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Calibration and performance of the CMS electromagnetic calorimeter in LHC Run 2

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on behalf of the CMS Collaboration
ECAL is crucial in CMS physics analysis

- New physics searches and Standard Model precision measurements with photons and electrons

**H → γγ**

**H → ZZ → 4l**

**Z' → ee**

- High energy resolution
- A wide range of $E_T$
- Position measurement
- High energy resolution
- Energy linearity
CMS Electromagnetic Calorimeter

- homogeneous, hermetic, compact, fine-grain PbWO₄ crystal calorimeter
  - 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
  - refractive index = 2.2
  - light yield spread among crystals 13% (RMS) from beam test

**Strengths:**
- precise e/γ energy and position measurements
- good timing resolution
- fast and efficient readout for online selection (DAQ and trigger)

<table>
<thead>
<tr>
<th>sub-detector</th>
<th>η-coverage</th>
<th>read-out channels</th>
<th>X₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td></td>
<td>η</td>
<td>&lt; 1.48</td>
</tr>
<tr>
<td>EE</td>
<td>1.48 &lt;</td>
<td>η</td>
<td>&lt; 3.0</td>
</tr>
<tr>
<td>ES</td>
<td>1.65 &lt;</td>
<td>η</td>
<td>&lt; 2.6</td>
</tr>
</tbody>
</table>

Compact enough to fit inside the 3.8T superconducting solenoid
Energy reconstruction

- Electrons and photons deposit energy over several crystals (70% in one, 97% in a 3\times3 array), spread in \( \Phi \), collected by clustering algorithms.

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

- the optimal performance was achieved by exploiting full statistics of one year.

- **CMS ECAL energy resolution :**
  - uniformity and stability resolution required \textit{in situ} < 0.5%
  - in barrel, 1% energy resolution achieved in Run I for unconverted/late-converting photons.
\[ E_{e,\gamma} = \left[ \sum_i \left( S_i(t) \times c_i \times A_i \times H_{i\eta} \right) \times G + E_{ES} \right] \times F_{e,\gamma} \]
Pulse reconstruction

- When LHC runs with 25-ns bunch-spacing, the level of out-of-time (OOT) pile-up increases
- to mitigate this effect → **Multifit algorithm**: pulse shape is modeled as a sum of one in-time pulse pluses OOT pulses

\[ \chi^2 = \sum_{i=1}^{10} \frac{(\sum_{j=1}^{M} A_j \times p_{ij} - S_i)^2}{\sigma_{Si}^2} \]

- up to 9 OOT pulses (one per time sample)
- minimize \( \chi^2 \) distribution for best description of the in-time amplitude
- baseline and electronic noise periodically measured from dedicated runs and used in the covariance matrix
- Minimization using non-negative least-squares: fast enough to be used both offline and online
Laser Monitoring

\[ E_{e,\gamma} = \left[ \sum_i \left( S_i(t) \times c_i \times A_i \times H_i \eta \right) \times G + E_{ES} \right] \times F_{e,\gamma} \]
Crystal response monitoring (1/2)

- ECAL radiation-induced effects, heavily $\eta$ dependent
  - change in crystal transparency
  - change in VPT response in endcaps
- channel response is constantly monitored with a laser system injecting light in every ECAL crystal
  - 1 calibration point per channel every 40 mins
  - corrections obtained and applied in ~48 hours for prompt reconstruction

- Steady recovery during shutdowns and inter-fills
- In the regions close to beam pipe, not fully recovered

tracker coverage $\rightarrow$ precision physics
high $\eta$ ($|\eta| > 2.5$) $\rightarrow$ jet/MET physics
Inter-calibration

\[ E_{e, \gamma} = \left[ \sum_i \left( S_i(t) \times C_i \times A_i \times H_i \right) \times G + E_{ES} \right] \times F_{e, \gamma} \]
**Inter-calibration (IC)**

- equalizes the response of each single crystal to the deposited energy

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \rightarrow \gamma\gamma$</td>
<td>In a $\Phi$ ring, use IC to improve $M_{\gamma\gamma}$ resolution for $\pi^0$ resonances</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>Utilize the reconstructed invariant mass of $Z$ bosons</td>
</tr>
<tr>
<td>electron E/p</td>
<td>Compare isolated electron energy from ECAL and tracker, compute IC to correct discrepancies</td>
</tr>
<tr>
<td>$\Phi$-symmetry</td>
<td>Energy flux around $\Phi$ rings (constant $\eta$) should be uniform - IC corrects for non-uniformity [for monitoring purpose only]</td>
</tr>
</tbody>
</table>
Inter-calibration (IC): precision

- the precision of each IC method is evaluated with the relative energy resolution of $Z \rightarrow ee$
- combined IC is obtained by weighting the respective precisions
- combined IC achieves the goal of 0.5% precision for the barrel region
\[ E_{e, \gamma} = \left[ \sum_i \left( S_i(t) \times c_i \times A_i \times H_{i, \eta} \right) \times G + E_{ES} \right] \times F_{e, \gamma} \]

ADC→GeV

Global Scale

\[ \eta\text{-scale} \]

equalize ring response wrt MC
$$E_{e,\gamma} = \left[ \sum_i \left( S_i(t) \times c_i \times A_i \times H_i \eta \right) \times G + E_{ES} \right] \times F_{e,\gamma}$$

Preshower energy
Preshower silicon sensors inter-calibration

- Preshower was operated in low gain mode ($S/N \sim 3$) for physics, but switched to high gain mode ($S/N \sim 10$) for calibration periodically (about every 10-20/fb)
- Charged particles produced in the collisions are used to calibrate

![Graph showing MIP response relative to the 2015 calibration vs. integrated luminosity.](Image)

- CMS Preliminary 2017

$\sqrt{s} = 13$ TeV

Preshower

MIP = 51.10 ± 0.10 ADC Counts

![Graph showing reconstructed hit energy vs. number of reconstructed hits.](Image)
Preshower energy correction

- the Preshower response decreases with time due to radiation damage
- the correction was computed by minimizing the $\chi^2$ value between the energy distribution of data and MC using $Z\rightarrow ee$ events
- after the correction, the Preshower energy measurement is stabilized
\[ E_{e, \gamma} = \left[ \sum_i \left( S_i(t) \times c_i \times A_i \times H_i \eta \right) \times G + E_{ES} \right] \times F_{e, \gamma} \]
Clustering and corrections

- Large amount of material before ECAL
- Dynamic clustering algorithm recovers energy radiated upstream of ECAL via bremsstrahlung or conversions
  - Super-cluster (SC) of clusters along Φ (bending direction)
  - Soft conversion legs/brem may not be included in SC
  - In the endcaps, preshower energy is also considered
  - Additional energy from pileup contaminates the shower
- The energy of supercluster is corrected using a multivariate approach that maximally exploits the information of the events → tuned on MC, validated on data
- Reconstructed Z mass in data with different levels of energy reconstruction and corrections
ECAL alignment

- position reconstructed from energy deposit exploiting ECAL high granularity
  - electron identification: prompt vs fake electrons
  - measurement of photon direction: $H \rightarrow \gamma\gamma$
- procedure based on matching position reconstructed by tracker and ECAL with low bremsstrahlung electrons from $Z \rightarrow ee$ events
- meet the requirement of the matched measurements between ECAL and tracker better than 0.004 units in $\eta$ and 0.02 radians in $\Phi$
Response stability

• response stability after corrections validated with physics signals, $Z \rightarrow ee$ events
• stable response over time $\sim 0.2\%$
• the shower shape variable $R_9(E_{3x3}/E_{SC})$, important for the electron and photon identification, is also found to be stable (relative spread $< 0.25\%$)
Energy and mass resolution

- derive electron energy resolution from $Z\rightarrow$ee peak width
- energy resolution affected by the material budget in front of the ECAL
- significant improvement with the refined conditions obtained with the full dataset
Performance in the Higgs mass measurement

- comparable to Run 1 performance despite more challenging conditions during data taking in Run 2
Conclusions

• The CMS electromagnetic calorimeter performs well during LHC Run 2 and plays a crucial role in physics beyond SM searches and precision measurements including Higgs physics

• More challenging conditions during data taking in Run 2 require to optimize the strategies for reconstruction and calibration

• Stable performance throughout Run 2
  • stable response
  • good energy resolution (2-4% in barrel and ~4% in endcap)
  • mass resolution of $H \rightarrow \gamma\gamma$ is comparable to Run 1
Spares
**Energy reconstruction**

- Electrons and photons deposit energy over several crystals (70% in one, 97% in a 3×3 array), spread in $\Phi$, collected by clustering algorithms.

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

- Qualification in beam tests:
  - No magnetic field, no material upstream of ECAL, no radiation damage, negligible systematic term from channel response variations.
  - Uniformity and stability resolution required *in situ* $< 0.3\%$.
  - In barrel, 1% energy resolution achieved in Run-I for unconverted/late-converting photons.

\[
\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} + \frac{0.128}{E(\text{GeV})} + 0.3\%
\]
Cluster energy in data

- Reconstructed Z mass in data with different levels of energy reconstruction and corrections
  - the long tail of lower $E_{5x5}$ in EB is due to the high fraction of showering electrons in the high-material region at $|\eta| > 1$
  - the energy scale is improved by adding the preshower energy to the crystal energy
Crystal response monitoring (2/2)

- the increase of the electronic noise was observed related to the increase of the APD dark current due to irradiation
- this effect is modeled in MC by taking the average performance over the year