS has extensive forward calorimetry.

The first level (L1) of the CMS trigger system[2], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select (in less than 1 μs) the most interesting events, reducing the rate from 40 MHz to 100kHz. The High Level Trigger processor farm further decreases the event rate from to 100 Hz, before data storage.

The Global Calorimeter Trigger (GCT) is the final stage of processing in the calorimeter trigger chain. Upstream of this system, signals from ECAL and HCAL are summed to form trigger towers, roughly 0.087×0.087 in azimuthal angle and pseudorapidity ($\eta \times \phi$). These are sent to the Regional Calorimeter Trigger (RCT), which identifies *isolated* and *non-isolated* e/γ candidates and further sums transverse energy (E_t) from 4×4 trigger towers into coarser granularity "trigger regions". The GCT receives the e/γ candidates and regions from 18 RCT crates, and performs the following baseline requirements.

- identify jets from the region sums, and classify as *central-*, *forward-* or *tau-jets*
- calculate total (E_t^{tot}) and missing (E_t^{miss}) transverse energy
- calculate total transverse energy identified in jets (H_t^{tot})
- sort objects in each of 5 categories (*iso* and *non-iso* e/γ, *central*, *forward* and *tau* jets) by E_t

The 4 highest E_t e/γ and jet objects in each category are forwarded to the Global Trigger, along with the 3 energy sums. The Global Trigger (GT) implements logical conditions on, and between, calorimeter and muon trigger objects, before making the final L1 accept decision. For each L1 accept, the GCT is required to send the input and output data to the data-acquisition system, for use in the Higher Level Trigger.

2. Trigger Algorithms

The main processing algorithm implemented in the GCT is the jet finder algorithm. The jet algorithm is based on a 3×3 window sliding over all trigger regions in $\eta \times \phi$. A jet is found if the central region E_t is greater than it's neighbours, and is above a programmable threshold. The jet is assigned the position of the central region, and E_t of the 3×3 sum. Once identified, jets are classified as central, tau, or forward. Forward jets are defined as those with $\eta > 3$. Central and tau jets (both with $\eta < 3$) are distinguished by tau-veto bits set in the RCT. These bits are set if the E_t fraction in up to 4 contiguous towers within

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the region is below a progammable fraction of the tower E_t. This allows a lower E_t threshold to be set for tau triggers than the regular single jet trigger. A programmable η-dependent correction to the jet E_t may be applied, to account for the effect of dead material, before the jets are sorted and the highest 4 in each category forwarded to the Global Trigger.

The energy sums algorithms are straightforward scalar (E_t^{tot}) and vector (E_t^{miss}) sums of region E_t. H_t^{tot} is the scalar sum of E_t identified in jets above a programmable E_t threshold.

3. Global Calorimeter Trigger Design

Problems with the original GCT hardware [3] led to a complete re-design of the system in 2006 [4][5]. The current hardware is based on large Xilinx Virtex-II Pro and Virtex-4 FPGAs and 2 Gb/s optical links, and comprises four types of card. The Source Cards receive data from the RCT on parallel ECL cables and convert this to optical fibre. The Leaf cards receive optical fibres from the Source Cards, and perform the bulk of data-processing. They can be programmed to perform either e/γ or jet processing. Two Wheel Cards hosts the 6 Jet Leaf Cards, and perform further jet sorting and global energy sum processing. Lastly, the Concentrator Card hosts 2 e/γ Leaf Cards, and receives data from 2 Wheel Cards. It performs the final stage jet sorting, energy sum processing, and provides central clock, control and readout facilities.

The GCT control, test and debug software utilises a layered design. The base layer consists of two C++ APIs, for the Source Cards and the GCT main crate system. Integration with CMS run control is achieved using a system of network-connected cells, and a database back-end for configuration data. However, since the system had to be integrated on a very short timescale, Python bindings were built for the low-level C++ API for the GCT main crate [6]. These allowed the hardware designers to quickly write test programs in Python that allowed fundamental tests and commissioning to be performed while the main control software was still under development.

The final component of the GCT system is the offline software. This comprises a full bit-level emulation of the GCT, along with components to interpret the raw data read out by the system. The GCT emulator provides the dual role of simulating the trigger response in Monte-Carlo data, and validating the hardware processing.

4. Performance during Cosmic Runs

The commissioning of the GCT is described in more detail elsewhere [7]. In summary, the system was constructed, installed and commissioned in two stages : first the components necessary to run the e/γ trigger, second the remaining components required for the jet and energy sum triggers. In both cases, the system was comprehensively tested by playing patterns from the Source Cards. These patterns were captured at many points throughout the system and read out. A suite of patterns was used, to test cabling, links, geometry and trigger algorithm processing. To test the processing, the bit-level emulation of the GCT was run on the same patterns, allowing a detailed comparison between the hardware and the emulator. Once the system performed well in pattern tests, single e/γ and jet triggers were run, triggering on cosmic rays and instrumental noise. As mentioned previously, for each L1 accept issued, the input and output of the GCT system is captured and read out. This allows the detailed emulator comparison to be performed for every triggered event. This was performed automatically online for a small rate of randomly selected events. Once the data was available offline, every single event was compared with the emulator. At the time of writing, around 20M calorimeter triggered events had been processed, giving the results below.

Figure 1 shows the E_t distribution of non-isolated e/γ candidates at the output of the GCT hardware, compared with that calculated by the emulator running on GCT input data. As can be seen, the agreement is perfect. Perfect agreement is also observed in the η, ϕ distributions of the e/γ candidates. Note that the RCT was programmed to produce only non-isolated e/γ candidates during the cosmic runs in question

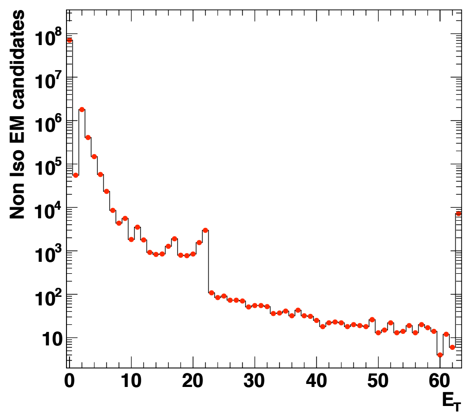

Figure 1: e/γ E_t distribution (in arbitrary units used by the hardware) from GCT hardware (points) compared with that calculated by the GCT emulator from GCT input data (solid line). The e/γ trigger threshold can be seen at 2 units. Peaks in the spectrum at higher E_t are due to instrumental effects.

While processing the jet data, some discrepancies between the hardware and emulator were discovered. These were found to be minor errors in the firmware, that caused around 0.1% of jets to be mis-classified. For future runs, the firmware has been corrected. After accounting for these known issues in the emulator, perfect agreement is observed between hardware and emulator in the E_t, η and ϕ distributions for all three types of jet. Space limitations prevent reproduction of all results here, although Figure 2 shows the tau jet E_t distributions from hardware and emulator, as an example. (During cosmic runs, when the calorimeter signals are from instrumental effects or cosmic rays, most L1 jets are identified as tau jets). It is worth noting that these figures only show statistical agreement between the data and the emulator. However, event by event comparisons of each bit of also showed perfect agreement between the two.

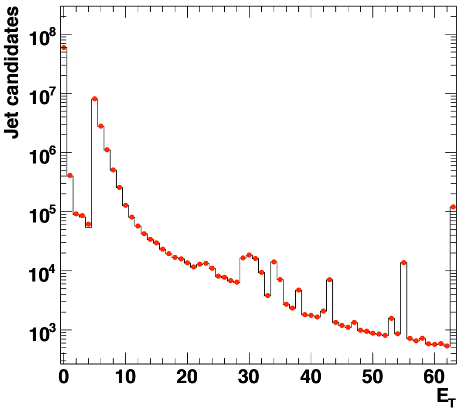

Figure 2: Tau jet E_t distribution (in arbitrary units used by the hardware) from GCT hardware (points) compared with that calculated by the GCT emulator from GCT input data (solid line). The jet trigger threshold can be seen at 5 units. Peaks in the spectrum at higher E_t are due to instrumental effects.

5. Extensions to the GCT Processing

Since the re-design of the system, the GCT baseline processing has been extended. Several quantities are calculated from the forward calorimeter data, that are useful for generating minimum bias triggers in early LHC running. The forward calorimeter trigger regions include a bit that is set if a single tower within the region is above a programmable threshold. The GCT counts the number of bits set, and forwards the total to the GT, which may then trigger on the number of towers over threshold. The GCT also sums E_t in rings close to the beampipe, such that the GT may form a trigger by applying a threshold. These "ring sums" are calculated for forward and backward detectors separately, and over two ranges in η, to provide robustness against beam backgrounds.

Triggers based on these quantities have not yet been run, but the GCT processing was validated using data taken with the jet trigger. Figure 3 shows the emulator-data comparison for the E_t sum over trigger towers with $-5 < \eta < -4.5$ for the same 20M events used in the previous section. Perfect agreement is observed for all four ring sums.

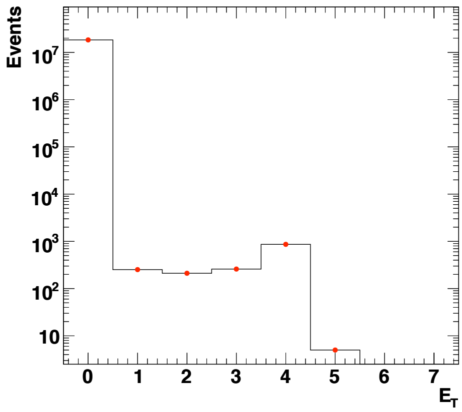

Figure 3: E_t sum distribution from towers with $-5 < \eta < -4.5$, for emulator (solid line) and GCT hardware output (points). E_t is in arbitrary units used by the hardware.

6. Conclusions

The Global Calorimeter Trigger has been designed and constructed on a short timescale. Since the processing it performs is complex, a detailed comparison with simulation has been an essential tool in commissioning the system. The e/γ and jet triggers have been commissioned and have recorded several tens of millions of events for CMS during cosmic runs in 2008. Analysis of this data has shown that the hardware is in full agreement with the emulator for the e/γ, jet and "ring sum" triggers. The remaining energy sum triggers will be commissioned during cosmic runs in 2009, in good time to provide triggrs for CMS during the first LHC collisions.

Acknowledgments

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