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Performance of the CMS Electromagnetic Calorimeter in pp collisions

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Abstract

The CMS Electromagnetic Calorimeter (ECAL) is a high resolution, finely grained instrument devised to measure photons and electrons at LHC. Built of lead tungstate crystals, it will play a crucial role in the search for new physics as well as in precision measurements in the standard model. Thanks to this detector, the CMS collaboration was able to reconstruct di-photon states within minutes from the first LHC collisions. We will report on the commissioning and performance of the detector with 2009 and 2010 collision data, providing details about its calibration and synchronization, showing how well the challenging design goals were met.

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Performance of the CMS Electromagnetic Calorimeter in pp Collisions

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Abstract—The CMS Electromagnetic Calorimeter (ECAL) is a high resolution, finely grained instrument devised to measure photons and electrons at LHC. Built of lead tungstate crystals, it will play a crucial role in the search for new physics as well as in precision measurements in the standard model. Thanks to this detector, the CMS collaboration was able to reconstruct di-photon states within minutes from the first LHC collisions. We will report on the commissioning and performance of the detector with 2009 and 2010 collision data, providing details about its calibration and synchronization, showing how well the challenging design goals were met.

I. INTRODUCTION

THE CMS experiment at the Large Hadron Collider at Cern (European Center for Nuclear Research, Geneva, Switzerland) has the typical structure of an hermetic collider experiment, with several layers of detectors of different kinds arranged around the interaction point [1]. The Electromagnetic Calorimeter (ECAL) is the second detector after the silicon tracker and before the hadron calorimeter. Placed inside the superconducting solenoidal coil, it is an instrument of high precision devoted to the measurement of electrons and photons.

II. DESCRIPTION OF THE DETECTOR

The ECAL [2] is composed of a cylindrical barrel and two endcaps. The barrel consists of 36 *supermodules* each of 1700 lead tungstate crystals (PbWO_2), while the two endcaps are composed of two D-shaped structures each of 3662 crystals. The crystals are 25.8 radiation length long and their front face measures $2 \times 2 \text{ cm}^2$. The Molière radius in PbWO_2 is 2.2 cm, resulting in a fine segmentation. In the barrel, the crystals are read out by avalanche photo diodes (APD) and in the endcaps by vacuum photo triodes (VPT). A silicon preshower placed in front of each endcap provides better π^0 rejection.

III. PERFORMANCES IN PP COLLISIONS

The instrument was extensively tested before its installation. The tests consisted of laboratory measurements of each crystal, bench characterisation of the electronic chain, study of test beam performance and response to cosmic rays. For the first time it is possible to study the behavior of the detector in proton proton collisions.

Fig. 1. The di-photon invariant mass at low energies resulting from the analysis of 250 nb^{-1} . The solid line is the result of a fit to a Gaussian function plus a polynomial background

A. Energy resolution

The energy resolution of the ECAL was measured with an electron test beam in an energy range spanning from 10 GeV to 180 GeV [3]. In this section we report about the study of energy resolution that was performed on collision data by use of the π^0 resonance. A special trigger is devoted to the collection of π^0 candidates. Thanks to this dedicated calibration stream a high number of events could be collected. Figure 1 shows the di-photon invariant mass in the barrel resulting from 250 nb^{-1} of data.

The apparent width of the resonance (or di-photon invariant mass resolution) is due to the energy resolution and angular resolution of the detector. This has been studied as a function of the transverse momentum (p_T) of the π^0 candidate. The result is shown in figure 2, where data (in black) and monte-carlo (in red) are compared. To gain an insight of the interplay between energy and angular resolution the purple points show the resolution from Monte Carlo using the generated energy, while the blue points show the same quantity in case the generated π^0 decay angle is used. The di-photon invariant mass resolution has also been studied as a function of the pseudorapidity, as shown in figure 3 for data (in black) and Monte Carlo (red). We conclude that, even at these low energies, the mass resolution is below 10 %.

Fig. 2. Di-photon invariant mass resolution as a function of the p_T of the π^0 candidate for data (black) and monte carlo (red). The purple points show the expectation in the case where the true monte carlo energy is used, while the blue points show the expectation in the case the true monte carlo angle is used.

Fig. 3. Di-photon invariant mass resolution as a function of pseudorapidity η for data (black) and monte carlo (red)

B. Time Resolution

The signal coming from the Ecal crystals is sampled every 25 nanoseconds. In figure 4 the shape of a pulse is shown. Determining the timing of a signal means measuring the time T_{MAX} when the pulse reaches the maximum amplitude A_{MAX} . The time reconstruction is performed by using the so called *ratio method*. The ratio is defined as

$$R(t) = \frac{A(t)}{A(t + 25ns)}$$

the quotient between the amplitudes at time t and $t + 25ns$, or between subsequent samples. The dependence of the quantity T_{MAX} from $R(t)$ was derived experimentally and parametrized. Therefore, the measurement of $R(t)$ can be used to measure the time of A_{MAX} . The performances of this method were studied by considering the time spread of the signal from two adjacent crystals in the same electromagnetic

Fig. 4. The shape of the signal from an ECAL crystal, sampled every 25 ns

Fig. 5. ECAL time resolution obtained from the spread in time of two adjacent crystals

shower. The result is shown in figure 5. In abscissa the quantity A_{eff}/σ_N is reported, where A_{eff} is the effective amplitude, or the normalized product of the amplitude from the two signals, and σ_N is the noise variance. A value of A_{eff}/σ_N of 100 corresponds to about 4 GeV. It can be seen that for energies above 4 GeV a time resolution better than 500ns is obtained.

C. Calibration

The ECAL detector was calibrated with good precision by combining different pre calibration and *in situ* methods. About 1/4 of the channels in the barrel were exposed to an electron test beam. The intercalibration precision achieved with this method is about 0.5%. All the channels were exposed to cosmic ray muons, yielding to a precision ranging from 1.4% to 3.5%. Additionally, the light yield of all crystals, which is

Fig. 6. Intercalibration precision obtained with the azimuthal symmetry method

Fig. 7. Intercalibration precision obtained with the combination of the three *in situ* methods

the main source of spread in the response of the channels, was measured with a precision of 4.5-6%. In the endcap, only 450 channels were exposed to test beam, reaching a precision around 1%. Here laboratory measurement of the light yield reached a precision around 8%. In addition, the *beam dump* method was applied to reach a precision of around 6%. This method exploited the fact that the LHC beam was stopped by beam collimators upstream of CMS in several occasions, resulting in a nearly uniform flux of muons impinging on the detector.

When *pp* collisions became available, the barrel could be calibrated using additional *in situ* methods: azimuthal symmetry and π^0 resonance. The azimuthal symmetry method is based on the assumption that, integrating over a large number of events, the particle flux from minimum bias events impinging on crystals at the same pseudorapidity should be the same. This allows to perform the intercalibration of the channels with a precision ranging from 1.4% to 3% depending on pseudorapidity, as shown in figure 6. The π^0 resonance method corrects iteratively the calibration constant of the channels in order to obtain the minimal discrepancy of the measured π^0 peak position from the nominal one. The intercalibration precision obtained with 250 nb^{-1} ranges from 1.3% in the central region to around 3% at high pseudorapidity.

The combination of the three *in situ* methods allowed to reach an intercalibration precision of 0.5% in the central region, as shown in figure 7

D. Energy Scale

The energy scale of the calorimeter was preliminarily set using electrons of known energy measured during the test beam campaign. The long term strategy foresees that the energy scale is set by studying the $Z \rightarrow \mu^+ \mu^- \gamma$, $Z \rightarrow e^+ e^-$ and $J/\psi \rightarrow e^+ e^-$ reactions. With low integrated luminosity, it was possible to perform a preliminary check, by comparing

Fig. 8. Distribution of the spread in temperature in time from various sensors in the barrel (EB) and endcap (EE)

the measured position of the π^0 and η peak with the position obtained from the reconstruction of Monte Carlo events. An agreement better than 1% in the barrel and 3% in the endcap was found, giving an indication that the energy scale is accurate at least to these levels.

E. Stability

The stability of the calorimeter has been studied with several respects. The temperature stability is very important, because a change in temperature reflects in a variation in the transparency of the crystals. The instrument is extensively equipped with temperature sensors to provide accurate monitoring. In figure 8 we show the RMS variation in time of the sensors in the barrel and endcap. The measurement of the π^0 peak position as a function of time gives a physical way to assess the stability

Fig. 9. Stability of the π^0 peak position in time

Fig. 10. Signal shape originating from a regular shower (green) and anomalous signals (red)

of the detector. In figure 9 we show the result from the data analyzed in the period from March 30, 2010 to May 17th, 2010. The RMS spread of the points is 0.14%. An additional method to measure stability is offered by the laser monitoring system, which constantly illuminates the crystals with light of three different wavelengths [8].

IV. ANOMALOUS SIGNALS

With the start of the proton-proton collision run, an unexpected rate of high energy signals was registered. These signals are not originating from electromagnetic showers, but probably by fake energy deposits caused by direct ionization in the depleted silicon of the APD. These deposits seem to stem from two distinct sources: particles coming directly from the interaction point and particles arriving at a later time, probably as a consequence of back showering from the hadron calorimeter or neutron decay.

It is possible to distinguish anomalous signals from electromagnetic showers by considering timing and topology. The signal from a regular electromagnetic shower is the result of the light collection component and the response of the APD and its readout electronics. In the anomalous signal, the light collection component is missing, resulting in a steeper rise time, biasing time reconstruction toward earlier times (see

Fig. 11. Distribution of the quantity $1-E4/E1$ for data and Monte Carlo. The Monte Carlo used here does not include a detailed simulation of the APD volume. The peak at values near one are due to anomalous signals.

Fig. 12. The energy spectrum measured by the ECAL before (black) and after (red) a topological cut is applied. The solid line shows the Monte Carlo expectation

figure 10). A selection on the time of arrival is therefore effective for rejection of unwanted signals.

In addition, electromagnetic showers involve many crystals, while anomalous signals tend to interest individual channels. We define the quantity $E1/E4$ as the ratio of the signal from the most energetic crystals in a 3×3 matrix over the sum of the signals from the four crystals in the North, South, East and West positions from the most energetic one. The distribution of the quantity $(1-E4/E1)$ is shown in figure 11 for data (points) and Monte Carlo (line). The Monte Carlo used to produce the solid line does not include a detailed simulation of the APD volume. The peak around the value of one is due to anomalous signals. Figure 12 shows the energy spectrum with (red) and without (black) the topological cut.

Fig. 13. Reconstructed dielectron invariant mass with 3.1 pb^{-1}

V. CONCLUSIONS

We have reported about the performance of the CMS Electromagnetic Calorimeter in proton-proton collisions. We have verified *in-situ* the timing performances. The π^0 mass resolution agrees well with Monte Carlo expectations. We have checked the good stability of the device. Pre-calibrations were combined with *in-situ* methods to achieve an intercalibration precision of around 0.5% in the central region of the barrel. We have estimated that the energy scale is accurate within 1% in the barrel and 3% in the endcap. As a further proof of the nice behaviour of the instrument, figure 13 shows the dielectron invariant mass over a large range in energies, where some well known features of the Standard Model are clearly visible. We believe the instrument is ready for exciting discoveries.

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