Improving the Performance of the CMS ECAL Trigger Energy Reconstruction Algorithms for LHC Run 3

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Introduction

• CMS is a general purpose detector at CERN

• The CMS Electromagnetic Calorimeter (ECAL) uses a fast energy reconstruction algorithm to perform energy measurements of $e/\gamma/\text{jets}/\text{missing energy}$

• These are used to identify potentially interesting physics events and trigger on them

• Despite challenging conditions, the best possible trigger performance must be maintained for LHC Run 3 (2021-23) to maximise physics

• This project focuses on improving the ECAL energy reconstruction algorithms
CMS

- Comprises four concentric subsystems that provide information about the LHC collisions
- 14,000 tons, 15m diameter and 28.7m long
- The LHC collides at 40 MHz and produces ~ 1 billion events per second
- CMS trigger selects only interesting physics events based on subsystem data
Level-1 Trigger

- The Level-1 trigger (L1T) takes place on-detector

- Identifies objects used in physics searches

- ECAL sends transverse energy sums to L1T to form $e/\gamma$ candidates – called Trigger Primitives (TPs)

- If these TPs are inaccurate, events will be triggered on **unnecessarily** or **missed** entirely

- Better trigger performance = more physics recorded
ECAL

- Scintillation calorimeter, comprising 75,848 PbWO$_4$ crystals (a)

- Endcaps (EE) are organised into 11 concentric rings of crystals (b)

- High energy resolution for e/γ, vital for 2012 Higgs discovery: $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow γγ$ decay channels

- Important for reconstruction of jets (QCD) and missing energy (SUSY and new particle searches)
Trigger Primitive Generation

- Digitised signals from 5 crystals are summed into a ‘strip’ pulse
- Digital filter applied, with a weighted sum, to estimate the maximum signal amplitude:

\[ \hat{A} = \sum_{i=1}^{n} S_i w_i \]

where \( \hat{A} \) is the signal amplitude estimator, \( S_i \) is the signal value at time sample \( i \) and \( w_i \) is the corresponding weight factor.

- Weights calculated by variance minimisation of \( \hat{A} \) when applied to a known template pulse [1]
- Maximum signal amplitude forms the TP

Example strip pulse with the weights applied
Current Weights

- Two sets of five weights: **one** each for EB and EE
- Weights calculated from 2003 electron test beam on new crystals
- Used **unchanged** in ECAL ever since

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My Project
Project Rationale – Crystal Damage

- ECAL crystals **permanently damaged** by the LHC radiation

  Crystal light response as a function of time [3]

  - Changed pulse shapes will **reduce** the accuracy of the energy reconstruction

  **CMS Preliminary**

  - Pulse shape for 3 different crystals with an electron test beam [2]
Project Rationale – Increased Pileup

- **Pileup (PU)** - number of proton-proton collisions occurring at each LHC bunch crossing

- Signals from different bunch crossings **constructively** interfere in the same crystal

- **Reduces** the energy measurement **accuracy** of physics objects

- **Increases** the trigger rate, resulting in an energy threshold increase and **fewer** recorded events
Project Rationale – LHC Filling Schemes

- The configuration of the LHC bunch train – filling scheme, effects detector performance

- 2017 8b4e
  - Large variation in out-of-time PU
  - Increased trigger rate
  - Strong bunch position dependence

- 2018 48b
  - More stable out-of-time PU contribution

- For LHC Run 3, the filling scheme is under debate
Project Questions

• How well are the current weights reconstructing the energy of 2018 data?

• Could updated weights, suited for present-day detector conditions, improve the energy reconstruction?

• Could more granular weights or weights optimised for PU improve performance further?
Project Method

1. Using 2018 crystal pulse shapes, weights were computed for each crystal and then averaged across the desired granularity.

2. An emulator was used to produce new TPs with the updated weights.

3. Online TP energy compared to the offline energy, which:
   - Is calculated off-detector with time consuming algorithms
   - Uses PU templates to subtract any PU contribution

4. Performance of the different weight configurations studied:
   - Online/offline energy differences
   - Bias in the absence of PU
   - Bias dependence on eta ring, bunch position and energy in the presence of PU
   - $\text{Bias} = \frac{\text{Online energy}}{\text{Offline energy}} - 1$
Results and Conclusions
• Current weights **greatly** overestimating TP energies in rings 27 and 28
• **Large** spread with current weights, especially in ring 28
• Average EE bias and spread **reduced** with updated ‘New Avg’ weights
• Limited by being an average for the whole EE - could more granular weights improve performance?
Increased Weight Granularity – No PU

- Weights used to reconstruct the maximum amplitude of known signal pulses.
- Increased weight granularity **significantly reduces** the average bias and spread.

### Simulation

**EE+**

- **Per XTAL**
  - Entries: 7160
  - Mean: -0.0002479
  - Std Dev: 0.004952

- **Per strip**
  - Entries: 7160
  - Mean: -0.0005023
  - Std Dev: 0.007318

- **Per ring**
  - Entries: 7160
  - Mean: 0.002887
  - Std Dev: 0.01201

- **New Avg**
  - Entries: 7160
  - Mean: 0.009999
  - Std Dev: 0.01369

- **Current**
  - Entries: 7160
  - Mean: 0.02096
  - Std Dev: 0.01382
**Increased Weight Granularity – PU 30**

- **Big** improvement with updated weights, especially in rings 27 and 28
- Small improvement when increasing weight granularity
- PU has a large contribution and **limits** the improvements of increased granularity
- Could weights optimised for PU perform better?
PU Optimised Weights

• Using a PU Monte Carlo Simulation [7], weights optimised for different levels of PU and signal were computed.

![Graph of Weight change as a function of PU]
Endcap Ring Dependence
• **Large** biases/spreads with current weights in rings 27 and 28
• Increased granularity **reduces** spread
• Average bias/spread most **reduced** by PU optimised weights - 29%
Again, large biases/spreads with current weights in rings 27 and 28

Spread most reduced by PU optimised weights
Interim Conclusions

- Across both filling schemes and PU levels, bias of current weights heavily dependent on eta ring

- Updating to any updated weights configuration reduces this dependence

- The biases in 48b are significantly smaller than in 8b4e - current weights bias in eta ring 28 for 48b is 57% that of 8b4e.

- For every weight configuration, the average spread increases at higher PU

- PU optimised weights reduce the spread more at higher PU than lower PU

- PU optimised weights perform the best at reducing the average spread - resolution improvement for physics objects
Bunch Position Dependence
• **Large** bunch position dependence - **Largest** bias with current weights in position 2 – 80%
• Updating to any new weights configuration **reduces** bias and position dependence
• `New Avg’ give **lowest** average bias. **Lowest** spread and flattest response with PU optimised weights
Bunch Position Dependence – 48b PU 50

- **Large** biases at the start of the train, region of stability in the center
- Increased granularity **improves** performance
- **Flattest** response, **lowest** average bias and spread with PU optimised weights
Interim Conclusions

- Across both filling schemes and PU levels, bias of current weights *heavily dependent* on bunch train position.

- Updating to any updated weights configuration *reduces* this dependence.

- Larger biases with 8b4e than with 48b.

- PU optimised weights are more effective at higher PU.

- PU optimised weights provide the *flattest* response and *lowest* average spread across both filling schemes and PU levels.
Energy Dependence
Energy Dependence – PU 50

For both filling schemes:
- Large positive bias at low energy with the current weights
- Which is reduced by updating to any of the updated weights configurations
- Average EE behaviour is dominated by rings 26 – 28
- Updated weights perform the best
Summary and Final Conclusions
Summary and Final Conclusions

- Different weight configurations have been computed and their energy reconstruction performance compared.

- The current weights are no longer optimal for present-day conditions:
  - **Large** biases/spreads in eta rings 27 and 28, especially at low energy
  - This **reduces** the reconstruction accuracy of jets and missing energy
  - **Strong** dependence on bunch position for both 8b4e and 48b

- Updated weights and increased granularity:
  - **Reduce** eta ring, bunch position and energy scale dependence
  - Will result in **improved** trigger performance, with **more** physics being recorded and with **reduced bias**

- PU optimised weights matching the PU/S level:
  - Provide the **best** performance in the majority of cases
  - Will be **important** as the PU level increases – **fully** utilise the increased number of collisions

- **These new weights will be used in Run 3 and will result in improved trigger performance for physics**
Future Work

• L1 Trigger team - re-emulate L1 physics objects with updated weights
  • Check trigger rates/efficiencies

• Use the PU MC simulation to investigate advantages of a possible 6\textsuperscript{th} additional weight and a second set of weights for each strip

• Using a test bed with ECAL front-end and off-detector boards:
  • Check functionality of a 6\textsuperscript{th} weight and a 2\textsuperscript{nd} set of weights in hardware
  • Check electronics configuration time of per strip weights
Thank you for listening

Thanks and acknowledgements to:

- Stefano Moretti, the course leader
- My supervisor, David Petyt
- Abe Tishelman-Charny, for his updated weights computations
- Davide Valsecchi, for his PU Monte Carlo simulation and PU optimised weights
References


• [5] Figure from CMS Web Based Monitoring rate plots


CMS Trigger System

LHC proton bunches collide in CMS → Level-1 Trigger (40 MHz) → High Level Trigger (100 kHz) → Stored to Disk (1 kHz)
L1T Allocation

L1 Trigger bandwidth allocation for different physics analysis groups. ‘Base’ refers to general purpose triggers such as single electron, single muon, single tau or single jet, that are not specific to any one analysis. Data from 2017 Fill 6358.

<table>
<thead>
<tr>
<th>category</th>
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</tr>
<tr>
<td>higgs</td>
<td>8.6</td>
</tr>
<tr>
<td>exo</td>
<td>0.02 (w/o NotBptxOR seeds)</td>
</tr>
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<td>top</td>
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<tr>
<td>btv</td>
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Higgs Production/Decays

(a) $H \rightarrow W^+ W^-$

(b) $H \rightarrow Z^* Z^*$

(c) $H \rightarrow \gamma \gamma$

Same-sign $W^-$ pairs fusing into a doubly charged Higgs boson that decays into same-sign electrons.
Both simulations and TB data predict a variation of the pulse shape as a function of the radiation damage of crystals.
(from 14.5 ns for low $\mu_{\text{ind}}$ to 6.5 ns for $\mu_{\text{ind}} \approx 10 \text{ m}^{-1}$)

Figure: TB results presented by A. Singovski during CMS Upgrade Workshop in May 22, 2012 and simulations with Geant4+Slitrani by A. Ledovskoy during Forward Calorimetry Task Force Meeting in June 7, 2012.
Crystal Damage 1

- Two main mechanisms contribute to this darkening and crystal transparency loss:

1. The formation of colour centres, caused by the ionising radiation displacing anions within the crystal lattice, which then get filled with unpaired electrons and absorb light.

2. The direct collision of high energy hadrons with the nuclei in the crystal lattice. The nuclei split into charged fragments and propagate through the crystal, ionising other nuclei within the crystal and creating permanent colour centres.
Crystal Damage 2

- $e/\gamma$ create EM showers in the crystals
- Light from EM shower is produced along the crystal
- Colour centres/defects are present
- Light from far end is less likely to reach the photodetector
- Only light from nearest region will not be absorbed
- The apparent arrival time of the pulse is therefore earlier
Jets in ECAL

- Jets are composed of 25% photons 15% neutral hadrons 60% charged hadrons
- Jets deposit 50% of their energy in ECAL in the endcaps 25% directly from photons ($\pi^>-\gamma\gamma$)
- 25% from hadrons (50% of hadrons EH hadrons, depositing 2/3 of energy to ECAL)
- QCD (jet) interactions are more probable at low transverse energy, therefore inner EE
- No tracker above eta >2.5, therefore rings 27 and 28 are important for jet reconstruction
Increased Weight Granularity

- Finest granularity possible on-detector is **per strip**
- 2018 pulse shapes were used to compute weights per strip and per ring
- These weights were then encoded for use on-detector
- Involves rounding to nearest 1/64 multiple and places a **limit** on the number of different weights possible
- For example, 1468 unique decimal weights per strip in EE+ becomes 74 unique encoded weights (right)
- These studies focus on EE, as the radiation damage and therefore number of encoded weights is greatest
Changing OOT PU Problem

• \( \hat{A} = \sum S \cdot w \) with \( S = S_t + p \) where \( p \) is a fixed pedestal
• \( \hat{A} = \sum (S_t + p) \cdot w = \sum S_t \cdot w + \sum p \cdot w = \sum S_t \cdot w + p \sum w \)
• But, \( \sum w = 0 \) by design
• Therefore, \( \hat{A} = \sum S_t \cdot w + 0 \)

• A constant pedestal, from noise or non-changing OOT PU has no impact on the amplitude reconstruction
• However, a changing OOT PU contribution (i.e. \( p(t) \)) will have an impact
# Bias vs Eta Ring Data

Data for bias against eta ring. Numbers in bold show the best performing weights for that metric.

<table>
<thead>
<tr>
<th>Data</th>
<th>Weights</th>
<th>Average Bias</th>
<th>Flatness</th>
<th>Average Spread</th>
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<td>Current</td>
<td>0.1884</td>
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<td>PU 30 S2</td>
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### Bias vs Bunch Position Data

Data for bias against BX position. Numbers in bold show the best performing weights for that metric.

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Bias vs Energy Data

Data for bias against energy. Numbers in bold show the best performing weights for that metric.

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Spread vs Energy – 8b4e rings 26-28

Data from Nov 2017
Eta Rings 26-28 (|eta| > 2.322)
Spread vs Energy – 48b rings 26-28

Data from July 2018
Eta Rings 26-28 (|eta| > 2.322)
Per Strip Weights in EB

- 17 sets of unique encoded weights in EB from 12240 decimal per strip weights