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Calibration of the CMS Hadron Calorimeter in Run 2

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Abstract

Various calibration techniques for the CMS Hadron calorimeter in Run2 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 *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 $|\eta| < 2$) and is dominated by the systematic uncertainty due to pileup contributions.

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Calibration of the CMS hadron calorimeter in Run 2

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KEYWORDS: Hadron calorimeter, calibration methods, radiation damage

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Contents

1	Introduction	1
2	Radiation damage monitoring and corrections	2
3	Intercalibration methods	2
3.1	Phi-symmetry technique	3
3.2	Calibration with muons	3
4	Energy scale calibration	4
4.1	Isolated charged hadrons technique	4
4.2	Forward region calibration with $Z \rightarrow ee$ technique	5
5	Summary	6

1 Introduction

The general-purpose CMS (Compact Muon Solenoid) detector was designed to study proton-proton collisions at record centre-of-mass energies at luminosities up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and successfully operates at the LHC at CERN. The high magnetic field provided by the superconducting solenoid allows high-precision vertex and track reconstruction by the all-silicon pixel and strip trackers. The CMS calorimeter system includes lead-tungstate scintillating-crystals 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 at $3.0 \leq |\eta| \leq 5.2$. The segmentation of HB and HE is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ (0.17×0.17) 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 *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 is 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 by means of the measurement with the dedicated laser system.

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. 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 ϕ -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 ϕ -symmetry correction factors. Both methods equalize the response over ϕ for each $i\eta$ ring and longitudinal depth segment.

- **Iterative method** utilizes the physics data sample and equalizes the mean of readout energies. The energy spectra are obtained using the following thresholds: the lower threshold of 4–10 GeV and the upper threshold of 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. One can see good agreement between corrections obtained using different methods. Some disagreement is caused by the different sources of systematic uncertainties of the methods used. The intercalibration precision is within 3%.

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 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. Muon signal energy distributions are normalized by their path length in the scintillators for different HO segments. The energy distribution in each channel is fitted by the convolution of the Landau and Gaussian functions. The

relative correction factors are calculated using the most probable values (MPV) extracted from the fit. Resulting intercalibration precision is $\sim 2\%$.

4 Energy scale calibration

4.1 Isolated charged hadrons technique

The energy scale of the CMS HCAL is calibrated using isolated charged hadrons with the momenta from 40 to 60 GeV. The main goal is to ensure the uniformity of response to hadrons as a function of η and establish an absolute energy scale. This technique can be used in the areas covered by the tracking system, where the momenta of charged particles 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_{hcal} , is calculated as the sum of hits in the cone of radius $R_{\text{cone}} = 35$ cm around the impact point of the selected track with measured momentum, p_{track} . The response is defined as the ratio $E_{\text{hcal}}/(p_{\text{track}} - E_{\text{ecal}})$, where E_{ecal} is the energy in the electromagnetic calorimeter calculated in the cone of radius 14 cm around the track impact point.

Basic selection criteria include the 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 at pileup conditions results in a very low selection efficiency in the endcap region of the HCAL. To increase the efficiency of selection of the isolated charge hadron candidates, loose constraint on charge isolation is 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 each $i\eta$ 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 developed procedure of correction for pileup tuned on simulated samples was checked using 8 fb^{-1} of collected data from pp collisions at 13 TeV in 2016. The pileup level is defined based on the number of reconstructed vertices, N_{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 all sample and high-pileup subsample to the response of 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 ($1.2 < |\eta| \leq 2.0$).

Figure 3. Left: Number of selected isolated tracks per $i\eta$ 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 $i\eta$ 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 $i\eta$ rings of the all sample (red) and high-pileup subsample (blue) to the response of low-pileup subsample. The uncertainty of the low-pileup subsample is shown with the gray band [3].

The calibration of the HCAL energy scale in Run 2 using isolated charge hadron technique was performed for the subdetectors in the range $-2 \leq \eta \leq 2$. The correction factors for subdetectors 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 $i\eta$ rings and the response distribution in HE before and after equalization is 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 $Z \rightarrow ee$ technique

The energy scale of the forward calorimeters, which are outside the tracker coverage, is calibrated using $Z \rightarrow ee$ events. Two selection conditions must be satisfied: one electron candidate is required

Figure 5. Left: The MPV of response to isolated charged hadrons from pp collision data in η rings. Right: Response distribution in HE (points) and fit with Landau@Gaussian function (curves). The results are shown before (black) and after (red) calibration [3].

to be reconstructed in the electromagnetic calorimeter, while another candidate must be detected in HF. The invariant mass of di-electron system is reconstructed. The peak position from the data distribution is compared to that obtained from simulated sample. The peak of the invariant mass distribution obtained for $Z \rightarrow ee$ events from 2016 data sample is below the mass of Z boson due to a leakage into the noninstrumented region. The higher tails and wider mass peak in data compared to simulations do not affect a calibration based on the peak position. 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 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 η ranges in HF was established by means of $Z \rightarrow ee$ technique.

Acknowledgments

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