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The CMS High-Level Trigger

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Abstract

At the startup of the LHC, the CMS data acquisition is expected to be able to sustain an event readout rate of up to 100 kHz from the Level-1 trigger. These events will be read into a large processor farm which will run the ”High-Level Trigger” (HLT) selection algorithms and will output a rate of about 150 Hz for permanent data storage. In this report HLT performances are shown for selections based on muons, electrons, photons, jets, missing transverse energy, tau leptons and b quarks: expected efficiencies, background rates and CPU time consumption are reported as well as relaxation criteria foreseen for a LHC startup instantaneous luminosity.

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The CMS High-Level Trigger

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Abstract. At the startup of the LHC, the CMS data acquisition is expected to be able to sustain an event readout rate of up to 100 kHz from the Level-1 trigger. These events will be read into a large processor farm which will run the "High-Level Trigger" (HLT) selection algorithms and will output a rate of about 150 Hz for permanent data storage. In this report HLT performances are shown for selections based on muons, electrons, photons, jets, missing transverse energy, τ leptons and b quarks: expected efficiencies, background rates and CPU time consumption are reported as well as relaxation criteria foreseen for a LHC startup instantaneous luminosity.

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THE CMS DETECTOR AND TRIGGER SYSTEM

The CMS detector [1] at the LHC accelerator, must be endowed with a highly selective online trigger system. At the design LHC center-of-mass energy and instantaneous luminosity, respectively 14 TeV and 10^{34} cm^{-2} s^{-1}, the bunch-crossing rate will be 40 MHz, corresponding to about 10^9 proton-proton interactions per second, when event pile-up is taken into account. Comparing this rate with the achievable mass storage rate of about 150 Hz, the online selection has to provide a total rejection factor of 10^6-10^7.

Unlike most experiments at hadronic machines, which are based on a three-level trigger logic, CMS has a trigger designed in only two levels:

- The Level-1 trigger (L1) decision is made by custom synchronous processors which exploit coarse granularity information from calorimeters and muon detectors to identify: electromagnetic clusters (e/γ), muons, jets and missing tranverse energy ($\not{E}_T$). The L1 processing time per event is O(μs).
- The High-Level Trigger (HLT) step is run on an asynchronous farm of commercial CPUs: it has access to event data with full granularity, allowing for precise object reconstruction and energy/momentum evaluation. At this step electrons, photons, muons, jets, $\not{E}_T$ reconstruction and selection, as well as simple b- and τ-tagging can be performed using matching of different sub-detectors.

The choice of a single HLT step has several advantages, mainly the flexibility coming from accessing the full event data and the possibility to implement algorithms as similar as possible to off-line reconstruction. On the other hand, the large L1 input rate poses challenges due to the high rejection power needed and the CPU timing limitations.

HIGH-LEVEL TRIGGER ALGORITHMS

The HLT algorithms share some common features that result in a significant saving of CPU time:

- *"On-demand" reconstruction*. Any step of the reconstruction is performed only if the candidate is accepted by the previous selections in the trigger path.
- *Regional unpacking and reconstruction*. At HLT reconstruction of hits and physics objects is done only in given "regions of interest" around L1 objects.
- *Conditional tracking*. When track reconstruction (the slowest process in CMS HLT) is required in a trigger path, the pattern recognition is stopped after a given number of found hits, i.e. after a given $\sigma(p_T)/p_T$ is reached.

Unless otherwise specified, performances and background rates in the following are estimated for a LHC luminosity of 10^{32} cm^{-2} s^{-1} [2].

Muons

In the first step of the HLT muon selection, referred to as "Level-2 (L2) reconstruction", L1 muon candidates are used to seed the reconstruction of tracks in the muon chambers. L2 muons are required to exceed p_T threshold values that depend on the trigger path, with a typical p_T resolution of 12-17% at this stage. The Level-3 (L3) reconstruction is carried out by combining L2 muons and charged-particle tracks reconstructed in the central tracker. The final filtering step is applied on the precisely measured ($\sigma(p_T)/p_T \sim 1.5\%$) L3 muons.

Isolation is an optional step in HLT reconstruction to reject non-prompt muons and muons from B and D decays. Due to the limited CPU resources the isolation requirements are applied as soon as more detailed information on a muon becomes available: calorimeter-based isolation is applied first after L2 reconstruction and is then followed by track-based isolation at L3, being applied to regionally-reconstructed tracks.

The typical efficiency for a non-isolated muon trigger is 87% on $W \to \mu\nu$ events determined from MC. Fig. 1 shows the rate of background events as a function of the p_T threshold at L2/L3 steps: the optimal value for a non-isolated trigger is 16 GeV/c.

Electrons and photons

The HLT selection for electrons and photons is similar and is based on L1 seeds which can have two levels of HCAL isolation requirements ("isolated" and "relaxed"), which also correspond to different E_T thresholds.

Reconstruction of clusters in the ECAL within regions corresponding to L1 objects in the event is performed. Super-clusters (groups of clusters along a road in the ϕ direction) are constructed to collect bremsstrahlung radiated from electrons or converted photons. The super-cluster transverse energy, E_T, is then required to exceed a given threshold. ECAL isolation and cluster shape criteria may then be required at this stage.

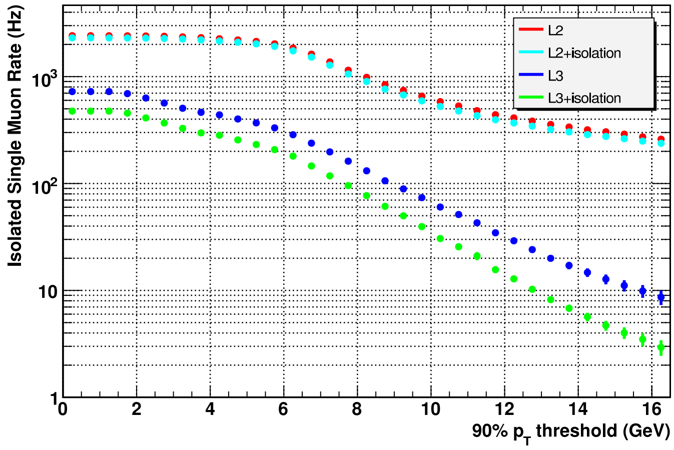

FIGURE 1. HLT rates for the non-isolated and isolated single-muon path on a muon-enriched QCD sample. For the non-isolated a $p_T > 16$ GeV corresponds to an expected HLT rate of ~ 20 Hz.

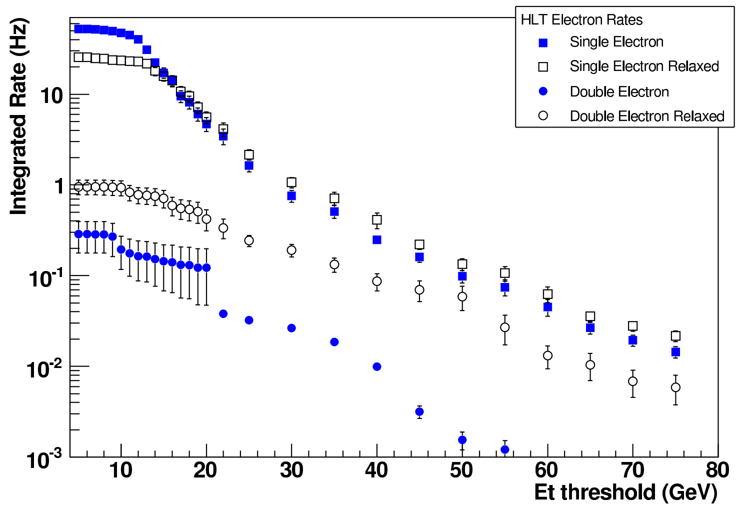

FIGURE 2. HLT rates for isolated and relaxed electron path on an inclusive QCD sample. The thresholds are chosen to keep the total rate to ~ 10 Hz for the single and < 1 Hz for the double triggers.

For electrons triggers only, the energy and position of the super-cluster are used to propagate back through the magnetic field to search for compatible hits in the layers of the pixel detector. The electron track is reconstructed starting from pixel hit pairs. This is followed by the application of cuts on the track-supercluster geometrical matching. For electrons, a threshold may be then applied on the p_T sum of tracks within a cone around the electron direction, but outside a smaller veto cone in order to exclude the electron track itself. For photons, a solid cone is used for track isolation.

The typical efficiency for an electron trigger is 63% on $W \to e\nu$ events determined from MC. Fig. 2 shows the rate of background events as a function of the p_T threshold for single and double electron paths.

Jets and missing transverse energy

At HLT, jets are reconstructed using an iterative cone algorithm with cone size $R = 0.5$. The inputs to the jet algorithm are calorimeter towers, which are constructed from one or more projected HCAL cells and corresponding projected ECAL crystals, and satisfy certain threshold requirements after energy corrections. As is the case with jet reconstruction, $\not{E}_T$ is calculated with the same algorithm used offline.

Four single-jet trigger paths are proposed with E_T thresholds for these paths are 200, 150, 110, and 60 GeV. In addition to the single-jet paths, double, triple, and quad-jet triggers and a $\not{E}_T$ path with threshold of 65 GeV have also been included.

The absolute efficiency of the $\not{E}_T$ path for an invisible Higgs signal in a vector-boson fusion process, defined with respect to the number of generated events, is 79.1% for a Higgs mass of 200 GeV/c^2 and 77.8% for 160 GeV/c^2.

Other triggers

Other HLT algorithms not described before include:

- Hadronic-τ triggers: they are based on a "narrow-jet" reconstruction in the calorimeters, followed by track isolation at two different levels.
- b-tagging triggers:
  - *b-lifetime*: after jet reconstruction, pixel tracks are used to determine the position of the primary vertex in the event. b-jet tagging is based on having at least 2 tracks with a 3-D impact parameter significance $d_0/\sigma_{d0} > 3.5$.
  - $b \to \mu$: after jet reconstruction, L3 muons are used to select muon-in-jets events by imposing the requirement $\Delta R(\mu - jet) < 0.4$. For some trigger paths, a further requirement on $p_T^{rel} > 0.7$ GeV/c of the L3 muons with respect to the jet axis is imposed.
- Triggers on multiple objects, e.g. electron plus jets or muon plus jets to keep high efficiency on semi-leptonic $t\bar{t}$ events with low background rate.

TIMING PERFORMANCES

The timing performances of CMS HLT have been tested by running the full set of paths on simulated QCD events. The test has been repeated using a mixture of several "signal-like" events to ensure that the estimate is unbiased. Both tests yield an average time per L1-accepted event of (42.9 $\pm$ 5.6) ms, which is consistent with the capabilities of the Filter Farm.

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