Design and object performance of the CMS High Granularity Calorimeter Level 1 trigger

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On behalf of the CMS collaboration

See N. Akchurin’s talk for an overview of the CMS HGCAL upgrade

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Challenges of HL-LHC for L1 trigger

- **Significant changes in LHC conditions for Phase 2:**
  - increase in luminosity by up to a factor 4
  - interactions per bunch crossing (pile-up) up to 200

- **Very challenging conditions for L1 trigger:**
  - high occupancy in the detector
  - higher rates
  - higher radiation dose

- CMS physics programme for HL-LHC includes study of rare electroweak processes
  \[\Rightarrow\] **Phase-1 trigger thresholds must be maintained**
Changes in CMS L1 trigger and endcaps for HL-LHC

- Brand new endcap detectors based on high-granularity calorimetry = HGCAL
  - better radiation-hardness
  - better granularity
  - new longitudinal information to be exploited
  - 6M readout channels over 52 layers
  => huge data volume!

- CMS L1 trigger upgrade phase 2:
  - increased bandwidth (750 kHz)
  - increased latency (12.5 μs)

- New track trigger primitives => Particle-Flow algorithm at L1 trigger

- Good position resolution and shower separation of the calorimeter trigger primitives needed for track-cluster matching

- L1 tracks only up to |η|=2.4, standalone cluster needed for 2.4<|η|<3.0

see A. Zabi’s talk
HGCAL trigger: on- and off-detector processing

• Reduction of data-flow to send off-detector at 40 MHz in front-end ASICS

• Kept simple to:
  - minimise power consumption
  - maximise flexibility

• More involved processing to be done in off-detector FPGAs:
  - Stage 1: 2D clustering layer by layer
  - Stage 2 (Time-Multiplexed Trigger architecture): 3D objects built combining 2D objects along longitudinal direction

• Trigger primitives sent to central Level 1 trigger:
  - 3D clusters, including position, energy and topological variables
  - projective energy map to evaluate unclustered energy
**HGCAL front-end for data-flow reduction**

- **Sensor cells**
- **Trigger cells**
- **Trigger cells over threshold**

- **Half of EM layers** used for triggering

- **Trigger cells** (TCs) built by summing energy from 2x2 or 3x3 neighbouring sensor cells (~4.5 cm²)

- **Threshold** applied before sending TCs to back-end

- **Energy sums of all TCs covered by one read-out chip** (~36 cm²) also sent
Clustering in the back-end: implementation

- **2D dynamic clustering performed layer by layer** (Stage 1):
  - inspired by good performance of Phase 1 L1 calorimeter trigger
  - nearest neighbour clustering around seed TCs
  - topological variables computed for background discrimination

- **3D clusters built by combining 2D clusters** (Stage 2):
  - new longitudinal dimension to be exploited
  - several approaches under study (cone-based, likelihood-based…)
  - additional discrimination variables computed
  - weighted energy sum to define 3D cluster energy

- Different energy reconstruction strategies could be considered for different kinds of clusters
Clustering in the back-end: impact of thresholds

- Various thresholds used in the different clustering steps to:
  - limit impact of electronic noise and pile-up
  - keep the number of objects produced within bandwidth constraints

- Effect on response corrected with cluster calibration

- Impact on resolution of hadronic objects could be recovered by combining information from energy sums

**HGCal Simulation**

- Number of 2D-clusters
- Max. allowed in bandwidth

**Number of 3D-clusters out of trigger Layer-2**

- ET>0.5 GeV
- ET>1 GeV
- ET>2 GeV
- ET>3 GeV

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Object performance: e/γ ID

- Calorimeter-only trigger object reconstruction developed to estimate impact of trigger primitive generation steps
  => final trigger performance will also benefit from L1 track information in central L1 trigger

- Electrons and photons = single 3D cluster

- ID variables used to reject background:
  - First layer
  - Layer with max energy
  - Consecutive shower length
  - Transverse width in radial direction

- Combined in a BDT used to define ID working points

- Will be complemented with tracking ID variables in central L1 trigger where possible
Object performance: $e/\gamma$ resolution, efficiency and rate

- Overall good performance for HGCAL trigger for electromagnetic objects:
  - good resolution
  - high plateau efficiency

- Sizeable rate reduction obtained thanks to electron ID criteria

- Rate increase from PU 140 to 200 kept under control by limiting the size of 2D clusters
Object performance: jet pile-up subtraction and calibration

- Jet reconstruction in the endcaps will be essential to study VBF/VBS processes during Phase 2

- Jets built from 3D clusters using anti-kT algorithm with $\Delta R=0.2$: small cone size to limit impact of PU

- Energy corrections:
  - $\eta$-dependent pile-up subtraction (=PUS)
  - $p_T$-dependent calibration used to correct energy scale wrt anti-kT $\Delta R=0.4$ jets

Estimated PU contamination in L1 jets
Object performance: jet efficiency and rate

- Overall good performance of single and double jet triggers: **limited impact of PU**

- **Longitudinal and transverse information** expected to further improve **PU rejection**

- Large improvement of jet trigger performance also expected to come from **Particle-Flow at Level 1 implementation**

- **Topological requirements** can be exploited to significantly reduce the rates
Conclusion

• HL-LHC conditions will represent a major challenge for the CMS trigger system

• New HGCAL detector presents **important challenges** in terms of **trigger data bandwidth and processing**
  => developing effective data reduction strategy with limited impact on physics

• A lot of new opportunities to be exploited for trigger object reconstruction:
  - new longitudinal information to be used for PU mitigation and rate reduction
  - fine granularity to be exploited for correlations with other subdetectors

• **HGCAL trigger object performance very promising:**
  very useful to assess impact of choices regarding the HGCAL trigger primitive generation
Back-up
Back-end TPG hardware

- Trigger primitive generation requires boards with high I/O + significant processing power

- Generic boards developed for whole CMS trigger + DAQ systems:
  - ATCA format
  - 96 I/O links up to 16 or 25 Gb/s
  - Ultrascale+ FPGA(s) for processing

- **Stage 1**: 0.5 to 2 boards per layer

- **Stage 1 to Stage 2 transmission x24 time multiplexed**: all data from one endcap to be processed by one single FPGA

- Firmware implementation and software developments of trigger algorithm closely follow each other

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**CMS Serenity board**

![CMS Serenity board](image)

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**RAW**, **FW**, and **SW** graphs illustrate the data processing stages.
### Table 8.1: Concept for the layer header data sent from Stage 1 to Stage 2.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Bits</th>
<th>Total bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total transverse energy, BX number, number of 2D clusters</td>
<td>16, 8, 8</td>
<td>32</td>
</tr>
<tr>
<td>Energy map 15 ($\eta$) $\times$ 72 ($\phi$)</td>
<td>12</td>
<td>12960</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>12992</strong></td>
</tr>
</tbody>
</table>

### Table 8.2: Concept for data per 2D cluster sent from Stage 1 to Stage 2.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Bits</th>
<th>Total bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$, $y$, transverse $E_T$</td>
<td>12, 12, 8</td>
<td>32</td>
</tr>
<tr>
<td>Number of cells and local maxima, size in $x$ and $y$, quality flags</td>
<td>8, 2, 8, 8, 6</td>
<td>32</td>
</tr>
<tr>
<td><strong>Minimum total</strong></td>
<td></td>
<td><strong>64</strong></td>
</tr>
<tr>
<td>Optional local maximum 0 $\Delta x$, $\Delta y$, normalised $E_T$</td>
<td>8, 8, 8</td>
<td>24</td>
</tr>
<tr>
<td>Optional local maximum 1 $\Delta x$, $\Delta y$, normalised $E_T$</td>
<td>8, 8, 8</td>
<td>24</td>
</tr>
<tr>
<td>Optional local maximum 2 $\Delta x$, $\Delta y$, normalised $E_T$</td>
<td>8, 8, 8</td>
<td>24</td>
</tr>
<tr>
<td>Optional local maximum 3 $\Delta x$, $\Delta y$, normalised $E_T$</td>
<td>8, 8, 8</td>
<td>24</td>
</tr>
<tr>
<td><strong>Maximum total</strong></td>
<td></td>
<td><strong>160</strong></td>
</tr>
</tbody>
</table>

### Table 8.3: Concept for the header data sent to the central L1T correlator per BX.

<table>
<thead>
<tr>
<th>Quantities</th>
<th>Bits</th>
<th>Total bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy, BX number, number of clusters</td>
<td>16, 8, 8</td>
<td>32</td>
</tr>
<tr>
<td>Energy map 15 ($\eta$) $\times$ 72 ($\phi$)</td>
<td>16</td>
<td>17280</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>17312</strong></td>
</tr>
</tbody>
</table>
Impact of cluster size restriction

- Early versions of the 2D clustering did not include size restriction of the clusters
  => large rate of large high-energy clusters at high $\eta$ due to high PU activity
- Improved in later versions

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Object performance: jets

- Response

- Resolution
Object performance: hadronic taus

• Hadronic tau decays important for Higgs physics in LHC Phase 2: VBF production, double Higgs production…

• Good trigger performance already achieved with simple adaptation of jet

• Reconstruction of individual calorimeter clusters combined with tracks to be exploited:
  - in dedicated reconstruction of individual hadronic tau decay modes
  - in definition of PU resilient isolation criteria
Object performance: hadronic taus

- Response

- Resolution
Object performance: hadronic taus

SingleJet

SingleTau