Calibration of the CMS Electromagnetic Calorimeter with LHC collision data

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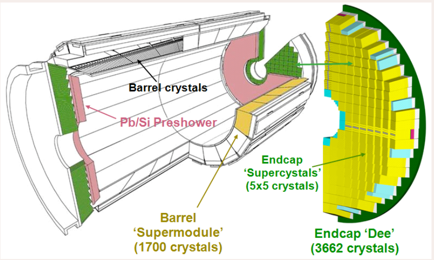
Introduction

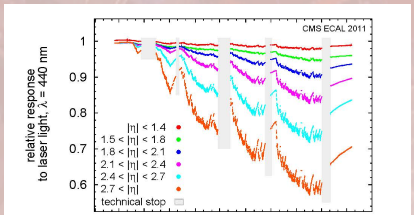
The electromagnetic calorimeter (ECAL) of the CMS experiment is a homogeneous, hermetic detector with high granularity. It is made of 75,848 lead-tungstate ($PbWO_4$) crystals. The central *barrel* calorimeter (EB) is organized into 36 supermodules (SM) and it is closed at each end by an *endcap* calorimeter (EE) consisting of two "*dees*". For the collection of light it is equipped with avalanche photodiodes (APD) in the barrel part and vacuum phototriodes (VPT) in the endcaps. A silicon/lead pre-shower detector (ES) is installed in front of the calorimeter in the endcaps in order to improve the γ/π^0 discrimination.



ECAL is one of the highest resolution electromagnetic calorimeters ever constructed, but relies upon precision calibration in order to achieve and maintain its design performance. Variations in channel response from the lead tungstate crystals, due to intrinsic differences in crystals/ photodetectors, as well as, for example, variations with time due to radiation damage, need to be taken into account. Sophisticated and effective methods of inter-crystal and absolute calibration have been devised, using collision data from the 2011 LHC run and a dedicated light injection system. For inter-calibration, low-mass particle decays (π^0 and η) to two photons and W->eν events are exploited, as well as the azimuthal symmetry of the average energy deposition at a given pseudorapidity. Absolute calibration has been performed using Z decays into electron-positron pairs. The light injection system monitors the channel response in real-time and enables the re-calibration of the measured energies over time. This is cross-checked by the comparison of E/p measurements of electrons from W decays (where the momentum is measured in the CMS tracker) with/without these re-calibrations applied.

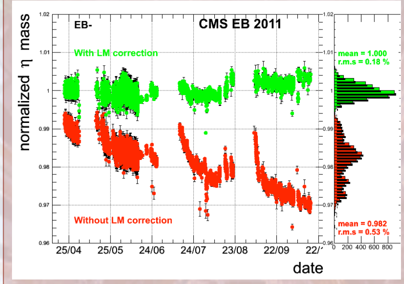
Correction of the radiation induced response change of the ECAL channels

During LHC cycles the ECAL response varies depending on the irradiation conditions. The predominant loss of channel response is from crystal transparency degradation. This effect takes place on a time scale of hours and can cause transparency changes of a few percent during LHC fills/interfills periods, depending on the instantaneous and integrated luminosity. To maintain the ECAL design performance, a laser monitoring (LM) system was designed to monitor the response change for each channel at the level of 0.2%.
The response of each channel is monitored every 20 to 30 minutes by means of a blue laser with a wavelength (λ=440 nm) close to the $PbWO_4$ emission peak. During the LHC beam abort gaps, laser pulses are injected into each crystal via a system of optical fibres. The channel response is normalized to the laser pulse magnitude, measured using silicon PN photo-diodes. To provide corrections with the required precision, the signal is corrected for laser pulse width and amplitude change.

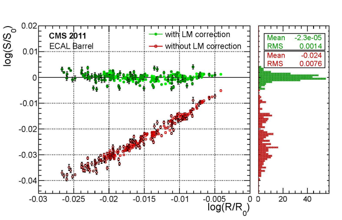


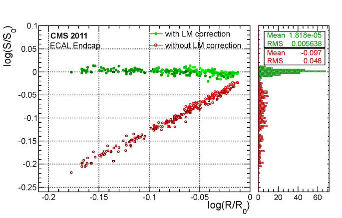
The plot beside shows the relative response to laser light (440 nm) as measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity η for the 2011 data taking.
The observed response variation has an exponential behaviour and reaches a saturation level which depends on the dose rate. The average change is about 2–3% in the barrel and reaches 40% for $|\eta| = 2.7$ in endcap, in agreement with the expectations for the achieved instantaneous luminosity.
The spontaneous recovery of the crystals during periods without irradiation is clearly visible.

Several methods have been developed to validate the response corrections.



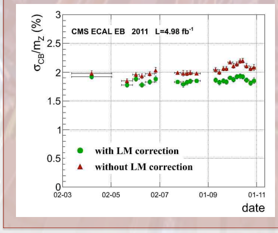
1. The response corrections are validated before the CMS prompt data reconstruction takes place, that is 48 hours after data-taking, studying the variation of the reconstructed η mass from di-photons pairs as a function of time.
The plot shows that after the correction for the response change, the energy scale measured with this method was found to be stable within 0.18% in the barrel over a period of 6 months

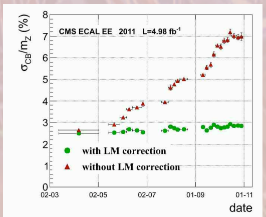




2. The stability of the energy scale is also measured in W → eν decays by comparing the energy reconstructed by ECAL and the track momentum estimated from the tracker. The relative variation of the E/p scale for electrons (S/S_0) is shown in the plot beside as a function of the response change as measured by the laser monitoring system (R/R_0).
The energy scale is found to be stable within 0.14% (0.56%) in the barrel (endcap) after the response corrections have been applied.

The response change as measured by the laser monitoring system has to be scaled by a factor α to optimally correct the signal from electromagnetic showers. This scale factor has been measured in a test beam to be 1.52. A residual slope in the corrected data can be interpreted as a deviation of this scale factor from the test beam value. In the barrel the scale factor agrees within error with the test beam value. In the endcap an effective scaling of α has been introduced to optimize the resolution performance.





3. To cross-check the corrections applied to the channel response, Z->e^+e^- events are used. The resolution of the e^+e^- invariant is dominated by the energy resolution of the electron reconstruction.

The mass resolution of the Z peak is shown as a function of time for the barrel (right plot) and the endcap (left plot). Plots show that without correcting for response variation, during the 2011 data taking the resolution worsened by approximately 15% in the barrel and by more then 100% in the endcap; **applying laser corrections the relative mass resolution was found stable within 4% in all ECAL.**

Single crystal inter-calibration

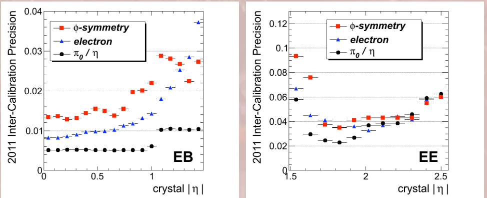
ECAL has been pre-calibrated prior to installation with laboratory measurements (crystal light yield and photo-detector gain - all EB and EE channels), with test-beam electrons (9 EB SM and ~ 500 EE crystals) and with cosmic ray muons (all EB channels). After installation in the LHC, "splash" events have been used to improve pre-calibration precision in the EB and EE.

Several methods have been developed to perform "in situ" calibration with collision data. The inter-calibration coefficients are obtained after the transparency corrections are applied.

The ***ϕ-symmetry* method** is based on the assumption that for a large number of minimum bias events the total transverse energy (E_T) deposited should be the same for all crystals in a ring at fixed pseudorapidity (η). Inter-calibration in ϕ can be performed by comparing the total transverse energy (ΣE_T) deposited in one crystal with the mean of the total ΣE_T collected by crystals at the same absolute value of η. The ϕ Inhomogeneities of the detector are taken into account Introducing data-driven corrections. The precision of the method is shown in the plots on the right. In 2011 phisymmetry was able to produce inter-calibrations in short time (~2 weeks). The ratio of the coefficients obtained in different periods was used to correct the inter-calibration derived with other analysis in longer periods of time.

In the **π^0/η method**, the invariant mass of photon pairs from $\pi^0/\eta \rightarrow \gamma\gamma$ is used to obtain the inter-calibration constants. The photon candidates are reconstructed using a simple 3X3 window clustering algorithm. The cluster energy is computed as the sum of crystal energies $S_9 = \Sigma_{3X3}\, c_i \bullet E_i$ where c_i denotes the calibration constant and E_i the energy deposited in each i-th crystal. An iterative procedure is applied: the π^0/η mass peak of the events collected in each crystal is fitted with a gaussian and a fourth order polynomial describing the background, and the calibration constants are updated to correct the fitted mass value.

Precision achieved in 2011 by the different in situ inter-calibration methods as a function of pseudorapidity



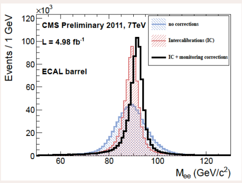
During the 2011 run it was possible to derive one set of inter-calibration constants per month in EB and one set every 3 months in EE with the precision shown in the plots above.

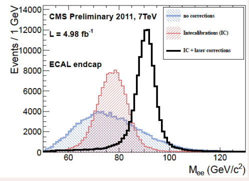
The W **electron method** uses the single electrons from W→ eν decays. The ratio of the electron energy E measured by ECAL to the electron momentum p measured by the tracker is computed for each crystal. The resulting distribution is fitted to a reference E/p distribution obtained by Monte Carlo simulation in each η ring. An iterative procedure is used to evaluate the inter-calibration coefficients. Using the entire sample accumulated in 2011 it was possible to provide for the first time an inter-calibration with this method; the achieved precision is shown in the plots above.

The mass resolution of the Z detected in e^+e^- decay was used for the validation of the inter-calibration coefficients.

Impact on the Z→ee energy scale and resolution from the inter-calibration and response corrections.

Plots are produced with 2011 data.





During 2011 data taking a lot of effort was put to reach and maintain ECAL design performance. The light monitoring system was able to provide adequate corrections for response changes. The channel inter-calibration was performed with different methods (*ϕ*-symmetry, π^0/η and W electron) independently. Results were found in good agreement and combined. The precision of the resulting inter-calibration constants is 0.5% for the central barrel and better than 1% in the rest of EB. EE inter-calibration precision is around 2% in the central part and better then 4 % at the edges.

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