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CMS high-level trigger selection

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Abstract. The CMS High-Level Trigger (HLT) is based on sets of dedicated commercial processors, whose goal is to reduce the Level-1 trigger rate of 100 kHz to ≈100 Hz, a value compatible with permanent storage of data. In this report the results from the recently published DAQ TDR are presented. The offline code with little modifications can be used in the trigger chain soon after Level 1 by making use of regional and conditional analyses. For the benchmark channels considered, the signal efficiencies and background rejection factors, obtained within ≈500 ms of a recent CPU (1 GHz processor), are competitive with full offline analyses done without any timing limitation.

PACS. CMS Compact muon solenoid experiment – HLT High-Level Trigger

1 Introduction

The CMS experiment [1] will be installed at LHC, a pp collider with a beam energy of 7 TeV and a planned luminosity ranging from $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ("low luminosity phase") up to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ("high luminosity phase"). The bunch crossing rate will be 40 MHz. Depending on the luminosity, a number of inelastic pp collisions per bunch crossing ranging from ≈2 to ≈20 is expected. A very good trigger system is therefore required in order to reduce the event rate to a value that can be reasonably written to mass storage ($\mathcal{O}(10^2)$Hz) preserving the analysis and discovery capabilities of the experiments.

2 Physics requirements and trigger strategy

At the design luminosity of the LHC the maximum event storage rate corresponds to a cross section of ≈10 nb which is comparable to the $\mathrm{W}^+ \to \mathrm{e}^+\nu_\mathrm{e}$ production cross section alone. A significant physics selection has therefore to take place on-line.

The CMS trigger is organized in two levels:

– a Level-1 trigger, with a total processing time of 3μs, which performs the first stage of event selection reducing the event rate from 40 MHz to 100 kHz. Level 1 is based on custom electronics that process data from a subset of the CMS detector.
– a High-Level Trigger (HLT), with a total processing time of up to ≈ 1s, which must reduce the event rate output from Level-1 trigger by a factor ≈ 1000 for a total output to storage of ≈ 10^2 Hz. The HLT will run on a farm of commercial processors (Filter Farm) and is described in detail in the following.

The key aspect of the HLT is the real-time nature of the selection which imposes significant constraints on the resources. Since the events rejected by the HLT are lost forever, the correct functioning of the HLT is a key issue.

The design of the CMS HLT system must fulfil the following requirements:

– satisfy the CMS physics program with high efficiency;
– perform an inclusive event selection in order to make possible the discovery of unexpected physics;
– not rely on a precise knowledge of the calibration and of the run conditions;
– give the possibility to measure the trigger efficiency from the data alone;
– use algorithms as close as possible to the quality of the offline reconstruction.

Another basic design principle of the HLT is the scaling capability which addresses the fact that both the accelerator and experimental conditions as well as the physics program are expected to evolve with time. The CMS event building and HLT step is organized in independent "slices". Adding more slices to the system allows for a higher sustainable event rate.

A possible issue is whether the system can provide enough throughput for the entire set of events accepted by the Level 1 to be forwarded to a given processor of the Filter Farm.

The demonstration of this possibility as well as the description of the scaling capabilities of the system can be found on CMS DAQ TDR [2] and is not covered in this report.

2.1 Regional and conditional reconstruction

In order to minimize the CPU time the HLT algorithms are based on the fundamental concepts of regional and conditional reconstruction, i.e. the reconstruction of the event only in the region(s) considered interesting by Level 1. As an example, for an event accepted by the Level-1 trigger in the inclusive muon stream, only the parts of the muon chambers pointed to by Level-1 trigger information, and the corresponding road in the tracker, need to be considered for the validation of the muon. Furthermore the reconstruction is stopped if the information is enough to discard a given event (Conditional Reconstruction). As an example the tracker reconstruction of a Level-1 muon candidate is stopped when the number of hits used is enough to reach the desired momentum resolution.

2.2 Trigger levels definition

In the HLT there is no sharp division between the Level-2 and Level-3 trigger steps. The algorithms based on the faster sub-detectors (muon chambers and calorimeters) are conventionally called Level-2 algorithms, while the Level 3 usually refers to selections that includes the tracker reconstruction. Sometime a step is called Level-2.5 trigger to indicate the fact that a partial tracker information has been used.

3 Physics objects selection

The HLT performance have been analysed for the four basic objects categories defined already at Level 1: a) electrons/photons, b) muons, c) jet channels, d) τ and b jets. For each algorithm the background rejection capability, the signal efficiency and the required CPU time have been studied in detail taking into account several benchmark channels. Standard Monte Carlo generators such as PYTHIA and ISAJET, have been used to simulate the pp collisions at a centre-of-mass energy of 14 TeV. The produced signal and "pile-up" events have been processed through CMSIM, a detector simulation program based on GEANT3. The digitization and reconstruction have been done with the standard CMS Object-Oriented reconstruction program ORCA [3].

3.1 electrons and photons selection

The HLT selection of electrons and photons proceeds in three steps. The first step (Level 2), uses the ECAL clusters alone to find electron candidates.

The next step (Level 2.5) requires the presence of hits in the pixel detectors in a position geometrically consistent with a Level-2 electron candidate. If no matching hits are found the cluster is considered a photon candidate. In the final step (Level 3) the electron candidate is fully reconstructed in the tracker.

Electrons radiate in the material between the interaction point and ECAL and the bending in the 4T field produces a spread along the azimuthal coordinate ϕ of the energy reaching ECAL. The Level-2 reconstruction tries to collect the radiated energy by forming a "super-cluster" along the ϕ direction. The electron (or photon) candidate is the super-cluster with the highest transverse energy E_T and with $E_{HCAL}/E_{ECAL} < 0.05$. At Level 2.5 at least two of the three possible pixels hits are required to match with the direction of the Level-2 candidate. Matching hits are given by most electrons and by few photons since most of the tracker material lies after the pixel detector and most electrons do not radiate significantly before pixels while most photon conversions take place after pixels. At Level 3 the electron candidate is reconstructed in the tracker by using as seed the pixel hits found in the Level-2.5 step. This step is done with loose requirements in track finding to enhance the efficiency with radiating tracks. Cuts are made on both the E_{ECAL}/P_{track} ratio and on the distance between the super-cluster position and the extrapolated track position in the ECAL.

3.2 muons selection

The muon HLT selection proceeds in two steps. At Level 2 the muon candidates found by the Level-1 Global Muon Trigger are reconstructed in the muon chambers with a Kalman filter technique. The Level-1 P_T measurement is refined using more precise information and imposing the beam constraint in the fit. The resulting trajectories are used to validate the Level 1 decisions. At Level 3 a region of interest around the Level-2 muon trajectory extrapolated at vertex is defined where the algorithm looks for geometrically compatible pixel hits. These hits are used as seed to propagate a track from innermost layers, including also muon hits in the global fit. A much improved momentum resolution (≈ 10 times better then the Level-2 fit) is found. In order to suppress non-prompt muons from b, c, π, and K decays isolation criteria are applied at Level 2 using the calorimetric energy sum in a cone around the muon, and at Level 3 using the P_T of tracks in a region around the projected muon trajectory. The HLT single or di-muon candidates are then selected by imposing cuts on the reconstructed P_T.

3.3 Jets and missing energy

The HLT jet finding is based on a simple iterative cone algorithm which has the basic advantage of being fast.

The jet rates at LHC are very high and consequently the thresholds for triggers which use only jets are also very high. As an example, at low luminosity, the following thresholds have to be applied to have a rate of 1 Hz: ≈ 650 GeV(1 jet), ≈ 250 GeV(3 jets), ≈ 150 GeV(4 jets). High-Level Trigger on physics channels need something besides jets to have an acceptable rate and acceptably low thresholds on jet E_T. This additional condition is usually not difficult to find for SUSY or Higgs channels.

Neutrinos and other not-interacting particles can be detected by looking for missing transverse energy (E_T^{miss}) in the calorimeter. The HLT algorithm calculates E_T^{miss} as a simple vector sum of the towers over a given threshold (E_T(tower) > 500 MeV). There are no plans at HLT for triggers requiring only E_T^{miss} and no other physics object, like a jet or a lepton.

3.4 Tracker at HLT

At HLT, the speed of the reconstruction algorithm is more important than the ultimate resolution on track parameters. It has been found that the time needed for track reconstruction increases linearly with the number of hits and that five hits are enough to have a good momentum and impact parameter resolution. Together with the regional reconstruction, this makes possible to use the tracker very early in the trigger chain as it has already been discussed for the electrons and muons selection.

Another very successful application of the tracker at HLT is the selection of the hadronic decays of isolated taus such as those expected in the MSSM Higgs boson decay $A^0/H^0 \to \tau\tau$ and $H^+ \to \tau\nu$. The τ decays hadronically 65% of the time, producing a "τ-jet", a jet-like collimated cluster in the calorimeter containing a small number of charged and neutral hadrons. The Level-1 τ-jet can thus be defined in the calorimeters by using an isolation criteria. The tracker is able to improve the effectiveness of the isolation algorithm. A very high background rejection ($\approx 10^3$ after Level 1) is obtained with a good signal efficiency ($\approx 50\%$ in the channel $A^0/H^0 \to \tau\tau$).

Similar results could be obtained by making use of the tracker for b tagging both in inclusive and exclusive rare decays, especially at low luminosity.

4 HLT performance

The current plans for CMS foresee a staged installation of the DAQ system so that at start-up the maximum allowed Level-1 trigger rate will be 50 kHz (increasing up to 100 kHz at high luminosity). To take into account all the uncertainties in the simulation of the basic physics processes, of the CMS detector and of the beam conditions, the maximum allowed bandwidth is divided by a safety factor of three (i.e. 15 kHz at low luminosity). The expected cumulative rate after HLT is ≈100 Hz.

Table 1 shows the performance of the HLT algorithms for the most relevant physics objects at low luminosity ($2 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$). The rightmost column lists the average CPU time needed by the various algorithms to process one event on a 1 GHz Pentium III CPU. Considering the expected Level-1 rate for the various physics objects a total average time of ≈300ms/event is found, which implies that 15000 PIII 1 GHz CPUs would be needed to run HLT at 50 kHz.

Table 1. Level-1 trigger rates, HLT thresholds, trigger rate after HLT and CPU time (1 GHz PIII CPU) needed by the HLT algorithms for various channels. The quoted CPU time and Level-1 rate are added up for e and γ channels as well as for jets and jet*Miss-E_T channels. The 2-jets trigger is not considered because a single QCD jet is always associated with a second jet of comparable energy

Trigger objects	L1 Rate kHz	HLT Thresh. GeV	HLT Rate Hz	CPU ms
1e, 2e	4.3	29, 17	34	160
$1\gamma, 2\gamma$		80, (40*25)	9	
$1\mu, 2\mu$	3.6	19, 7	29	710
$1\tau, 2\tau$	3.0	86, 59	4	130
jet*Miss-E_T	3.4	180*123	5	50
1,3,4 jets		657, 247, 113	9	
e * jet	0.8	19*52	1	165
incl. b-jets	0.5	237	5	300

At LHC start-up (2007), the computers will be ≈ 8 times faster than now. The CMS Filter Farm can be realized with ≈2000 CPUs. It must also be said that some of the algorithms, like the muon selection, are expected to be optimized, thus improving substantially the performance.

5 Conclusions

The LHC is expected to be a discovery machine. A maximum flexibility has to be put in the trigger system in order to be able to cope with unforeseen situations. As shown in this report and in the DAQ TDR [2], this flexibility is realized by the CMS HLT design based on a purely software event selection made on commercial processors.

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References

1. CMS Collaboration: The Compact Muon Solenoid TDR, CERN/LHCC 94-38 (1994)
2. CMS Collaboration: Data Acquisition and High Level Trigger TDR, CERN/LHCC 2002-26
3. CMS OO Reconstruction http://cmsdoc.cern.ch/orca