The Compact Muon Solenoid Experiment
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Performance of the CMS Electromagnetic Calorimeter at the LHC

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Abstract

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Abstract—The CMS Electromagnetic Calorimeter (ECAL) is a high resolution, fine-grained calorimeter devised to measure photons and electrons at the LHC. Built of lead tungstate crystals, it plays a crucial role in the search for new physics as well as in precision measurements of the Standard Model. A preshower detector composed of sandwiches of lead and silicon strips improves π^0/γ separation in the forward region. The operation and performance of the ECAL during the 2010 run at the LHC, with pp collisions at $\sqrt{s} = 7$ TeV will be reviewed, and to some extent for the 2011 running as well. Pure samples of electrons and photons from decays of known resonances have been exploited to improve and verify the trigger efficiency, the reconstruction algorithms, the detector calibration and stability, and the particle identification efficiency. A review of these aspects will be given.

I. DESCRIPTION OF THE DETECTOR

THE Compact Muon Solenoid (CMS) [1] electromagnetic calorimeter (ECAL) [2] at the Large Hadron Collider (LHC) [3] is an hermetic, homogeneous calorimeter comprising 61200 lead tungstate (PbWO_4) crystals mounted in the central Barrel part, closed by 7324 crystals in each of the two Endcaps (see Fig. 1). The use of PbWO_4 crystals has allowed

Fig. 1. View of the CMS ECAL structure: Barrel (one supermodule in yellow), Endcap (in green), Preshower (in red).

the design of a compact calorimeter inside the solenoid that is fast, has fine granularity, and is radiation resistant. The Barrel section (EB) has an inner radius of 129 cm, and is structured as 36 identical “supermodules”, each covering half the barrel length and corresponding to a pseudorapidity interval of $0 < |\eta| < 1.479$. The crystals have a front face

cross-section of about $22 \times 22 \text{ mm}^2$ and a length of 230 mm, corresponding to $25.8 X_0$. The Endcaps (EE) are located at a distance of 314 cm from the vertex and cover a pseudorapidity range of $1.479 < |\eta| < 3.0$. The endcap crystals have a front face cross section of $28.6 \times 28.6 \text{ mm}^2$ and a length of 220 mm, corresponding to $24.7 X_0$. A Preshower detector (ES) is placed in front of the crystal calorimeter over the endcap pseudorapidity range $1.653 < |\eta| < 2.6$. Its active elements are two planes of silicon strip detectors, with a pitch of 1.9 mm, which lie behind disks of lead absorber at depths of $2 X_0$ and $3 X_0$. The calorimeter is immersed within the 3.8 T magnetic field produced by the CMS solenoid. The scintillation light produced in the crystals is read-out by a pair of avalanche photodiodes (APD) for each EB crystal, and a vacuum phototriode for each EE crystal. The small Molière radius ($R_M = 2.2 \text{ cm}$) in combination with the large number of crystals results in a fine granularity for the lateral shower shape. In the forward region the granularity is further improved by the Preshower detector. An extended description of the ECAL detector is provided in Ref. [4].

The ECAL detector has a crucial role in the physics program of CMS. Its design has been driven by the requirement of an excellent energy resolution [5]. This is needed in particular for the search of the Higgs boson in the $H \rightarrow \gamma\gamma$ decay channel, one of the primary goals of the LHC physics program, where a good di-photon invariant mass energy resolution is essential to discriminate a signal with a small cross section over a large irreducible Standard Model background.

The ECAL energy resolution measured in electron test beams is parametrized as

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%, \quad (1)$$

for electrons incident on the center of crystals [6]. The three contributions correspond to the stochastic term, the noise term and the constant term. The stochastic term depends on the event-by-event fluctuations in the electromagnetic shower development, on the photo-statistics and on the photodetector excess noise factor. The noise term depends on the level of the electronic noise and event pile-up. The constant term depends on the non-uniformity of the longitudinal light collection, on the leakage of energy from the rear face of the crystals and on the accuracy of the detector inter-calibration constants. For electromagnetic showers of energies above 100 GeV the energy resolution is dominated by the constant term. As a consequence, in the CMS environment the detector’s performance will depend mainly on the quality of its inter-calibration and monitoring [7].

II. STATUS AND STABILITY

During the first months of collisions at LHC, in 2010 and 2011, the percentage of fully working channels in the ECAL Barrel and Endcap detectors is about 99.2% and 98.7%, respectively. For the Preshower, the same percentage is around 95.1%. The stability of the calorimeter as a whole is crucial to reach the design goal for the constant term in the energy resolution. In particular, the monitoring of the temperature of the ECAL detectors is very important, since any change affects both the crystal transparency ($-2.2\%/^{\circ}\text{C}$) and the APD gain ($-2.4\%/^{\circ}\text{C}$). The calorimeter has thus been instrumented with nearly 7000 thermistors to provide accurate monitoring. Fig. 2 shows the RMS deviation of the temperature measurements for each sensor: the results are well within the stringent requirements (0.05°C for the Barrel and 0.1°C for the Endcap) imposed to achieve a constant term in the energy resolution of 0.5% [7].

Fig. 2. Distribution of the spread in the temperature measurements of the ECAL Barrel and Endcap thermistors in the second half of 2010.

III. ENERGY CALIBRATION

The ECAL energy reconstruction aims at the most accurate measurement of the scintillation light produced by the crystals from the energy impinging on the calorimeter. A digital filtering technique is applied to the reconstructed signal amplitudes in the Barrel and Endcap crystals, starting from the samples of the pulse shape coming from the photodetectors, amplified and then digitized by the front-end electronics [8]. The energy deposited in a single crystal is proportional to the amplitude of the digital pulse. The response of the individual channels are equalized by means of inter-calibration coefficients. Since an electromagnetic shower spreads over more than one crystal (only about 70% of the energy of an unconverted photon impinging on the centre of a Barrel crystal is contained within that crystal), to achieve the best estimate of the energy of the incoming particle, algorithms for clustering the energy deposits have been developed. The energy of electrons and photons can thus be expressed as:

$$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_{xtal} L_{xtal}(t) \cdot C_{xtal} \cdot A_{xtal}, \quad (2)$$

where the sum is performed over the crystals in a cluster, A_{xtal} is the measured APD's/VPT's raw ADC amplitude, C_{xtal} is the crystal inter-calibration coefficient, $L_{xtal}(t)$ is the time-dependent correction for the radiation-induced transparency loss, G is the ADC-to-GeV energy scale, and $F_{e,\gamma}$ is an

additional correction factor, which depends on the type of the particle and on its energy, and takes into account geometry and material effects like shower leakage and bremsstrahlung losses. The ECAL detector has been calibrated prior to the LHC startup with an overall precision of 0.5% – 2% in the Barrel, and 5% in the Endcap, using a combination of laboratory measurements of the light yield and photodetector gain (with a precision of 4.5% – 6%), electron test beam measurements (for 25% of the channels in the Barrel, with a precision of 0.5%), and muons from cosmic rays (with a precision of 1.4% – 3.5%) and beam dumps (with a precision of about 6%). Before the installation in CMS, the global energy scale has been defined using test beam data, and then tuned by reconstructing di-photon and di-electron invariant mass peaks of known particles with unconverted photons and electrons with very low bremsstrahlung [7].

A. Inter-calibration

The start-up calibration precision is improved using proton-proton collision data, combining different methods [9]:

- the azimuthal symmetry method, exploiting the energy-flow invariance around the beam axis in minimum bias events, to inter-calibrate crystals at the same pseudorapidity;
- π^0 and η resonances inter-calibration, using the invariant mass peaks of di-photon events from $\pi^0(\eta) \rightarrow \gamma\gamma$ candidates (also useful to monitor the energy scale);
- isolated, high energy electrons from $W \rightarrow e\nu$ and $Z \rightarrow ee$ decays, comparing the energy measured in ECAL with the track momentum measured in the CMS silicon Tracker;
- radiative Z decays, using $Z \rightarrow \mu\mu\gamma$, assuming the correct muon energy scale, to check the photon energy scale.

Fig. 3 shows the precision of the inter-calibration coefficients, C_{xcal} , as a function of the crystal η index for the azimuthal symmetry method, and limited by the inhomogeneities in the material in front of the calorimeter to about 1.5% – 3% depending on the pseudorapidity. Fig. 4 shows the precision

Fig. 3. Calibration precision from the azimuthal symmetry method, from minimum-bias events, for the ECAL Barrel detector.

obtained combining all the different calibration strategies, resulting in a precision of less than 0.5% at low values of $|\eta|$, and increasing due to the material in front of the detector

for $|\eta| > 1$ in the ECAL Barrel, and less than 2% for $1.65 < |\eta| < 2.6$ in the Endcap, corresponding to the region covered by the Preshower detector.

Fig. 4. Combined inter-calibration precision for the ECAL Barrel (EB, left) and Endcap (EE, right) detectors.

B. Crystal transparency monitoring

The design energy resolution of the ECAL detector depends on the accurate measurement and correction of the time-dependent changes in the crystal light yield caused by light transmission losses due to radiation damage, $L_{xtal}(t)$ [6]. The ECAL monitoring system is required to monitor transparency changes at the level of 0.2%, with one measurement every 20 – 30 minutes. It consists of two different lasers: a blue laser with a wavelength (400 nm) close to the emission peak of scintillation light from the PbWO_4 crystals, and an infra-red laser (796 nm), to compensate for variations that are not due to the transparency loss. Fig. 5 shows the double-ratio of the blue and infra-red laser measurements, for typical crystals in the ECAL Barrel and Endcap detectors. The effects of the transparency loss due to irradiation (about 1% in the Barrel and about 4% in the Endcap detector), and subsequent recovery, are clearly seen and are in good agreement with the expectations from the LHC instantaneous luminosity. Fig. 6

Fig. 5. Measured crystal transparency loss due to irradiation in 2010 for the ECAL Barrel (left) and Endcap (right) detectors.

shows the π^0 invariant mass history plot for photons in the ECAL Barrel detector, before and after the corrections to the crystal energy due to the transparency loss are applied. The invariant mass is normalized to unity at the beginning of the period considered. The uncorrected plot shows a 1% drop over this period. After correction, the invariant mass distributions are flat to within 0.2% for the majority of the running period. Fig. 7 shows the history plot of the ratio E/p of the electron energy E as measured in the ECAL Barrel detector, to the electron track momentum p as measured by the CMS silicon

Fig. 6. π^0 invariant mass history plot in 2010 for the ECAL Barrel detector, before and after the corrections for the crystal transparency loss.

Tracker, for electrons from $W \rightarrow e\nu$ decays, before and after the applying the transparency loss corrections. The ratio is normalized to unity at the beginning of the period considered. The uncorrected ratio shows a drop of 1.5% in the Barrel detector (and correspondingly 6% in the Endcap detector) during this period. After correction, the E/p histories are flat to within 0.2% and 1%, respectively.

Fig. 7. E/p history plot, with E = ECAL electron energy, p = Tracker electron momentum, for $W \rightarrow e\nu$ decays measured in 2010 with the ECAL Barrel detector.

IV. ENERGY SCALE

The energy scale, G , initially set using electron test beam measurements, has been tuned using $Z \rightarrow ee$ events from LHC collisions for both the ECAL Barrel and Endcap detectors [4]. Fig. 8 shows the invariant mass distribution for di-electron events from $Z \rightarrow ee$ events, for both data and Monte Carlo simulation. Data events are corrected for the crystal transparency losses. The left-hand plot shows only events where both electrons are in the barrel region, the right-hand plot contains only events where both electrons are in the endcap regions. The plots show good agreement between data and simulation. The total systematic uncertainty on the ECAL energy scale is 0.6% for the Barrel and 1.5% for the Endcap detectors. Fig. 9 shows the ratio $E_{reco}/E_{kin} - 1$ for $Z \rightarrow \mu\mu\gamma$ events, in the ECAL Barrel (left) and Endcap (right) detectors, where E_{reco} is the measured energy of the photon, and E_{kin} is the predicted photon energy from the difference between the Z mass [11] and the invariant mass of the $\mu\mu$ system. Energies are corrected for the crystal transparency losses. The photon energy scale agrees well with the expectations at the 1% level.

Fig. 8. Invariant mass distribution for $Z \rightarrow ee$, with both electrons in the ECAL Barrel (left) and Endcap (right) detectors. Data and Monte Carlo distributions are shown.

Fig. 9. Estimation of the photon energy scale from $Z \rightarrow \mu\mu\gamma$ events, for photons in the ECAL Barrel (left) and in the Endcap (right) detectors.

V. ENERGY RESOLUTION

The energy resolution performance has been measured with an electron test beam in the energy range between 10 GeV and 180 GeV [10]. After the installation, the resolution has been studied using di-photon pairs from π^0 decays and $Z \rightarrow ee$ events produced in proton-proton collisions [6]. Fig. 10 shows the invariant mass distributions for di-electron events, for data and Monte Carlo simulation. On the left-hand, the full sample of events with both electrons in the barrel region are shown. On the right-hand the sub-sample of non-showering (low bremsstrahlung) electrons is shown. The distributions are

Fig. 10. Invariant mass distribution for $Z \rightarrow ee$ events in the ECAL Barrel detector: (left) full sample of $Z \rightarrow ee$ events, (right) sub-sample of non-showering electrons (low bremsstrahlung). Data and Monte Carlo distribution are shown.

fitted to a convolution of a Breit-Wigner (BW) and a Crystal-Ball (CB) function using an unbinned likelihood fit, to extract the Z peak shape parameters from the values of Δm_{CB} , the difference (in GeV) between the CB mean and the Z mass [11], and σ_{CB} , the width of the CB function. The BW parameters are fixed to their PDG values [11]. There is a good agreement between the CB width for data and Monte Carlo distributions,

showing the good detector modeling in the simulation, with the CB width being around 1 GeV for non-showering electrons.

VI. SUMMARY

The CMS ECAL detector status and performances with the first proton-proton collisions at the Large Hadron Collider have been presented. The results match extremely well the expectations, thanks to the impressive preparatory work, and are close to the design goals.

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