Calibration and Performance of the CMS Electromagnetic Calorimeter in LHC Run 2

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On behalf of the CMS collaboration

1: Northeastern University of Boston
ECAL: Compact, homogeneous, hermetic and fine grain calorimeter
- Embedded in 4 T magnetic field
- 75848 lead-tungstate (PbWO$_4$) scintillating crystals
- Intrinsic light yield 100$\gamma$/MeV $\rightarrow$ 4p.e./MeV on the APDs
- Detector designed for excellent energy resolution for photons with 0.1 MeV-1.5 TeV

Excellent resolution and electron/photon ID of the CMS ECAL crucial for discovery and characterization of the 125 GeV Higgs Boson

H$\rightarrow$ZZ$\rightarrow$4$\ell$ CERN-EP-2017-123

H$\rightarrow$YY CERN-EP-2018-060
ECAL Detector

- **Barrel (EB):**
  - 36 supermodules (1700 channels)
  - Total of 61200 PbWO₄ crystals
  - Avalanche Photo-Diode readout (APD)
  - Coverage $|\eta| < 1.48$

- **Endcaps (EE):**
  - Four half-disk Dees (3662 channels)
  - Total of 14648 PbWO₄ crystals
  - Vacuum Photo Triode readout
  - Coverage: $1.48 < |\eta| < 3.0$

- **Preshower**
  - Two Lead/Si planes
  - 137,216 Si strips (1.8 × 61 mm²)
  - Coverage: $1.65 < |\eta| < 2.6$
Energy Reconstruction

\[ E_{e,\gamma} = F_{e,\gamma} \left[ \sum_{i}^{\text{crystals}} \left( A_i \times S_i(t) \times C_i \times H_{i\eta} \right) \right] + E_{ES} \]

- **Energy regression**
- **Amplitude:** extracted from the multifit
- **Laser-Correction:** correct for transparency loss
- **Intercalibration:** equalizing crystals response
- **\( \eta \)-scale:** equalizing ring response wrt MC

**ADCtoGeV:**
- 0.04 GeV in EB
- 0.06 GeV in EE

Preshower energy
Energy Reconstruction

\[ E_{e,\gamma} = F_{e,\gamma} \sum_{i}^{\text{crystals}} G \times A_i \times S_i(t) \times C_i \times H_{i\eta} + E_{ES} \]

- **Energy regression**
- **Amplitude: extracted from the multifit**
- **Laser-Correction: correct for transparency loss**
- **Intercalibration: equalizing crystals response**
- **ADC to GeV:**
  - 0.04 GeV in EB
  - 0.06 GeV in EE

Preshower energy

CMS simulation, \( \sqrt{s}=13 \text{ TeV} \)

PU=20/BX, 25 ns

- Observed signal
- Total pulse
- In-time pulse
- Out-of-time pulses
Energy Reconstruction

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

Response variation in time due to the radiation:

→ Transparency loss of the crystals
→ Electronic noise increase (APDs only)
→ Pedestal increase (APDs only)
→ Pulse shape variations
Response Variation

→ During data calibration of ECAL:
  - Make the response flat in time (e.g. correct for the transparency loss)
  - Cope with the electronic noise increase

→ MC:
  - Conditions are taken from the data, in a moment representative of the average performance over the year
Response Stability

Take care of response variation → make response stable <<1%
Energy Reconstruction

\[ E_{e,\gamma} = F_{e,\gamma} \left[ G \sum_{i}^{\text{crystals}} (A_i \times S_i(t) \times C_i \times H_{i\eta}) \right] + E_{ES} \]

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Preshower energy
Intercalibrations

Crystal by crystal equalization because different light-yield and photodetector response, through dedicated data streams (intercalibrations derived per ring):

- **Φ-symmetry**: equalization of the average energy in channels located at a constant value of $\eta$

- **$\pi^0$ mass**: iterative method exploiting the invariant mass reconstructed from unconverted photons arising from the decays of $\pi^0$

- **E/p**: iterative method, comparison of the ECAL energy to the tracker momentum for isolated electrons.

- **Zee**: exploit the invariant mass reconstructed from $Z \rightarrow e^+ e^-$

Calibrations at $|\eta|>2.5$ (no tracking)
- 1 electron with $|\eta|<2.5$
- 1 SC with $|\eta|>2.5$
Intercalibrations: Precision

- **Precision**: performance of the IC method on the relative energy resolution of Zee
- **Combination performed reweighting on the precision**
Energy Reconstruction

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Preshower energy

\( \eta \)-scale: equalizing ring response wrt MC
Energy Reconstruction

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- Amplitude: extracted from the multifit
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Preshower energy
ES Calibration

- Sensor by sensor calibration performed using the MIPs
- Every ~10/fb, special runs are taken for MIP calibration
Performance

CMS Preliminary 2017  41.5 fb\(^{-1}\) (13 TeV)

- Preliminary (\(\sigma/\mu=2.0\%\))
- Refined (\(\sigma/\mu=1.8\%\))

ECAL Barrel

CMS Preliminary 2017  41.5 fb\(^{-1}\) (13 TeV)

- Preliminary (\(\sigma/\mu=3.5\%\))
- Refined (\(\sigma/\mu=2.9\%\))

ECAL Endcaps

\(m_{ee}\) (GeV)

01/08/19  Badder Marzocchi
Performance

→ EB resolution improvement at least 0.5%
→ EE resolution improvement of about few percent
Summary

- **CMS ECAL detector designed for excellent energy resolution for photons with 0.1 MeV-1.5 TeV:**
  - → 75848 lead-tungstate (PbWO$_4$) scintillating crystals
  - → Signal read by APDs (in EB) and VPTs (in EE)

- **Final recalibration: best possible performance for legacy analyses**
  - → Response uniformity in space and time
  - → Optimal energy resolution

- **2017 data recalibration:**
  - → Long procedure to reach the best performance
  - → EB resolution improvement at least 0.5%
  - → EE (|η|<2.5) resolution improvement of about few percent
Amplitude Reconstruction: Multifit

- Estimation of in-time signal amplitude and up to 9 out of time amplitudes by minimization of the $\chi^2$:

$$\chi^2 = \left( \sum_{j=1}^{N_{\text{pulse}}} A_j \vec{p}_j - \vec{S} \right)^T C^{-1} \left( \sum_{j=1}^{N_{\text{pulse}}} A_j \vec{p}_j - \vec{S} \right)$$

$$C = C_{\text{noise}} \oplus \sum_{j=1}^{N_{\text{pulse}}} A_j^2 C_j^{\text{pulse}}$$

$A_i =$ amplitude, $S =$ 10 samples, $p_i =$ template pulshapes, $C =$ covariance matrix
Transparency corrections

Crystal transparency changes are measured with a laser monitoring system, injecting laser light into the crystals continuously (at 100 Hz):

\[
\text{Laser-Correction} = (R/R_0)^\alpha, \quad R = \text{PhotoDetector}/\text{PN}_{\text{ref}}
\]

\(\alpha\) = empirical parameter taking into account the differences between laser light and EM shower

\(\text{PN}_{\text{ref}}\) = reference PN photodiode, lit by the split laser light

L1

PN

L1
Pedestals

CMS Preliminary 2017 46 fb⁻¹ (13 TeV)

Pedestal mean (ADC counts)

ECAL Endcap
Non-collision runs (long term variation)
Collision runs (short term variation)
1 ADC count = 60 MeV

Date (time/month)

24 May 23 Jun 23 Jul 22 Aug 21 Sep 21 Oct 20 Nov

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Performance: Low Bremsstrahlung

**CMS Preliminary 2017** 41.5 fb⁻¹ (13 TeV)

- Preliminary (σ/μ=1.5%)
- Refined (σ/μ=1.3%)

ECAL Barrel Low Bremsstrahlung

- Preliminary (σ/μ=3.3%)
- Refined (σ/μ=2.4%)

ECAL Endcaps Low Bremsstrahlung
Performance: Low Bremsstrahlung

![Graph showing performance of low Bremsstrahlung](graph.png)
Performance: High Bremsstrahlung

**CMS Preliminary 2017** 41.5 fb\(^{-1}\) (13 TeV)

- **Preliminary** (\(\sigma/\mu=2.3\%\))
- **Refined** (\(\sigma/\mu=2.0\%\))

**ECAL Barrel**
High Bremsstrahlung

**CMS Preliminary 2017** 41.5 fb\(^{-1}\) (13 TeV)

- **Preliminary** (\(\sigma/\mu=3.6\%\))
- **Refined** (\(\sigma/\mu=3.2\%\))

**ECAL Endcaps**
High Bremsstrahlung

![Graph](image-url)