The Compact Muon Solenoid Experiment

Conference Report

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Calibration and performance of the CMS electromagnetic calorimeter during the LHC Run II

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Abstract

Many physics analyses using the Compact Muon Solenoid (CMS) detector at the LHC require accurate, high resolution electron and photon energy measurements. Excellent energy resolution is crucial for studies of Higgs boson decays with electromagnetic particles in the final state, as well as searches for very high mass resonances decaying to energetic photons or electrons. The CMS electromagnetic calorimeter (ECAL) is presently operating at the LHC with proton-proton collisions at 13 TeV center-of-mass energy, 25 ns bunch spacing, and an unprecedented instantaneous luminosity. High pileup levels and the ageing of crystals from exposure to large particle fluences necessitate a retuning of the ECAL readout, trigger thresholds, and reconstruction algorithms, to maintain the best possible performance in these increasingly challenging conditions. In addition, the energy response of the detector must be precisely calibrated and monitored, injecting laser light to correct for crystal transparency changes due to irradiation. A dedicated calibration of each detector channel is performed with physics events exploiting electrons from W and Z boson decays, photons from π^0/η decays, and from the azimuthally symmetric energy distribution of minimum bias events. This talk presents the new reconstruction algorithm and calibration strategies that have been implemented and the excellent performance achieved by the CMS ECAL throughout Run II.

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Calibration and performance of the CMS electromagnetic calorimeter during the LHC Run II

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Abstract. Many physics analyses using the Compact Muon Solenoid (CMS) detector at the LHC require accurate electron and photon energy measurements. Excellent energy resolution is crucial for the study of Higgs boson decays with electromagnetic particles in the final state, as well as searches for very high mass resonances decaying to energetic photons or electrons. The CMS electromagnetic calorimeter (ECAL) is presently operating at the LHC with proton-proton collisions at 13 TeV center-of-mass energy, 25 ns bunch spacing, and an unprecedented instantaneous luminosity. High pileup levels and the ageing of crystals from exposure to large particle fluencies necessitate a retuning of the ECAL readout, trigger thresholds, and reconstruction algorithms, to maintain the best possible performance in these increasingly challenging conditions. In addition, the energy response of the detector must be precisely calibrated and monitored, injecting laser light to correct for crystal transparency changes due to irradiation. A dedicated calibration of each detector channel is performed with physics events exploiting electrons from W and Z boson decays, photons from π^0 decays, and from the azimuthally symmetric energy distribution of minimum bias events. This talk presents the new reconstruction algorithm and calibration strategies that have been implemented and the excellent performance achieved by the CMS ECAL throughout LHC Run II.

1 Introduction

The Compact Muon Solenoid (CMS) experiment produced a wide range of physics results exploiting the proton-proton and heavy-ion collision data at the Large Hadron Collider at CERN (LHC). These include the discovery of the standard model (SM) Higgs boson, as well as searches for physics beyond the standard model (BSM). The electromagnetic calorimeter (ECAL) [1] is crucial for the identification and reconstruction of photons and electrons and contributes to the measurement of jets and missing transverse energy. Excellent energy resolution and efficient photon identification are required for the $H \rightarrow \gamma\gamma$ decay process, for measurement of Higgs

boson self-couplings and of other related parameters. Precise measurements of the energy of electrons are important for the measurement of Higgs properties in leptonic final states and for many BSM searches.

The ECAL is a hermetic, homogeneous calorimeter made of lead tungstate (PbWO_4) crystals, 61200 crystals mounted in the central barrel part, and 7324 crystals in each end-cap. Lead tungstate scintillating crystals have a short radiation length ($X_0 = 0.89$ cm) and a small Molière radius ($R_M = 2.2$ cm); they also have a fast response time, as the 80% of the scintillation light is emitted within 25 ns, and radiation hard. However, the relative low light yield (30 photons/MeV) requires the use of photodetectors with intrinsic gain that can be operated in a magnetic field. In the barrel, silicon avalanche photodiodes (APDs) are used as photodetectors, while vacuum phototriodes (VPTs) have been chosen for the endcaps because of their high radiation hardness. A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is placed in front of the endcap crystals. Electrons and photons are typically reconstructed in terms of pseudorapidity up to $\eta < 2.5$, the region covered by the silicon tracker, while jets are reconstructed up to $\eta < 3$.

2 Reconstruction, calibration and performance of ECAL at the LHC Run II

Since the transverse size of a PbWO_4 crystal in ECAL is approximately equal to its Molière radius, deposits from high energy electromagnetic showers are typically spread over several crystals and clustered with dedicated algorithms. The algorithm starts with a basic cluster, which is the local maximum of the energy deposited. Due to the material in front of ECAL and the strong magnetic field, photons convert and electrons emit bremsstrahlung photons, further resulting in a spread of the energy in the transverse plane. Such energy spread is recovered by extending the basic clusters to a supercluster (SC). The total energy of an electron or photon is given by the sum over all crystals in the supercluster:

$$E_{e,\gamma} = F_{e,\gamma} \times \left[E_{ES} + G \times \sum_i C_i \times S_i(t) \times A_i(t) \right],$$

where the index, i , represents individual crystals within the supercluster, $A_i(t)$ is the single channel reconstructed amplitude, $S_i(t)$ is the time-dependent crystal response correction, and C_i is the channel inter-calibration constant. The quantity G is an absolute energy scale factor, E_{ES} is the energy deposited in the preshower, and $F_{e,\gamma}$ are supercluster energy corrections (different for photons and electrons).

As during Run II the LHC colliding bunches are separated by 25 ns and the signal pulses cover more than one 25 ns time sample, the recorded pulse will be the sum

of in-time and out-of-time (OOT) pulses. A dedicated pulse reconstruction algorithm termed 'multifit', is used to minimize the OOT contribution to the signal. This algorithm estimates the in-time signal amplitude and up to 9 out-of-time amplitudes by minimization of a χ^2 :

$$\chi^2 = \sum_{i=1}^{10} \frac{(\sum_{j=1}^M A_j \times p_{ij} - S_i)^2}{\sigma_{S_i}^2}$$

where A_j are the amplitudes of up to $M = 10$ interactions, $\vec{p_j}$ – the pulse templates of each bunch crossing j , which have the same shape but are shifted in time by multiples of 25 ns within a range of -5 and $+4$ bunch crossings around the in-time signal, S_i – pedestals measured in dedicated pedestal runs, as well as σ_{S_i} - covariance matrix of electronic noise. Example of one fit for signal in the barrel is shown in Fig. 1.

Fig.1. Example of fitted pulse for simulated events with 20 average pileup interactions and 25 ns bunch spacing. Dots represent the 10 digitized samples, the red distributions (other light colors) represent the fitted in-time (out-of-time) pulses with positive amplitude. The dark blue histograms represent the sum of all the fitted contributions.

Due to radiation damage, the ECAL crystal response changes with time, and partially recovers through self-annealing during periods without radiation. The response change in ECAL $S_i(t)$, is continuously measuring by a laser monitoring system [2] by injecting laser light and measures the response of each channel; the corrections are then delivered in less than 48 hours for the prompt reconstruction of the data. The measured relative response to laser light from the start of the LHC running until May 2018, along with the LHC instantaneous luminosity, is shown in Fig. 2.

Fig.2 History of the relative response to laser light injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity η , with the CMS magnetic field at 3.8 T. Measurements from March 2011 to May 2018 are shown. The bottom plot shows the instantaneous LHC luminosity delivered during this period.

The relative calibration [3], denoted by inter-calibration constant C_i , equalizes the different crystal+ APD/VPT responses among different channels using the following main methods:

- **ϕ -symmetry:** the energy flow in a given η ring is supposed to be uniform, thus the C_i is obtained by equalizing the average transverse energy in crystals at constant η ;
- **π^0 mass:** this method utilizes the invariant mass of the two photons from $\pi^0 \rightarrow \gamma\gamma$ decay; it is an iterative procedure in which the C_i of the central crystal in the photon cluster gets updated in each iteration based on the reconstructed invariant mass and the iteration stops when the precision converges;
- **E/p :** this is also an iterative method based on ECAL energy and tracker momentum for isolated electrons from Z or W boson decays.
- **$Z \rightarrow ee$ method:** a fit is performed to derive C_i parameters from the invariant mass of $Z \rightarrow ee$ decays.

The final set of C_i is then taken as a weighted combination of the last three methods above, while the ϕ -symmetry technique is mainly used for monitoring purposes.

The precision of the combined inter-calibration is about 0.3% in the center of the detector and up to 1% in the high η region of the barrel, as shown in Fig. 3.

Fig.3. Precision of the per-channel energy inter-calibration, plotted as a function of the pseudorapidity η in the ECAL barrel, for data collected in 2017. The precision is shown for the individual inter-calibration methods and for their combination.

The absolute energy scale factor, G , is obtained by matching the invariant mass distributions of $Z \rightarrow ee$ events in data to that of the simulation.

The raw energy of a supercluster calculated from the sum of individual hits is further corrected for the material budget in front of the ECAL, as well as partial shower containment due to gaps and cracks between crystals. Such supercluster energy corrections, $F_{e,\gamma}$ are derived by a multivariate technique trained separately for electrons[4] and photons[5] with simulated events in which the true energy is known. The relative ECAL energy resolution σ_E/E is extracted from an unbinned likelihood fit to $Z \rightarrow ee$ events. The relative electron energy resolution for low bremsstrahlung electrons, unfolded in bins of pseudorapidity η for the barrel and the endcaps, is shown in Fig. 4. The conditions used in the simulation reflect the status of the detector after 25 fb^{-1} of data taking in 2017. Degradations observed in the vicinity of the η cracks between ECAL modules (indicated by the vertical lines in the figure) correspond to energy lost in these regions. Significant improvement in the resolution is observed after a dedicated recalibration performed in early 2018 using the full 2017 dataset (blue points) in comparison with the end-of-year 2017 calibration (gray points) where only corrections for certain time dependent effects observed in 2017 data were applied. With the full recalibration, ECAL achieved an energy resolution which ranges from 1.5 to 3.4% in the barrel and from 3.6 to 4.8% in the endcaps for $Z \rightarrow ee$ low bremsstrahlung electrons. This shows that the excellent performance of the ECAL has been preserved in Run II, despite the significantly higher LHC luminosities and pileup.

Fig.4. Relative electron energy resolution plotted for data and Monte Carlo events, unfolded in bins of pseudorapidity η for low bremsstrahlung $Z \rightarrow ee$ electrons. The data resolution obtained after corrections for certain time-dependent effects is shown in gray. The resolution obtained from a full recalibration using the entire 2017 dataset is shown in blue.

3 Conclusions

The CMS electromagnetic calorimeter has efficiently operated during LHC Run I and Run II matching the design requirements. For Run II at $\sqrt{s} = 13$ TeV, a new ECAL amplitude reconstruction method has been introduced in order to deal with the increased pileup conditions. The performance of ECAL, such as the response stability and the calibration precision, are constantly monitored and improved, resulting in excellent energy resolution for photons and electrons. This outstanding performance has played a crucial role in several analyses, such as the observation of the Higgs boson at 13 TeV in the $H \rightarrow \gamma\gamma$ channel, and the searches of exotic resonances in di-electron and di-photon final states.

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