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The CMS electromagnetic calorimeter calibration during Run I: progress achieved and expectations for Run II

Alessio Ghezzi, on behalf of the CMS Collaboration
University of Milano-Bicocca, Physics Department, P.zza Della Scienza 3, Milano
E-mail: alessio.ghezzi@mib.infn.it

Abstract. The CMS ECAL is a high-resolution, hermetic, and homogeneous electromagnetic calorimeter made of 75,848 scintillating lead tungstate crystals. It 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 of the different calibration techniques are discussed along with the performance evolution during Run I. The impact on physics performance is illustrated through the successful quest for the Higgs boson via its electromagnetic decays, and the subsequent mass measurement of the newly discovered particle. Conclusions are drawn for the performance to be expected from 2015 onwards, following the start of the LHC Run II.

1. Introduction
The Compact Muon Solenoid (CMS) experiment [1] is a general purpose experiment at the Large Hadron Collider (LHC) at CERN, designed to search for the standard model (SM) Higgs boson and for new physics beyond the SM. Many of these searches involve electrons or photons in the final state, and the electromagnetic calorimeter (ECAL) plays an essential role in their reconstruction and identification.

1.1. The CMS electromagnetic calorimeter
The CMS ECAL [2] has been designed to achieve an excellent energy resolution, which is a key requirement in the searches of the Higgs boson in final states involving electromagnetic particles and in particular in the \(H \rightarrow \gamma \gamma\) channel, and to guarantee a good hermeticity, allowing good performances on the measurement of the missing energy. It is a homogeneous and hermetic calorimeter containing 61200 lead tungstate \((PbWO_4)\) scintillating crystals mounted in the barrel (EB), closed at each end by endcaps (EE) each containing 7324 crystals. The choice of the \(PbWO_4\) with a radiation length \(X_0=0.85\) cm and a Moliere radius \(R_0=2.19\) cm ensures the compactness of the detector and the radiation hardness necessary to cope with the harsh environment of the collisions at LHC. The scintillation light is detected by avalanche photodiodes (APDs) and vacuum phototriodes (VPTs) in the EB and
In the EB, which covers the pseudorapidity region $|\eta| < 1.48$, the crystals have a truncated pyramidal shape ($2.2 \times 2.2 \text{ cm}^2$ on the frontal face, and a length of 23 cm) and they are organized in 36 supermodules, 18 on each side of the beam interaction point, each with 20 channels along $\phi$ and 85 along $\eta$, divided in four modules along $\eta$. The EE extends the coverage to $|\eta| = 3.0$, with the crystals ($2.86 \times 2.86 \text{ cm}^2$ on the frontal face, and a length of 22 cm) arranged in an x-y grid.

A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is installed in front of EE covering a fiducial region $1.65 < |\eta| < 2.6$.

The ECAL is installed inside the CMS superconductive coil and operates in the strong magnetic field of 3.8 T, used to reconstruct the momentum of charged particle in the CMS silicon tracker which covers the region up to $|\eta| = 2.5$.

### 1.2. Energy reconstruction for electrons and photons

Electrons and photons deposit their energy over many ECAL channels. In fact the electromagnetic shower is not completely contained in a single crystal and, more importantly, the presence of material in front of ECAL causes radiation of energy (conversion of photons and bremsstrahlung from electrons) which is spread along $\phi$ by the strong magnetic field. Clustering algorithms are used to collect the particle energy, be it directly deposited in ECAL or radiated in the tracker material to then reach the calorimeter.

The electron or photon energy is then estimated as:

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

(1)

where, the sum is performed over all the channels, labelled by $i$, which are part of the cluster. $A_i$ is the digital amplitude measured in the channel, $S_i(t)$ is a time dependent correction that account for time variation of a channel response mainly due to changes in the crystal transparency, $C_i$ is a relative calibration constant which takes into account differences in the crystal light yields and photodetector responses and $G$ is a scale factor converting the digital scale into GeV. For clusters in the endcap region the corresponding energy in the preshower ($E_{ES}$) is added. Finally $F_{e,\gamma}$ is particle dependent correction applied to the clustered energy. It accounts for effects related to the geometry of the detector, the upstream material, and the clustering of energy emitted by bremsstrahlung or photon conversion.

This factorization of the various contributions to the electromagnetic energy determination allows for the channels’ stability and intercalibration to be studied separately from material and geometry effects.

Measurements with electron beams [3] demonstrated that the ECAL crystals meet the requirement for an excellent energy resolution, with a stochastic term of 2.8% GeV$^{1/2}$ and a noise term of 12% GeV. The measured constant terms of 0.3% demonstrates an excellent shower containment and longitudinal uniformity of the light collection. Compared to the measurements with the electron beams, the energy resolution for electrons and photons in situ at CMS receives additional contributions from the presence of pile-up, from the material in front of ECAL, and from detector instabilities and channel-to-channel response spread. In order to profit on the excellent intrinsic energy resolution the two latter contributions must be kept to within 0.4%.

In the following the calibration of the ECAL response and the resulting performance in the data collected in the 2012 are illustrated. For detailed description of the ECAL performance in 2011 the reader is referred to [4].
2. Corrections for the change of the response in time

Radiation can create color centers in the crystals reducing their transparency and therefore reducing the measured response to the deposited energy. The color centers partially anneal with thermal energy so that the loss in transparency depends on the dose rate, which for ECAL varies along $\eta$. In absence of radiation a partial recovery of the transparency is observed. While an intense R&D program led to the production of radiation resistant PbWO$_4$ crystals, a residual radiation damage remains and needs to be corrected for. Thus, the changes in transparency are measured by a dedicated laser monitoring system [5] (LM) which injects every 40 minutes a laser pulse ($\lambda = 440$ nm, close to the peak of the scintillation light spectrum for PbWO$_4$) into each single crystal. The relative change in transparency ($R/R_0$) does not directly measures the relative change in response for the scintillation light ($S/S_0$) since the two have different spectra and the optical photons travel different paths to reach the photodetectors, but they can be related by a power law:

$$
\frac{S}{S_0} = \left( \frac{R}{R_0} \right)^\alpha
$$

The measured loss in transparency at the end of the LHC Run I in 2012 is less than 6% in EB and less than 30% in the EE region within the tracker acceptance ($|\eta| < 2.5$), while it reaches 70% in the most forward EE region. The corrections for transparency loss (LC) can be validated with collisions data, by monitoring the stability of the reconstructed invariant mass of $\pi^0$ and of the distribution of $E/p$ for isolated electrons, where $E$ is the energy measured in the calorimeter and $p$ is the momentum measured in the tracker.

Applying the LC the stability is better than 0.1% in the barrel and 0.4% in the endcaps. As an example the stability during 2012 measured with the $E/p$ distribution is reported in figure 1.

Measurements performed with electron beams on a small ensemble of crystals show a dispersion in the values of $\alpha$ of 10% [6]. In deriving the LC according to equation 2 a common value (one for EB and one for EE) is used. The resulting residual imperfection of the LC due to the dispersion in the values of $\alpha$ can be recovered by allowing a time dependence of the calibrations constants as explained in the next section.

Figure 1. Stability of the $E/p$ scale during 2012, before (red) and after (green) the LC, for the ECAL barrel. Each point is obtained with a statistic of 20000 electrons. The projections along the Y axis are shown in the histograms on the right side.
3. Relative calibration and energy scale

The relative calibration ("intercalibration" IC) is obtained in situ employing collision data, after applying the LC, with different methods employing, the azimuthal symmetry of the energy flow ("φ-symmetry"), photons pairs from the $\pi^0$ decay, and isolated electrons ($E/p$). Hereafter these methods and their performances are briefly described, for a detailed description the reader is referred to [4] and references therein.

The φ-symmetry method is based on the equalization of the average energy measured in the different channels placed at the same $\eta$. It employs a dedicated data stream with a very reduced event information allowing to store a high rate of events (∼ 1.5 kHz), and it reaches for each LHC fill cycle a statistical accuracy better than 0.2% (0.4%) in the barrel (endcap). The accuracy of the method is indeed limited to few percents by the systematic uncertainty in the knowledge of the material in front of ECAL. Since the systematic does not vary with time the method can be used to track possible time dependencies of the IC values. Indeed in 2012 a drift of the ICs was observed ascribable to imperfections of the laser corrections [7].

The $\pi^0$ mass method is based on the reconstruction of the peak in the spectrum of the invariant mass of unconverted photon pairs due to $\pi^0$ and $\eta$ decays. The photons are reconstructed as $3 \times 3$ matrices of calorimeter channels, and an iterative method is used to determine the IC value of each single channel. It employs a dedicated data streams at high rate (∼ 7 kHz) and it reaches a 0.5% precision in the central barrel, dominated by systematics when using a data sample corresponding to about 45 days of data taking. With the high pile-up of the LHC running in 2012 the reconstruction of the peak of $\pi^0$ in the region at $|\eta| > 2$ is challenging and only the peak from $\eta \rightarrow \gamma \gamma$ is used.

The $E/p$ method is based on the comparison of the energy measured in the calorimeter (eq 1) to the momentum measured by the tracker for isolated electron, and an iterative procedure is used to extract the IC value for each channel. The method requires the full 2012 dataset and in the central barrel its precision reaches the systematic limit of 0.5%, while for $|\eta| > 1$ the statistical contribution is still significant.

These methods may be affected by $\eta$ dependent systematics due for instance to the effect of pile-up or of the material in front of ECAL, therefore they are employed to obtain a relative calibration of the channels within a ring at constant $\eta$ ("$\eta$ ring"), and their results are combined accordingly to their precision. The precision of the different methods and of their combination is reported in figure 2. In the region $|\eta| > 2.5$, above the tracker acceptance, the $E/p$ method can not be used and the high pile-up prevents the reconstruction of the invariant mass peak from $\pi^0$ or $\eta$, therefore only the ICs from the φ-symmetry are available.

To compensate for the imperfection in the LC, the time dependence observed in the ICs from the φ-symmetry method is propagated to the final calibration, in time intervals of the order of one month.

The relative calibration of the $\eta$ rings ($\eta$ scale) is obtained from the Z boson peak in the distribution of the invariant mass of electron pairs, selecting a sample of electrons with low emission of bremsstrahlung. The $\eta$ scale is set to match the expectation from a detailed Monte Carlo simulation of the detector response to $pp \rightarrow Z X \rightarrow e^+e^- X$.

Finally the overall energy scale $G$ is set, separately for EB and EE, such that the reconstructed Z peak in data matches the one in the MonteCarlo.
4. Performance of the detector

The energy resolution for electrons and photons plays a crucial role in the search for the Higgs with electromagnetic final states, and needs to be precisely estimated, in particular for the search in the Higgs decays channel $H \rightarrow \gamma\gamma$, since it affects the modelling of the expected signal. The accuracy of the calibration directly contributes to the energy resolution with a dilution factor $\sim 0.7$ due to the sharing of the energy among different channels. Indeed the actual energy resolution for electrons can be measured from the shape of the invariant mass distribution of electron pairs in the region dominated by $Z \rightarrow e^+e^-$ events. Figure 3 reports the measured energy resolution as a function of $|\eta|$. The calibration available at the beginning of 2012 has been used for a prompt reconstruction of the data. The performance of the prompt reconstruction (grey) can be compared with the one from a calibration based on the full 2012 dataset (blue) and an improvement can be seen in particular in the endcaps. The figure reports also the expected resolution from a Monte Carlo simulation. The discrepancy between data and Monte Carlo measured for electron is propagated to the Monte Carlo simulation of processes involving photons.

Figure 2. Precision of the calibration coefficients as a function of $|\eta|$, for the barrel (left) and the endcaps (right). The precisions of the different methods and of their combination are reported.

Figure 3. Energy resolution for electrons as a function of $|\eta|$. The performance with an initial (grey) and after the final (blue) calibration are reported, as well as the expected values (red) from a Monte Carlo simulation of the detector.
5. Plans for the LHC Run II

The LHC Run II in 2015 will be characterized by an increased center of mass energy ($\sqrt{s} = 13$ TeV) and by an increase of about a factor two in the instantaneous luminosity and therefore by an increase of the pile-up.

While the overall strategy for the calibration and monitoring of the ECAL performance is planned to follow the run1 strategy, some optimizations and development are foreseen. In particular the calibration data-streams for the $\pi^0$ and $\eta$ methods are being optimized to cope with the increased pile-up and to improve the accuracy in the endcaps, and a dedicated stream with a reduced event information for the calibration with $E/p$ is being developed to fully profit of the increase in the rate of isolated electron from $W \rightarrow e\nu$.

Additional methods have been developed to calibrate the endcap region employing an invariant mass constraint on $Z \rightarrow e^+e^-$ events. Preliminary studies indicates that this can improve the accuracy of the calibration in the endcap region covered by the tracker and it can also be extended to the region at $|\eta| > 2.5$ by reconstructing one of the two electrons employing only the calorimetric information. In fact, even if in this case the effectiveness of the electron identification is reduced, it has been shown that the level of background in the invariant mass region close to the Z mass remains marginal.

The calibration procedure with this method is being finalized and it is expected that it will be part of the calibration routine in 2015.

During the LHC Run I the imperfection of the LCs due to the spread of the value of $\alpha$ (equation 2) was effectively recovered by time-dependent ICs with a negligible impact on the energy resolution. With the increased dose rate expected in Run II it might become useful to determine the value of $\alpha$ per channel, in particular in the region at high $\eta$. Indeed during 2012 different methods have been developed to measure in situ the value of $\alpha$, by comparing the variation of the response to a reference signal with the change in transparency measured by the laser monitoring system ($R/R_0$ in equation 2). As reference signal we have investigated the $E/p$ distribution for isolated electrons, the $\pi^0$ peak in the invariant mass distribution of photon pairs and the energy flow in each channel. The different methods can determine the value of $\alpha$ with different granularity: in groups of 100 and 25 channels with respectively the $E/p$ and $\pi^0$, and for each single channel with the energy flow. The study of the optimal combination of the different measurements is ongoing and different $\alpha$ values for the LC are expected to be available to be used in 2015, where relevant.

References