ECAL Trigger performance in Run 2 and improvements for Run 3

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1. **Introduction**

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   - Detector evolution and trigger calibration
   - Anomalous signals suppression
   - Overall performance

3. **Improvements for Run 3:**
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   - Performance on data and MC
   - Further developments

4. **Conclusions**
CMS detector at LHC and L1 trigger

- The Compact Muon Solenoid is a general purpose detector at Large Hadron Collider (CERN)
  - Tracking detectors, muon chambers, **electromagnetic** and hadronic **calorimeters** with a 3.8 T magnetic field
- The LHC collides trains of **bunches of protons** at **40 MHz** in the center of the detector at 13 TeV of center of mass energy.
- The **CMS L1 trigger** uses fast algorithms in custom electronics to select 100 kHz of **interesting** events out of 40 MHz of LHC collisions with a latency of 3.8 µs
ECAL detector

- The CMS ECAL is an homogenous and hermetic calorimeter made of 75,848 scintillating lead tungstate (PbWO₄) crystals, located inside the CMS solenoid.
- It is divided in ECAL Barrel EB (61,200 crystals) up to $|\eta| < 1.48$, and ECAL Endcaps EE (7,324 crystals each) reaching $|\eta| < 3$, read out by Avalanche Photo Diodes (APDs) in the EB and Vacuum Photo Triodes (VPTs) in EE.
- ECAL purpose is to measure precisely the energies of the electrons and photons, as well as the EM fraction of jets.
ECAL Trigger Primitives Generation (TPG)

- ECAL provides transverse energy sums (trigger primitives or TPs) of groups of crystals (25 in EB, 5-15 in EE) to L1 trigger to form e/γ and jet candidates at each bunch crossing (BX)

- **Amplitude reconstruction** and **BX energy assignment** performed on-detector by ASIC chips by applying a digital filter (configurable weights) on the digitized pulse for each strip (5 crystals line)

- The ECAL pulse extends over several 25ns samples: **readout window 10 BX, TP weights on 5 samples** both before and after the peak

- **A Strip Fine-Grained Veto Bit** (sFGVB) is computed to flag anomalous signals (spikes) registered by the electronics.

<table>
<thead>
<tr>
<th></th>
<th>w1</th>
<th>w2</th>
<th>w3</th>
<th>w4</th>
<th>w5</th>
</tr>
</thead>
<tbody>
<tr>
<td>EE</td>
<td>-0.656250</td>
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<td>0.250000</td>
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<td>0.406250</td>
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<tr>
<td>EB</td>
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<td>-0.546875</td>
<td>0.250000</td>
<td>0.484375</td>
<td>0.375000</td>
</tr>
</tbody>
</table>

Current sets of weights for EB and EE
APD anomalous signals (spikes)

- Large signal in a **single crystal** coming from **direct ionization** by hadrons of APD in the barrel.
- They would **saturate the L1 rate** at high ET if not identified and **removed**
LHC Run 2

- During Run 2 of LHC (2015-2018), ∼ 160 fb⁻¹ of collisions has been collected.

- The instantaneous luminosity has increased steadily during Run 2, as well as the mean number of pileup interactions (PU) up to < PU > ∼ 50 in 2018.

- These have been challenging data taking conditions for ECAL:
  - Larger crystal transparency loss compared to Run 1
  - Increase of noise due to ageing of APD photodetectors
  - More challenging pulse reconstruction with increasing out-of-time PU (OOT-PU)

Twice-weekly crystal response corrections needed to maintain stable trigger efficiency over time
ECAL Trigger calibrations

Regular updates to trigger primitive conditions and calibrations needed to maintain performance during Run 2.

- Spikes are removed at L1 trigger looking for isolated energy hits above a certain threshold
- Frequent pedestal updates needed to reduce as much as possible the fake rate at L1.

<table>
<thead>
<tr>
<th>$E_T$ threshold</th>
<th>Online pedestals</th>
<th>Updated pedestals</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 GeV</td>
<td>13%</td>
<td>11%</td>
</tr>
<tr>
<td>30 GeV</td>
<td>22%</td>
<td>19%</td>
</tr>
<tr>
<td>40 GeV</td>
<td>27%</td>
<td>21%</td>
</tr>
<tr>
<td>50 GeV</td>
<td>38%</td>
<td>32%</td>
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Run 2 performance

- During Run 2, the operational efficiency of ECAL has been better than 99%.
- Thanks to stable ECAL and HCAL calibrations and detector performance, CMS maintained excellent e/γ trigger efficiency at L1 during Run 2.
● Run 3 of the LHC from 2021 to 2023

● An integrated luminosity of $300 \text{ fb}^{-1}$ is expected → Larger loss of transparency at high $\eta$

● $< \text{PU} > \sim 55-60$ is expected → Larger out-of-time PU pulse contamination
ECAL Trigger performance in Run 2 and improvements for Run 3

- **Current ECAL TPG weights** (1 set for EB, 1 set for EE) computed from test beam (2003) data using *undamaged* crystals

- No more optimal especially at high $\eta$ because of radiation-induced changes to pulse shapes:
  - **Large bias in energy estimate**

- The re-optimisation of weights is proceeding by steps:
  - Recompute weights using pulse shapes measured from data during 2018
  - Increase weights granularity: optimised for each strip separately instead of whole EB/EE

TPs bias spread and average improves a lot

\[
\text{Fractional bias} = < \frac{ET_p}{ET_{true}} > - 1
\]

\[
\text{Fractional spread} = \frac{\text{RMS} \left( \frac{ET_p}{ET_{true}} \right)}{< \frac{ET_p}{ET_{true}} >}
\]
Weights optimisation for out-of-time PU

- OOT PU from LHC collisions trains **distort** the ECAL pulse.
- Developed **standalone MC** to simulate **OOT PU effects:**
  - simulate PU pulses → **optimize** weights for distorted pulse → **extract best** weights using many events.
- The optimisation depends on the relative magnitude of signal amplitude and PU level.
- **PU optimised weights can further reduce TP energy bias and spread.**

Several **sets of weights** have been compared:

- **Current:** existing weights (1 set EB, 1 EE)
- **PU0 new avg:** updated average weights (1 set EB, 1 EE)
- **PU0:** updated per-strip weights: using only signal pulse shape
- **PU50 S2:** updated per-strip weights - optimised for PU=50 and $E_T=2$ GeV signals
- **PU50 S30:** updated per-strip weights - optimised for PU=50 and $E_T=30$ GeV signals

![Plot showing comparison of weights](image)
The performance of the new sets of weights is evaluated in terms of bias and resolution of the TPs.

Studied bias and resolution of TPs by BX position along the train and by signal $E_T$ bins.

Used events from 2017 and 2018 CMS Data with different LHC filling schemes:
- The pulse distortion depends on the position of the signal within the LHC bunch train.
- Different LHC schema have different effects on TPs.
- 8b4e scheme, with continuously varying OOT PU, is most challenging for ECAL TPs.

Improving the weights by optimising for PU will improve the average behaviour, but cannot account for pulse-to-pulse and BX-to-BX distortion.
There is a strong bunch position dependence to the amplitude bias intrinsic to the method.

- Using PU optimised weights improves the TP resolution and reduces variations along the LHC train.
There is a strong $E_T$ dependence to the amplitude bias and resolution, especially at low energy TPs.

There are measurable resolution improvements observed when using PU optimised weights.
Further developments

- Not all the FENIX features have been used:
  - 6 weights available: 5 used until now
  - 2 parallel filter + peak finder blocks available: 1 used until now

- Potential improvements are under study
  - Pulse timing estimation:
    - potential to improve spike rejection at L1 with a simple timing cut
    - not yet understood if possible with current electronics
  - The interplay of the 2 sets of filters is being explored to understand what is possible in hardware

- We are testing new features directly on the test bench ECAL DAQ electronics in 904 Lab @CERN

![Graph](image-url)  
**Offline simulation** of best case scenario
Conclusions

- **ECAL Trigger Run 2 performance:**
  - **Challenging** data taking conditions: high luminosity and PU
  - Followed **detector evolution** to maintain stable trigger efficiencies and rates
  - Minimum downtime and **excellent e/γ Level-1 trigger efficiency**

- **Improvements for Run 3:**
  - Plan to **deploy optimised amplitude weights** to account for larger radiation damage and higher PU
  - **Testing new features** to improve **OOT PU discrimination** and **spike rejection:**
    - Tests ongoing on ECAL electronics
    - The potential improvements will be quantified using data and MC before deciding on final implementation
Thanks for your attention
Backup
ECAL Geometry in CMS detector

Fig. 1.2: Schematic view of one quadrant of the calorimetry and tracking system.
ECAL on-detector electronics

Strip waw samples

Linealiser, calibration, compute $E_T$

Strip pulse

Digital filter (weights)

Filtered pulse

Peak finder, assign BX

Strip $E_T$
Amplitude weights derivation

- Amplitude weights can be derived for a given waveform
- This is done by a $\chi^2$ minimization which takes in a waveform and noise correlation matrix. [CMSNOTE2006/037]

Equation for pedestal subtracting weights, assuming no noise correlation between samples

$$W_{A,i} = \frac{f_i - \frac{\sum_j^N f_j}{N}}{\sum_j^N f_j^2 - \frac{(\sum_j^N)^2}{N}}$$

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Current weights
PU optimised weights
Timing weights for spikes discrimination

- FENIX weights can be optimized to **estimate timing** of the pulses
- **Spikes** and EM shower pulses have small **timing difference**
- Apply a timing cut would have a great impact on **spike discrimination**
- **Not yet understood if possible** to implement this strategy in FENIX
Data / MC comparison, bias by BX

Comparison of the performance of new weights on TP bias along the train, in standalone MC and data.
Comparison of the performance of new weights on TP resolution along the train in standalone MC and data.