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Performance of the CMS electromagnetic calorimeter in the LHC Run II

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Abstract

Many physics analyses using the CMS detector require accurate, high resolution electron and photon energy measurements. The increase of instantaneous luminosity and of the number of concurrent p-p collisions (pileup) makes precise energy reconstruction more challenging. Presented are the performance of the CMS ECAL during LHC Run II, as well as the calibration and monitoring strategies to keep these effects to the minimum.

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Performance of the CMS electromagnetic calorimeter in the LHC Run II

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ABSTRACT

Many physics analyses using the CMS detector require accurate, high resolution electron and photon energy measurements. The increase of instantaneous luminosity and of the number of concurrent p–p collisions (pileup) makes precise energy reconstruction more challenging. Presented are the performance of the CMS ECAL during LHC Run II, as well as the calibration and monitoring strategies to keep these effects to the minimum.

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1. Introduction

One of the primary goals of the Compact Muon Solenoid (CMS) experiment [1] was the observation of the Higgs boson and measurement of its properties. A crucial component of the CMS detector that makes this possible is the electromagnetic calorimeter (ECAL), which measures energies of electromagnetically interacting particles with high precision. The recent measurement of the $H \rightarrow \gamma\gamma$ production cross section [2] is a perfect demonstration of the main aspects of the ECAL. Precise measurement of the diphoton invariant mass peak with resolution up to 1% requires precise energy reconstruction of each individual photon, as well as its positions.

Furthermore, high statistical precision of this measurement is possible thanks to increased instantaneous luminosity provided by the LHC during Run II. This poses additional challenges in terms of higher radiation levels and more energy deposits originating from concurrent (pileup) p–p collisions.

2. Structure of the CMS ECAL

The CMS ECAL is a compact, hermetic, homogeneous calorimeter with a fine spatial granularity, which is small enough to fit inside the superconducting solenoid, while providing excellent energy resolution. It consists of 75,848 PbWO_4 scintillating crystals, arranged in a central barrel section (EB) and two endcaps (EE). Each crystal has a length

of about 27 (26) radiation lengths in EB (EE) and lateral dimensions comparable to a Molière radius. In front of EE there is also a preshower detector (ES) with 3 radiation lengths of tungsten absorber followed by silicon strip sensors to discriminate between photons and π^0 s.

The light from each crystal is read out by an avalanche photodiode (APD) in EB or a vacuum phototriode (VPT) in EE. Light yield of the crystals and the gain of the photodetectors strongly depend on temperature, therefore ECAL is operated at very stable $T = 18 \pm 0.05$ °C, which is maintained by a dedicated water cooling system and temperature monitoring sensors.

3. Energy reconstruction and calibration

High energy electromagnetic showers are typically spread over multiple crystals. Furthermore, presence of dead material in front of the ECAL leads to electron bremsstrahlung and photon conversions that form additional energy deposits spread in ϕ by the strong magnetic field. In order to collect all this energy, *superclusters* of crystals are formed, starting from smaller clusters around local maxima of energy deposits, which are then dynamically combined with other clusters in ϕ to recover potentially radiated energy. Full energy of the shower is then reconstructed by summing signal amplitudes from each crystal in the supercluster and applying a number of corrections:

$$E_{e/\gamma} = F_{e/\gamma} \cdot [G \cdot \sum_i S_i(t) C_i A_i] + E_{\text{ES}}. \quad (1)$$

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Fig. 1. (a) Improvement to the $Z \rightarrow e^+e^-$ energy scale and mass resolution from the application of superclustering and cluster corrections. (b) Example of fitted pulses for simulated events with 20 average pileup interactions and 25 ns bunch spacing, for a signal in the endcaps.

Fig. 2. Evolution of the average hit time during 2017 for the positive and negative sides of EB and EE. Mild recovery is visible in the absence of irradiation.

Fig. 3. Relative energy resolution for electrons with minimal effect of bremsstrahlung: $E_{3 \times 3}/E_{\text{supercluster}} \geq 0.94$.

In Eq. (1) the global ADC to GeV scale (G) is applied to a sum of signal amplitudes (A_i) from each crystal i of the supercluster, corrected by intercalibration coefficients (C_i), accounting for variations of individual crystal responses and readout efficiencies. A special multivariate correction ($F_{e/\gamma}$) is applied to the total supercluster energy, which takes

into account the particle type, geometry and material effects [3]. Energy deposit in the preshower (E_{ES}) is also added for showers in the endcap region. The effect of these corrections is shown in Fig. 1 (a).

The signal amplitude (A_i) from each crystal is corrected for potential pileup contributions before entering Eq. (1) making use of 10 consecutive samples of digitized APD/VPT pulse. While simply a weighted sum of the 10 samples was sufficient to calculate the pulse amplitude during Run I, a more sophisticated *multifit* approach is adopted for Run II [4]. This is primarily motivated by the dramatic increase of the out-of-time pileup contamination caused by a twice smaller bunch spacing of 25 ns, compared to 50 ns during Run I. Following this approach, a template fit of 1 in-time and up to 9 out-of-time pulses is performed to extract the desired pulse shape used for amplitude calculation, as shown in Fig. 1 (b) [5].

Finally, the light yield is affected by the reduction of crystal transparency under irradiation and its partial recovery through self-annealing in the absence of radiation [6]. The crystal transparency is continuously monitored with a dedicated laser system, and the corresponding corrections ($S_i(t)$) are regularly updated to minimize time variations of crystal response. These variations also affect the pulse timing, which is crucial for robust pileup suppression. Timing shifts below 200 ps have a negligible effect on reconstruction, thus timing conditions are updated in steps of 200 ps, as shown in Fig. 2 [6].

4. Energy resolution

The single-electron energy resolution is derived from the invariant mass resolution of $Z \rightarrow e^+e^-$ candidates. This evaluation is done separately for electrons strongly affected by bremsstrahlung and for electrons with almost no bremsstrahlung, which are presented in Fig. 3 [6]. Resolution up to 1.5% is achieved in the central region and is better than 5% in the forward most region. The dedicated calibration performed on the full 2017 dataset makes a significant improvement with respect to the end-of-year 2017 calibration, for which only time dependent effects from 2017 were considered.

5. Conclusion

The CMS ECAL has been operating with excellent performance throughout LHC Run II, providing a wide range of physics analyses with precise measurements of particle energies. This level of performance was achieved thanks to continuous monitoring of detector conditions and regular updates of calibration constants, as well as a number of improvements to the readout and reconstruction algorithms to cope with the increased pileup and radiation levels.

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