Commissioning and performance of the CMS Global Calorimeter Trigger

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***Abstract*—The CMS Global Calorimeter Trigger (GCT) is the device within the Level-1 CMS calorimeter trigger system which is assigned the tasks of finding and sorting forward, central and tau-jet candidates, sorting isolated and non-isolated electron candidates and reading out all of the calorimeter trigger data. The GCT system has been installed and commissioned in the CMS underground cavern. A sophisticated software package has been developed for controlling and configuring the GCT hardware and monitoring the GCT status. Over the past two years the GCT system has undergone detailed testing and its performance is well understood. The GCT design provides for buffers at the inputs to the GCT which have been used to inject energy depositions corresponding to electrons and jets and test the GCT functionality by comparing the GCT output with that of simulation. Monte Carlo events simulating the decay of Higgs particles and other processes have been used to validate the performance of the GCT. The GCT has also been commissioned with the other components of the Level-1 trigger chain in cosmic-ray muon runs. Results from these studies are presented.**

I. Introduction

THE Global Calorimeter Trigger (GCT) is the last stage of the Level-1 CMS calorimeter trigger chain. Its primary purpose is to reduce the number of calorimeter trigger objects that need to be processed by the Global Trigger (GT) to produce the Level-1 Accept (L1A) decision. The pipeline memories that store the event information prior to a L1A decision have only a limited depth and thus the trigger latency is limited to $3.2\mu s$. A detailed description of the GCT is beyond the scope of this paper and is covered in detail in the CMS Trigger TDR [1] and several subsequent CMS internal notes and conference papers [2], [3], [4].

The trigger objects computed by the GCT from data supplied by the Regional Calorimeter Trigger (RCT) are listed below and described in subsequent paragraphs.

- four isolated and four non-isolated electrons of highest rank
- four central, four forward and four tau clustered jets of highest rank
- total transverse energy
- missing transverse energy
- total jet transverse energy

The rank of an electron or jet is at present its transverse energy; however, in principle it could also be derived from jet location.

The electron sort operation must determine the 4 highest rank objects from 72 candidates, supplied by the RCT, for both isolated and non-isolated electrons from a significant data volume.

To sort the jet clusters according to rank the GCT must first perform jet cluster finding and convert the clustered jet energies to rank. The clustered jets are created from regional transverse energies supplied by the RCT. The latter are the sum of contributions from both the hadronic and electromagnetic calorimeters. This is a substantial extension of the GCT capability beyond that specified in the Trigger TDR. The jet cluster finding and subsequent sort is more challenging because of the larger data volume and the need to share or duplicate data between processing regions to perform cluster finding. The latter can require data flows of a similar magnitude to the incoming data volume depending on the clustering method used. The clusters, defined as the sum of 3x3 cells, are located using a new method [5]. It requires substantially less data sharing than the sliding window method. Jets are subdivided into central, forward and tau jets based on the RCT tau veto bits and the jet pseudorapidity, η.

The GCT must also calculate some additional quantities. The total transverse energy is the sum of all regional transverse energies. The total missing transverse energy is calculated by splitting the regional transverse energy values into their x and y components and summing the components. The resulting vector, after a rotation of $180°$, provides the magnitude and angle of the missing energy. The total jet transverse energy is the sum of all clustered jets found.

In addition to these tasks the GCT acts as a readout device for both itself and the RCT by storing information until receipt of a L1A and then sending the information to the DAQ. The GCT must also extract trigger information for the muon system from the calorimeter data stream.

This paper presents the GCT commissioning strategy and results for electrons and jets. A vital ingredient in the commissiong strategy was the development of a C++ based computer emulation of the GCT system. Since the GCT is an entirely digital system a perfect bit-level emulation of the hardware is possible. This was used extensively in the commissioning.

II. Commissioning with patterns

Four stages of commissioning were envisaged testing different aspects of the GCT performance using patterns.

A. Cabling verification tests

The optical fibres carrying the signals from the GCT input to the electronics performing the algorithm processing pass through a complicated patch panel. To ensure that the fibres were connected correctly a mode in which an identification number was sent on each fibre was used and the output compared to that expected by the cabling map implemented in software. The results of these tests were used to correct a small number of mis-cablings.

B. Link stability and relibility tests

Various patterns, including random numbers and a counter, were produced at the input to the GCT and sent through the system to test for data corruption and ensure reliable transmission. The internal links within the GCT are protected by a CRC check and checked for synchronisation loss. Reliable transmission was observed.

C. Geometry tests

In addtion to pattern generation, the GCT design provides for buffers at the inputs to the GCT which may be loaded with patterns of energy generated in software. This feature was used to test that the calorimeter geometry map within the GCT was correctly implemented, by comparing the positions of the energy deposits given by hardware and simulation. Various patterns of energy, increasing in complexity from single deposits to much more challenging patterns were used and the results allowed a small number of errors to be corrected in the η and ϕ of energy deposits.

D. Algorithm tests

The technique used in the geometry tests was also used to test the algorithms implemented in the GCT hardware. Patterns were designed to test the details of the algorithms. In particular the clustering of energy and data sharing at the boundaries between different sections of the calorimeters were tested. In many cases the expected result from the algorithms was too complex to be predicted by hand, and the software emulator became essential to the commissioning process. A small number of errors in both firmware and software were found using this technique and corrected. The most complex tests used were based on Monte Carlo simulations of various physics processes, including the decay of the Higgs boson. Up to 2048 Monte Carlo events were injected into the input of the GCT and the output compared with that expected by the software emulation. Results of these tests for electrons have been documented elsewhere [6].

III. Commissioning with cosmic-ray muon events

After satisfactorily completing the commissioning programme outlined above for electrons and jets, an end-to-end test of all facets of the GCT performance was performed by participating in global CMS cosmic-ray muon runs. In such runs the muon trigger system of the CMS experiment was used as the primary trigger source, and consequently the calorimeter data taken by these triggers was dominated by noise. However it was still possible with low thresholds and special calibration to test the calorimeter trigger chain for electrons and jets using this data.

An example of such testing is shown in Figure 1 for central jets. The E_T and η spectra for a recent run are shown. The GCT emulator software was run on the GCT input data and compared with the actual output of the hardware. The agreement between hardware and simulation is excellent. Figure 2 shows the results of the comparison between hardware and simulation in more detail. It can be seen that perfect agreement is achieved for electrons and forward jets, in more than 10,000 candidates recorded for each. The summaries for central and tau jets show a small number of jets which appear in data but not emulator or vice-versa. These were investigated further and a rare error in the transmission of the tau veto flag was discovered. This has been since corrected. An error such as this one, at the rate of one jet in more than two thousand illustrates the power of the comparison with software emulation to find and understand rare occurances.

IV. Algorithm development

Algorithms to calculate the remaining GCT trigger quantities, missing transverse energy, total transverse energy and total jet transverse energy have been implemented and are currently being tested and commissioned.

In the course of CMS commissioning much discussion centred on developing a trigger to take minimum bias data in very early LHC running. A novel idea was proposed based on summing the E_T in the rings of hadronic calorimeter towers closest to the beam-pipe holes. An alternative algorithm based on counting the number of hadronic calorimeter towers, in the same rings, above a threshold in energy was also studied. Both algorithms were implemented in the GCT and commissioned during cosmic-ray muon runs.

There are already studies on improving the GCT algorithms beyond the baseline specification, to improve the physics performance. Specifically by increasing the level of energy isolation in tau identification and calulating missing energy from jets. These possiblilties are under study.

V. Conclusions

The CMS Global Calorimeter Trigger has been thoroughly tested and commissioned for electrons and jets. Due to the complexity of the system and algorithms it was found that comparing the output from the hardware to that of a detailed computer simulation was hugely beneficial. Using this technique subtle features in the implementation of the algorithms that appeared very rarely were found and understood promptly.

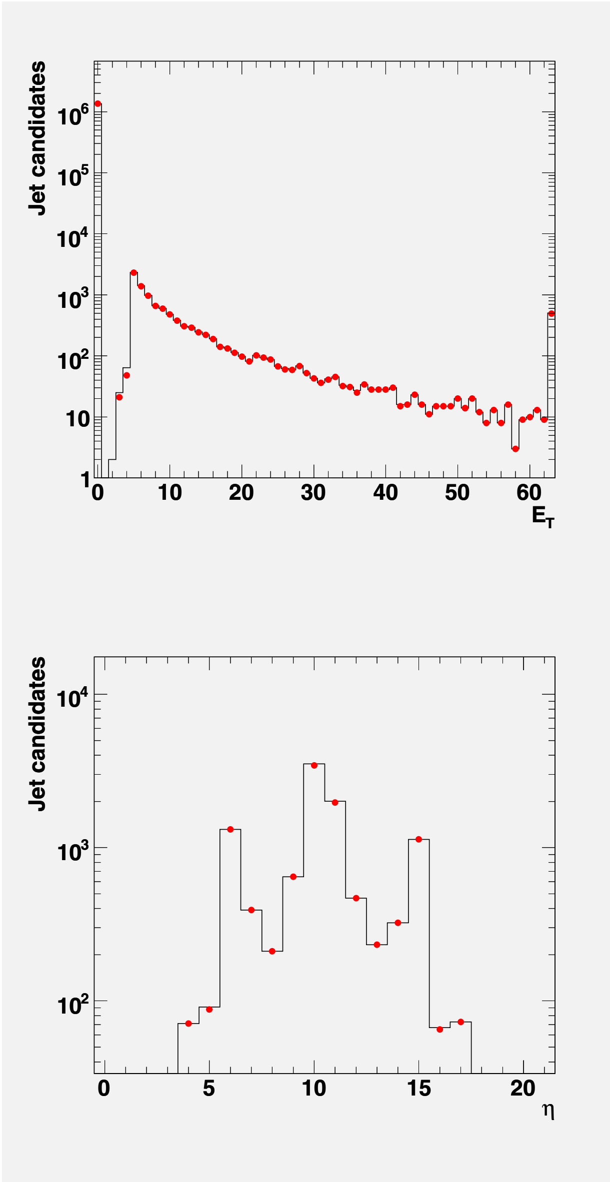

Fig. 1. Examples of the commissioning result histograms for central jets in a recent cosmic-ray muon run. Shown are (upper) the jet E_T distribution and (lower) the η of the jets found. The closed circles represent the data from the GCT hardware and the histogram represents the expectation, obtained by running the emulator on the input data. The E_T and η are in arbitary units used by the hardware.

The high bandwidth and flexibility of the algorithms that may be implemented in the GCT has already proven useful. A novel trigger to accept minimum-bias events tailored to LHC startup was designed, implemented and commissioned in a short time. In the future improvements and new algorithms are expected to be proposed as experience in running the trigger is gained. The flexibility to change exisiting and implement new algorithms is expected to be of significant benefit to the performance of the CMS experiment.

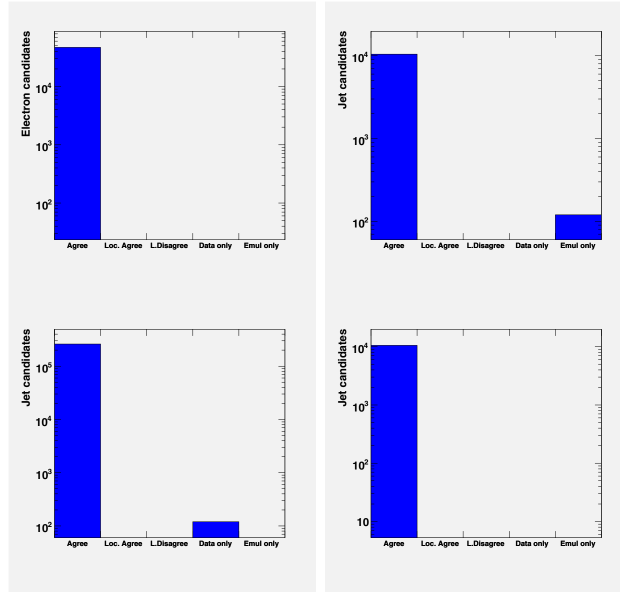

Fig. 2. Examples of the commissioning result histograms for non-isolated electrons (upper left), central jets (upper right), tau jets (lower left) and forward jets (lower right) in a recent cosmic-ray muon run. The histograms show the results of the comparison between data and emulator.

References

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