CMS High Level Trigger performance at 13 TeV

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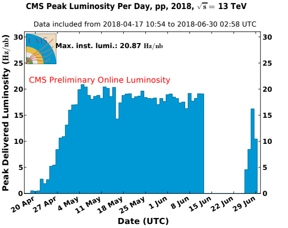
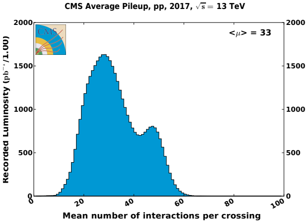
on behalf of the CMS Collaboration

July 5th, 2018

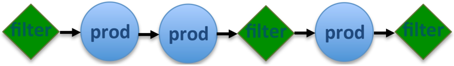
Introduction

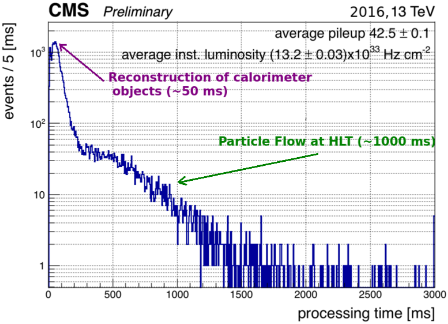
- With a collision rate close to 40 MHz, impossible to record and store all collisions happening at CMS.
- Trigger system implemented to keep only the "more interesting collisions".
- Achieved in a 2 step process at CMS:
  1. **Level 1 (L1) trigger**:
     -Customizable hardware (ASICs and FPGAs).
     -Output rate: 100 kHz (detector readout constraint).
     -Timing: 4μs (available buffer)
     $\rightarrow$ *See O. Davignon's talk in Detector R&D session.*
  2. **High Level trigger (HLT):**
     -Software system implemented on a PC farm.
     -Light version of the offline software.
     -Access to the full event information.
     $\rightarrow$ ***Topic of this talk***
- Big challenge for experiments in LHC Run 2: face the amazing performances of the machine.
  - Regular increase of the instantaneous luminosity. Up to 2$\times$ the designed value in 2018 !
  - Almost 60 pile up at the beginning of the fill in 2017





- $\approx$ 32000 CPU to process 100 kHz of L1 rate.
- **Time per event $\lesssim$ 320 ms.** (In fact up to $\approx$ 380 ms thanks to hyper-threading)
- HLT paths consist of succession of reconstruction and filtering modules to discard uninteresting events as soon as possible.
- Start with fastest steps (calorimeter based information)
- Most time consuming operations (tracking, full particle flow) only run for a fraction of the events.

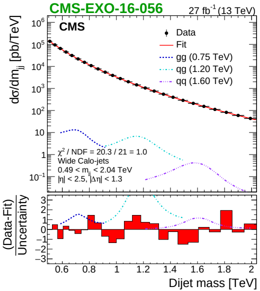




Computing constraints: Recording, transfer and processing at CERN Tier 0

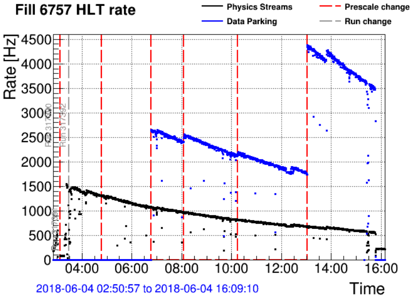
Data recording + transfer to CERN Tier 0.

- **Allowed bandwidth $\lesssim$ 5 Gb/s** on average.
- **HLT output rate limited to a few kHz** for nominal event size.
- Workaround: reduce event size by saving only trigger information.
  $\rightarrow$ "Scouting"
  (e.g.: "low" mass dijet resonances search)



Prompt offline reconstruction within 48 h.

- **Average HLT rate over a LHC fill constrained to $\lesssim$ 1 kHz.**
- Workaround: skip the prompt reconstruction and reconstruct the data later (during technical stops).
  $\rightarrow$ "Parking"
  (e.g.: trigger with low p_T objects)



Trigger menu in Run 2

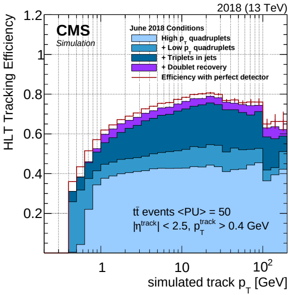
- Hundreds of HLT paths targeting a broad variety of topologies.
- Highest rate paths: isolated single muon/electron paths (limited by L1 thresholds).
- LHC production rate of $W \to \mu\nu$ at 13 TeV and 1.8×10^{34} Hz cm^{-2}: **360 Hz** !
- Some other important bandwitdth consumers: di-photon and di-tau paths.
- Various hadronic paths also present. Some using substructure/b-tagging.

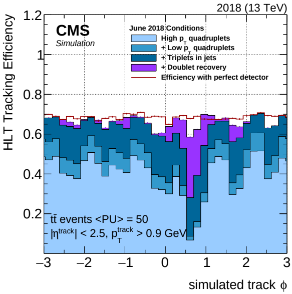
A few paths in CMS 2018 trigger menu (far from exhaustive)

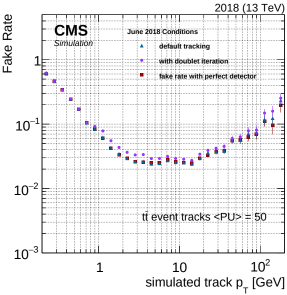
Description	Threshold	Rate in a certified run at PU 50 ($\mathcal{L}$= 1.8×10^{34} Hz cm^{-2})
Isolated single muon	$p_T(\mu) > 24$ GeV	235 Hz
Isolated single electron	$p_T(e) > 32$ GeV	165 Hz
Non isolated single muon	$p_T(\mu) > 50$ GeV	46 Hz
Non isolated single electron	$p_T(e) > 115$ GeV	17 Hz
Isolated 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, $\geq$ 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

(Rate uncertainties: $\approx$20% (rates < 10 Hz) / a few Hz (rates >10 Hz))

- Three tracking iterations performed successively (discarding hits already used):
  - high p_T tracks with 4 pixel hits.
  - low p_T tracks with 4 pixel hits.
  - Iteration with relaxed pixel hits ($\geq$3) condition. Restricted to vicinity of calorimeter jets or other tracks.
- In 2018, one additional pixel hit recovery iteration:
  - Allow 2 pixels hits in detector regions with 2 inactive pixel layers.
  - Limited to $p_T(trk) > 1.2$ GeV (timing constraint)
- Performances assessed in $t\bar{t}$ simulation and compared to a perfect detector (no missing modules).

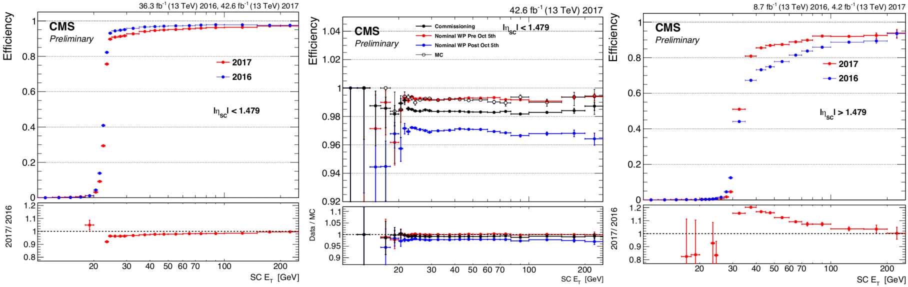






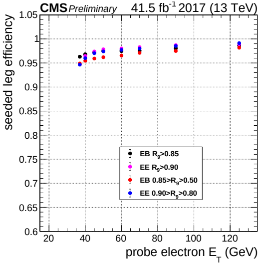
Various improvements during data taking.

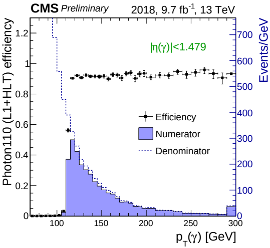
- Pixel matching condition retuned in 2017 to take advantage of the upgraded pixel detector. 70% rate reduction for dielectron trigger for the cost of 1-2% of inefficiency.
- Adjustement of identification and isolation conditions to achieve better resiliency vs pile up in the endcaps.
- 2018: pixel inefficiency mitigation deployed.

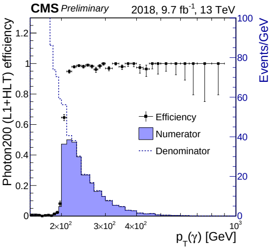


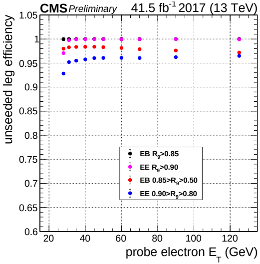
Photons at HLT

- Dedicated diphoton paths targeting $H \rightarrow \gamma\gamma$
  - Customized photon selection (good shower shape OR well isolated) to maximimize sensitivity and keep reasonable thresholds.
  - Standard path has $M(\gamma\gamma) > 90$ GeV.
  - Tighter version with $M(\gamma\gamma) > 55$ (0) GeV in 2016-2017 (2018) to extend the analysis to lower masses.
- Single photon paths
  - 2017-18: Non isolated photon path with $p_T > 200$ GeV.
  - 2018: New isolated photon trigger introduced (barrel only, $p_T > 110$ GeV).
- Efficiencies measured with $Z \rightarrow ee$ events.



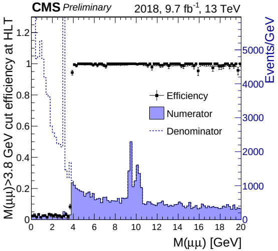


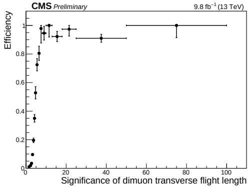


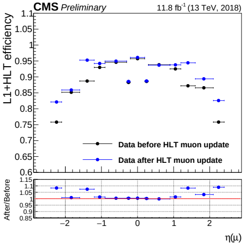


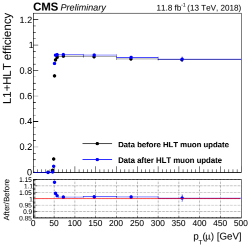
Longstanding development of HLT muons in Run 2.

- 2015-16: two separate reconstructions starting L1 muons or L2 muons (muon system only but more precise than L1).
  - L2 seeded muons with inside-out (IO) or outside-in (OI) tracking.
  - L1 seeded muons with IO tracking only.
- 2017: Both reconstructions merged, updated tracking.
- 2018: Update to recover efficiency/improve resolution.
  - Increased number of seeds.
  - Additional tracking iteration.
  - Simple identification criteria applied.



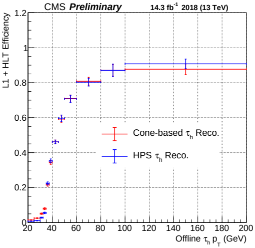




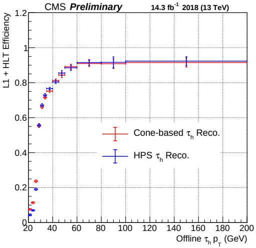


Excellent muon reconstruction at HLT allows one to select/reject low mass resonances, cut on vertex displacement.

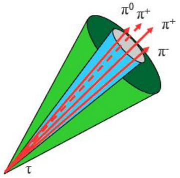
- 2015-17: Cone based reconstruction ($\Delta R \approx 0.1$). Includes all charged/neutral hadrons and photons in the cone.
- 2018: Hadron Plus Strip (HPS) implemented at HLT.
  - Reconstructs the various decay modes of a hadronic τ.
  - Combines charged hadrons and photons compatible with π^0 decays to find the most likely combination. Other objects in the cone are dropped.
  - Same algorithm used offline.
  - Improves $p_T(\tau_h)$ resolution.
  - Allows to relax isolation condition at HLT.
  - Di-tau trigger rate reduced by 20%.



Di-tau trigger: $p_T(\tau) > 35/35$ GeV, $|\eta(\tau)| < 2.1/2.1$

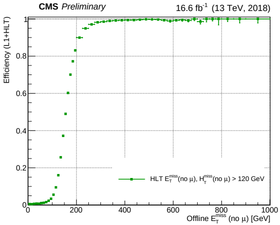


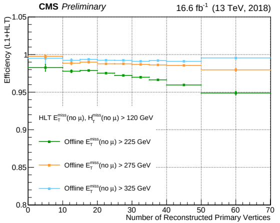
Mu+tau trigger: $p_T(\mu) > 20$ GeV, $p_T(\tau) > 27$ GeV, $|\eta(\tau)| < 2.1$

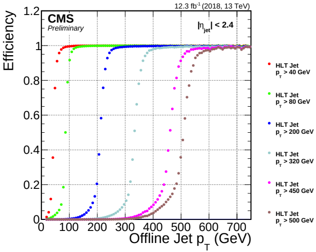


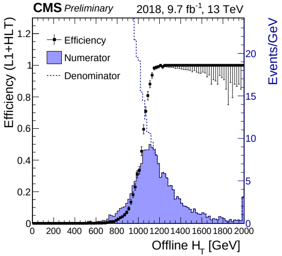
From https://wiki.nbi.ku.dk/hep/Public:Tau_project

- 2017: Closer definitions of jets entering the scalar p_T sum (H_T) between offline and HLT (η range, p_T threshold)
- 2018: Updated zero suppression thresholds in electromagnetic calorimeter to address the increasing level of noise in the forward region.
- Slow turn on for missing transverse energy (MET) triggers mostly due to L1 resolution and PU (HLT tracking less performant than offline at low p_T).





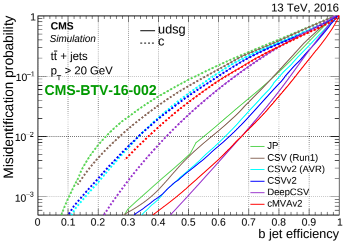


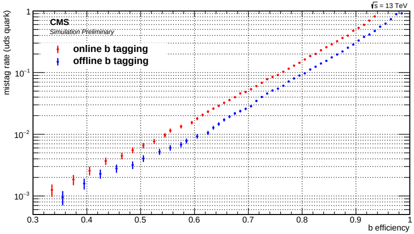


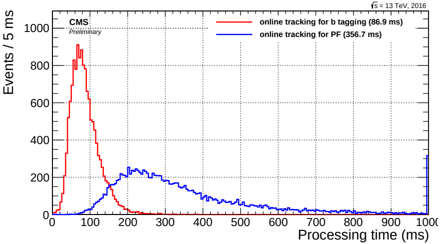
b-tagging at HLT

- HLT shows typically 5% lower efficiency than offline.
- Timing reduced at HLT by using regional tracking (tracking run only around the leading jets).
- 2018: Switch from CSV to DeepCSV discriminator.

Offline performances

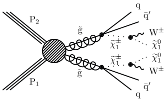


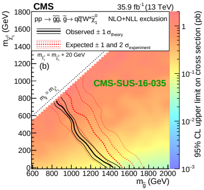


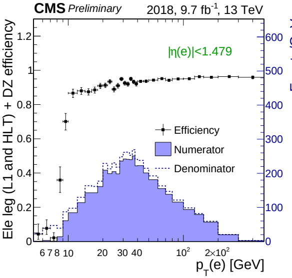


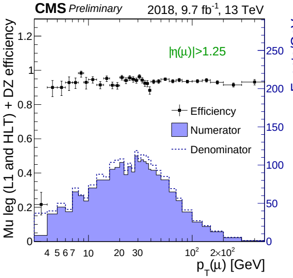
Cross triggers

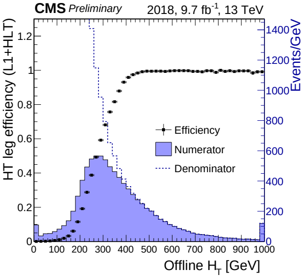
- Many cross triggers involving both leptons and jets/MET.
- Allows us to significantly reduce lepton p_T thresholds (down to 3-4 GeV for muons, 8 GeV for electrons) and drop isolation conditions.
- Usually used to target new physics scenarios with difficult signatures (e.g. compressed SUSY spectra).











Dilepton+HT trigger.

$p_T(e/\mu) > 8/4$ GeV, $PFHT > 350$ GeV.

Conclusions

- Strong constraints on the High Level Trigger of CMS in LHC Run 2.
  - Need to cope with the very broad physics program of the experiment...
  - ... and with the well above expectations performances of the LHC.
- Small changes in the object thresholds between the various years of Run 2.
- A lot of developments happened to make this possible.
  - Updated muon/tau reconstruction.
  - Taking advantage of our pixel upgrade in 2017.
  - General trend: bring HLT as close as possible to offline reconstruction.
- New algorithms (soft leptons+X)/ideas (parked data) developped to target more difficult topologies.
- First look at 2018 data confirm the very good performances of the HLT trigger already observed in the past years.

Next steps?

- Getting ready for Run 3.
- Take full advantage of CMS HCAL endcap upgrade at HLT.
- Upgrade the detector and the trigger to cope with up to 200 PU expected for the High Luminosity LHC !
  $\rightarrow$ *See S. Donato's talk in Detector R&D session.*

References

- Many new trigger results (mostly with 2018 data) for ICHEP:
  `https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIIResults`

Backup

Rate sharing