Performance of the CMS electromagnetic calorimeter during the LHC Run II

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Abstract. Many physics analyses using the Compact Muon Solenoid (CMS) detector at the LHC require accurate, high resolution electron and photon energy measurements. In particular, excellent energy resolution is crucial for studies of Higgs boson decays with electromagnetic particles in the final state, as well as searches for very high mass resonances decaying to energetic photons or electrons. Following the excellent performance achieved in Run I at center-of-mass energies of 7 and 8 TeV, the CMS electromagnetic calorimeter (ECAL) is operating at the LHC with proton-proton collisions at 13 TeV center-of-mass energy. The instantaneous luminosity delivered by the LHC during Run II has achieved unprecedented values, using 25 ns bunch spacing. High pileup levels necessitate a retuning of the ECAL readout and trigger thresholds and reconstruction algorithms, to achieve the best possible performance in these more challenging conditions. The energy response of the detector must be precisely calibrated and monitored to reach and maintain the excellent performance obtained in Run I in terms of energy scale and resolution. A dedicated calibration of each detector channel is performed with physics events exploiting electrons from W and Z boson decays, photons from π0/η decays, and from the azimuthally symmetric energy distribution of minimum bias events. This talk presents the new reconstruction algorithm and calibration strategies that were implemented to maintain the excellent performance of the CMS ECAL throughout Run II. Performance results from the Run II data taking period will be reported.

1. Introduction
The Compact Muon Solenoid (CMS) experiment has produced a wide range of physics results exploiting the proton-proton and heavy-ion collision data at the Large Hadron Collider at CERN (LHC). These include the discovery of the standard model (SM) Higgs boson, as well as searches for physics beyond the standard model (BSM). The electromagnetic calorimeter (ECAL) [1] is crucial for the identification and reconstruction of photons and electrons in CMS and contributes to the measurement of jets and missing transverse energy. Excellent energy resolution and efficient identification for photons are required for the $H \rightarrow \gamma\gamma$ decay process, for measurements of the self-coupling of Higgs bosons and other related parameters. Precise measurements of the energy and momentum of electrons are important for the measurement of Higgs properties and for many BSM searches.

The CMS electromagnetic calorimeter is a homogeneous calorimeter made of 75,848 lead tungstate (PbWO4) scintillating crystals, located inside the CMS superconducting solenoid magnet [1, 2, 3]. It is made of a barrel part, covering the region of pseudorapidity $|\eta| < 1.48$, and two endcaps, which extend the coverage up to $|\eta| = 3.0$. The photodetectors are avalanche
photo-diodes (APD) in the barrel and vacuum phototriodes (VPT) in the endcaps. The barrel region is made of 36 identical supermodules, and the endcaps are constructed from four half-disk ‘Dees’. A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is placed in front of the endcap crystals. Electrons and photons are typically reconstructed up to $|\eta| < 2.5$, the region covered by the silicon tracker, while jets are reconstructed up to $|\eta| < 3.0$. The ECAL energy resolution achieved during 2010–2011 in LHC Run I is described in Ref. [4] and ranged from 1.1 to 2.6% in the barrel and from 2.2 to 5% in the endcaps, for photons from the Higgs boson decays.

During Run II (2015-2018), the LHC delivered proton-proton collisions at an increased centre of mass energy of 13 TeV, with colliding proton bunches every 25 ns. The beam intensities were significantly higher than in Run I, reaching $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$, with up to 60 concurrent interactions per bunch crossing (termed pileup). In 2017, the LHC delivered an integrated luminosity of almost 50 fb$^{-1}$, and the CMS ECAL operated with more than 99% of its channels active, and achieved higher than 99.5% operational efficiency (by luminosity). This was due to several improvements in the the ECAL data acquisition and trigger systems, in particular the automatic recovery from single event upsets in the on-detector readout, caused by the higher beam intensities compared to Run I. The improvements made to the reconstruction algorithms and calibration strategies, needed to maintain the excellent energy resolution of ECAL with the Run II collision data, are described in the following sections.

2. Energy reconstruction

The energy deposits from a typical electron or photon shower are spread over several ECAL crystals. The energy is collected using a dynamic clustering algorithm. The clusters are extended in the $\phi$ direction to form superclusters (SC) which recovers energy lost due to photon conversions or electron bremsstrahlung. The reconstructed photon or electron energy, $E_{e,\gamma}$, is calculated using the following formula:

$$E_{e,\gamma} = F_{e,\gamma} \times \left[ E_{ES} + G(\eta) \times \sum_i C_i \times S_i(t) \times A_i(t) \right],$$

where the index, $i$, represents individual crystals within the supercluster, $A_i(t)$ is the single channel reconstructed amplitude, $S_i(t)$ is the time-dependent crystal response correction, and $C_i$ is the channel inter-calibration constant. The quantity $G(\eta)$ is the ADC to GeV absolute energy scale factor, $E_{ES}$ is the energy deposited in the preshower, and $F_{e,\gamma}$ are supercluster energy corrections (different for photons and electrons).

2.1. Pulse reconstruction and pedestals, $A_i(t)$

The reconstruction of ECAL deposits starts with the amplification and digitization of the signals from the photodetectors associated with the crystals. Ten consecutive samples, time spaced by 25 ns, are digitized and read out. These are used to perform the pulse reconstruction and amplitude extraction. Because the LHC colliding bunches are separated by 25 ns and the signal pulses span more than one 25 ns time sample, the recorded pulse will be the sum of in-time and out-of-time (OOT) pulses. During LHC Run II, a new pulse reconstruction algorithm termed ‘multifit’, is used to minimize the OOT contribution to the signal. It replaces the Run I method [5], where the amplitude was reconstructed as a weighted sum of the ten digitized samples. In the multifit method, the in-time pulse amplitude is estimated using a template fit to the time samples, minimizing:

$$\chi^2 = \sum_{i=1}^{10} \left( T_i - \sum_{j=1}^{M} A_j \times p_{ij} \right)^2 / \sigma_{T_i}^2.$$
The pulse reconstruction method is illustrated in Fig. 1. The ten digitized samples \( (T_i) \), shown as solid circles, are modelled as a sum of one in-time pulse template (red line peaking at time sample 5), plus up to 9 OOT templates (lines with different colors). These pulse templates, \( A_j \), are weighted by their respective amplitudes, \( p_{ij} \). The OOT templates are considered in a range of -5 to +4 bunch crossings around the in-time signal. The pulse templates are measured in data and updated periodically. The single sample noise, \( \sigma_{T_j} \), is measured in special runs without LHC collisions.

With the multifit method, the contribution of OOT pileup to the signal reconstruction is demonstrated to be negligible, both in data and in simulated samples. The energy resolution and response is improved with respect to the Run I method, especially for low \( p_T \) photons and electrons.

Since the multifit method uses a pulse template fit, it is necessary to measure and subtract the pulse baseline (pedestal) for each channel. The pedestals are measured during the beam abort gap as well as in special beam-off runs. Since 2016, radiation induced drifts in the pedestal values have been observed. Figure 2 shows the history of the pedestal values recorded for 2017 data for the ECAL barrel and endcaps. These show two effects: a long-term monotonic drift upwards (in red) and a short-term (in-fill) luminosity related effect (in blue). These effects are mitigated by frequently updating the pedestal values used in the multifit reconstruction.

**Figure 1.** Illustration of the multifit method. Fitted pulses for a simulated CMS event with 20 pileup interactions and 25 ns bunch spacing. Dots represent the 10 digitized samples (25 ns), the red distributions represent the fitted in-time pulses and the other light colors represent the fitted out-of-time pulses with positive amplitude. The dark blue histograms represent the sum of all the fitted contributions.

**Figure 2.** Measured pedestal values (in ADC counts) in the ECAL barrel (left) and endcaps (right) for the 2017 data taking period. In red, a long-term monotonic drift upwards is visible. In blue, short term (in-fill) luminosity related effects are evident.
2.2. Response correction, $S_i(t)$

A time-dependent correction, $S_i(t)$, must be applied to account for changes in detector response due to LHC irradiation. This change in response is the sum of two effects: crystal transparency variations, and changes in photodetector response (the latter chiefly in the endcaps).

A dedicated light monitoring system is used to measure and correct for these response changes [6]. It consists of a system of lasers (operating close to the wavelength of the light emission peak of lead tungstate crystals) that injects light in each ECAL crystal during the LHC abort gap. A measurement of the channel response for the entire detector is obtained every 40 minutes. These measurements are used to derive energy corrections that are applied to the reconstructed ECAL signal pulses from physics events.

Figure 3 shows the relative response to laser light (440 nm in 2011 and 447 nm from 2012 onwards) measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity $\eta$, from 2011–2018. The response change observed is up to 10% in the barrel and reaches 50% at $|\eta| = 2.5$, the limit of the tracker acceptance. The response change is up to 90% in the regions closest to the beam pipe. The recovery of the response during periods without collisions is visible. However, the response is not fully recovered, particularly in the region closest to the beam pipe. The monitoring corrections are validated using the stability of the $E/p$ ratio: the isolated Z/W electron energy measured by ECAL ($E$) divided by the momentum measured by the CMS Tracker ($p$). They are also monitored and validated using the stability of the $\pi^0$ invariant mass versus time (see details in T. Mudolkhar report at this conference).

![Figure 3](image)

**Figure 3.** History of the relative response to laser light injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity $\eta$, with the CMS magnetic field at 3.8 T. Measurements from March 2011 to May 2018 are shown. The bottom plot shows the instantaneous LHC luminosity delivered during this period.
2.3. Single channel inter-calibration, $C_i$

A relative calibration procedure in all ECAL channels is performed to ensure the uniformity of the energy response across the detector. Several different methods are used to calculate the inter-calibration constants ($C_i$), which are then combined. The methods are the same as were used in Run I [4].

The $\pi^0/\eta$ method involves the reconstruction of the invariant mass of these resonances decaying to two photons and equalises the position of the mass peaks in each crystal. In this procedure, the $C_i$ of the central crystal in the photon cluster is updated at each iteration based on the reconstructed invariant mass and the iteration stops when the constants converge. In the $Z \rightarrow ee$ method, a fit is performed to derive the $C_i$ parameters from the invariant mass of $Z \rightarrow ee$ decays. The $E/p$ method compares the reconstructed supercluster energy, $E$, from isolated electrons from $Z$ and $W$ decays, to the electron momentum $p$ measured in the tracker. An iterative method is also used to minimize the spread of the $E/p$ distribution. Finally, the $\phi$-symmetry method relies on the expectation that, for a large sample of minimum bias events, the total deposited transverse energy should be the same in all crystals at the same pseudorapidity.

The inter-calibration precision achieved with 2017 data is shown in Fig. 4 for the ECAL barrel. The precision for measuring the inter-calibration constants from the $Z \rightarrow ee$, $\pi^0 \rightarrow \gamma\gamma$, and $E/p$ methods is shown as a function of $\eta$. The precision of the $Z \rightarrow ee$ and $\pi^0$ inter-calibrations are at the level of their respective systematic errors. The precision of the $E/p$ inter-calibrations is still dominated by statistical uncertainties for $|\eta| > 1$. The black points represent the precision of the combination of the three methods, obtained from the mean of the individual method constants at a fixed value of $\eta$ weighted by their respective uncertainties. The uncertainty of an inter-calibration method, is defined as the spread of the difference between the individual method constants and those derived from the other methods at a fixed value of $\eta$. The combination yields a precision of around 0.3% for the central region of the barrel $|\eta| < 0.7$, and better than 1% for $|\eta| = 1.5$.

![Figure 4. Precision of the per-channel energy inter-calibration, plotted as a function of the pseudorapidity $\eta$ in the ECAL barrel, for data collected in 2017. The precision is shown for the individual inter-calibration methods and for their combination.](image)

2.4. Absolute energy scale, $G_\eta$

$Z \rightarrow ee$ events are used to set the relative energy scale as a function of $\eta$, and the absolute energy scale [4]. The first correction is made to ensure that different $\eta$ regions have the same relative response, while the second (performed separately for barrel and endcaps) sets the absolute energy
scale to match a full Monte Carlo simulation of the detector. Figure 5 shows a comparison between the dielectron invariant mass distributions of $Z \rightarrow ee$ events in data and simulation (after energy smearing is applied to account for the difference in resolution between data and Monte Carlo). In this comparison, the electrons are reconstructed using the energy corrections relevant for photons. The comparison is shown for non-showering (before entering the crystals) electrons ($R_9 = E_{3x3}/E_{SC} > 0.94$) for events with both electrons in the barrel (left), and for the remaining events (right). The simulated distributions are normalized to the integral of the data distribution in the range $87 < m_{ee} < 93$ GeV to highlight the level of agreement in the bulk of the distributions.

The absolute energy calibration was validated with high energy photons and electrons used in analyses searching for high mass resonances decaying into those particles. The validation was performed by checking data and Monte Carlo simulations in high energy electrons from $Z \rightarrow ee$ decays. The energy scale was stable to 0.5% (0.7%) for electrons up to $p_T = 150(100)$ GeV in the barrel (endcap). Possible saturation effects were corrected with a multivariate technique, but those effects were found to be less than 2% for photons with $M(\gamma\gamma) < 1.4$ TeV (see details in J. Rembser report at this conference).

Figure 5. Comparison of the dielectron invariant mass distributions in data and simulation (after energy smearing) for $Z \rightarrow ee$ events where the electrons are reconstructed as photons. The comparison is shown requiring non-showering electrons $R_9 > 0.94$, for events with both photons in the barrel (left), and for the remaining events (right).

2.5. Supercluster energy corrections, $F_{e,\gamma}$

Figure 6 illustrates how the the $Z \rightarrow ee$ energy scale and resolution are improved by successive corrections to the energy measured by the ECAL. The invariant mass of the two electrons is reconstructed using all of the 2015 Run II ECAL data at $B=3.8$ T. First, the energy sum over a $5 \times 5$ crystal matrix centered around the seed crystal is shown. In general not all of the energy from showering electrons is collected within this region, particularly where there is significant dead material in front of the ECAL. The resolution is improved by using the supercluster algorithm, which incorporates cluster spread, especially in the $\phi$ direction, for showering electrons. For the endcaps, the energy scale is improved by adding the energy deposited in the preshower to the energy deposited in the crystals. A further correction to
the supercluster energy is made by applying a multivariate algorithm (MVA), separately for photons [7] and electrons [8]. The MVA aims to account for energy containment effects and to mitigate the dependence of the energy scale on pileup. It makes use of many ECAL variables, such as the cluster shape of the seed cluster and the characteristics of the most energetic subclusters within the supercluster.

Figure 6. Illustration of $Z \rightarrow ee$ invariant mass reconstruction improvements in the ECAL barrel (left) and endcaps (right), using a $5 \times 5$ crystal matrix, supercluster clustering algorithms for bremsstrahlung recovery, inclusion of the preshower energy (ES) for the endcaps, and energy corrections using a multivariate algorithm.

3. ECAL Energy resolution in 2017
The relative ECAL energy resolution $\sigma_E/E$ is extracted from an unbinned likelihood fit to $Z \rightarrow ee$ events, using a Voigtian (Landau convoluted with Gaussian) as the signal model. The relative electron (ECAL) energy resolution, unfolded in bins of pseudorapidity ($\eta$) for the barrel and the endcaps is shown in Fig. 7. The resolution is plotted for both data and MC events and is shown separately for very low bremsstrahlung electrons ($R_9 > 0.94$) and for bremsstrahlung electrons ($R_9 < 0.94$). The conditions used in the simulation reflect the status of the detector that corresponds to 25 $fb^{-1}$ of data taking in 2017. Degradations observed in the vicinity of the $\eta$ cracks between ECAL modules (indicated by the vertical lines in the figures) correspond to energy lost in these regions.

Significant improvements in the resolution can be observed after a dedicated recalibration performed in early 2018 using the full 2017 dataset (blue points). These are evident when compared to the end-of-year (EOY) 2017 calibration (gray points) where only corrections for certain time dependent effects in 2017 data were applied. With the full recalibration, ECAL achieved an energy resolution which ranges from 1.5 to 3.4% in the barrel and from 3.6 to 4.8% in the endcaps for $Z \rightarrow ee$ low bremsstrahlung electrons. This shows that the excellent performance of the ECAL has been preserved in Run II, despite the significantly higher LHC luminosities and pileup.

4. Summary
The CMS electromagnetic calorimeter has demonstrated excellent performance using LHC Run II data in 2017. Important improvements to the ECAL reconstruction and calibration methods have been made to meet the challenges of higher LHC luminosity and larger detector response...
Figure 7. Relative electron (ECAL) energy resolution plotted for data and Monte Carlo events, unfolded in bins of pseudorapidity ($\eta$) for low bremsstrahlung $Z \rightarrow ee$ electrons with $R_9 > 0.94$ (left) and for bremsstrahlung electrons with $R_9 < 0.94$ (right). The data resolution obtained after corrections for certain time-dependent effects is shown in gray. The resolution obtained from a full recalibration using the entire 2017 dataset is shown in blue.

variations in Run II. An effective suppression of out-of-time pileup has been achieved using the multifit algorithm. Regular monitoring and updates of crystal response and calibration, pedestal baselines, and signal pulse shapes have been crucial to maintain the stability of the ECAL energy scale and resolution. The excellent energy resolution and stability achieved during Run I have been preserved in Run II, and the improved algorithms and procedures that were required to obtain this result will be invaluable for Run III and beyond.

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