Calibration of CMS Electromagnetic Calorimeter at LHC startup

Riccardo Paramatti

Abstract. The first 7 TeV LHC collisions recorded with the CMS detector have been used to perform a channel-by-channel calibration of the electromagnetic calorimeter (ECAL). Decays of $\pi^0$ and $\eta$ into two photons as well as the azimuthal symmetry of the average energy deposition at a given pseudorapidity are utilized to equalize the response of the individual channels. The ECAL comprises a central barrel section and two endcaps. Based on an integrated luminosity of $\sim 100 \text{ nb}^{-1}$, a channel-by-channel in-situ calibration precision of 1.15% has been achieved in the barrel ECAL in the pseudorapidity region $|\eta| < 0.8$. The energy scale of the ECAL has been investigated and found to agree with the simulation to within 1% in the barrel and 3% in the endcaps.

1. Introduction

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment consists of a barrel section (EB) and two endcaps (EE). The EB contains 61,200 lead tungstate crystals arranged in 170 $\eta$-rings of 360 PbWO$_4$ crystals each (one crystal covers 1 degree in $\phi$). It is subdivided into 36 supermodules each containing 1700 crystals and provides coverage in pseudorapidity up to $|\eta| < 1.5$. The two ECAL Endcap (EE) subsystems consist of four half-disk Dees, each containing 3662 crystals. The EE provides a coverage of $1.5 < |\eta| < 3.0$. The scintillation light is detected by avalanche photodiodes (APDs) in the EB and vacuum phototriodes (VPTs) in the EE. The EE is additionally instrumented with a preshower detector (ES) on its front faces, consisting of a two layer lead-silicon sampling calorimeter. An extended description of the CMS ECAL is provided in [1]. The general performance and commissioning of the ECAL with the first 7 TeV data is described in [2]. A detailed description of the CMS experiment can be found in [3].

In the environment of CMS, for unconverted photons with energies in the range of interest for physics analyses, $E_{\text{shower}} \sim 100 \text{ GeV}$, the energy resolution will be dominated by the constant term. As a consequence, the performance of the CMS ECAL at the LHC will strongly depend on the quality of the calibration and monitoring. Achieving the design-goal inter-calibration precision of 0.5% will be particularly important for a discovery of the Higgs boson in the decay channel $H \rightarrow \gamma\gamma$, one of the primary goals of the LHC physics program.

This article describes results of the first crystal-by-crystal calibrations and global energy response measurements of the CMS ECAL at the LHC, performed during the first months of operation. The performance of the specialized ECAL calibration data-taking streams is also discussed.
2. The CMS ECAL calibration strategy

The ECAL was precalibrated before installation using several methods (section 2.1). The final calibration will be made in-situ at the LHC using collision data.

The estimated particle energy, obtained from the ECAL, can be expressed as:

\[ E = F \cdot \sum_{\text{cluster crystals}} G(\text{GeV/ADC}) \cdot C_i \cdot A_i \]  

(1)

where the sum is over the crystals in a cluster. \( A_i \) are the reconstructed amplitudes in ADC counts. \( C_i \) is the inter-calibration constant while \( G \) is the ECAL energy scale. The factor \( F \) is defined as an additional energy correction which depends on the type of the particle, its energy and pseudorapidity and in particular takes into account shower leakage and bremsstrahlung losses for electrons. This article describe the analysis focused on the determination of \( C_i \) and \( G \).

For the calibration in-situ at the LHC, the following strategies have been explored:

- \( \phi \)-symmetry inter-calibration (Section 3) is expected to provide a fast inter-calibration exploiting invariance around the beam axis of energy flow in minimum bias events [4]. This method inter-calibrates crystals at the same pseudorapidity, so that other methods are needed to inter-calibrate regions at different pseudorapidity.

- \( \pi^0 \) and \( \eta \) calibration (Section 4) uses the photon pairs selected as \( \pi^0(\eta) \rightarrow \gamma \gamma \) candidates [5].

At the startup, this method is also used to investigate the ECAL energy scale (Section 4.3).

- isolated electrons from \( W \rightarrow e\nu \) and \( Z \rightarrow e^+e^- \) decays can be used to compare the energy measured in ECAL to the track momentum measured in the silicon tracker. This method is expected to become the main channel-by-channel calibration tool when the integrated luminosity reaches several fb\(^{-1}\) [6]. The integrated luminosity accumulated so far is not sufficient to use this method. \( Z \rightarrow e^+e^- \) decays will be used also to monitor and correct the absolute ECAL energy scale [7].

In addition, variations in the crystal light output and transparency are monitored with a laser-based system [8]. With the present luminosity, the crystal transparency changes are negligible (and then they have no effect on ECAL response).

2.1. The pre-calibration

The CMS ECAL has been pre-calibrated prior to installation with laboratory measurements of crystal light yield and photo-detector gain during the construction phase (all EB and EE channels), with test beam electrons (9 EB supermodules and about 500 EE crystals) and with cosmic ray muons (all EB channels). After installation in the LHC, circulating beams were stopped in collimators 150 m away from CMS in September 2008 and November 2009. The resulting beam dump events have been used to improve pre-calibration precision.

Inter-calibration constants coming from different sources are combined as a weighted average. The precision of a given calibration method is determined empirically by comparing the new inter-calibration constants to those derived at the test beams. The comparison for the EE constants (derived from the combination of laboratory measurements and beam dump calibration) is shown in Figure 1 for a subset of the crystals exposed to beam. The results of these pre-calibrations have been reported in [9] and [1].

The channel-by-channel calibration precision at the start-up at 7 TeV is estimated to be:

- EB: about 0.5% for the 9 supermodules calibrated with test beams and 1.5% to 2.2%, depending on pseudorapidity, for the other 27 supermodules;

- EE: below 1% in the \( \sim 500 \) crystals calibrated with beam and about 5% elsewhere;

In the rest of the article, a crystal-by-crystal calibration constant is defined as a multiplicative factor \( c_i \) relative to the precalibration constant derived for this crystal: \( C_i = C_i^{\text{precalib}} \cdot c_i \).
3. Calibration with the $\phi$-symmetry method

The $\phi$-symmetry method is based on the expectation that for a large sample of minimum bias events the total deposited transverse energy ($E_T$) should be the same for all crystals in a ring at fixed pseudorapidity. Inter-calibration in $\phi$ is performed by comparing the total transverse energy ($\Sigma E_T$) deposited in one crystal with the mean of the total $\Sigma E_T$ collected by crystals at the same absolute value of $\eta$.

In the determination of the transverse energy sum, only deposits with energies between lower and upper thresholds are considered. The former is applied to remove the noise contribution and is derived by studying the noise spectrum in randomly triggered events. The latter is applied to avoid a possible bias from very high $E_T$ deposits (e.g. from electrons originating from W or Z decays).

In order to compare the relative supermodule scale in the EB with test beam and with other calibration methods, we derive the inter-calibration constants from a data sample obtained with an integrated luminosity of $8.8 \text{ nb}^{-1}$, corresponding to about $1.6 \times 10^8$ minimum bias events. For each of the 36 supermodules we study the distribution of the 1700 constants. We use the mean of the Gaussian fit to this distribution as our definition of SM scale. To estimate the systematic error, we have derived the distribution of the relative scale for those supermodules which were calibrated at the test beam, with a precision of several times better than expected from our method with the available data. The width of this distribution, about 0.5%, is the convolution of the precision of the test beam inter-calibration and the $\phi$-symmetry inter-calibration, and poses therefore an upper limit to our systematic error. In Figure 2, we show a comparison of the SM scale derived from 2009 data ($\sim 0.01 \text{ nb}^{-1}$ at $\sqrt{s} = 900 \text{ GeV}$) and 2010 data ($\sqrt{s} = 7 \text{ TeV}$).

3.1. Crystal-by-crystal calibration

We applied the $\phi$-symmetry inter-calibration procedure on $1.6 \times 10^8$ minimum bias events and derived inter-calibration constants $c_i$ for all crystals in the EB. To estimate the precision of our set of constants, we derived the distribution of the $c_i$ for each ring of constant $\eta$. The width of the
distribution gives the convolution of the precision of the pre-calibration with the precision of our method. For the nine test-beam calibrated supermodules, the expected pre-calibration precision is about 0.5%, several times better than expected for the $\phi$-symmetry method. Therefore, the width of distribution of the $c_i$ limited to those supermodules gives an upper bound of the inter-calibration precision achieved with the $\phi$-symmetry method. The width of the $c_i$ distribution is estimated by performing a Gaussian fit and extracting the sigma. In Figure 3, we show the estimated precision as a function of ring index. The pattern is due to the amount of material in front of ECAL, which is not constant in pseudorapidity.

4. Calibration with $\pi^0$ and $\eta$ decays
An inter-calibration technique based on reconstructing $\pi^0 \to \gamma\gamma$ decays has been studied using both the simulations and a dedicated test-beam study [5]. In this section the performance of the specialized $\pi^0$ and $\eta$ calibration streams and the first crystal-by-crystal calibration results are reported.

4.1. Performance of the calibration stream
In order to take advantage of the high rate of $\pi^0$ decays, a specialized data-taking stream has been developed. In this stream, the candidate di-photon decays are selected directly from events passing single-$e/\gamma$ and single-jet L1 triggers. After selection, only information about a limited region of ECAL (energy deposits in 20 to 40 individual crystals) near the $\pi^0$ candidates is stored for the actual calibration.

In the EB region, the photon candidates are reconstructed using a simple $3\times3$ window clustering algorithm that requires that the energy deposited in a seed crystal is above 0.5 GeV and no crystals are allowed to belong to more than one cluster. The cluster energy is then computed as the sum of nine crystal energies. Thus, the constructed clusters can comprise at most nine crystals with non-zero energy deposits. The shape of the cluster energy deposition should be consistent with that of an electromagnetic shower produced by an unconverted photon. In order to take into account the energy losses due to the noise suppression algorithm and shower leakage, we apply an energy correction derived as a function of the cluster energy and pseudorapidity (factor $F$ in eq. 1). The correction is derived using the simulation and applied both to the data and simulation, in the same manner.

To be considered in the combinatorial selection of di-photon pairs, a photon candidate is required to have a transverse energy above 0.8 GeV. The $\pi^0$ candidates are then selected by requiring their transverse energy to be above 1.6 GeV. The $\pi^0 \to \gamma\gamma$ candidate should also be isolated from other significant energy deposits. In addition, the $\pi^0$ candidates are required to have an invariant mass below 0.25 GeV/$c^2$. Figure 4 shows the invariant mass distributions of the selected $\pi^0$ candidates after all selection cuts both for data and simulated minimum bias events, for the EB. The distributions for data are obtained with 18.7 nb$^{-1}$. The number of events in the simulation distribution is normalized to that for the data.

To estimate the signal rate, the invariant mass distributions are fitted to a sum of a Gaussian and fourth order polynomial background. The signal-to-background ratio ($S/B$) is then estimated to be the ratio of the integral of the fitted signal and background functions in the mass window, $|M_{\text{inv}} - M_{\text{fit}}| < 2 \cdot \sigma_{\text{fit}}$. The $\pi^0$ peak width is found to be 8.2% in data and 8.1% for simulation. The $S/B$ is measured to be 2.3 and 2.4 in data and simulation, respectively.

A separate calibration stream has been implemented to select $\eta \to \gamma\gamma$ decays. The same selection and reconstruction methods are used except that the photon pair transverse energy cut is tightened to $E_{\text{tr}}^{\gamma\gamma} > 3$ GeV. In addition, a veto cut is applied to reject photons coming from di-photon candidates within the 3$\sigma$ window around the fitted $\pi^0$ peak.

In the EE, the on-line stream has also been implemented selecting $\pi^0$ and $\eta$ di-photon candidates using the same methods.
4.2. Inter-calibration Results

To investigate the potential of the $\pi^0 \to \gamma\gamma$ inter-calibration, we use two independent calibration algorithms [5]. Both algorithms are based on an iterative procedure where the inter-calibration constants are updated after each iteration step.

Nine supermodules in this region have been pre-calibrated to a precision of about 0.5% in the test-beams. Crystals in those supermodules are used to estimate the in-situ inter-calibration precision in the same way as for the $\phi-$symmetry method, as shown in Figure 5. In the region \(|\text{crystal } \eta \text{ index}| \leq 45\), the crystal-by-crystal calibration precision is found to be 1.4% which is consistent with the expectation from Monte Carlo studies which give $1.3\pm0.3\%$. The systematic limit on the precision of this method has not yet been reached and the current inter-calibration accuracy is dominated by the statistical uncertainty.

4.3. The ECAL energy scale with $\pi^0$ and $\eta$ decays

The absolute scale of the ECAL, the G factor defined in eq. 1, has been measured during the test beam campaign for EB and EE separately. In-situ, the ECAL energy scale will be determined by reconstructing di-electron and di-photon invariant mass peaks. While the $Z \to e^+e^-$ samples collected so far are not sufficient to measure the energy scale, a first measurement can be done using $\pi^0$ and $\eta$ reconstructed decays.

The energy scale is derived by measuring the ratio of the reconstructed invariant mass peak position between data and Monte Carlo. Assuming perfect simulation of the material in front of ECAL and alignment of the detector, this ratio provides the correction to be applied to the ECAL scale. More conservatively, we consider this measurement as an indication of the current ECAL scale accuracy.

Systematic uncertainties have been investigated separately for EB and EE. The error sources considered for the mass shift are the systematics due to the pseudorapidity cut (0.5% in EB and 1.3% in EE), due to the transverse energy cut variation (0.6% in EB and 1.7% in EE) and due to the energy corrections (0.4% in EB and 0.5% in EE).

The EB scale is found to agree with the simulation at a level of 1%, with the measured mass shift (data vs simulation) of $-0.7\% \pm 0.02\% \text{ (stat.)} \pm 0.9\% \text{ (syst.)}$. In the EE, the scale is...
found to agree with the simulation to about 3%. The average mass shift is measured to be $+2.5\% \pm 0.2\%$ (stat.) $\pm 2.2\%$ (syst.).

5. **Combination of the $\pi^0$ and $\phi$-symmetry inter-calibration results**

The inter-calibrations with the $\pi^0$ and $\phi$-symmetry methods are performed independently and a comparison between their results provides a useful cross-check. We combine the crystal-by-crystal calibration constants obtained with the two methods. As shown in Figure 6, for the central barrel region ($|\text{crystal } \eta \text{ index}| \leq 45$) the combined inter-calibration precision is found to be $1.15\%$ which is in good agreement with the expectation of 1.1% coming from the estimated precisions of the two methods (see Figures 3 and 5).

![Figure 5](image1.png)  
**Figure 5.** Inter-calibration precision as a function of $\eta$-index. The expected precision estimated from simulation studies is also shown.

![Figure 6](image2.png)  
**Figure 6.** Distribution of the combined inter-calibration constants in the central region $|\text{crystal } \eta \text{ index}| \leq 45$.

6. **Conclusions**

Using the first $\sim 100 \text{nb}^{-1}$ collected with the CMS detector in 2010 at a center of mass energy of 7 TeV, studies of the CMS ECAL calibration methods and procedures are carried out. The achieved channel-to-channel calibration precision in the central barrel with the sample size currently available is 1.15%, in good agreement with the expectation from Monte Carlo studies.

The global energy response scale of the ECAL is also studied, and found to agree with the expectation to within about 1% in the barrel and 3% in the endcaps. In addition, the performance online calibration streams is found to be consistent with the simulation. The calibration of the CMS ECAL will continue with the upcoming LHC data, with collection of large samples of neutral pion decays as well as W and Z bosons decaying into energetic and isolated electrons.

**References**

[1] CMS Collaboration, “Performance and operation of the CMS electromagnetic calorimeter”, JINST 5 (2010) T03010.

[2] CMS Collaboration, “Performance and operation of the CMS electromagnetic calorimeter”, CMS Note 2010/012.

[3] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 0803 (2008) S08004.

[4] D. Fetrian and C. Seez, “Intercalibration of ECAL crystals in $\phi$ Using Symmetry of Energy Deposition”, CMS Note 2002/031.
[5] V. Litvin, “Inter-calibration of the CMS barrel electromagnetic calorimeter using $\pi^0 \rightarrow \gamma\gamma$ decays”, CMS Conference Report 2007/069.
[6] L. Agostino et al., “Inter-calibration of the CMS electromagnetic calorimeter with isolated electrons”, J. Phys. G33 (2007) N67-N84.
[7] P. Meridiani and R. Paramatti, “Use of $Z \rightarrow e^+ e^-$ events for ECAL calibration”, CMS Note 2006/039.
[8] M. Anfreville et al., “Laser monitoring system for the CMS lead tungstate crystal calorimeter”, CMS Note 2007/028.
[9] P. Adzic et al., “Intercalibration of the barrel electromagnetic calorimeter of the CMS experiment at start-up”, JINST 3 (2008) P10007.