Calibration of the CMS hadron calorimeter in Run 2

M. Chadeeva\textsuperscript{a,b,1} and N. Lychkovskaya\textsuperscript{c} on behalf of the CMS collaboration

\textsuperscript{a}NRNU MEPhI, 31, Kashirskoe shosse, Moscow, Russia
\textsuperscript{b}P.N. Lebedev Physical Institute, 53, Leninsky prospect, Moscow, Russia
\textsuperscript{c}ITEP, 25, B. Cheremushkinskaya, Moscow, Russia

E-mail: marina.chadeeva@cern.ch

ABSTRACT: Various calibration techniques for the CMS Hadron calorimeter in Run 2 and the results of calibration using 2016 collision data are presented. The radiation damage corrections, intercalibration of different channels using the phi-symmetry technique for barrel, endcap and forward calorimeter regions are described, as well as the intercalibration with muons of the outer hadron calorimeter. The achieved intercalibration precision is within 3\%. The \textit{in situ} energy scale calibration is performed in the barrel and endcap regions using isolated charged hadrons and in the forward calorimeter using the $Z \rightarrow ee$ process. The impact of pileup and the developed technique of correction for pileup is also discussed. The achieved uncertainty of the response to hadrons is 3.4\% in the barrel and 2.6\% in the endcap region (at the pseudorapidity range $|\eta| < 2$) and is dominated by the systematic uncertainty due to pileup contributions.

KEYWORDS: Calorimeters; Detector alignment and calibration methods (lasers, sources, particle-beams); Performance of High Energy Physics Detectors

\textsuperscript{1}Corresponding author.
1 Introduction

The general-purpose CMS (Compact Muon Solenoid) detector was designed to study proton-proton collisions at record centre-of-mass energies up to 14 TeV and successfully operates at the LHC at CERN. The high magnetic field provided by the superconducting solenoid allows a high-precision charged particle momentum reconstruction by the all-silicon pixel and strip trackers. The CMS calorimeter system includes lead-tungstate scintillating-crystal electromagnetic calorimeter, a brass-scintillator sampling hadron calorimeter and steel-quartz-fiber forward sampling calorimeters. The hadron calorimeter (HCAL) plays a crucial role in the measurements of jet and missing transverse energy. It consists of the barrel (HB) at $|\eta| \leq 1.3$, endcaps (HE) at $1.3 \leq |\eta| \leq 3.0$, outer calorimeter (HO) or tail catcher, which roughly maps the towers of the barrel part and is placed outside the solenoid, and forward calorimeters (HF), which cover the pseudorapidity range $3.0 \leq |\eta| \leq 5.2$. The segmentation of HB and HE is $\Delta \eta \times \Delta \phi = 0.087 \times 0.087$ ($0.17 \times 0.17$) for $|\eta| < 1.6$ ($|\eta| \geq 1.6$), while HF has a coarser segmentation increasing with pseudorapidity. The detailed description of the detector layout including its longitudinal segmentation can be found in ref. [1]. Hereinafter, the notation $i\eta$ ($i\phi$) means the number of the corresponding pseudorapidity ring (azimuthal segment).

The embedded radioactive source, laser and LED systems are used to monitor the performance of the CMS HCAL. For \textit{in situ} calibration, several techniques were developed, which include a channel-by-channel intercalibration using a phi-symmetry technique for the HB, HE and HF and a response to muons for the HO. The energy scale calibration is done using the isolated charged hadrons technique for the barrel and endcaps and $Z \rightarrow ee$ technique in the forward region outside the tracker coverage. The main goals of the calibration are to keep a stable energy scale of all channels during a long term data taking period (within 3–5%) and provide an agreement of the HCAL energy scale between data and simulations within 3–5%.
2 Radiation damage monitoring and corrections

The high level of radiation originating from particles produced in beam-beam interactions leads to a deterioration of the light collection from the active material of the HCAL calorimeters. The radiation dose strongly depends on the luminosity provided by the LHC machine, and leads to a time-dependent degradation of calorimeter response. The irradiation depends also on the angle and depth at which particles penetrate the detector. The effect of radiation damage on the HE and HF performance in Run 2 data taking period is investigated in the offline analysis based on the collision data and the dedicated laser measurements \[1\].

The radiation damage measurement with the collision data relies on a time-dependent comparison of energy deposition in calorimeter channels using the events of inclusive Z boson production. The radiation damage is calculated with respect to pseudorapidity ring $|\eta| = 16$ and normalized to the response at the beginning of the data taking period. Figure 1 (left) shows the relative radiation damage as a function of delivered luminosity for the first depth of the HE. The results of HF radiation damage estimates in Run 1 and Run 2 are presented in figure 1 (right). The precision of the relative corrections is within 3\%. The laser and collision data measurements of the radiation damage in the HE give consistent results.

![Figure 1](image1.png)

**Figure 1.** Left: radiation damage in HE as a function of delivered luminosity in 2016. Right: radiation damage measured in the long fiber cells of HF from the beginning of Run 1 up to the end of 2016 versus delivered luminosity. For 7 and 8 TeV, luminosity was scaled by a factor of 0.75 according to the difference in dose rates. The curves show exponential fits \[2\].

3 Intercalibration methods

The intercalibration is performed to equalize the response over azimuthal angle for each $\eta$ ring in HB, HE and HF calorimeters. The intercalibration of HO is aimed at equalization of response in the cells of outer calorimeter using minimum ionizing particles.
3.1 Phi-symmetry technique

The procedure of equalization of response in the different \(i\phi\) channels takes advantage of the azimuthal symmetry of the detector and the corresponding \(\phi\)-symmetric energy deposition for events collected in minimum-bias and physics data streams. Two independent calibration procedures, which utilize different data samples, are used to extract \(\phi\)-symmetry correction factors. Both methods equalize the response over \(\phi\) for each \(i\eta\) ring and longitudinal depth segment.

- **Iterative method** utilizes the physics data sample and equalizes the mean of readout energies. The lower threshold of the energy spectra (4–10 GeV) is set above the pedestal high energy tail. The upper threshold is set to 100–150 GeV to exclude accidental high-energy hits.

- **Method of moments** utilizes the minimum-bias data sample and equalizes mean or variance of the reconstructed hit energy distributions in the full energy range (without any threshold for non-zero-suppressed mode).

Final correction factors for the HCAL calibration coefficients are estimated as the error-weighted averages of corrections obtained by the iterative method and method of moments. The iterative method uses the reconstructed hits from higher energy range compared to the method of moments. Therefore, when combined, wider energy range is covered, and some crosscheck of the results is available. Comparison of the azimuthal corrections obtained by two methods using 2016 collision data is shown in figure 2 for HB, HE and HF and demonstrates a good agreement between the methods. The residual disagreement can be explained by the fact that the sources of systematic uncertainties are different for two methods. The intercalibration precision is within 3%.

![Figure 2](image_url)

**Figure 2.** Typical distributions of the ratios of correction factors from the iterative method to those from the method of moments, \(\text{Corr(Iterative method)}/\text{Corr(Method of moments)}\), in HB (left), HE (middle), and HF (right) obtained from 2016 data samples for the integrated luminosity of \(8 \text{ fb}^{-1}\) [2].

3.2 Calibration with muons

The channel-by-channel intercalibration of the outer hadron calorimeter is performed using either cosmic ray muons and/or \(W \rightarrow \mu\nu\) and \(Z \rightarrow \mu\mu\) events from proton-proton collision data. For calibration, well reconstructed and isolated muons are selected and energy distributions are normalized by muon path length in the scintillators of HO segments. The relative correction factors are calculated using the most probable values (MPV) extracted from the fit of energy distributions by the convolution of Landau and Gaussian functions. Resulting intercalibration precision is \(~2\%\).
4 Energy scale calibration

4.1 Isolated charged hadrons technique

The energy scale of the CMS HCAL is calibrated using isolated charged hadrons with momenta from 40 to 60 GeV. The main goal is to ensure the uniformity of response to hadrons as a function of $\eta$ and establish an absolute energy scale. This technique can be used in the areas covered by the tracking system, where the momentum of a charged particle, $p_{\text{track}}$, can be measured with a very high degree of precision and associated to the energy deposition in the calorimeter. For each event, the energy of the isolated cluster, $E_{\text{hcal}}$, is calculated as the sum of energies of the cells, which contribute to the cylinder of radius $R_{\text{cone}} = 35$ cm oriented along the particle momentum direction at the HCAL surface. The response is defined as the ratio $E_{\text{hcal}}/(p_{\text{track}} - E_{\text{ecal}})$, where $E_{\text{ecal}}$ is the energy in the electromagnetic calorimeter calculated within a radius of 14 cm around the track impact point.

Basic selection criteria include requirements on primary vertex and track reconstruction quality, constraint on the energy deposition in the electromagnetic calorimeter ($E_{\text{ecal}} < 1$ GeV), constraint on the energy deposition in the HCAL ($E_{\text{hcal}} > 10$ GeV) to exclude punch-through events. The additional requirement on charge isolation is important to guarantee the absence of contributions to the measured cluster from other particles and restricts the maximal momentum of the neighbor tracks found in the isolation cone of radius 64 cm around the track of interest. The tight isolation constraint is 2 GeV. Such a requirement results in a very low selection efficiency in the endcap region of the HCAL at pileup conditions. To increase the efficiency of selection of the isolated charged hadron candidates, a loose constraint on charge isolation was implemented (10 GeV) and the technique for event-by-event pileup correction was developed. The method of correction for pileup was tested using simulated pion samples generated with and without pileup conditions. Figure 3 (left) shows the number of events selected from the simulated sample with and without pileup using tight and loose isolation constraints. The loose constraint helps to achieve efficiency comparable with that for the sample without pileup.

The calibration technique utilizes the iterative procedure and provides one energy scale correction factor per $i\eta$ ring and depth segment. The goal is to get the MPV of response equal to 1 in the rapidity range covered by the HCAL barrel and endcap. The MPV of response is extracted from the two-step Gaussian fit to the response distributions. The results of equalization of response for simulated samples is shown in figure 3 (right). The achieved uncertainty of the energy scale in simulations is 0.5% in HB ($|\eta| \leq 1.2$) and 1.2% in HE ($1.2 < |\eta| < 2.5$), including statistical uncertainty of 0.2%.

The procedure of correction for pileup was tuned on simulated samples and was checked using 8 fb$^{-1}$ of data from pp collisions at 13 TeV collected in 2016. The pileup level is defined based on the number of reconstructed vertices, $N_{\text{vtx}}$, which distribution is shown in figure 4 (left). The low-pileup and high-pileup subsamples contain events with $N_{\text{vtx}} < 10$ and $N_{\text{vtx}} > 25$, respectively. Figure 4 (right) shows the ratio of the response in $i\eta$ rings of the whole sample and high-pileup subsample to the response of the low-pileup subsample. The estimated residual uncertainty of MPV due to correction for pileup is $\sim 3\%$ in HB ($|\eta| \leq 1.2$) and $\sim 2\%$ in HE ($1.2 < |\eta| \leq 2.0$).

The calibration of the HCAL energy scale in Run 2 using isolated charged hadron technique was performed for the subdetectors in the range $-2 \leq \eta \leq 2$. The correction factors for subdetectors
Figure 3. Left: number of selected isolated tracks per $\eta$ ring for the simulated samples of 50 GeV charged pions without pileup (black) and with pileup and tight (red) and loose (blue) isolation constraints applied. Right: MPV of response to simulated charged pions in $\eta$ rings before (black) and after (red) equalization, loose isolation constraint is applied [3].

Figure 4. Left: distribution of the number of reconstructed vertices for the events selected from the pp collision data sample at 13 TeV. Right: ratio of the response in $\eta$ rings of the whole sample (red) and high-pileup subsample (blue) to the response of the low-pileup subsample. The uncertainty of the low-pileup subsample is shown with the gray band [3].

outside this range were set to 1. Calibration improves the HB energy scale by $\sim 1\%$ and the energy resolution in transition region between barrel and endcap by $\sim 6\%$. The MPV in $\eta$ rings and the response distributions in HE before and after equalization are shown in figure 5 on the left and on the right panel, respectively. The bias of $\sim 2\%$ of the energy scale in HE was removed by calibration.

4.2 Forward region calibration with $Z \to ee$ technique

The energy scale of the forward calorimeters, which are outside the tracker coverage, is calibrated using $Z \to ee$ events. Two selection conditions must be satisfied: one electron candidate is required to be reconstructed in the electromagnetic calorimeter, while another candidate must be detected in HF. The invariant mass of dielectron system is reconstructed. The peak of the invariant mass
distribution is below the mass of $Z$ boson due to a leakage into the noninstrumented region. The peak position from the data distribution is compared to that obtained from the simulated sample. The difference in the width of the dielectron invariant mass between simulation and data, which is attributed to an underestimation of HF electromagnetic shower energy resolution in simulation, does not affect the determination of the invariant mass peak position. The effect of the background on the peak determination was studied by varying the electron selection criteria in data and was found to be negligible. The precision of the energy scale achieved by this method is about 3%.

5 Summary

Different calibration techniques for the CMS hadron calorimeter developed during the Run 1 are adjusted and successfully applied for the calibration of the HCAL in Run 2. The relative equalization of response within 3% over azimuthal sectors of the HB, HE and HF was achieved using the phi-symmetry technique. The intercalibration precision of HO cells with muons is about 2%. The response to 40–60 GeV hadrons was equalized to the unit level within 3.4% in HB and 2.6% in HE (up to $|\eta|<2$) using isolated charged hadron technique. An agreement between data and simulations within 3% over all $\eta$ ranges in HF was established by means of the $Z \rightarrow ee$ technique.

Acknowledgments

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References

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