Abstract

This note presents the performance of the ECAL trigger primitive algorithms in LHC Run 2, focusing on the reconstruction of signal amplitudes in the ECAL barrel and endcaps, and the rejection of anomalous signals in the ECAL barrel photodetectors. Results are also presented on potential improvements in these algorithms that are being considered for LHC Run 3.
ECAL trigger plots for approval for upcoming conferences

The ECAL group

July 2019
1) L1 spike killer plots
Spike contamination in ECAL TPs: 2018

![Graph showing spike fraction vs. TP E_T threshold (GeV)](image-url)
Caption

- This plot shows the fraction of ECAL trigger primitives (TPs) in the ECAL Barrel, above a given $E_T$ threshold, that are due to spikes.
  - From ZeroBias data (Run 319347) recorded in July 2018 with a peak pileup of 50.
- The two curves show the residual spike fraction estimated for two sets of pedestal values:
  - pedestals used online: from Run 305848, recorded in October 2017.
  - updated pedestals: from Run 319111, recorded in July 2018.
- The table below shows the fraction of TPs due to mis-identified spikes, for several representative $E_T$ thresholds.
  - it improves when the pedestals are more up-to-date. The pedestals are observed to drift with time, and they are explicitly used in the L1 spike killer.

<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>
</tr>
</tbody>
</table>

2018 performance = 2017 performance if pedestals are updated.
Spike killer plots - L1EG turn-on curve
The upper panel shows the efficiency of the Level-1 electron/photon (EG) trigger plotted as a function of the offline electron supercluster transverse energy.

- Using data recorded in July 2018, with an integrated luminosity of around 530 pb⁻¹
- The efficiency is measured from Z→ee events using a tag-and-probe method. Only candidates in the Barrel region of CMS (|η|<1.48) are used
  - Events are selected using a single electron High Level Trigger
  - The offline electron, satisfying the medium electron ID, with a transverse energy greater than 30 GeV, which is geometrically matched to the HLT electron triggering the event, is called the tag
  - The other electrons in the event are unbiased by the trigger selection, and are called probe(s). They satisfy the loose electron ID and are used to evaluate the L1 e/γ efficiency.
  - The invariant mass of the dielectron system must satisfy 60<mₑₑ<120 GeV
  - The efficiency is plotted for L1 EG candidates with Eₜ>40 GeV
- The efficiency is computed for data EG trigger candidates (recorded with Oct 2017 pedestals) and from those re-emulated from data with July 2018 pedestals.
  - a sigmoid function is fitted to the points, and is represented by the solid grey (2017 pedestals) and dashed black (2018 pedestals) lines
The lower panel shows the difference in efficiency between the two sets of points, and between the two separate fits:

- There is no significant change in the EG trigger efficiency with the new pedestals.
- This shows that the improvement in spike killing efficiency seen when updating pedestals has no significant effect on the efficiency for triggering on electrons and photons.
Spike killer failure modes

(supplementary plots)
- These plots show examples of ECAL trigger towers containing spikes that are identified as such offline, but are not flagged by the online sFGVB algorithm.

An ECAL trigger tower is composed of a 5x5 matrix of crystals, organised into 5 strips (corresponding to one very-front-end card), each containing 5 channels.

- The z-axis scale represents the amplitudes of the signals (in ADC counts) for each channel.

  - 1 ADC count corresponds to roughly 40 MeV transverse energy at $|\eta|=0$.

  - The spike is always the most energetic channel in the tower (corresponding to the largest ADC value).

  - The sFGVB single channel transverse energy threshold (used to check isolation) is approximately 450 MeV at $|\eta|=0$.

- The spikes are flagged offline via RecHit severity level (3 or 4), which correspond to cuts on the rechit timing and Swiss-cross variables.
The four different plots illustrate various failure modes of the sFGVB algorithm:

- **top-left**: two channels in a different strip (strip 4) are above threshold and cause the sFGVB algo to fail.
- **top-right**: one channel adjacent to the spike in strip 1 is above the sFGVB threshold.
- **bottom-left**: one channel adjacent to the spike in strip 3 is significantly above the sFGVB threshold.
- **bottom-right**: one channel near to the spike in strip 4 is slightly above the sFGVB threshold.
2) Amplitude weight plots
ECAL trigger primitive amplitude reconstruction uses a digital filtering algorithm implemented in on-detector electronics

- 5 non-zero FIR weights applied to the 25ns samples around the peak of the pulse
  - weights optimised to give best amplitude reconstruction performance, derived from pulse shapes measured at ECAL test beams
  - one set of weights for EB and another for EE

<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>
<td>-0.515625</td>
<td>0.250000</td>
<td>0.515625</td>
<td>0.406250</td>
</tr>
<tr>
<td>EB</td>
<td>-0.562500</td>
<td>-0.546875</td>
<td>0.250000</td>
<td>0.484375</td>
<td>0.375000</td>
</tr>
</tbody>
</table>

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

\[ \sum_{i=1}^{n} w_i f_i = 1 \quad \text{and} \quad \sum_{i=1}^{n} w_i = 0 \]

unbiased, pedestal subtracting weights
Preamble

• Increasing evidence that current weights are not optimal
  - due to radiation-induced changes in pulse shapes, most significant in forward regions of EE
  - this creates an amplitude bias, that increases with eta and time
• Can in principle be corrected by measuring pulse shapes from data, and re-deriving weights
  - pulse shapes were measured for each crystal during special data-taking runs in June 2018 and September 2018
• Further improvements possible by increasing granularity of weights
  - currently only one set for EB (61200 crystals) and one set for EE (14648 crystals)
  - can theoretically apply a different set of weights for each VFE (group of 5 crystals)
• May further improve by defining pileup optimised weights
  - account for “average” distortions in pulse shape due to the presence of overlapping pulses from other bunch crossings
Current weights amplitude bias
The plot shows the amplitude reconstruction bias induced by radiation-induced changes in ECAL pulse shapes.

- CMS data from September 2018 (corresponding to a total delivered luminosity of \(\sim 160 \text{fb}^{-1}\)) are used to derive individual pulse shapes for each crystal in ECAL.
- These shapes are parametrised (using the alpha,beta formulation) and are used to produce simulated pulses, with a known amplitude, \(A_{\text{true}}\).
- The existing amplitude weights are then applied to these pulses, providing a reconstructed amplitude estimate, \(A_{\text{reco}}\).
- The fractional amplitude bias is defined as: \((A_{\text{reco}}/A_{\text{true}}) - 1\).

- The bias is plotted versus eta.
  - The mean value for each eta region is plotted, as well as error bands corresponding to 68, 90, 99.5% of the crystals within each eta region.
  - The endcap region (|\(\eta|>1.48\)) shows larger biases and spreads due to the larger radiation damage, and hence larger changes in the crystal pulse shapes.
  - The bias reaches \(\sim 4\%\) in the forward regions of EE, with a large spread.
Impact of improved weight granularity - PU=0

ECAL Endcaps

$\eta > 1.48$
• The plot shows the amplitude reconstruction bias induced by radiation-induced changes in ECAL pulse shapes

  • CMS data from June 2018 (corresponding to a total delivered luminosity of ~140 fb\(^{-1}\)) are used to derive individual pulse shapes for each crystal in ECAL

  • The same method is used to simulate and calculate the fractional amplitude bias as in the previous plot

• The bias is plotted for different sets of amplitude weights, for the positive endcap (\(\eta>1.48\))

  • Current: existing weights (one set for the whole EE) - do not account for crystal damage

  • per EE/EB: updated average weights (one set for the whole EE) - accounting for crystal damage

  • per ring: updated eta-dependent weights (for 22 eta-rings in EE) - accounting for crystal damage

  • per strip: updated weights for each strip (5 crystal regions) - accounting for crystal damage

  • per xtal: updated weights for each crystal - accounting for crystal damage

• Finer weight granularity improves amplitude bias and spread

  • residual bias can be calibrated out, but spread is an intrinsic property of the TP algorithm

  • per-strip granularity is the best achievable on-detector
Improved weight granularity - unique weight sets (supplementary plot)

ECAL Endcaps

\[ \eta > 1.48 \]

Crystal iy index

Crystal ix index
• Number of unique weight sets (per-strip) that can currently be implemented in EE
  • although it is theoretically possible to apply an unique set of weights for each 1x5 strip of channels in EB and EE, there is a limitation imposed by the front-end electronics
    • the weights are encoded using 6 bits of precision, which means that only decimal values in quanta of 1/64 can be applied
    • any weights that differ by less than this value will be encoded to the same decimal value online
      • this limitation is why the amplitude bias plot on slide 24 does not become a delta function if per-crystal optimised weights are used
  • the plot shows that, with this limitation, 74 unique sets of weights can currently be encoded in the positive endcap ($\eta>1.48$)
    • the variations are larger in the forward regions of EE, close to the LHC beam pipe
Impact of improved weights, PU=30 data

ECAL Endcaps

\[ \eta > 2.65 \]
\[ <\text{PU}>=30 \]
• Amplitude bias of ECAL trigger primitives before and after updated weights are applied
  • Using ZeroBias data recorded in July 2018
  • Only one lumisection (23.3 sec) is used, corresponding to a mean pileup of 30
  • Trigger primitives from the most forward eta ring ($\eta > 2.65$) are used, and are calculated using both the current weights, and updated weights averaged over the entire EE
  • The amplitude bias is computed relative to the transverse energies computed offline, using the “Multifit” algorithm, which efficiently removes contributions from out-of-time pileup
    • Bias = online-offline
  • Updating the weights significantly improves the bias and spread in the trigger primitive amplitude reconstruction
Effect of PU on optimal amplitude weights

CMS Simulation Preliminary

ET=10 GeV per strip
2.7<|\eta|<3

PU=0
PU=10
PU=20
PU=30
PU=40
PU=50
PU=60
PU=80
PU=100
PU=150
PU=200

Weight position
This plot shows how the optimum weights are modified by pileup

- a signal with transverse energy of 10 GeV is generated, with $|\eta|>2.7$
- signals from pileup originating from neighbouring bunch crossings (separated by 25 ns) are also simulated, and overlayed on top of the signal pulse
  - different pileup values are simulated, sampling from a Poisson distribution, with mean values ranging from 0 to 200 PU
  - the pileup energy is sampled from a pdf obtained from simulation
  - optimum weights are derived for this specific pulse shape, which includes both in-time and out-of-time pulses
  - this procedure is repeated for many events and the mean of each of the five amplitude weights is computed

The difference in the weights relative to the PU=0 case are plotted

- in units of encoding precision, corresponding to $1/64=0.015625$

The plot shows that the optimal weights are significantly modified by pileup

- with increasing PU, the first two weights become more negative
- the remaining weights become more positive, to compensate for this
Effect of PU on optimal amplitude weights (supplementary plots)
This plot shows how the distributions of the 5 optimum weights vary for different values of pileup.

- A signal with transverse energy of 10 GeV is generated, with $|\eta|>2.3$.
- The events are generated in the same way as described in the previous plot, with out-of-time signals overlayed on the in-time pulse.

The plot shows that the optimal weights are significantly modified by pileup, compared to the PU=0 case (vertical lines).

- There is a systematic shift in the preferred values, as PU increases.
- There is a significant broadening of the distributions with larger PU.
Amplitude bias with improved weight granularity - PU=50 MC
The plot shows the potential improvements in amplitude reconstruction made possible by the use of pileup-optimised weights.

- The same method is used to simulate and calculate the fractional amplitude bias as in the previous plots.
- This plot is the corollary of the plot shown on slide 23, but with PU included.
- The 2018 LHC colliding bunch structure is simulated, with 48 colliding bunch trains separated by 7 empty bunches - both in-time and out-of-time PU are included.
- A simulation of the peak finder is applied - the amplitude is computed for signals in a -1 to +1 BX window around the signal, and only events where the maximum amplitude is in the signal BX are used.
  - This has a large effect on the current weights, where many events have peak amplitudes in neighbouring BX.

The bias is plotted for different sets of amplitude weights, for the forward region of the endcap ($|\eta|>2.3$), and for $2.5<E_T<3.5$, and $25<E_T<35$ GeV signals respectively:

- **Current: existing weights** (one set for the whole EE) - do not account for crystal damage.
- **New (avg): updated average weights** (one set for the whole EE) - accounting for crystal damage.
- **Per-stripe: updated weights** for each strip (5 crystal regions) - accounting for crystal damage.
- **PU50 ET2: updated per-strip weights** - optimised for PU=50 and $E_T=2$ GeV signals.
- **PU50 ET30: updated per-strip weights** - optimised for PU=50 and $E_T=30$ GeV signals.
• **PU optimised weights give the best performance (improved resolution and bias)**
  
  • **The energy used for the optimisation matters** - the best performance is generally achieved for weights which are optimised for the same energy range as the signal
  
  • 2.5 to 3.5 GeV: lowest bias achieved with weights optimised for PU 50 and $E_T=2$ GeV signals. Spread is not significantly improved
  
  • 25 to 35 GeV: lowest bias and best resolution achieved with weights optimised for PU 50 and $E_T=30$ GeV signals. All updated weights provide better resolution than the “current” weights but PU50, $E_T=30$ is the best.
  
  • PU50, $E_T=2$ weights generate a significant bias when applied to high $E_T$ signals. This is because they are optimised for an energy regime where the OOT PU significantly distorts the pulse, which is a much smaller effect at high $E_T$
  
  • **Performance at low $E_T$ is impacted by large out-of-time PU.** Updating the weights can improve performance (bias and width) somewhat, but the pulse to pulse fluctuations, which cause a large spread in the bias at low $E_T$, cannot be completely removed via these weights configurations
  
  • this motivates exploring ways to further improve the TP algorithm (adding a 6th weight and/or applying a second set of weights)
3) Timing weight plots
Potential to use second set of timing-sensitive weights? For information


Appendix: Weights derivation

In order to derive optimal weights, a least squares method is used. The $\chi^2$, defined in Sect. 2, can be written in matrix notation as

$$\chi^2 = (S - G(A, \delta t, P))^\top C^{-1} (S - G(A, \delta t, P)),$$  

(A.1)

where $S$ is a vector of the time samples $S_i$ with $N$ elements, $C$ is the noise covariance matrix, and $G(A, \delta t, P)$ is a vector describing the mean of the measurements, modeled by

$$G(t_i; A, \delta t, P) = Af(t_i + \delta t) + P.$$  

(A.2)

Here $A$ is the amplitude of the signal, $f(t)$ is the function which corresponds to the time development of the signal pulse, $\delta t$ is a possible timing jitter, and $P$ is the pedestal.

Amplitude weights derived by minimising $\chi^2$ vs A

Timing (jitter) sensitive weights can also be separately derived

FENIX chip allows for the possibility of two independent sets of weights - currently studying how these could be used to improve spike rejection and out-of-time PU rejection.
Weights optimisation for $A$, $dt$

**Amplitude-sensitive weights**
amplitude measurement bias vs jitter

**Timing-sensitive weights**
time measurement bias vs jitter

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$-3.0 < \eta < -2.65$

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$-3.0 < \eta < -2.65$
These plots show the performance of amplitude and timing optimised weights on simulated pulse shapes in the ECAL barrel. CMS data from September 2018 are used to derive individual pulse shapes for each crystal. These shapes are parametrised (using the alpha, beta formulation) and are used to produce simulated pulses, with a known amplitude, $A_{true}$ and timing jitter $t_{true}$. Optimised amplitude and timing weights are then applied to these pulses, providing a reconstructed amplitude estimate, $A_{reco}$, and a reconstructed timing jitter $t_{reco}$. The pulse shapes are simulated without pileup.

The fractional amplitude bias is defined as: 

$$\frac{A_{reco}}{A_{true}} - 1$$

The timing bias is defined as: $t_{reco} - t_{true}$

The bias is plotted versus timing jitter of the signal pulse. The mean value for each eta region is plotted, as well as error bands corresponding to 68, 90, 99.5% of the crystals. The innermost ring of the negative endcap is used ($-3.0 < \eta < -2.65$).

The amplitude and timing jitter biases are small, for small values of timing jitter. This validates the functionality of the timing-optimised weights.
Spike and scintillation pulse shapes
Sample spike and scintillation pulse shapes used to verify the performance of the timing optimised weights

- Parametrised pulse shapes are obtained for EM signals and spikes in EB, using CMS data.
- These waveforms are then generated with a specific energy, timing jitter, and digitization phase.
  - The EM signal is defined to peak at an average of 124.3 ns.
  - The spike signal is generated in-time with the rise of the EM signal for the left-hand plot (prompt spike) and with a delay of +10 ns in the right-hand plot (delayed spike).
- The energy and timing pdfs for EM signals and spikes are derived from CMS data and GEANT4 simulation.
- The pulses are digitized every 25 ns (red, green dots).
- There are intrinsic differences in the shape of these pulses.
  - The spike signal rises faster to the peak, since it does not include any scintillation light, which has a characteristic emission time constant of around 9 ns.
Spike and scintillation jitter - simulation

linear scale

log scale
• Output of the timing optimised weights on simulated spike and scintillation pulses
  • parametrised pulse shapes are obtained for EM signals and spikes in EB, using CMS data
  • pdfs of spike and scintillation energy and timing distributions (derived from data and GEANT4 simulation) are used to generate the pulses
  • The EM signal timing jitter distribution is centred around zero
  • The spike signal timing jitter distribution is offset from zero, with a long tail
    • this is because of the intrinsic differences in pulse shapes and the long tail in the spike arrival time (see 2012 approved plot)
  • Theoretically, a cut on the reconstructed timing of ±2.5ns (dashed vertical lines) would reject 55% of the spikes
    • with a negligible impact on EM signal efficiency
Spike and scintillation jitter vs amplitude - data

Offline EM shower

Offline spike

Reconstructed amplitude (ADC)

Reconstructed time (ns)

CMS Preliminary

0.24 fb$^{-1}$ (13 TeV)

EM-like signals
-5<t<-20ns: 98.4 %

Spike-like signals
-5<t<-20ns: 61.1 %
Caption

• Output of the timing and amplitude optimised weights on November 2017 CMS data using spike and scintillation pulses, from ECAL Trigger Primitives with $E_T>16$ GeV

• spikes and EM signals are identified offline, using topology (Swiss-cross) and signal timing cuts

• There is a significant difference in the behaviour of these two samples
  • the spike signals have a larger slope in the 2D distribution of reconstructed amplitude and jitter

• Theoretically, a cut on the reconstructed timing of $-5 < t < +20$ ns (vertical dashed lines) would reject 60% of the spikes
  • with a small impact on EM signal efficiency
Potential impact of a timing cut on spikes that fail sFGVB algorithm
• Possible impact of a cut on the reconstructed timing jitter of spikes that are not flagged by the sFGVB algorithm online
  • spikes are identified offline, using topology (Swiss-cross) and timing cuts
  • A theoretical cut on the reconstructed timing of \(-5 < t < +20\) ns is applied
    • the TP \(E_T\) distributions are shown for all TPs above 16 GeV, and for those TPs that are matched to offline spikes, before and after the timing cut
  • NB: this should not be considered a prediction of the performance of L1 timing weights
    • that can only be determined once a specific implementation of timing-sensitive and amplitude-sensitive weights is implemented and tested.
    • It is yet to be shown that this is possible to implement in the FENIX
  • However, should it be possible, this plot gives an estimate of the potential gains
Potential impact of a timing cut on spikes that fail sFGVB algorithm
• This plot shows the fraction of ECAL trigger primitives (TPs) in the ECAL Barrel, above a given $E_T$ threshold, that are due to spikes
  - From ZeroBias data recorded in November 2017 with a peak pileup of 55

• The two curves show the residual spike fraction estimated using:
  - the online sFGVB algorithm with no timing cut
  - the sFGVB algorithm plus a putative timing cut on the spike pulse of $-5 < t < +20$ ns

• NB: this should not be considered a prediction of the performance of L1 timing weights:
  - that can only be determined once a specific implementation of timing-sensitive and amplitude-sensitive weights is implemented and tested.
  - It is yet to be shown that this is possible to implement in the FENIX
  - However, should it be possible, this plot gives an estimate of the potential gains