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**CMS CR -2012/266**

The Compact Muon Solenoid Experiment

**Conference Report**

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

**12 October 2012 (v2, 13 October 2012)**

# Operational Experience with the CMS Hadronic Calorimeter in the 2011 LHC run

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The Hadronic Calorimeter (HCAL) of the CMS experiment has successfully recorded data at a center-of-mass energy of 7 TeV during the 2011 LHC run. Performance of the HCAL detector components and operational experience gained will be reviewed, as well as the overall impact of the HCAL on the physics reach of the CMS experiment.

Presented at *CALOR 2012: 15th International Conference on Calorimetry in High Energy Physics*

# Operational Experience with the CMS Hadronic Calorimeter in the 2011 LHC run

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**Abstract.** The Hadronic Calorimeter (HCAL) of the CMS experiment has successfully recorded data at a center-of-mass energy of 7 TeV during the 2011 LHC run. Performance of the HCAL detector components and operational experience gained will be reviewed, as well as the overall impact of the HCAL on the physics reach of the CMS experiment.

## 1. Introduction

The CMS detector at the CERN Large Hadron Collider has been constructed to study a range of high-energy processes involving diverse signatures of final states, by using various objects such as electrons, muons, taus, photons, jets, and missing transverse energy [1, 2]. The hadronic calorimeter (HCAL) plays a crucial role in the measurement of hadron jets and exotic particles with missing transverse energy signatures.

The barrel (HB) and endcap (HE) calorimeters are positioned behind the tracker and electromagnetic calorimeters, while inside the 3.8T magnet solenoid. The outer hadron calorimeter (HO) lies outside the solenoid, to identify late starting showers and to measure the shower energy deposited after HB. The barrel, endcap, and outer detectors contain active plastic scintillator tiles interspersed between stainless steel and brass absorber plates. They are read out with custom made hybrid photo-detectors (HPD) [3] designed to operate in magnetic fields up to 4T. The forward hadron calorimeters (HF) are positioned 11.2m away from the interaction point and are made of steel absorbers and embedded quartz fibers, which are read out with conventional photomultiplier tubes (PMTs) [4]. The calorimeters extend to pseudorapity $|\eta| = 5$.

Throughout the first year of operation, timing and calibration measurements were continuously made to optimize HCAL performance. In this note, we will review the initial, and in-situ calibration of HCAL throughout the first full year of the LHC run.

## 2. Monitoring HCAL Status

The low and high voltage of HCAL is monitored through PCs in the CMS control room. Additionally, HCAL is equipped with laser, LED, and radiation damage monitoring systems. The pedestal values of the individual channels are periodically checked by using dedicated pedestal runs, and are adjusted if significant drifts from the initial pedestal values are observed. The signal synchronization (timing) of the HCAL channels is performed with the laser system, which consists of a single UV laser which can illuminate portions of the sub-detectors at once through a series of optical splitters. The stability of photo-detector gains is monitored using the LED system. Calibration and monitoring data is collected during dedicated calibration session in which there is no beam in the LHC, and during data taking in orbits which do not contain proton bunches. The data collected is used to produce relevant histograms and tables for monitoring the status of HCAL. Experts continuosly monitor this data, and take corrective action when necessary, to ensure quality data taking.

## 3. HCAL Calibration

Prior to the LHC startup, charge injection calibration (fC/ADC) as part of incoming QC was performed. This was followed by calibration from $Co^{60}$ radioactive sources and cosmic ray muons in the underground hall. The absolute energy scale was determined with pion and electron test beams on selected modules, and carried over using radioactive sources. At the start-up of the LHC, additional calibration was performed with proton bunches hitting collimators upstream of CMS, which resulted in a large horizontal flux of muons traversing CMS detectors (splash events). Collisions data was then used to obtain calorimeter response corrections, which include the following methods discussed below: $\Phi$-symmetry (Sec. 3.2); the method of isolated hadrons for HBHE (Sec. 3.4); and $Z \rightarrow ee$ scale for HF (Sec. 3.5).

### *3.1. Monitoring HPD and PMT Gain Drift*

Approximately 4% of barrel and endcap channels exhibited gain drifts of 10% from Oct-2010 to Sep-2011. The remaining channels were stable at the level of 2-3% over a period of one year (Fig. 1). In the forward calorimeters, LED and laser data showed an $\eta$-dependent drop in response in the PMTs, with a systematic gain loss vs. integrated luminosity. There was a drop of 3% for $5fb^{-1}$ range and up to 10% for high $\eta$ in 2011.

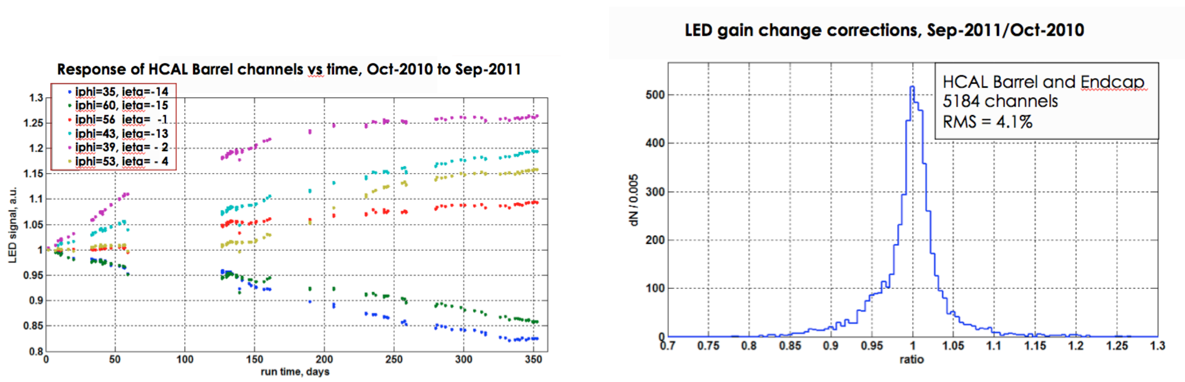


**Figure 1.** Response of selected barrel channels to LED signals vs time (left), and LED gain change corrections Sept-2011 / Oct-2010 (right).

### *3.2. $\Phi$-Symmetry Calibration*

Two methods were used to determine the relative response of HCAL channels at fixed $\eta$, and estimate corrections to produce a uniform response in $\Phi$, without changing the overall energy scale. Corrections to calibration coefficient were found under the requirement that all channels with the same $\eta$ have their total energy depositions, estimated within chosen thresholds, equal to the average energy of channels at this $\eta$ (iterative method). The second method (method of moments) uses non-zero-suppressed data to determine corrections for the calibration coefficients, under the requirement that all channels with the same $\eta$ ring have the same mean or same variance - in the variance case, the contribution from noise is subtracted. The scatter plot on Fig. 2 (left) shows the correlation between the two methods, and the final correction (right), which is obtained from an error weighted average of the two methods, in the initial 2010 data.

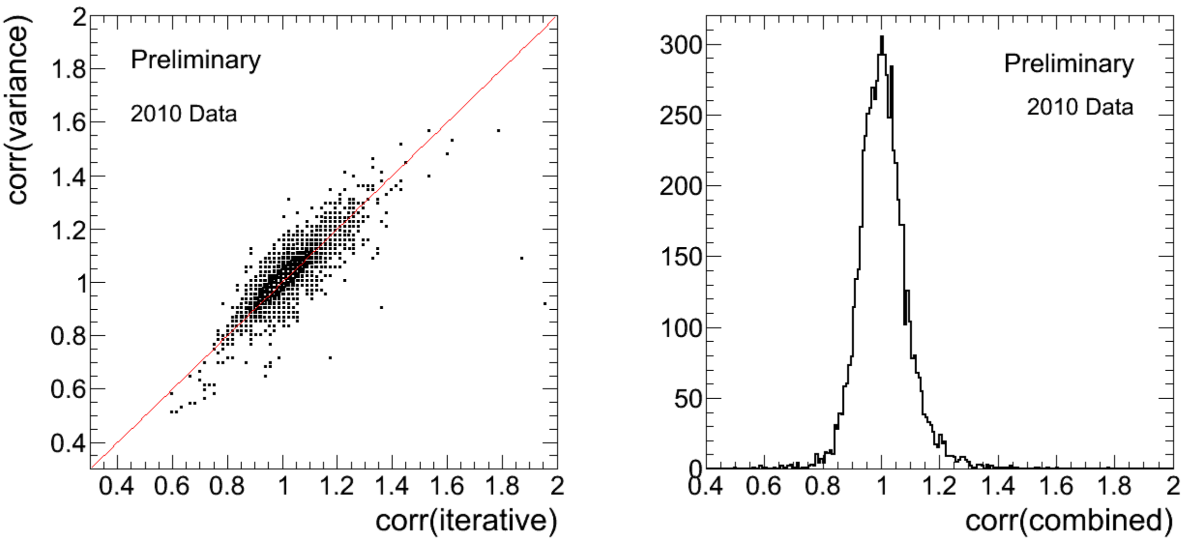


**Figure 2.** Comparison of corrections obtained using the Φ-symmetry calibration methods (left), and the final corrections determined by an error-weighted average of the two methods (right) with initial 2010 data.

### *3.3. Φ-Symmetry Calibration with LED Corrections*

The gain corrections are based on monitoring the HPD response to LED signals. With the LED, each channel can be individually corrected, while with the Φ-symmetry method, the corrections are obtained in rings of $\eta$, and are not as precise. However, solely correcting with LED data is insufficient, as it is not known if the LED pulsers consistently put out the same energy. To verify if there was indeed a gain drift, the Φ-symmetry calibration is performed both with and without the LED corrections. The right plot of Fig. 3, which shows the result of the Φ-symmetry calibration without, and with the LED gain corrections, confirms that the LED corrections reduce the spread of 2011 Φ-symmetry calibration w.r.t. the 2010 results.

### *3.4. Isolated Hadron Response for HBHE*

Isolated tracks are used to apply an $\eta$-dependent energy correction to the data in the region with tracker coverage ($|i\eta| \leq 22$), to set the absolute energy scale. A dedicated trigger is used to select events with isolated tracks with $p_T > 40$ GeV. The left plot on Fig. 4 show the response of the tracks used to derive the corrections. On the right, a cross-check is performed with lower $p_T$ tracks (38-40 GeV), showing that the response is corrected. The 2011 response correction was calculated on top of the 2010 absolute scale corrections with isolated tracks.

### *3.5. Absolute Scale for HF*

The absolute scale for HF is derived from $Z \to ee$ events. The LHC sends many $Z$ bosons far forward, with an electron hitting HF. The electromagnetic calorimeter is used to provide detailed inputs for the calibration and rejection of jet fakes. The position of the electrons are

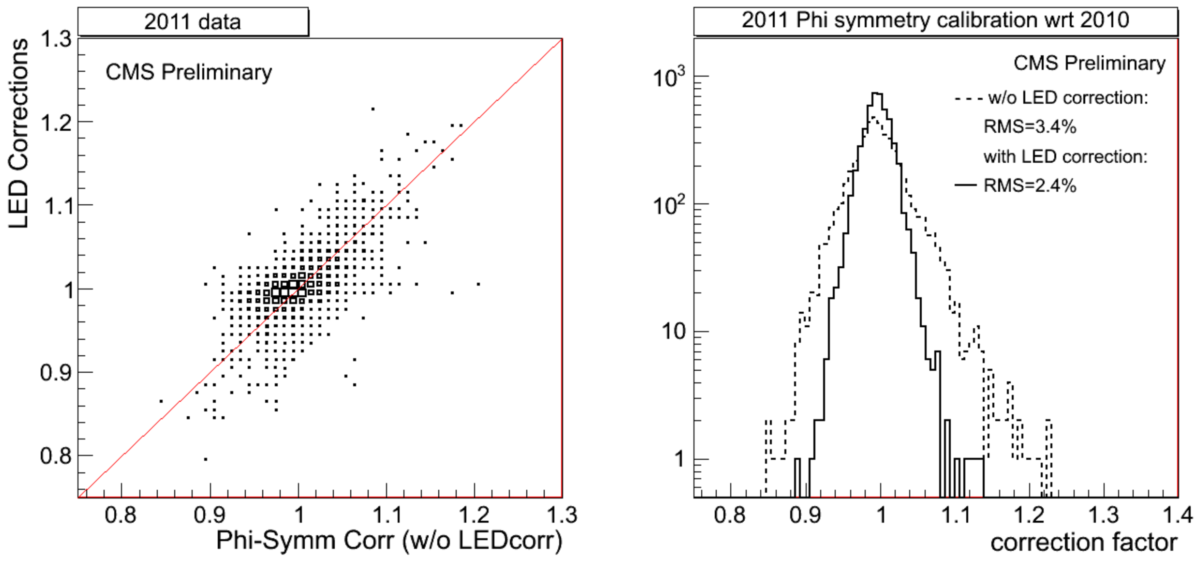


**Figure 3.** LED correction vs. Φ-symmetry correction before applying the LED correction (left), and the correction factor with and without the LED correction (right), for 2011 data.

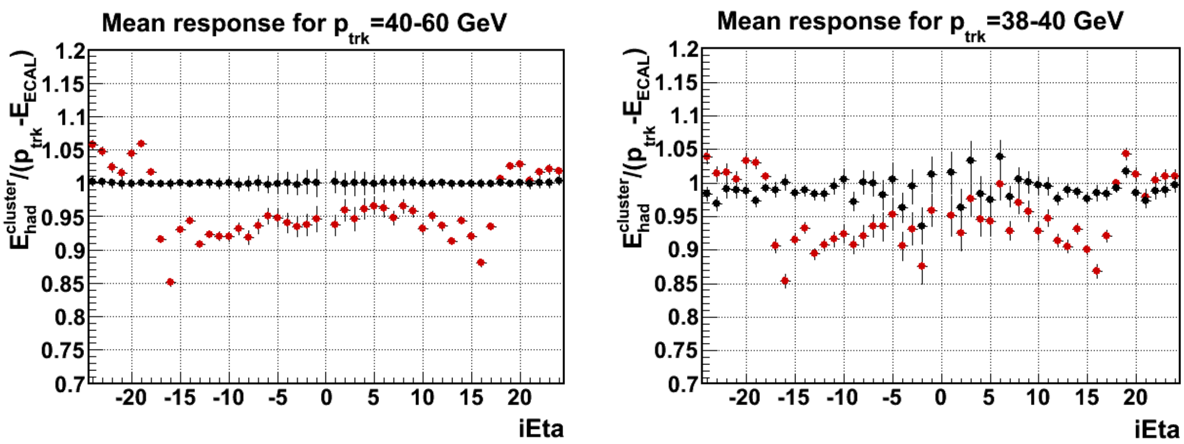


**Figure 4.** The mean response for $p_T = 40 - 60$ GeV tracks before (red) and after (black) corrections (left histogram). The right histogram shows a cross check performed with lower $p_T$ tracks (38-40 GeV). The sudden change in the response of the uncorrected tracks on the left histogram are at the last $\eta$ ring of HCAL barrel detector ($|\eta| = 1.4$).

reconstruced in HF, and the $Z$ mass constraint is used to derive the expected energy in HF via

$$E_H = \frac{m_Z^2\ cosh\eta_E\ cosh\eta_H}{2E_E(cosh(\eta_E - \eta_H) - cos(\phi_E - \phi_H))}. \tag{1}$$

A fit to the ratio of the expected and observed energy in HF as a function of the i$\eta$ of the seed tower is then performed (Fig. 5, left).

The calibration can be affected by pileup energy being added in the HF cluster (particularly neutral-pion energy). This effect is dependent on the number of interactions in the event. A vertex dependent correction is applied by fitting the calibration constant as a function of the vertex count to extrapolate to the one-vertex case (the vertex for the $Z$ production). The correction ratio as a function of the effective number of vertices is shown in Fig. 5, right.

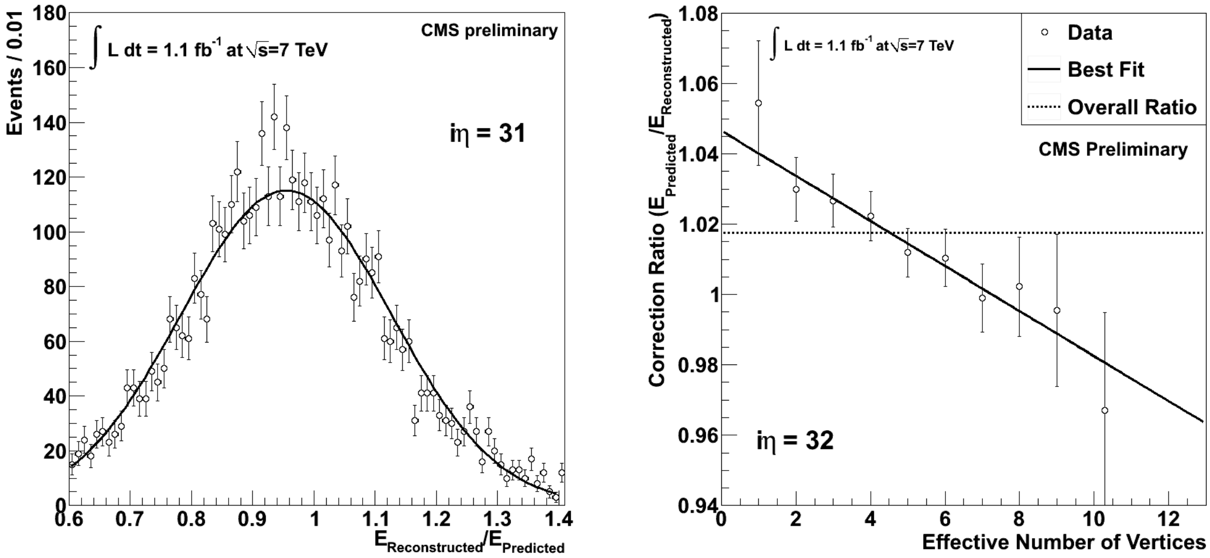


**Figure 5.** Fit to the ratio of expected and observed energy in HF for $i\eta = 31$ (left), and the dependence of calibration constants on the number of vertices (right).

## 4. Summary

The CMS HCAL has operated stably during the first years of running, with more than 99% of channels alive. It has, and continues to, deliver excellent quality data with high efficiency. The HCAL detector monitoring and in-site calibration account for the effect of gain shifts and pixel response drift to ensure optimal performance.

## References


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