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Obtaining the ultimate calibration and performance of the CMS Electromagnetic Calorimeter in LHC Run 2

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The electromagnetic calorimeter (ECAL) of the CMS experiment at the CERN LHC, due to its excellent energy resolution, is crucial for many physics analyses, ranging from Higgs boson measurements to new physics searches involving very high mass resonances. A precise calibration of the detector and all its individual channels is essential to achieve the best possible resolution for electron and photon energy measurements, as well as the measurement of the electromagnetic component of jets and the contribution to energy sums used to obtain information about particles that leave no signal in the detectors, such as neutrinos. To ensure the stability of the energy response over time, a laser monitoring system is employed to measure radiation induced changes in the detector hardware and compensate for them in the reconstruction. This talk will summarize the techniques used for the ECAL energy and time calibrations with the laser system and exploiting the full Run 2 (2015-2018) dataset, and will present the ultimate ECAL performance achieved for the legacy reprocessing of the Run 2 data.

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1. Introduction

The Compact Muon Solenoid (CMS) [1] at the CERN Large Hadron Collider (LHC) is a general-purpose detector with a broad physics programme ranging from testing standard model (SM) predictions to searching for new physics beyond the SM. The electromagnetic calorimeter (ECAL) [2] in CMS is designed to provide highly efficient and accurate reconstruction of photons and electrons. It plays a crucial role in many CMS physics analyses that involve these electromagnetic particles.

The ECAL is a compact, homogeneous, hermetic and fine-grain crystal calorimeter consisting of 75848 lead tungstate ($PbWO_4$) scintillating crystals. The $PbWO_4$ crystals are characterized by a high density of 8.3 , a short radiation length of 0.89 cm, a small Moliere radius of 2.2 cm, and a fast light emission which is about 80% in ~25 ns. The choice of $PbWO_4$ ensures the compactness of the detector and its radiation hardness in the harsh environment of the LHC.

ECAL is made of a barrel (EB) part with pseudorapidity coverage $|\eta| < 1.48$, and two endcap (EE) regions with the coverage $1.48 < |\eta| < 3.0$. Preshower (ES) is used to discriminate between prompt photons and photons from π_0 decays and it covers the pseudorapidity range of $1.65 < |\eta| < 2.6$. The scintillation light from each ECAL crystal is detected by avalanche photodiodes (APD) in EB and a vacuum phototriode (VPT) in EE. The laser light injected in ECAL crystals is also sent to a set of reference PN diodes through optical fibers for monitoring purpose.

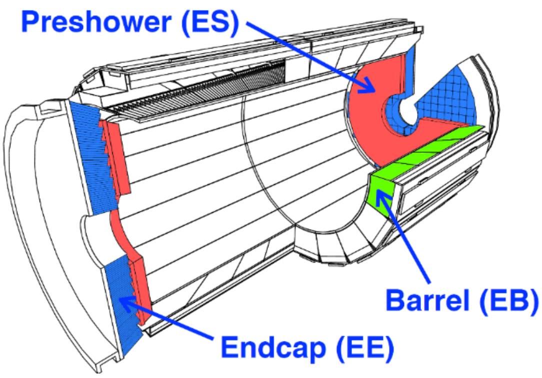


Figure 1: Schematic ECAL layout.

2. Energy reconstruction of electrons and photons

Electromagnetic particles deposit their energy over several ECAL crystals. A dynamic clustering algorithm [3] is used in CMS to collect the energy deposits in ECAL. The reconstructed energy of electrons and photons is estimated by:

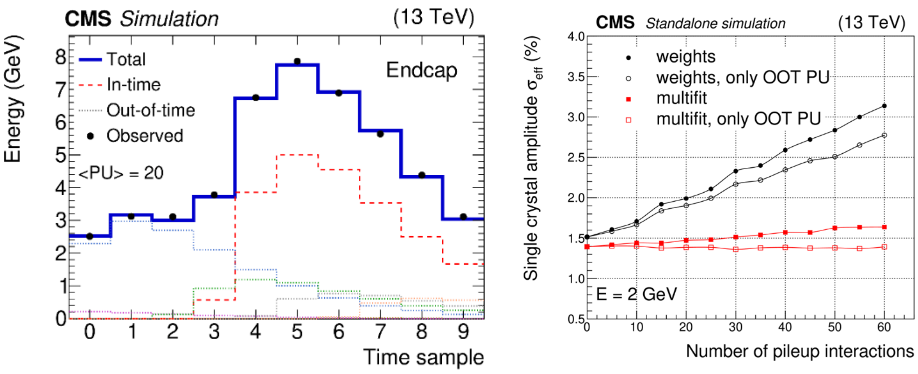
$$E_{e,\gamma} = F_{e,\gamma} \times [G \times \sum_i (A_i \times LC_i \times IC_i) + E_{ES}],$$

where the index i represents individual crystals within the supercluster, A_i is the single channel reconstructed amplitude, LC_i is the laser correction for the crystal response variation over time, and IC_i is an intercalibration constant measured in-situ for each channel i

by equalizing the response of all channels located at the same η. The quantity G is the ADC to GeV absolute energy scale factor, E_{ES} is the energy deposited in the preshower, and $F_{e,\gamma}$ is a correction applied to the supercluster energy.

3. Signal amplitude reconstruction

The electrical signal from the photodetectors is digitised by analog-to-digital converters running at a frequency of 40 MHz, and the signal amplitude is reconstructed from ten consecutive time samples, one every 25 ns. The recorded pulse is the sum of in-time and out-of-time (OOT) pulses. In LHC Run 1, the weights method [4] was used to reconstruct the signal as a weighted sum of the ten digitized samples. In Run 2, a new algorithm called "multifit" [5] was introduced to minimize the impact of OOT pileup contribution. This algorithm estimates the in-time signal amplitude and up to 9 OOT amplitudes using a template fit method. An example of the fitted pulses using the multifit algorithm can be found in **Fig. 2a**. The multifit reconstruction method proves to be robust against pileup increase as shown in **Fig. 2b**.



(a) (b)

Figure 2a: Example of fitted pulses using the multifit reconstruction algorithm, for simulated events with 20 average pileup interactions and 25 ns bunch spacing. **Figure 2b:** Effective resolution for the single crystal amplitude as a function of pileup for the weights and multfit methods.

4. Laser montoring system and crystal response corrections

The ECAL channel response varies with time because of radiation-induced effects stemming from two sources: changes in crystal transparency due to radiation damage, and ageing of the photocathode with accumulated charge. In CMS, the response of each ECAL channel is monitored using a dedicated laser system [6] which injects laser light with a wavelength of 447 nm into each crystal. **Fig. 3** shows the evolution of the ECAL response to laser light since 2011. The crystals in the barrel and endcap regions until $|\eta| < 2.4$ have suffered a moderate transparency loss on average, albeit with a strong eta dependence. The crystals in the forward region, closer to the beam pipe and exposed to higher radiation rates, have been subject to larger transparency loss. Partial recovery of transparency is observed in the absence of radiation.

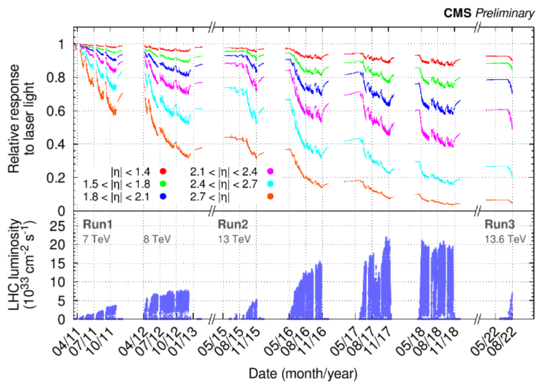


Figure 3: Evolution of the ECAL channel response to laser light versus time since 2011. The channels are subdivided in ranges of η. The bottom panel shows delivered instantaneous luminosities.

The laser monitoring system is designed to provide corrections for ECAL crystal transparency changes. The ECAL channel response variation over time measured by the laser system $R(t)$ are related to changes in the scintillation signal $S(t)$ using:

$$\frac{S(t)}{S(0)} = \left(\frac{R(t)}{R(0)}\right)^{\alpha},$$

where $S(0)$ and $R(0)$ are reference responses to laser light and electromagnetic shower measured at the beginning of each data taking. The α parameter depends on η and evolves with integrated luminosity. It is periodically re-computed to ensure energy scale stability and high resolution. The laser monitoring system performs the crystal-by-crystal scan every 40 minutes during data taking, with crystal response corrections provided within 48 hours for the prompt reconstruction.

In addition to the crystal response corrections, a residual correction is needed to account for the response drift of the reference PN diodes used in the laser system to monitor the injected laser light in the crystals. The residual energy-scale corrections are derived by comparing the ECAL energy over the tracker-measured momentum of electrons from W and Z bosons decays (E/p ratio). **Fig. 4** shows the ratio of the laser amplitude measured inside ECAL to the reference measurement by the PN diode, as a function of the date in 2018. The residual energy-scale variation is a few persent throughout the whole year and independent of instantaneous luminosity.

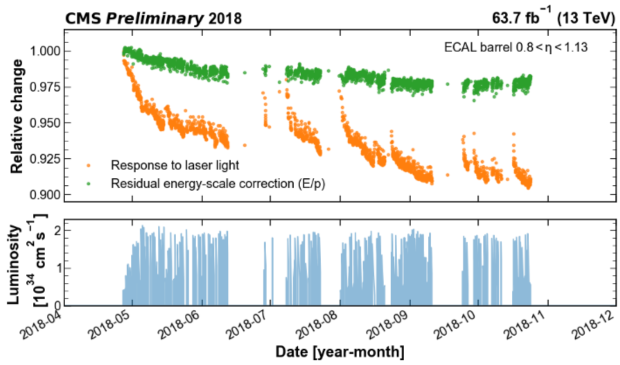


Figure 4: Ecal response to the laser lights and the residual energy-scale correction in 2018.

5. Intercalibration procedure

Intercalibration constants are derived to equalize the ECAL response for different crystals at the same η coordinate to ensure a homogeneous behavior over the detector. Three independent methods based on different physics signals are exploited in Run 2 in CMS. The π_0 mass method explores $\pi_0 \rightarrow \gamma\gamma$ decays, iteratively correcting each crystal energy using the π_0 mass peak shift between the measured position and the PDG [7] π_0 mass value. The E/p method uses the comparison of the ECAL energy to the tracker momentum for isolated electrons from W and Z boson decays, assigning corrections to each crystal to obtain a uniform average E/p ratio. The $Z \rightarrow ee$ method exploits the invariant mass reconstructed with electron pairs from Z decays, maximizing a likelihood comparing the reconstructed mass distribution with the Monte Carlo prediction.

The final intercalibration constants are derived combining the three methods with weights proportional to their respective precisions. As shown in **Fig. 5**, ECAL intercalibrations in Run 2 reach very good precision, with <0.5% at the barrel region and <1% at the endcap region.

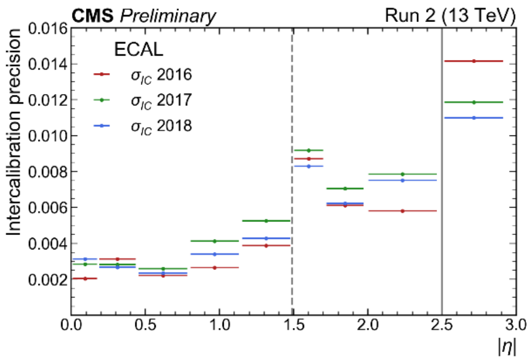
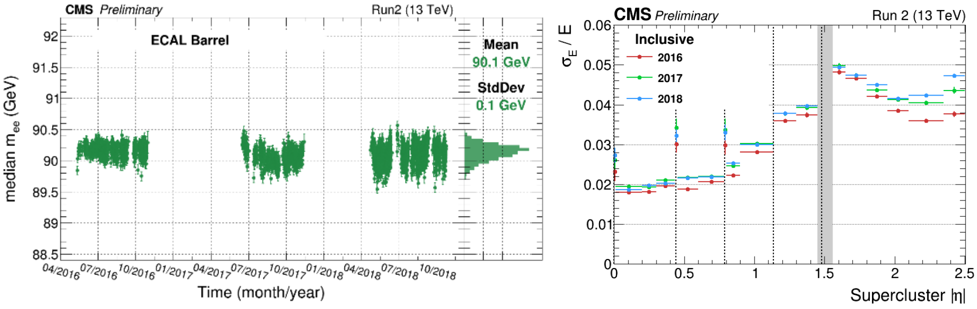


Figure 5: Intercalibration precision computed from the combination as a function of η for different years of data-taking.

6. ECAL performance in Run 2

Events with $Z \rightarrow ee$ decays are used to evaluate the ECAL performance after the full Run 2 detector calibration. The stability of the di-electron mass scale as a function of time is shown in **Fig. 6a**, and it is within 1% across the three years of Run 2. The relative electron energy resolution is shown in **Fig. 6b**, comparing different data-taking periods from 2016 to 2018. ECAL achieved an excellent resolution in Run 2, ranging from ~2% in the central barrel to less than 5% in the forward region.



(a) **(b)**

Fig. 6a: Time stability of the di-electron invariant mass distribution in Run 2 using $Z \rightarrow ee$ events. **Fig. 6b**: Relative electron energy resolution as a function of η for different years in Run 2.

7. Conclusion

The CMS ECAL has faced many challenges during the LHC Run 2, stemming from the increased instantaneous luminosity and the detector ageing. A refined calibration and a novel signal amplitude reconstruction method have been exploited to ensure good energy resolution for electromagentic particles and the stability of the ECAL performance. The CMS ECAL demonstrated outstanding performance in Run 2, with very stable energy response over time at the level of ~1%, and with excellent resolution of electrons between 2% and 5%. The ECAL is expected to preserve this performance throughout Run 3 with the development of an automated calibration framework and more frequent updates of calibrations.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, JINST. 3, S08004 (2008).

[2] CMS Collaboration, *The electromagnetic calorimeter project*, Technical Design Report, CERN/LHCC 97-33, CMS TDR 4 (1997).

[3] CMS Collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, Journal of Instrumentation 16 (05) (2021) P05014.

[4] P. Adzic et al., *Reconstruction of the signal amplitude of the CMS electromagnetic calorimeter*, Eur. Phys. J. C 46 (2006) 23

[5] CMS Collaboration, *Reconstruction of signal amplitudes in the CMS electromagnetic calorimeter in the presence of overlapping proton-proton interactions*, JINST 15 P10002 (2020).

[6] M. Anfreville et al., *Laser monitoring system for the CMS lead tungstate crystal calorimeter*, Nucl. Instrum. Meth. A 594 (2008) 292.

[7] P.A. Zyla et al. (Particle Data Group), *The Review of Particle Physics (2020)*, Prog. Theor. Exp. Phys. 2020, 083C01 (2020).