PROCEEDINGS OF SCIENCE

CMS High Level Trigger performance at 13 TeV

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The CMS experiment selects events with a two-level trigger system: the Level-1 trigger (L1) and the High Level Trigger (HLT). The HLT is a farm made of approximately 30k CPU cores that reduces the rate from 100 kHz to about 1 kHz. The HLT has access to the full detector readout and runs a dedicated online event reconstruction to select events. In 2017, LHC instantaneous luminosity during standard operations was about $1.5 \cdot 10^{34}$Hz cm^{-2} with pile-up of 55, well above the design values, and it is expected to exceed $2 \cdot 10^{34}$Hz cm^{-2} in 2018 by increasing the number of proton bunches. In these conditions, the online event selection is very challenging.

We present the most recent HLT performance results and the methods used at HLT to cope with a high pile-up environment.

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1. The CMS High Level Trigger

The CMS detector [1] is a general purpose experiment installed at the CERN LHC where proton beams were collided at a centre of mass energy of 13 TeV during the Run 2 data taking (2015-2018). In 2018, a collision rate close to 40 MHz and a peak instantaneous luminosity of $2\cdot 10^{34}$Hz cm^{-2} was reached at CMS. In order to control the amount of recorded data, CMS uses a trigger system [2] selecting the most promising collisions. It is made of two steps: the Level 1 trigger, a custom-built electronics system that reduces the rate down to 100 kHz, and the High Level trigger (HLT), a software system running a light version of the offline reconstruction and made of hundreds of algorithms ("paths"). At HLT, several constraints must be considered:

- The number of available CPU cores (32000 in 2018) sets the maximal processing time per event to 320 ms (in practice "hyperthreading" increases this number by around 20%).
- The data recording and its transfer to the CERN Tier 0 limits the allowed bandwidth to $\approx$5 Gb/s on an average LHC fill, resulting in a maximal HLT output rate of a few kHz for the regular event size of collisions recorded by CMS.
- The prompt reconstruction of the data performed at Tier 0 with the offline software furthermore limits the average HLT rate to be around 1 kHz.

The HLT timing is kept under control thanks to the design of the HLT paths that are made of a sequence of reconstruction and filtering modules, the most time consuming ones (e.g. running the Particle Flow algorithm[3]) being run for a small fraction of the events. A typical distribution of the 2016 HLT processing time at an average pile-up of 43 is presented in figure 1 (left).

In order to meet the Tier 0 transfer condition, a possible strategy, called "scouting", is to strongly reduce the event size by only saving objects reconstructed at HLT. This is for example the approach followed in [4] where large trigger rates are unavoidable.

Finally, the option exists to skip the prompt reconstruction and reconstruct the data later with the available computing resources. In 2018 such "parked" data were collected by CMS for b-physics studies. The HLT rate for a specific LHC fill in 2018 is shown in figure 1 (right).

Table 1 presents a list of some common HLT algorithms used in 2018.

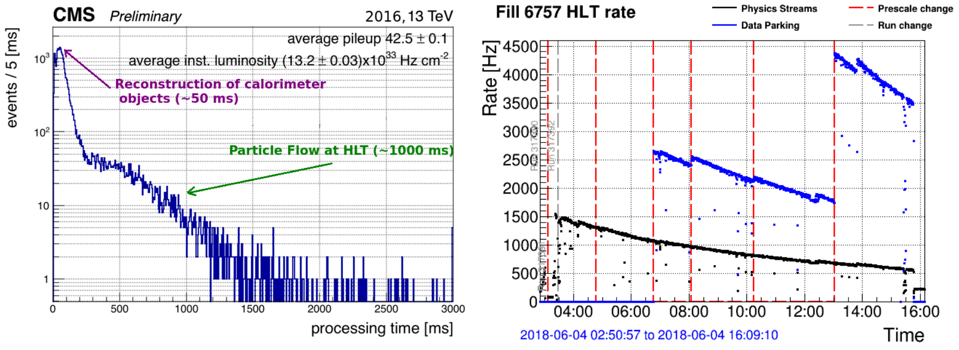

Figure 1: Left: HLT processing time distribution at an average pile-up of 43 in 2016. Right: HLT rate for a LHC fill in 2018, both for "physics streams" (promptly reconstructed data) and for parked data.

Description	Condition	Rate in a certified run at PU 50 ($\mathscr{L}$= 1.8×10^{34} Hz cm^{-2})
Isolated single muon	$p_T(\mu) > 24$ GeV	235 Hz
Isolated single electron	$p_T(e) > 32$ GeV	165 Hz
Non isolated single muon	$p_T(\mu) > 50$ GeV	46 Hz
Non isolated single electron	$p_T(e) > 115$ GeV	17 Hz
Isolated di-photon	$p_T(\gamma) >$ 30/22 GeV, $M(\gamma\gamma) > 90$ GeV	40 Hz
Isolated di-tau	$p_T(\tau) >$ 35/35 GeV, $\lvert\eta(\tau)\rvert <$ 2.1/2.1	40 Hz
Isolated di-electron	$p_T(e) >$ 23/12 GeV	25 Hz
Isolated di-muon	$p_T(\mu) >$ 17/8 GeV, $M(\mu\mu) > 3.8$ GeV	28 Hz
Isolated electron-muon	$p_T(e) >$ 23(12) GeV, $p_T(\mu) >$ 8 (23) GeV	7.5 (4) Hz
Single jet	$p_T(j) > 500$ GeV	11 Hz
Hadronic transverse energy	$H_T > 1050$ GeV	10 Hz
Missing transverse energy	PFMET> 120 GeV, PFMHT> 120 GeV	33 Hz
Hadronic $t\bar{t}$	H_T >380 GeV, ≥ 6 jets (p_T>32 GeV), 2 b-tagged jets	9 Hz
Boosted heavy jets	$p_T(j) > 400$ GeV, M(j)> 30 GeV	27 Hz
Isolated single photon	$p_T(\gamma) > 110$ GeV, $\lvert\eta(\gamma)\rvert < 1.479$	12 Hz
Non isolated single photon	$p_T(\gamma) > 200$ GeV	13 Hz
Triple muon	$p_T(\mu) >$ 5/3/3 GeV, $M(\mu\mu) > 3.8$ GeV	9 Hz
isolated di-muon+electron	$p_T(\mu) > 4$ GeV, $p_T(e) > 9$ GeV	4.5 Hz
Displaced $J/\psi \to \mu\mu$	$p_T(\mu) >$ 4/4 GeV, 2.9< $M(\mu\mu) < 3.3$ GeV + displaced vertex	33 Hz

Table 1: Some common HLT paths used in the 2018 data taking, together with their rate for an instantaneous luminosity of $1.8 \cdot 10^{34}$Hz cm^{-2} and a pile-up of 50. The rate uncertainties are at most a few Hz.

2. HLT performances

Tracking at HLT consists of three iterations performed successively. The first two target respectively high p_T and low p_T tracks. Finally an iteration allowing a missing pixel hit is run only in the vicinity of calorimeter deposits or other tracks. In 2018, a fourth iteration allowing two missing pixel hits was also added. The HLT tracking efficiency in simulated $t\bar{t}$ events is presented in figure 2 as a function of the track p_T and ϕ.

The electron and photon reconstruction starts from a deposit in the electromagnetic calorimeter. Electrons are then identified by the presence of hits in the pixel detector. This pixel matching was retuned in 2017 to take advantage of the upgraded pixel detector, reducing the rate of a dielectron trigger by 70% for the cost of only 1-2% of efficiency. Various conditions on the shower shape and isolation were adapted to achieve better pile-up resiliency.

In 2018, the offline algorithm that aims at reconstructing the various decay modes of a hadronic tau was implemented at HLT. For a similar efficiency, a 20% rate reduction was achieved for double tau triggers with respect to the previous algorithm.

Muons are seeded by segments of hits in the muon chambers. Inside-out and outside-in tracking is then performed. In the middle of Run 2, the various reconstructions were merged. More seeds were allowed and loose identification criteria were added. Fig 3 illustrates the use of the dimuon mass or displacement information at HLT.

Jets are usually reconstructed using the calorimeters only as a first step. Tracking and particle flow can then be run. HLT b-tagging is performed using regional tracking around the leading jets. An important improvement in 2018 is the switch to a b-tagger based on a deep neural network. For a same mistag rate, HLT b-tagging is typically 5% less effient than offline.

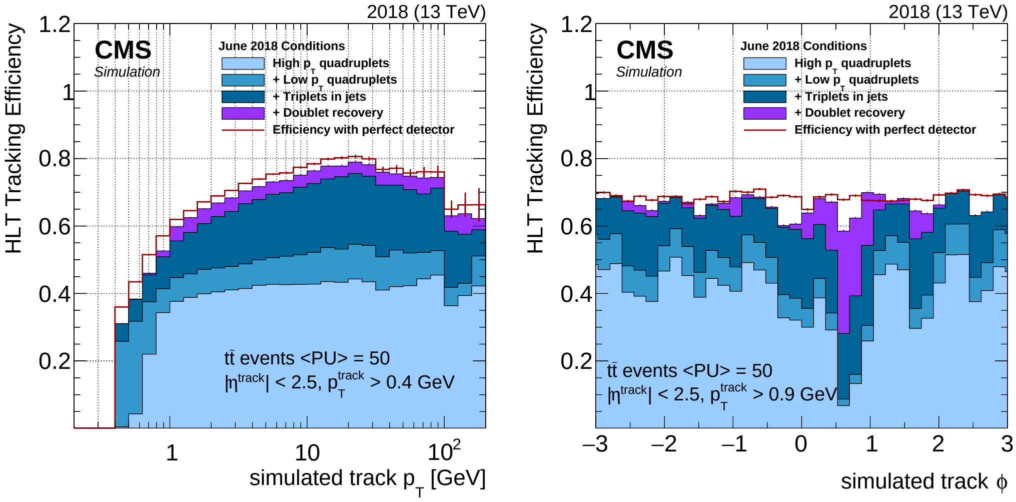

Figure 2: The cumulative efficiency of the various tracking iterations used at HLT in 2018 in simulated $t\bar{t}$ events as a function of the track p_T (left) and ϕ (right). The fourth iteration recovers inefficiency in the $\phi = 0.7$ region where two pixel layers are partiallly off. [5]

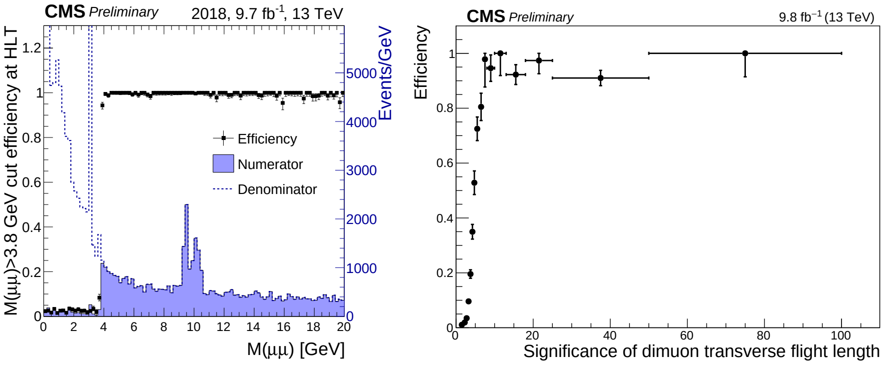

Figure 3: Left: Efficiency of $M(\mu\mu)$ >3.8 GeV at HLT for pairs of offline muons with p_T >20 GeV. Right: efficiency of a displacement cut at HLT as a function of the significance of the offline dimuon pair tranverse flight length. [5]

References

[1] The CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 S08004 (2008).

[2] The CMS Collaboration, “The CMS trigger system”, JINST 12 P01020 (2017).

[3] The CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, JINST 12 (2017) P10003

[4] The CMS Collaboration, “Search for narrow and broad dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter mediators and other new particles”, JHEP 08 (2018) 130

[5] The CMS Collaboration, “HLT Run 2 results”, https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIIResults