Calibration and Performance of the CMS Electromagnetic Calorimeter in LHC Run2

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The CMS Detector

- CMS is a general-purpose detector designed to test Standard Model (SM) predictions and search for new physics beyond the SM.

- The electromagnetic calorimeter plays a crucial role in many CMS physics analysis that involve electrons or photons.

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CMS Detector Specifications:

- **CMS DETECTOR**
  - Total weight: 14,000 tonnes
  - Overall diameter: 15.0 m
  - Overall length: 28.7 m
  - Magnetic field: 3.8 T

  **STEEL RETURN YOKE**
  - 12,500 tonnes

  **SILICON TRACKERS**
  - Pixel (100x150 µm) ~16 m^2 ~66 M channels
  - Microstrip (80x180 µm) ~100m^2 ~9.6 M channels

  **SUPERCONDUCTING SOLENOID**
  - Nibium titanium coil carrying ~18,000 A

  **MUON CHAMBERS**
  - Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
  - Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

  **PRESHOWER**
  - Silicon strips ~16 m^2 ~137,000 channels

  **FORWARD CALORIMETER**
  - Steel + Quartz fibres ~2,000 Channels

  **CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
  - ~76,000 scintillating PCWO, crystals

  **HADRON CALORIMETER (HCAL)**
  - Brass + Plastic scintillator ~7,000 channels
CMS Electromagnetic Calorimeter (ECAL)

- **ECAL**: compact, homogeneous, hermetic and fine-grain crystal calorimeter
  - designed to provide highly efficient and accurate reconstruction of photons and electrons

- 75848 PbWO4 crystals
- high density of 8.3 g/cm³
- short radiation length 0.89 cm
- small Moliere radius 2.2 cm
- fast light emission: ~80% in ~25 ns

**Coverage:**
- **Barrel (EB)**: $|\eta| < 1.48$
- **Endcap (EE)**: $1.48 < |\eta| < 3.0$
- **Preshower (ES)**: $1.65 < |\eta| < 2.6$

*(ES: discriminate between prompt photons and photons from $\pi_0$ decay)*

**ECAL challenges in LHC Run 2:**
- higher pileup and noise, increased exposition to radiations
- a larger variation of the calorimeter response that must be corrected for
The electromagnetic particles deposit their energy over several ECAL crystals. Dynamic clustering algorithms used to collect the energy deposits in ECAL.

The reconstructed energy of electrons and photons is estimated by:

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

- Cluster correction obtained from a regression method
- The reconstructed signal amplitude
- Preshower energy
- Global scale factor for the ADC-to-GeV conversion
- Laser correction: correct for crystal transparency loss
- Intercalibration: equalize the channel response at same \( \eta \)
10 digitized ECAL pulse samples recorded for signal amplitude reconstruction

- Run 1: Amplitude was a weighted sum of all 10 samples.
- Run 2: ‘multifit’ reconstruction method is explored to mitigate higher pileup.
  - Pulse shape is modeled as a sum of one in-time pulse and up to 9 out-of-time (OOT) pulses

The ‘multifit’ reconstruction method is robust against pileup increase.
ECAL channel response varies with time due to radiation-induced effects
- crystal transparency changes over time
- photocathode aging with accumulated charge
A dedicated laser monitoring system is designed to provide corrections for this.

- injects laser light with a wavelength of 447nm into each crystal
- relates ECAL channel response variation to changes in the scintillation signal
- measures the calibration point per crystal every 40 minutes
- obtains and applies corrections within 48 hours for the prompt reconstruction

Relative response = \( \frac{\text{APD}(\text{VPT})}{\text{PN}} \)

- \( \alpha \) parameter depends on \( \eta \) and evolves with integrated luminosity
  - periodically computed to ensure energy scale stability and high resolution
Laser Correction (LC)

- Orange: relative response variations to laser light injected in the ECAL crystals
- Green: the residual energy-scale correction after the application of the laser corrections
  - correction needed due to a drift of the response of the PN diode used in the laser-based calibration system
  - correction determined by comparison with the tracker-measured momentum of electrons from W/Z bosons (E/p ratio)
  - a few percent variation during the year and independent on instantaneous luminosity
Intercalibration (IC)

- IC: equalize the ECAL response for different crystals at the same $\eta$ coordinate.
- A combination of several methods based different physics signals
  - $\pi^0$ mass: exploit reconstructed $\pi^0$ mass with its decay of photon pairs
  - $E/p$: comparison of the ECAL energy to the tracker momentum for isolated electrons from W/Z boson decay
  - Zee: exploit the invariant mass reconstructed with electron pairs from Z decays
  - $\phi$-symmetry: correct non-uniformed energy flux around $\phi$ rings based azimuthal symmetry of minimum bias event, not used in combination due to bad precision
Final intercalibration combines different methods by weighting their respective precision

- precision evaluated with the relative energy resolution of Zee

- IC reaches very good precision
  - <0.5% at barrel region
  - <1% at endcap region
  - dominant factor of the constant term in the final energy resolution
Preshower Calibration

- Preshower calibrated using minimum ionizing particles (MIPs)
  - channel by channel calibration
  - special runs taken for calibration every 10 $fb^{-1}$
  - correction computed by minimizing the $X^2$ value between the energy distribution of data and MC using $Z \rightarrow e e$ events
  - Measured energy of ES cluster is stabilized by applying the correction.
ECAL Performance in Run 2

- ECAL response is stable over time after corrections
  - validated with $Z \rightarrow ee$ physics signals
- Energy scale stable at ~1% level across 3 years
- Shower shape variable (R9) also stable over time with spread <<1%
  - Important variable for the electron and photon identification
ECAL Performance in Run 2

- Energy and mass resolution with ECAL calibration

- clear improvements after refined calibration
- stable performance within Run 2
- similar performance in Run 2 and Run 1
Summary

- Challenging CMS ECAL calibration in Run 2 due to increased instantaneous luminosity and detector aging

- A range of recalibration and optimization has been exploited with full Run 2 data
  - new multifit method for amplitude reconstruction
  - laser correction to stable ECAL response over time
  - intercalibration to stable ECAL response in different crystals at same $\eta$
  - corrections to stable measured energy in preshower

- Excellent performance is achieved with ECAL calibration in Run 2
  - stable ECAL response over time with spread at $\sim$1% level
  - resolution for electrons from Z-boson decays better than 2% in the central region of the ECAL and 4% elsewhere
  - similar ECAL performance achieved in Run 2 in comparison with Run 1 despite much harsher environment