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Concepts and design of the CMS high granularity calorimeter Level-1 trigger

Jean-Baptiste Sauvan, on behalf of the CMS Collaboration
CERN, CH-1211 Geneva 23, Switzerland
E-mail: jean-baptiste.sauvan@cern.ch

Abstract. The CMS experiment has chosen a novel high granularity calorimeter for the forward region as part of its planned upgrade for the high luminosity LHC. The calorimeter will have a fine segmentation in both the transverse and longitudinal directions and will be the first such calorimeter specifically optimised for particle flow reconstruction to operate at a colliding beam experiment. The high granularity results in around six million readout channels in total and so presents a significant challenge in terms of data manipulation and processing for the trigger; the trigger data volumes will be an order of magnitude above those currently handled at CMS. In addition, the high luminosity will result in an average of 140 to 200 interactions per bunch crossing, giving a huge background rate in the forward region that needs to be efficiently reduced by the trigger algorithms. Efficient data reduction and reconstruction algorithms making use of the fine segmentation of the detector have been simulated and evaluated. They provide an increase of the trigger rates with the luminosity significantly smaller than would be expected with the current trigger system.

1. Introduction

The Compact Muon Solenoid (CMS) detector [1] has been designed to study proton–proton and heavy ion collisions produced by the LHC. Only a few hundreds of events per second can currently be recorded offline and a trigger system is used to select events of interest [2]. The trigger is organised in two stages: the Level-1 (L1) hardware-based trigger reduces the rate to 100 kHz, and the High-Level Trigger (HLT), based on a farm of computers, reduces the rate to 300 to 600 Hz. This system has been performing extremely well during the Phase 0 (from 2010 to 2012) and the beginning of the Phase 1 (since 2015) of the LHC, even under the highest luminosity conditions achieved. During the high-luminosity phase of the LHC (HL-LHC, or Phase 2) that will start around 2025, the instantaneous luminosity will be 3 to 4 times higher than during Phase 1, with an average number of simultaneous interactions per bunch crossing (pile-up) up to 200. For the desired energy thresholds the current trigger system would give a L1 rate of at least 1500 kHz, while only 100 kHz are available. To avoid a significant increase in the energy thresholds, which would be detrimental for physics, an upgrade of the L1 trigger system is required [3]. The future high granularity calorimeter (HGCal) of CMS [3] will provide new inputs to this upgraded trigger system with detailed information for the reconstruction and selection of objects of interest.

In the following, the conceptual design of the HGCal L1 trigger architecture and the associated data flow are discussed. Concepts of algorithms for the reconstruction and identification of electromagnetic objects and jets are described and their expected performance are shown.

2. The HGCal trigger architecture and data processing

Though the precise architecture of the system is not yet known, the first part of the data processing will be performed inside on-detector ASICs in order to reduce the amount of data to be sent off-detector. The second part of the data processing related to the reconstruction algorithms, such as energy clustering and pile-up estimation, will be done in off-detector FPGAs. This off-detector processing will be shared between several layers connected together via high-speed optical links. The result will be the production of HGCal trigger primitives, which will be used, together with primitives from other sub-detectors, to reconstruct higher-level objects such as electrons, photons, tau leptons and jets.

In order to fit within the available bandwidth for transferring trigger data out of the detector, a reduction factor of about 20 in data size is needed. This reduction factor is obtained in several ways:

- The dynamic range and resolution of the measured energies are reduced and the timing information is discarded.
- The HGCal sensor cells are grouped into larger trigger cells.
- Only the most energetic trigger cells are selected and sent off-detector.

The last two of these steps are illustrated in Figure 1. The reduced data will be sent off-detector via a mixture of optical and electrical links. Optical links at 10 Gb/s will be used in the low pseudorapidity region where radiation hardness requirements are less stringent. Electrical links at 5 Gb/s will be used in the high pseudorapidity region, with electrical to optical conversion located in the back of the calorimeters.

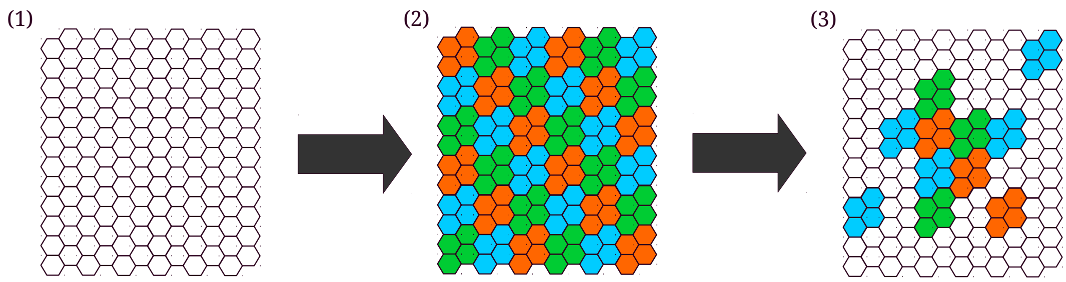

Figure 1. Illustration of trigger data reduction performed in the front-end ASICs. HGCal sensor cells (1) are grouped into trigger cells (2). Only the most energetic ones (3) are selected and transfered.

The back-end electronics will decode the incoming trigger data and perform a subsequent and more sophisticated reduction of the information with a three-dimensional clustering of the energies. This process can be done in different ways and the final algorithm has not been chosen yet. The choice of the type of algorithm will depend on both the triggering performance and the hardware feasibility. The formation of clusters can be done in two steps, starting with two-dimensional clusters built in each layer independently, followed by a linking procedure of these two-dimensional clusters. The clusters can also be built directly using the full three-dimensional information, which would benefit from more information but would need more hardware resources. The latter scenario has been explored so far.

In the process of energy clustering the estimation of the level of pile-up is of paramount importance in order to reduce the sensitivity of the trigger to pile-up. This pile-up estimation will be done event-by-event and regionally, in order to better catch local fluctuations (in time and space). The number of trigger cells above a given energy threshold is highly correlated with the number of additional interactions and is very simple and fast to compute. It is therefore a good estimator of the level of pile-up. In order to improve further this correlation and reduce the bias coming from the presence of energetic objects, this cell counting is limited to the first layers of the HGCal, which are dominated by the energy deposits of low-energy particles coming from minimum-bias interactions. This number of cells is then used to compute several quantities, such as clustering thresholds and energy corrections in order to reduce their sensitivity to additional energy not coming from the hard interaction. It can be mentioned that, though not studied so far, timing information could eventually provide an additional handle for the mitigation of pile-up, if propagated through the trigger processing chain.

Clusters will suffer from energy non-containment and inefficiencies and will not be able to catch the total energy in the events. Therefore, in addition to three-dimensional clusters, projective trigger towers with a coarser transverse granularity will be produced. This will provide a complete map of the energy and complement the localized aggregated energy.

3. From trigger primitives to object reconstruction

The HGCal trigger system will produce three-dimensional clusters and trigger towers and send them to the global CMS trigger system. Together with the energy of the clusters, information on their shape and quality will be sent. Given the fine segmentation of the calorimeter, both transverse and longitudinal, the shape information provides an efficient discrimination between electromagnetic and hadronic showers. In particular, information on the start, on the maximum and on the tail of the shower can be condensed into simple variables easily used at the L1 trigger for cluster identification. The physics object reconstruction (such as electrons, photons and jets) will be performed outside of the HGCal trigger system and combine information from several sub-detectors. But algorithms using solely the HGCal trigger primitives described above have been developed and studied in order to evaluate the triggering performance of this detector.

Electrons and photons are reconstructed from clusters identified as electromagnetic energy deposits. Electrons and photons can produce several nearby reconstructed clusters, spread in the azimuthal direction due to the magnetic field, in case of bremsstrahlung and photon conversion. The granularity of the HGCal L1 trigger will be sufficiently fine to separate these nearby clusters; it is therefore necessary to sum their energy together in subsequent trigger stages in order to recover this energy spread. Electromagnetic clusters will also be matched to tracks reconstructed by the future track trigger in order to separate electrons and photons. The results presented in the next section do not include this matching though; the HGCal is used in a standalone way, without combination with other subdetectors.

Jets are objects very sensitive to pile-up due to their large transverse size. In order to reduce the number of reconstructed jets, mostly dominated by pile-up energy, the jet reconstruction is seeded by high-density clusters and built from trigger towers around these seeds. The size of the jets is also optimized such that the energy fluctuations coming from pile-up energy and non-containment are as small as possible. A small jet radius of the order of $\Delta R = 0.2$ is obtained with this procedure.

4. Performance

The efficiencies and background rates obtained with the electron and photon and jet reconstruction algorithms using only the HGCal information have been compared with those obtained with the algorithms currently used during the Phase 1 of the LHC. The Phase 2 conditions have been used for the HGCal case, with an average of 140 interactions per bunch crossing, while the Phase 1 conditions have been used for the latter case, with an average of 40 simultaneous interactions. In both cases a full simulation of the detectors has been performed for the estimation of the performance of the trigger algorithms. In the Phase 1 case the rate computation has been restricted to the endcaps for a direct comparison with the HGCal results.

In all the considered scenarios the algorithms are giving selection efficiencies of signal objects close to 100%. For these high efficiencies, the background rates are given in Figure 2. For an increase of the instantaneous luminosity by a factor of the order of 3.5 the expected rates are increased by a factor of 2.5 to 3 at most. In some regions this increase of rates is even limited to a factor less than 1.5. This good control of the rate despite the large increase in luminosity is obtained in particular with the usage of the longitudinal segmentation of the detector, giving an efficient estimation and rejection of pile-up energy contributions.

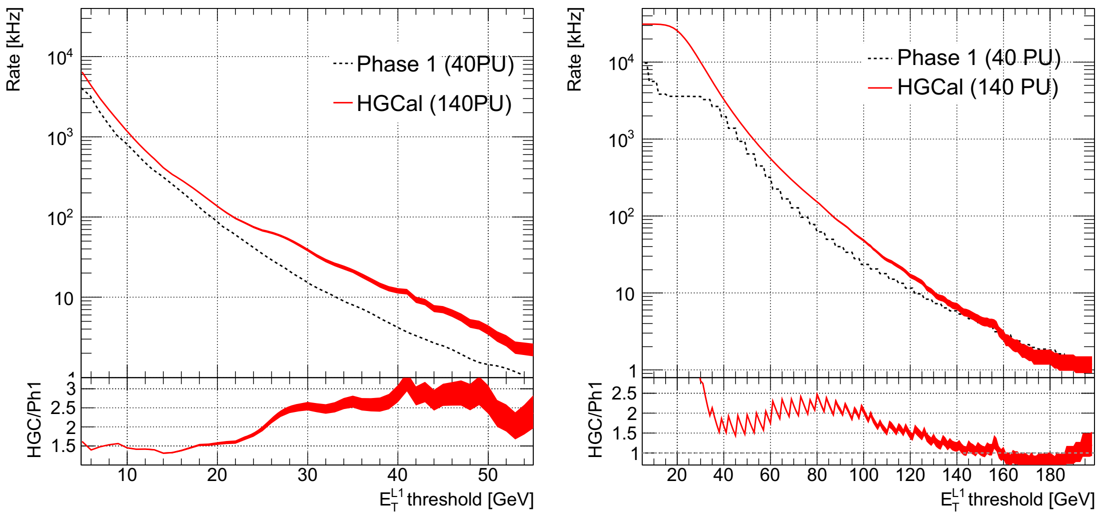

Figure 2. Background rates obtained with electron and photon (left) and jet (right) triggers. Rates obtained with the HGCal with 140 simultaneous interactions are compared with those obtained with the Phase 1 trigger, restricted to the endcaps, with 40 simultaneous interactions. The stepwise decrease of the Phase 1 jet rate is due to the discontinuous digital values of energy.

5. Conclusion

Due to the intense instantaneous luminosity and the harsh pile-up conditions expected during the high luminosity phase of the LHC, the L1 trigger system has to be upgraded. In particular the new HGCal subsystem must be designed to provide inputs to the upgraded L1 trigger. Preliminary design concepts for the HGCal L1 trigger, particularly in terms of data handling and processing, have been developed and evaluated. It has been shown that simple techniques can provide effective data reduction in the front-end ASICs, and efficient pile-up mitigation can be obtained using the three-dimensional information of the particle showers. For similar efficiencies on signal objects (electrons, photons and jets) as those obtained with the Phase 1 system, the background rate is increased by a factor of between 2.5 to 3 at most, and down to less than 1.5, for an increase of the instantaneous luminosity by a factor of around 3.5.

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