Performance and upgrade of the CMS electromagnetic calorimeter trigger for Run II

Jean-Baptiste Sauvan
On behalf of the CMS Collaboration

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Introduction

- Given the luminosity and pile-up conditions during LHC-Run 1 (2010-2012), the current system has performed extremely well.

- Post LS1: running conditions beyond specifications:
  - $> 10^{34}$ cm$^{-2}$s$^{-1}$ and pile-up (PU) $\approx$ 45 or even higher
  - Maximum level-1 trigger rate of 100 kHz: energy thresholds would need to be increased significantly with the current system
    - This would be detrimental for physics

- Upgrade of the level-1 trigger is required to maintain and improve the current performance in these intense conditions [CMS-TDR-12]

- Two-stage approach to optimise reliability and performance:
  - 2015-2016: Commissioning
    - In parallel to operating Run-1 system
  - 2016 $\rightarrow$ LS3: used for physics
Two stages for data rate reduction of $\approx 10^5$

- **Level 1 trigger**
  - Coarse data from calorimeters and muon systems
  - Custom made hardware

- **High Level Trigger**
  - Partial reconstruction of the event with full sub-detector readout
  - Farm of computers

Clock frequency (40 MHz)

L1 trigger (max. output 100 kHz)

HLT (300-600 Hz in 2012) (up to 1kHz in 2015)
CMS electromagnetic calorimeter

- Homogeneous ECAL calorimeter
  - Made of PbWO$_4$ crystals
  - Barrel ( |$\eta$|<1.48 )
  - Endcaps ( 1.48<|$\eta$|<3 )

- L1 trigger primitive
  - Trigger tower (TT)
    - = matrix of 5x5 crystals

ECAL calorimeter overview

ECAL trigger tower (TT)
Energy = $\sum$ 5x5 crystals
Run-1 level-1 calorimeter trigger path

Data reduction

Trigger Primitives Generator (TPG)

Regional Calorimeter Trigger (RCT)

Global Calorimeter Trigger (GCT)

ECAL, HCAL trigger towers
8 bits $E_T$ + fine grain bit

Electron/photon (e/γ) identification,
4x4 energy Sums

One region = 4x4 TT
Output objects per crate (16 regions):
4 highest isolated e/γ
4 highest non-iso e/γ
$E_T$ sums

Objects per event:
4 isolated e/γ
4 non-iso e/γ
4 forward, central, τ jets

L1 accept

Global Trigger (GT)

L1 muons
**Minimum granularity = trigger tower (TT)**

- ECAL energy = $\sum$ 5x5 crystals

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**L1 e/γ candidate = $\sum$ 2 Trigger Towers**

**Hadronic veto:** $H/E < 5\%$ for EM showers

**“Fine Grain” veto:** 5x2 crystal strip $E_T > 90\%$

**Isolation “quiet corner”:** $\sum$ 5 TT < 3.5 GeV

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**Candidate Energy:**

- Max $E_T$ of 4 Neighbors
- Hit + Max $E_T >$ Threshold

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**Sliding window centered on all ECAL/HCAL trigger tower pairs**

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**Position of an e/γ object:**

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**RCT region**

- $\sum$ 4x4 trigger towers

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**Position of an e/γ object**
Why a new architecture is needed?

- Without any change, substantial increase in trigger thresholds would be required by the end of Run 2
  - Detrimental impact on the physics acceptance (e.g., $H \rightarrow ZZ \rightarrow 4l$)

- And given the lack of pile-up corrections in the algorithms, isolation efficiency decreases with increasing number of interactions

- Refined algorithms which are pile-up aware need a new architecture
  - Full calorimeter view at trigger tower level (higher bandwidth links) and computing power (faster & larger FPGA)

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**Rates [kHz] (CMS-TDR-12)**

<table>
<thead>
<tr>
<th>Examples of trigger thresholds</th>
<th>Typical 2012. $BS^* = 50$ ns. $PU=15. L = 0.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$</th>
<th>$\sqrt{s} = 14$ TeV. $BS^* = 50$ ns. $PU=50. L = 1.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (extrapolated with MC sample)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single iso e/γ (18 GeV)</td>
<td>6.3</td>
<td>40</td>
</tr>
<tr>
<td>Double e/γ (13, 7 GeV)</td>
<td>5.4</td>
<td>47</td>
</tr>
</tbody>
</table>

* BS = Bunch Spacing

Total bandwidth of 100 kHz!
Run-2 level-1 calorimeter architecture

- μTCA crates (replacing VME)
  - High speed serial links, more bandwidth
- Trigger processing cards based on Xilinx Virtex-7 FPGA
  - **Layer 1**: Data formatting, pre-processing
  - **Layer 2**: Object reconstruction and identification
    - Large number of optical inputs and outputs (2 x 72@ 10.3 Gb/s)
    - Full individual events at tower level on single FPGA → **HLT at L1**!

Currently being installed for commissioning in parallel with current system in 2015

Current L1 Trigger System

- oSLB=optical Serial Link Board
  - 4.8 Gb/s
  - Replacing SLB (4 x 1.2 Gb/s)
  - 2 outputs for path duplication
- oRM=optical Receiver Mezzanine
  - Replacing RM

Upgrade L1 Trigger System
Run-2 level-1 calorimeter architecture

- oSLBs have been produced and the testing is now ongoing on TCC boards (Trigger Concentrator Cards) in the experiment service cavern.

- The algorithms are being implemented as firmware. First version are being tested in the Layer 2 cards.

TCC (Trigger Concentrator Card)
Future e/γ algorithm

Dynamic clustering with shape constraints

- Fine grain position using shower shape
- Seed tower
- Neighbor towers
- Better energy containment
  - Showering electrons, converted photons
- Small impact of pile-up

Examples of cluster shapes

- e/γ like
- jet like

Isolation (ECAL+HCAL)

\[ \Sigma E_T (9 \times 5 \text{ TT} - \text{e/γ footprint}) < \text{cut}(PU, \eta) \]

- HCAL footprint
- ECAL footprint
- \( \Sigma E_T \) in isolation region

Use an isolation \( E_T \) cut that is a function of pile-up

- Use the number of trigger towers above a threshold as pile-up estimator
- Tuned for constant 90% efficiency vs \( \eta \) and PU

Discriminate e/γ against jets

Veto clusters with specific (jet-like) patterns
Performance comparison (1/2)

- Comparison between Run-1 trigger and upgrade algorithm
- Tower granularity: much improved position resolution
  - For correlation between objects
- Dynamic clustering → ~30% better energy resolution
  - Recover showered electron energy
  - Sharper efficiency turn-on

Z → ee, Data 2012, Efficiency vs offline $E_T$ for 20 GeV L1 threshold

- Barrel
- Endcaps
New algorithm allows improved e/γ vs jet discrimination without isolation
- Using cluster shapes: rate reduction with negligible efficiency loss (few %)

Isolated e/γ triggers: preliminary studies show a factor of 2 rate reduction relative to current algorithm, with similar signal efficiencies

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“95% threshold”:
- Offline $E_T$ where trigger reaches 95% of the plateau efficiency (see previous slide)
- The L1 threshold corresponding to a given 95% threshold depends on the L1 energy scale and resolution
Conclusion

- New L1 calorimeter trigger architecture and algorithms needed
  - To deal with running conditions in phase 1
- Design using fast optical links and modern FPGAs has been developed
  - High level trigger functionalities at L1!
- Novel algorithms for e/γ make use of the new hardware capabilities
  - The goal is to extract the maximum information from the events
    - Locally, at the trigger tower level. And globally, for pile-up estimation.
  - Position resolution improved by more than a factor of 4
  - Energy resolution improved by 30%
  - Factor 2 rate reduction for isolated objects (with constant 90% efficiency vs PU)
  - Strong activity on these algorithms at the moment
    - Room for further improvements
- The new trigger will be commissioned with the first Run-2 data (2015-2016)
- And will be used for physics by the end of Run-2 until LS3 (~2023)