The challenges involving the calibration of the CMS Electromagnetic Calorimeter at the LHC

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Abstract

The CMS ECAL is a high resolution electromagnetic crystal calorimeter which relies on precision calibration in order to achieve and maintain its design performance. A set of inter-calibration procedures is carried out to normalize the differences in crystal light yield and photodetector response between channels. Different physics channels such as low mass di-photon resonances, electrons from W and Z decays and the azimuthal symmetry of low energy deposits from minimum bias events are used. A laser monitoring system is used to measure and correct for response changes, which arise mainly from the harsh radiation environment at the LHC. The challenges, techniques and results are discussed and include the combined precision of the inter-calibration and absolute energy calibration for the three year period from 2010-2012. An assessment is made for the performance to be expected from 2015 onwards following the re-start of the LHC.

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The challenges involving the calibration of the CMS Electromagnetic Calorimeter at the LHC.

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1. Introduction

The electromagnetic calorimeter (ECAL) [1] of the Compact Muon Solenoid (CMS) experiment at CERN is a homogeneous, quasi-hermetic detector made of 75848 lead-tungstate (PbWO$_4$) scintillating crystals, organized in a barrel (EB), with pseudorapidity coverage up to $|\eta|=1.48$, closed by two endcaps (EE) that extend up to $|\eta|<3$. For light collection each crystal is equipped with avalanche photodiodes (APD) in EB and vacuum phototriodes (VPT) in EE. A silicon/lead pre-shower detector (ES) is installed in front of the endcaps to improve the $\gamma$ identification capabilities. We define as an "$\eta$-ring" a group of crystals located at the same pseudo-rapidity $\eta$. In ECAL there are $85 \times 2$ $\eta$-rings with 360 crystals each in the barrel and 39 $\eta$-rings with a variable number of crystals in each endcap.

ECAL is the first crystal calorimeter installed at a hadron collider. This choice was made to optimize the energy resolution, but the harsh LHC radiation environment makes it challenging to maintain the high design performance. During CMS operation, the contributions to the energy resolution due to detector instabilities, channel-to-channel response spread and radiation induced response variations, have to be kept to within 0.4%. In the following sections the procedure developed to correct for these effects will be discussed and the results obtained during the 2012 data taking period will be presented. For a detailed description of 2011 ECAL performances, refer to [2].

2. Electromagnetic shower reconstruction and energy calibration

Electrons and photons deposit their energy over several ECAL crystals. Clustering algorithms are used to sum together energy deposits belonging to the same electromagnetic shower. After the clustering, the energy of the $e/\gamma$ candidates is estimated as:

$$E_{e,\gamma} = F_{e,\gamma} \times \left[ G \times \sum_{\text{crystal}} IC_{\text{crystal}} S(t)_{\text{crystal}} A_{\text{crystal}} + ES \right]$$

(2.1)

where the sum is over all the crystals belonging to the same cluster. $A_{\text{crystal}}$ is the signal amplitude of the individual channel in ADC counts; $S(t)_{\text{crystal}}$ are the time dependent corrections for radiation induced response variations; $IC_{\text{crystal}}$ are the intercalibration factors used to equalize the response of the ECAL channels; $G$ is the ADC-to-GeV conversion factor (absolute energy scale); $F_{e,\gamma}$ are the particle-dependent corrections, applied at the cluster level, to take into account the $\eta$- and $\phi$-dependent geometry and material effects. ES is the energy measured by the preshower to be added to the cluster energy in EE. This factorization of the various contributions to the electromagnetic energy determination permits stability and intercalibration issues to be studied separately from material and geometrical effects.

2.1 Correction for radiation-induced response changes, S(t)

During LHC cycles the ECAL response varies depending on the irradiation conditions. The predominant loss of response is due to the formation of color centres that reduce the transparency of the lead tungstate. This effect takes place on a time scale of hours and can cause transparency changes of a few percent during LHC fill/interfill periods, depending on the instantaneous and integrated luminosity, and on the position in the detector, i.e. on the dose rate absorbed by the crystal.
The crystal transparency partially recovers in the periods without irradiation through spontaneous annealing [3]. Another important radiation-induced effect, which currently cannot be disentangled from the transparency loss, is the conditioning of the VPT.

A laser monitoring (LM) system [4], based on the injection of laser light at 447 nm (440 nm in 2011), close to the emission peak of PbWO₄ scintillation light, is used to track and correct these variations. During the LHC beam abort gaps, laser pulses are injected into group of crystals via optical fibres. The LM system cycles through all 75848 crystals every 40 minute. The channel response is normalized to the laser pulse magnitude, measured using silicon PN photo-diodes. A group of crystals whose response is normalized using the same PN signal is referred to as a laser monitoring region.

The spectral composition and the path of the light collection at the photodetectors are different for the laser and the scintillation light. The relationship between the response variation \( \frac{R(t)}{R(0)} \) measured by the laser and the response variation to the scintillation light generated by electromagnetic showers \( \frac{S(t)}{S(0)} \) has been studied in test beams and can be described by a power law:

\[
\frac{S(t)}{S(0)} = \left( \frac{R(t)}{R(0)} \right)^\alpha
\]

where \( R(0) \) and \( S(0) \) are the initial response to the laser and the scintillation light, respectively. The corrections derived according to 2.2 are validated by applying them to the data and checking the stability of the reconstructed di-photon mass from \( \pi^0/\eta \rightarrow \gamma\gamma \) decays. This procedure takes place within 48 hours after the data-taking, before the CMS prompt data reconstruction starts. In 2012 these \( S(t) \) factors were also used to correct the response of endcap channels, where the transparency changes are more significant than the barrel, at the trigger level.

The stability of the energy scale is constantly checked by comparing the energy, \( E \), reconstructed by ECAL to the track momentum, \( p \), measured by the tracker system for electrons produced in \( W \rightarrow e\nu \) decays. The \( E/p \) scale studied as a function of time in 2012 was found to be stable to within 0.11% in the barrel and 0.37% in the endcaps after the response corrections had been applied. These results were obtained using the same value of the \( \alpha \) parameter for all EB (EE) crystals despite a spread of 10% being observed in test beams. This spread limits the precision of the LM corrections; a long-term effect became visible in 2012, especially in the ECAL regions where the applied corrections became large. This effect was corrected with a time-dependent calibration, as explained in the next section.

### 2.2 Single channel calibration, IC

The different ECAL channel response is mainly due to crystal light yield variation and, in EE, to the gain and quantum efficiency spread of the VPTs. The normalization of the response across channels has been performed in various steps.

To provide an acceptable initial performance at startup of the data-taking, channels were pre-calibrated [5] with laboratory measurements of crystal light yield and photo-detector response, electron beams, cosmic ray muons and muons from beam dumps at the LHC, reaching an average precision of 1.5% in the barrel and 5% in the endcaps. To further improve and maintain this precision during the LHC data taking, several methods have been developed.

The intercalibration of all the crystals located in the same \( \eta \)-ring is performed with three different methods applied, after LM correction, to collision data.
i) The $\phi$-symmetry method is based on the assumption that for a large number of minimum-bias events the total deposited transverse energy ($\Sigma E_T$) is the same for all crystals located at the same pseudorapidity. The intercalibration is performed by comparing the $\Sigma E_T$ deposited in one crystal with the mean $\Sigma E_T$ collected by crystals in the same $\eta$-ring. The precision of the method ranges between 1.4% in the central barrel ($|\eta| < 1$) to 4-6% in the endcaps and is limited by the non-uniformity of the material in front of ECAL. However, this procedure provides rapid feedback (one intercalibration per LHC fill in 2012) and can be used to monitor the relative stability of the overall calibration.

ii) The decay of $\pi^0/\eta$ into two photons is exploited to intercalibrate ECAL crystals by using the $\gamma\gamma$ invariant mass distribution. Only unconverted photons reconstructed in 3x3 crystal matrices are used. One set of intercalibration constants per LHC run period ($\sim$3 months) was provided with a precision of 0.5 (1)% in the central (outer) barrel and between 2% and 6% in the endcaps. The precision is dominated by systematic errors. The reconstruction of the $\pi^0$ peak was challenging in 2012 due to the high level of pile-up. Crystals at $|\eta| > 2$ were calibrated using only $\eta \rightarrow \gamma\gamma$ decays.

Dedicated data acquisition paths were implemented for the $\phi$-symmetry and $\pi^0/\eta$ methods, to collect calibration data at high rate while limiting the impact on the CMS bandwidth for physics analyses.

iii) The $E/p$ method uses electrons from $W \rightarrow e\nu$ and $Z \rightarrow ee$ decays. The calibration is performed by fitting, in an iterative procedure, $E(\text{ECAL})/p(\text{tracker})$ distributions for each crystal. One set of intercalibration factors was provided in 2012, achieving a precision of 2% in the endcaps and ranging between 0.5% ($|\eta| < 1$) and 1.5% in the barrel. The precision for $|\eta| > 1$, using the 2012 dataset, is still limited by statistics.

Results from the three intercalibration methods were compared, found to be in good agreement and combined. The achieved precision of the resulting intercalibration constants was 0.4% for the central barrel and 0.8% in the rest of EB; in EE it is $\sim$1.6% in the central part ($1.6 < |\eta| < 2.3$) and better than 3.5% at the edges. The $\eta$-rings were intercalibrated using the $Z \rightarrow ee$ invariant mass peak. With the entire 2012 data sample a statistical uncertainty of 0.05% was reached. $Z \rightarrow ee$ events were also used to determine the absolute energy scale (G). Specifically, the $Z \rightarrow ee$ invariant mass peak was required to agree between data and MC, separately for EB and EE. The systematic uncertainty in the determination of G was estimated to be 0.4% in EB and 0.8% in EE.

The stability of the ECAL calibration was monitored at the crystal level using the $\phi$-symmetry methods and, at the LM region level, with the $E/p$ method. The time evolution of the $\phi$-symmetry intercalibration coefficients (IC) is monitored by using the standard deviations obtained from the ratio of coefficients from different sets of intercalibration constants, as shown in Figure 1. The red circles represent the ratio $\frac{IC_{n}}{IC_{n-1}}$ between two consecutive intercalibration sets; for the blue squares the first set of intercalibration constants derived in 2012 ($IC_0$) is used as reference. The increasing value of $\sigma(\frac{IC_{n}}{IC_{0}})$ (blue squares) indicates a drift of the intercalibration constants. This effect can be explained through using imperfect laser monitoring corrections, mainly ascribable to the uncertain knowledge of the parameter $\alpha$. The plot indicates that, to achieve and maintain an optimal ECAL performance, a frequent calibration is needed. A time-dependent calibration was provided in 2012 using the $E/p$ and the $\phi$-symmetry method to correct the IC versus time in EB and EE respectively.

The final check of the intercalibration and response corrections is performed using $Z \rightarrow ee$ events. The study of the Z mass resolution as a function of time in 2012 (see Figure 2) showed
that a very good stability was reached in all ECAL when the final time-dependent calibrations were applied (black circles). The mass resolution was improved by $\sim 4\%$ in EB and $\sim 20\%$ in EE with respect to the prompt reconstruction.

**Figure 1**: Time evolution of the standard deviation $\sigma$ distribution of the ratio between two sets of intercalibration constants (IC) derived using the $\phi$-symmetry method.

**Figure 2**: Time dependence of the $Z \rightarrow ee$ invariant mass resolution for EB (left) and EE (right) during 2012 data taking. The prompt reconstruction is given by the blue triangles; the first set of intercalibration constants, derived in 2012 after the first 3 months of data taking, are used for all the year. The final time-dependent intercalibration, called the ‘Winter 2013 re-reconstruction’, is shown by the black circles.

**References**


