CMS High Level Trigger performance at 13 TeV

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on behalf of the CMS Collaboration

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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: 4 µs (available buffer)
   → 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.
   → **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
Computing constraints: timing

- ≈ 32000 CPU to process 100 kHz of L1 rate.
- **Time per event** ≈ 320 ms. (In fact up to ≈ 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.

![Diagram of HLT process]

**Figure**: CMS Preliminary 2016, 13 TeV
- average pileup 42.5 ± 0.1
- average inst. luminosity (13.2 ± 0.03)×10^{33} Hz cm^{-2}

- Reconstruction of calorimeter objects (~50 ms)
- Particle Flow at HLT (~1000 ms)
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.
    → “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).
  → “Parking” (e.g.: trigger with low $p_T$ objects)

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**Fill 6757 HLT rate**

![Graph showing HLT rate over time](Image)
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 $W \rightarrow \mu \nu$ at 13 TeV and $1.8 \times 10^{34}$ Hz cm$^{-2}$: $360$ Hz!

Some other important bandwidth 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)

<table>
<thead>
<tr>
<th>Description</th>
<th>Threshold</th>
<th>Rate in a certified run at PU 50 $(L= 1.8\times10^{34}$ Hz cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated single muon</td>
<td>$p_T(\mu) &gt; 24$ GeV</td>
<td>235 Hz</td>
</tr>
<tr>
<td>Isolated single electron</td>
<td>$p_T(e) &gt; 32$ GeV</td>
<td>165 Hz</td>
</tr>
<tr>
<td>Non isolated single muon</td>
<td>$p_T(\mu) &gt; 50$ GeV</td>
<td>46 Hz</td>
</tr>
<tr>
<td>Non isolated single electron</td>
<td>$p_T(e) &gt; 115$ GeV</td>
<td>17 Hz</td>
</tr>
<tr>
<td>Isolated di-photon</td>
<td>$p_T(\gamma) &gt; 30/22$ GeV, $M(\gamma\gamma) &gt; 90$ GeV</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Isolated di-tau</td>
<td>$p_T(\tau) &gt; 35/35$ GeV, $</td>
<td>\eta(\tau)</td>
</tr>
<tr>
<td>Isolated di-electron</td>
<td>$p_T(e) &gt; 23/12$ GeV</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Isolated di-muon</td>
<td>$p_T(\mu) &gt; 17/8$ GeV, $M(\mu\mu) &gt; 3.8$ GeV</td>
<td>28 Hz</td>
</tr>
<tr>
<td>Isolated di-electron</td>
<td>$p_T(e) &gt; 23(12)$ GeV, $p_T(\mu) &gt; 8$ (23) GeV</td>
<td>7.5 (4) Hz</td>
</tr>
<tr>
<td>Single jet</td>
<td>$p_T(j) &gt; 500$ GeV</td>
<td>11 Hz</td>
</tr>
<tr>
<td>Hadronic transverse energy</td>
<td>$H_T &gt; 1050$ GeV</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Missing transverse energy</td>
<td>$\text{PFMET} &gt; 120$ GeV, $\text{PFMHT} &gt; 120$ GeV</td>
<td>33 Hz</td>
</tr>
<tr>
<td>Hadronic $t\bar{t}$</td>
<td>$H_T &gt; 380$ GeV, $\geq 6$ jets ($p_T &gt; 32$ GeV), 2 b-tagged jets</td>
<td>9 Hz</td>
</tr>
<tr>
<td>Boosted heavy jets</td>
<td>$p_T(j) &gt; 400$ GeV, $M(j) &gt; 30$ GeV</td>
<td>27 Hz</td>
</tr>
<tr>
<td>Isolated single photon</td>
<td>$p_T(\gamma) &gt; 110$ GeV, $</td>
<td>\eta(\gamma)</td>
</tr>
<tr>
<td>Non isolated single photon</td>
<td>$p_T(\gamma) &gt; 200$ GeV</td>
<td>13 Hz</td>
</tr>
<tr>
<td>Triple muon</td>
<td>$p_T(\mu) &gt; 5/3$ GeV, $M(\mu\mu) &gt; 3.8$ GeV</td>
<td>9 Hz</td>
</tr>
<tr>
<td>isolated di-muon+electron</td>
<td>$p_T(\mu) &gt; 4$ GeV, $p_T(e) &gt; 9$ GeV</td>
<td>4.5 Hz</td>
</tr>
<tr>
<td>Displaced $J/\psi \rightarrow \mu\mu$</td>
<td>$p_T(\mu) &gt; 4/4$ GeV, $2.9 &lt; M(\mu\mu) &lt; 3.3$ GeV + displaced vertex</td>
<td>33 Hz</td>
</tr>
</tbody>
</table>

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

- 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.
- Adjustment 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 maximize 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.

- 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.
- 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 $\tau$.
- Combines charged hadrons and photons compatible with $\pi^0$ 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, $|\eta(\tau)| < 2.1$
2017: Closer definitions of jets entering the scalar $p_T$ sum ($H_T$) between offline and HLT ($\eta$ 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.
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).

\[ \chi \sim m_g \]

Dilepton+HT trigger.

\[ p_T(e/\mu) > 8/4 \text{ GeV}, \; PFHT > 350 \text{ GeV}. \]
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!
  → 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

CMS Preliminary (13 TeV, 2018, 20 Hz/nb)

- Calibration: 231 Hz, 14%
- Higgs: 230 Hz, 14%
- B Physics: 230 Hz, 14%
- Exotica: 218 Hz, 13%
- Objects: 194 Hz, 12%
- SUSY: 184 Hz, 11%
- SM: 173 Hz, 10%
- Top: 117 Hz, 7%
- B2G: 92 Hz, 6%

CMS Preliminary (13 TeV, 2018, 20 Hz/nb)

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