The CMS Trigger Upgrade for the HL-LHC

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High Luminosity Large Hadron Collider

Full exploitation of the LHC: highest priority of the European Strategy for Particle Physics.

Ultimate parameters

- $\sqrt{s} = 14$ TeV
- Luminosity: $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- Pileup: 200

3000/fb integrated by 2035.
The CMS Phase-II Upgrade

Goal: maintain performance in efficiency, resolution and background rejection for all physics observables.

Key Detector Improvements:

- New Silicon Tracker:
  - 40 MHz stub readout
  - Backend: track finding, $p_T > 2$ GeV $|\eta| < 2.4$ in 4 µs

- New ECAL barrel electronics
  - Full granularity readout
    (eta-phi 0.02 X 0.02) @ 40 MHz.

- (Endcap) High-Granularity Calorimeter
  - Longitudinal layer-by-layer readout
  - Enables Particle Flow

- MIP Timing Detector
  - MIP production time with 30—60 ps resolution

- ... among others!
But How To Take The Data?

<table>
<thead>
<tr>
<th>CMS detector</th>
<th>LHC Run 2</th>
<th>HL-LHC Phase-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (PU)</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>L1 accept rate (maximum)</td>
<td>100 kHz</td>
<td>500 kHz</td>
</tr>
<tr>
<td>Event Size</td>
<td>2.0 MB</td>
<td>5.7 MB</td>
</tr>
<tr>
<td>Event Network throughput</td>
<td>1.6 Tb/s</td>
<td>23 Tb/s</td>
</tr>
<tr>
<td>Event Network buffer (60 s)</td>
<td>12 TB</td>
<td>171 TB</td>
</tr>
<tr>
<td>HLT accept rate</td>
<td>1 kHz</td>
<td>5 kHz</td>
</tr>
<tr>
<td>HLT computing power</td>
<td>0.5 MHS06</td>
<td>4.5 MHS06</td>
</tr>
<tr>
<td>Storage throughput</td>
<td>2.5 GB/s</td>
<td>31 GB/s</td>
</tr>
<tr>
<td>Storage capacity needed (1 day)</td>
<td>0.2 PB</td>
<td>2.7 PB</td>
</tr>
</tbody>
</table>

Trigger and DAQ system
- Balance efficiency, rates, event size and timing
- Level 1 Trigger (hardware) + High-Level Trigger (software)
- Baseline: all data saved in RAW format and promptly reconstructed

7.5 kHz assumptions
- 750 kHz L1T output in 12.5 μs
  - L1 Track-Trigger and Particle Flow
- 1/100 reduction at HLT (!)

HLT farm implications
- 18 X more CPU power
- 27 X more storage

More details on the DAQ system side:
go and see M. Dobson’s talk!
- Baseline DAQ and HLT systems
- Evolution of HS network fabrics
- Performance of general-purpose CPUs
- DAQ and Timing Hub (DTH) board
Level 1-Trigger for CMS Phase-II

From Rick Cavanaugh
Track-Finding @ Level-1 Trigger

Two processing layers
- DAQ, Trigger and Control (DTC)
- Track Finding Processor (TFP)
  - Regional (1/9 of tracker)
  - Time-multiplexed

Different tracking algorithms
- 2D Hough Transform
- 3D Kalman Filter
- Tracklet seed, projection, $X^2$ fit

More details on the L1 track finding: go and see T. James’ talk!
Particle Flow at Level-1

Ingredients

- Track trigger
  - Rate ~ 4 MHz without it
- Better calorimeter granularity
  - HCAL, ECAL, HGCAL
- More powerful FPGAs

Case in point: PUPPI

- All identified particles
- Weight $w \sim$ PU probability
- Global event quantities (MET, $H_T$)
- Better than calorimeter-only or TK-only
Coming soon...

- Expect significant improvements with respect to the L1T interim TDR (pictured in the right)

Enhanced physics acceptance:

- Leptonic paths with extended eta
- Light mesons reconstruction
- Displaced objects
- Machine learning paths
- LLP with timing information

TDR expected early 2020!

<table>
<thead>
<tr>
<th>Trigger algorithm</th>
<th>Rate [kHz]</th>
<th>Offline threshold(s) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Mu (tk)</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>Double Mu (tk)</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Ele$^*$ (iso tk) + Mu (tk)</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Single Ele$^*$ (tk)</td>
<td>16</td>
<td>38</td>
</tr>
<tr>
<td>Single iso Ele$^*$ (tk)</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>Single $\gamma^*$ (tk-isochronal)</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>Ele$^<em>$ (iso tk) + e/$\gamma^</em>$</td>
<td>11</td>
<td>7.3</td>
</tr>
<tr>
<td>Double $\gamma^*$ (tk-isochronal)</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>Single Tau (tk)</td>
<td>13</td>
<td>38</td>
</tr>
<tr>
<td>Tau (tk) + Tau</td>
<td>32</td>
<td>55</td>
</tr>
<tr>
<td>Ele$^*$ (iso tk) + Tau</td>
<td>7.4</td>
<td>23</td>
</tr>
<tr>
<td>Tau (tk) + Mu (tk)</td>
<td>5.4</td>
<td>6</td>
</tr>
<tr>
<td>Single Jet</td>
<td>42</td>
<td>69</td>
</tr>
<tr>
<td>Double Jet (tk)</td>
<td>26</td>
<td>43</td>
</tr>
<tr>
<td>Quad Jet (tk)</td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td>Single ele$^*$ (tk) + Jet</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Single Mu (tk) + Jet</td>
<td>8.8</td>
<td>12</td>
</tr>
<tr>
<td>Single ele$^*$ (tk) + $H_T^{miss}$ (tk)</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Single Mu (tk) + $H_T^{miss}$ (tk)</td>
<td>2.7</td>
<td>8</td>
</tr>
<tr>
<td>$H_T$ (tk)</td>
<td>13</td>
<td>24</td>
</tr>
</tbody>
</table>

Rate for above triggers: 180 [kHz]
Est. rate (full EG eta range): 390 [kHz]
Est. total L1 menu rate (× 1.3): 260 [kHz]
High-Level Trigger – Where We Stand

Timing
- Superlinear with instantaneous luminosity.
- Dependency with pileup? With pileup density?

Rates
- No heavy hitters – 25% single leptons
- Linear for some (µ’s), problematic for others (MET)
High-Level Trigger – Computing

Increased challenge
- Higher PU, more complicated detectors, 7.5 X event rate

CMSSW: fully multithreaded
- Full usage of multicore systems
- Very good for RAM usage
- Bit less good for CPU efficiency

Organic software enhancement
- NOT for free though!
- Same 2011 run same machine: x16 speedup in 6 years
- 5% increase / year until 2026?

CHF/HS06 decreases?
- Not to the tune of 20% / year

More details on the computing model: go and see D. Lange’s talk!
High-Level Trigger – Alternative Approaches

Scouting: shrink size, increase rate
- HLT calo: simpler objects, limited by L1 thresholds and rate
- HLT PFlow: complex objects, limited by HLT timing
- L1 – new proposal!
  See E. Meschi’s talk for more details!

Heterogeneous architecture
- GPUs, ARM + GPUs, ...
- Currently: pixel tracking with GPUs
  - To be deployed at Run 3
- See A. Bocci’s talks for more details!
Conclusions

The High-Luminosity LHC will bring the harshest conditions in a high-energy collider experiment up to date.

- The jump in computing needs will be even bigger than the start of the LHC era.

CMS is undergoing a full upgrade program in order to meet the challenge.

- Complete new subsystems (HGCAL, MTD) and enhancements to existing ones.

Trigger and Data Acquisition remain one of the hardest problems to tackle

- Better hardware (FPGAs, GPUs), algorithms (PUPPI, ML), paradigms (scouting) are key.

Stay tuned for Level 1 Trigger and DAQ/HLT Technical Design Reports!
Thank You!