CMS ECAL Monitoring and Calibration in LHC Run 2

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On behalf of the CMS Collaboration

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Outline

1. Introduction
   • ECAL Building Blocks

2. Calibration
   • Inter-calibration: Motivation
   • Inter-calibration: Methods
   • Inter-calibration: Results
   • Preshower Calibration

3. Monitoring and Validation using physics events
   • Motivation and methods
   • Energy scale
   • Shower shape

4. Summary
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4 Summary
The CMS Electromagnetic Calorimeter consists of 75848 scintillating PbWO$_4$ crystals and 137216 sampling Si strips with Pb absorber.
Building Blocks: ECAL Barrel + Endcaps

The CMS Electromagnetic Calorimeter consists of 75848 scintillating PbWO$_4$ crystals and 137216 sampling Si strips with Pb absorber.

**Barrel APDs**
- Attached to 61200 crystals
- Crystal dimensions: $2.2 \times 2.2 \times 23 \text{ cm}^3$
- Designed to operate at 4 T, gain 50

**PbWO$_4$ crystals:** $\rho = 8.28 \text{ g cm}^{-3}$

$X_0 = 0.89 \text{ cm}$, $R_M = 2.19 \text{ cm}$

**Endcap VPTs**
- Attached to 14648 crystals
- Crystal dimensions: $2.9 \times 2.9 \times 22 \text{ cm}^3$ (front face)
- Higher radiation tolerance, gain 10
Building Blocks: ECAL Preshower

The CMS Electromagnetic Calorimeter consists of 75848 scintillating PbWO₄ crystals and 137216 sampling Si strips with Pb absorber.

Assembled Preshower Module used in beam tests

ECAL Preshower

- ECAL Preshower consists of four planes, two in front of each endcap
- Thickness of lead plates: $\approx 3X_0$
- Each Si sensor consists of 32 “strips”, oriented along X in one plane and along Y in the other at both endcaps
- Strip size: $2.0 \times 63 \times 0.3$ mm$^3$

Higher spatial resolution helps distinguish genuine high-energy photons from close photon pairs (e.g. those resulting from $\pi^0$-decay).
An algorithm identifies a list of crystals (a “supercluster”) in which a photon or electron from the collision is likely to deposit energy.

\[ E_{e,\gamma} = F_{e,\gamma} \times \left[ G(\eta) \times \left\{ \sum_{i \in SC} S_i(t) \times C_i \times A_i \right\} + E_{\text{preshower}} \right] \]

This talk focuses on how we obtain the inter-calibration coefficients \( C_i \), and validate and monitor physics quantities over the data-taking period.
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Inter-calibration: motivation

- The laser monitoring signal $L$ is used to correct the scintillation signal $S$ for short term effects (e.g. radiation-induced damage to crystals during fills), using the formula:

$$\frac{S}{S_0} = \left( \frac{L}{L_0} \right)^\alpha$$

- Residual long term drifts of the individual crystal response remain after the laser corrections, which are due to different effects. (e.g. the values of $\alpha$ could be slightly different for each crystal, or other ageing effects . . . )

- These effects can be monitored and corrected for using physics channels, e.g. by exploiting the azimuthal symmetry of the energy deposits in minimum bias events.

Plots on the left (barrel) and right (endcap), show the dispersion of the inter-calibration coefficients versus time during 2016 data taking, obtained with the azimuthal symmetry method.
Inter-calibration: Methods

- We use three methods to inter-calibrate crystal response.
  1. $\pi^0 \rightarrow \gamma\gamma$ energy distribution peak
  2. Comparing reconstructed energy with independent measurement of momentum from tracker
  3. $Z \rightarrow ee$ distribution

- Each method gives independent inter-calibration coefficients which we then combine for a final measurement.
Inter-calibration method 1: $\pi^0 \rightarrow \gamma\gamma$

- One can use the reconstructed invariant masses of photon pairs from $\pi^0$ to inter-calibrate crystal response, using:

**Method**

The peak of the fitted $m_{\gamma\gamma}$ distribution is ensured to be the same value for each crystal.

- For each crystal, we obtain this fit using all events with one hit in that crystal. Then,

$$C_i = \frac{m_{\pi^0} \text{(measured with crystal } i)}{m_{\pi^0} \text{(PDG)}}$$

- Repeated iteratively until convergence.

- Dataset: Special stream of data from dedicated trigger that selects diphoton events close to the $\pi^0$ resonances, allowing sufficient statistics for inter-calibration and monitoring.
Inter-calibration method 1: $\pi^0 \rightarrow \gamma \gamma$

Examples of $m_{\gamma\gamma}$ distributions, with fits to the data, for selected crystals in the barrel (left) and in the endcaps (right).
Inter-calibration method 2: $E/p$ ratio

- One can use the momentum reconstructed by the CMS tracker (strips + pixels) as a reference.

**Method**

The fraction $E/p$ in each crystal is made to fit a common underlying template, where $E =$ ECAL supercluster energy, $p =$ tracker momentum.

We obtain the template from a very high purity sample of high energy electrons from $W/Z$ decay.

We derive the crystal inter-calibrations by iteratively scaling the coefficients $C_i$ until the $E/p$ distribution in each crystal converges to the template.
Inter-calibration method 3: $Z \rightarrow ee$

- One can use the known mass and lifetime of $Z \rightarrow ee$ as a reference.

**Method**

The overall $Z$-peak as reconstructed from data in all crystals is fitted to a convolution of the known natural $Z$–shape (which depends on $Z$–mass and lifetime), and a spread due to resolution effects.

- The mass and decay width of $Z$ are obtained from PDG.
- We use a likelihood maximization algorithm, with the inter-calibration coefficients $C_i$ as parameters.
- In addition to the inter-calibration parameters, we include the resolution in several $\eta$– bins as parameters, allowing us to obtain estimates of the $\eta$–binned energy resolution.
Inter-calibration: Combination

Assuming no correlation between the three different methods used to inter-calibrate crystal response, we have: (n.b. both systematic and statistical uncertainty are included in the estimates of the precision)

\[
\begin{align*}
\sigma_1^2 + \sigma_2^2 &= \sigma_{1-2}^2 \\
\sigma_1^2 + \sigma_3^2 &= \sigma_{1-3}^2 \\
\sigma_2^2 + \sigma_3^2 &= \sigma_{2-3}^2
\end{align*}
\]

\[
\begin{align*}
\sigma_1^2 &= \frac{1}{2} (\sigma_{1-2}^2 + \sigma_{1-3}^2 - \sigma_{2-3}^2) \\
\sigma_2^2 &= \frac{1}{2} (\sigma_{2-3}^2 + \sigma_{1-2}^2 - \sigma_{1-3}^2) \\
\sigma_3^2 &= \frac{1}{2} (\sigma_{1-3}^2 + \sigma_{2-3}^2 - \sigma_{1-2}^2)
\end{align*}
\]

Finally the combined inter-calibration value for each crystal is obtained as the weighted mean of the values obtained by each individual method.

Note: For the endcaps in 2017, we only use the \(Z \rightarrow ee\) method because it is much more precise than the other methods; therefore, we do not have estimates of the precision from the system of equations.
Inter-calibration: 2017 Precision

Individual and combined inter-calibration precision: compare 2015 results (on the left) with 2017 results (on the right). For 2017 results, the precision from $Z \rightarrow ee$ and $\pi^0 \rightarrow \gamma\gamma$ decays is at the level of the systematic error, while the statistical errors are still dominant for the $E/p$ precision at $|\eta| > 1$. The black points represent the combined weighted precision.
Preshower calibration

- Calibration of the preshower involves calculating the conversion from ADC counts to GeV.
- A few times per year we take a special run with the preshower in high gain mode; this allows us to see the MIP peak and calibrate the preshower sensors.
- We reconstruct MIP peak per channel $\rightarrow$ gives ADC-to-MIP conversion.
- MIP-to-GeV conversion is known: 1 MIP $= 80.4$ keV

Fitted around the peak to a Landau convoluted with a Gaussian.

Diagram: Preshower calibration data with fitted line and MIP peak information.
Preshower MIP stability

MIP response evolution with respect to beginning of 2017 in the preshower.

ES sensors in high $\eta$ regions are affected more by radiation damage.
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4 Summary
Motivation and Methods

- **Monitoring**: To ensure that reconstruction is stable throughout the year, we monitor some quantities obtained from reconstructed physics objects.

- **Validation**: At the end of the year, we apply all corrections (laser monitoring, inter-calibration coefficients, etc.), and plot the same quantities over the year, expecting that there should be no drift.

- **Quantities Monitored**:
  1. Energy scale: \( \pi^0 \)-mass, \( Z \rightarrow ee \)
  2. Shower shapes: \( Z \rightarrow ee \)
The relative energy scale measured from the invariant mass distribution of $\pi^0 \rightarrow \gamma\gamma$ decays in the ECAL Barrel remains stable throughout the year after applying transparency corrections (more on laser corrections in Amina’s talk).
$Z \rightarrow ee$ invariant mass

Validates: energy scale

The invariant mass in $Z \rightarrow ee$ events is observed to be stable throughout the year once all corrections have been applied.
$Z \rightarrow ee \ R_9$

Validates: shower shape stability

The variable $R_9 \equiv \frac{E_{3 \times 3}}{E_{SC}}$ is one of the variables typically used in CMS physics analyses to identify EM showers using their shower shape. It stays stable throughout the year in $Z \rightarrow ee$ events.
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Performance of 2017 calibration

Reconstruction with the latest calibrations significantly improves the resolution.

**Black:** reconstruction performed just at the end of data-taking; only low level parameters were optimized for this reconstruction with respect to the prompt processing due to short available time (pedestals, laser correction, timing, . . . )

**Blue:** reprocessing done with the new 2017 calibrations.
Performance of 2017 calibration

The $Z$-mass peak is visibly improved by updating the calibration.
Summary

- The LHC environment in 2017 has been challenging with high instantaneous luminosity, high pile-up and varying bunch filling schemes.
- The ECAL pulse amplitude reconstruction is robust with respect to pile-up effects and the many validation and monitoring methods that we have developed allow to follow and correct the evolution of the calorimeter.
- Thanks to the high integrated luminosity collected in 2017, we have calibrated the CMS ECAL exploiting many physics channels, including for the first time $Z \rightarrow ee$ at single crystal granularity.
- The new calibrations allow us to achieve a very good energy resolution in both the Barrel and the Endcaps.
BACKUP SLIDES
Inter-calibration using $\phi$-symmetry

Because of the symmetry of the CMS and ECAL around the beam axis, over a long enough time period:

**Assumption**

The net energy flux through a crystal should be independent of the polar angle $\phi$ of the crystal.

- The coefficients $C_i$ are then set such that in each $\eta$-ring, the average of the coefficients over all crystals is 1; allows for precise inter-calibration along $\phi$ but not along $\eta$. 
ECAL Alignment: EB + EE

\begin{align*}
\text{ECAL Barrel} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}

\begin{align*}
\text{ECAL Barrel Electron} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}

\begin{align*}
\text{ECAL Barrel Positron} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}

\begin{align*}
\text{ECAL Endcap} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}

\begin{align*}
\text{ECAL Endcap Electron} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}

\begin{align*}
\text{ECAL Endcap Positron} & \quad \Delta\eta \quad \Delta\phi \\
\text{MC (Z\to\ee)} & \quad \text{DATA after alignment} \\
\text{DATA before alignment} \\
\end{align*}
ES Alignment

![Graphs showing ES Alignment](image-url)
Timing

Validates: pulse shapes, rechit reconstruction

The timing drifts slightly throughout the year; however, this quantity is regularly monitored and pulse shapes are kept up-to-date to ensure that physics analyses are not affected.
Crystal noise

Validates: shower shape, lepton isolation

The RMS of the readout in absence of signal is a measure of the noise and slowly drifts upwards with radiation-induced damage to the APDs.
Measuring deposited energy

(Candidate $H \rightarrow \gamma\gamma$ event)

The energy reconstruction algorithm assigns an energy to an observed collection of crystal deposits.
Inter-calibration: more on $E/p$

\[
C_i^N = C_i^{N-1} \times \frac{\sum_{\text{good electrons}} F_i \times P\left(E_{SC}^{N-1} | p_{trk}\right) \times \frac{p_{trk}}{E_{SC}^{N-1}}}{\sum_{\text{good electrons}} F_i \times P\left(E_{SC}^{N-1} | p_{trk}\right)}
\]

superscript $N$, $N - 1 = \text{iteration index}$

$F_i = \text{fraction of } E_{SC} \text{ in crystal } i$

$P\left(E_{SC} | p_{trk}\right) = \text{probability of } E_{SC} \text{ given } p_{trk}$

(as found from $(E/p)$ template)
Inter-calibration: more on $Z \rightarrow ee$

- Likelihood function:

$$\mathcal{L} = \prod_{Z \rightarrow ee \text{ events}} \text{Voigt} (m_{ee}, \sigma_{ee}, M_Z, \Gamma_Z)$$

where

$$m_{e_1e_2} = \sqrt{2 \times E_{\text{corrected}} (e_1) \times E_{\text{corrected}} (e_2) \times (1 - \cos \theta_{12})}$$

$$\sigma_{e_1e_2} = \frac{1}{2} \times M_Z \times \left( \frac{\sigma_E}{E} (e_1) \bigoplus \frac{\sigma_E}{E} (e_2) \right)$$

$$E_{\text{corrected}} = \frac{E_{ECAL}}{r(\eta)} + E_{\text{Preshower}}$$

- Note that this also allows us to extract the energy resolution binned in $\eta$. 