Role of the CMS electromagnetic calorimeter in the measurement of the Higgs boson properties

Emanuele Di Marco (CERN & INFN Roma1) on behalf of CMS Collaboration

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ECAL: a homogeneous, hermetic, high granularity PbWO$_4$ crystal calorimeter

- density of 8.3 g/cm$^3$, radiation length 0.89 cm, Molière radius 2.2 cm
- ≈ 80% of scintillating light in ≈ 25 ns
- refractive index = 2.2
- light yield spread among crystals ≈ 10% (RMS)

ECAL fully contained in the 3.8T coil
Tracker acceptance: |η| < 2.5

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Barrel (EB)</td>
<td></td>
<td>61200 PbWO$_4$ Crystals</td>
<td>25.8 X$_0$</td>
<td>APDs</td>
</tr>
<tr>
<td>Endcap (EE)</td>
<td></td>
<td>14648 PbWO$_4$ Crystals</td>
<td>24.7 X$_0$</td>
<td>VPTs</td>
</tr>
<tr>
<td>Preshower (ES)</td>
<td></td>
<td>137200 Pb/Si</td>
<td>3 X$_0$</td>
<td>strips</td>
</tr>
</tbody>
</table>

ECAL targets:
- precise e/γ energy and position measurements
- good timing resolution
- fast response for trigger and DAQ
ECAL role in physics analysis

Search and measurements of narrow resonances with photons and electrons:

- \( H \rightarrow \gamma \gamma \): high energy resolution, position measurement to achieve high S/B

- \( H \rightarrow ZZ \rightarrow 2e2\mu, 4e \): energy reconstruction for a wide range of \( E_T \) for electron identification
  - and precise measurement of the Higgs boson properties: e.g. mass, couplings, \( J^{CP} \)...

- high mass \( X \rightarrow \gamma \gamma \) (EXO-16-027), \( Z' \rightarrow ee \) (EXO-16-031): high resolution and energy linearity

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**Fig. 6.** Distribution of the four-lepton reconstructed invariant mass

**H \rightarrow \gamma \gamma** (HIG-16-020)  
**H \rightarrow ZZ \rightarrow 4 \text{leptons}** (HIG-16-033)

**Run I ATLAS+CMS:**  
\( m_H = 125.09 \pm 0.24 \text{ GeV} \)  
(PRL 114 (2015) 191803)
Energy reconstruction

Electrons and photons deposit energy over several crystals (70% in one, 97% in a 3×3 array), spread in φ, collected by clustering algorithms:

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

**Pulse Amplitude**
**intercalibration**
**cluster corrections**
**time-dependent response corrections:**
**laser monitoring system**
**Global scale**

**Test Beam:** Perfect calibration, no B field, no material upstream, no irradiation
– energy resolution on 3x3 EB crystals:

\[
\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(\text{GeV})} \oplus 0.3\%
\]

_uniformity and stability required in situ < 0.5%_

**Run I:** in barrel, 1% energy resolution achieved for unconverted photons
Pulse reconstruction

With RunII LHC running with 25ns bunch-spacing, need a pulse reconstruction resistant to out-of-time (OOT) pile-up: **multifit algorithm**:

Pulse shape is modeled as a sum of one in-time pulse plus OOT pulses

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

- Up to 9 OOT pulses (one per time sample)
- Minimize $\chi^2$ distribution for best description of the in-time amplitude
- Pulse shapes (binned templates) extracted periodically from LHC isolated bunches
- Baseline and electronic noise periodically measured from dedicated runs and used in the covariance matrix
- Minimisation using non-negative least-squares: fast enough to be used both offline and in the high-level trigger

**Sample 01 234 567 89**

- **Calibrated/Pedestal-Subtracted Energy (GeV)**
- **CMS simulation, $\sqrt{s}=13$ TeV**
- **PU=20/BX, 25 ns**

- **Observed signal**
- **Total pulse**
- **In-time pulse**
- **Out-of-time pulses**
Response monitoring

Sources of response variations under irradiation:

- **crystal transparency** (time dependent)
- VPT conditioning in the endcaps

Response **monitored with a laser system** injecting light in every ECAL crystal

PbWO$_4$ crystals partially recover during periods with no exposure

- 1 calibration point / channel / 40min
- corrections injected in (prompt) reconstruction (~48h latency)

$|\eta| < 2.5$: tracker coverage
⇒ precision physics

Outer endcap: jet physics

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

Response stability after corrections validated with physics signals:

- $\pi^0$ invariant mass
- $E/p$ relative scale of $W$ and $Z$ electrons

Electrons $E/p$ history in barrel in 2015
- $\langle$signal loss$\rangle \sim 6\%$
- RMS after corrections: $\sim 0.14\%$
- similar to RunI

$\pi^0$ mass history in barrel in 1 fill
- $\langle$signal loss$\rangle \sim 1\%$
- RMS after corrections: $\sim 0.07\%$
- very fast monitoring: 1 point / 8 minutes
Energy intercalibration (IC)

Several methods used to equalize the response of each single crystal to the deposited energy. Same methods used as in Run I

<table>
<thead>
<tr>
<th>method</th>
<th>time needed</th>
<th>Run I precision</th>
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<tbody>
<tr>
<td>φ-symmetry</td>
<td>few days</td>
<td>1-3% in EB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-5% in EE</td>
</tr>
<tr>
<td>π⁰/η→γγ</td>
<td>1 month</td>
<td>0.5% in EB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3% in EE (</td>
</tr>
<tr>
<td>electron E/p</td>
<td>20 fb⁻¹</td>
<td>0.5% in EB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2% in EE</td>
</tr>
<tr>
<td>Z→ee mass</td>
<td>20 fb⁻¹</td>
<td>equalise the scale vs η in EE</td>
</tr>
</tbody>
</table>

φ-symmetry:
- In 2015 used to transfer 2012 calibrations
- in 2016 being used for time evolution of IC as in Run I
- systematically limited

E/p precision:
- was limited by W/Z statistics in 2015, especially for |η|>1
- combination then still dominated by Run I

With full Run II sample, expected similar precision as in Run I
Clustering and corrections

Dynamic clustering to recover energy radiated upstream of ECAL via bremsstrahlung or conversions

- Super-clusters of clusters along $\phi$ (bending direction)
- Soft conversion legs / brem may be not included in super-clusters
- In the endcaps, add also preshower energy
- Additional energy from pileup contaminates the shower

Algorithmic multivariate corrections used to maximally exploit the information of the event. Tuned on MC, validated on data.

![Diagram showing event reconstruction and photon mass resolution](image)

Visible improvement wrt Run I parametric corrections
Cluster energy in data

Reconstructed Z mass in data with different levels of energy reconstruction and corrections

- In EB, long tail to lower values of the $E_{5x5}$ due to the high fraction of showering electrons in the high-material region at $|\eta|>1$
- in EE, the energy scale is improved by adding the preshower energy to the crystals energy

![Graphs showing reconstructed Z mass in different regions (barrel and endcap)]
$R_9 = E_{3x3}/E_{SC}$ is an effective conversion tagging variable ($R > 0.94$ used to classify majority of unconverted photons / low-brem electrons)

Resolution improves after 2015 calibration:

- For $|\eta| < 1$, precision at the level of Run I
- elsewhere, limited by electron-sample statistics
- estimated with fit to $Z \rightarrow ee$ with BW convolved with a Crystal-ball

![Energy resolution graph](image-url)

CMS Preliminary

12.9 fb$^{-1}$ (13 TeV)

Data

$Z \rightarrow e^+e^-$ (MC)

MC stat. uncert.

Simulation (20 fb$^{-1}$ precision), $R_9 \geq 0.94$

Prompt reconstruction, $R_9 \geq 0.94$

Winter 2015-2016 re-reconstruction, $R_9 \geq 0.94$

Events/(0.5 GeV)

Supercluster $|\eta|$
Per-electron or per-photon resolution used to build a per-event mass resolution ($\sigma_m/m$), utilised to make optimal use of the highest resolution events:

- $H \rightarrow \gamma\gamma$: used to classify events in several “untagged” categories for $m_{\gamma\gamma}$ fit
- $H \rightarrow 4l$: per-event mass resolution used as a third variable in the fit for mass measurement
  - Validated in data with fits to $Z \rightarrow e^+e^-$ by comparing the predicted $\sigma_{m2l}/m_{2l}$
Possible sources of non perfect knowledge of the energy scale and resolution (after Run I, *re-estimated for ICHEP 2016*):

- Residual non-linearity in scale (mostly for $H \rightarrow \gamma \gamma$; in $H \rightarrow 4l$ mitigated by E-track momentum combination for the electron energy): $[0.1 - 0.2]\%$
  - extrapolation from $E$ measured at $Z$ peak (90 GeV) to $m_H$ (125 GeV)

- Electron/photon differences in the simulation (residual data wrt MC): $[0.15 - 0.5]\%$

- material distribution upstream ECAL: $0.17\%$
  - improved description at beginning of Run II

  - *longitudinal light-yield non-uniformity*: $0.07\%$

  - Geant4 (shower simulation): $0.05\%$

  - Shower shape modelling: $0.06\%$
Search of $X \rightarrow \gamma \gamma$ resonances: target RS gravitons, excluded $m_G \approx [2-4]$ TeV

- improved calibrations significant also for high-energy photons

- electronics saturation accounted by the multivariate cluster corrections

  - single channel saturation in barrel: $E \sim 1.6$ TeV

  - impact on energy scale < 2%

- residual non-linearity checked with boosted $Z \rightarrow ee$: < 0.5% (0.7%) for photons up to 150 GeV in the barrel (endcap)
Conclusions

- Continuous developments and understandings of the detector details:
  - New amplitude reconstruction algorithm in place to cope with $\approx 40$ pileup interaction
  - ready for even higher values expected in 2017
  - energy measurement, calibrated with the 2.5 fb$^{-1}$ of 2015 data, is as good as in Run I in the most precise region

- The CMS ECAL has played a crucial role in the re-assessment of the Higgs boson and its measurements with Run II data
  - $> 5\sigma$ signal in each of the two high-resolution channels, $H\rightarrow\gamma\gamma$ and $H\rightarrow4l$
  - re-calibration with 2016 data ongoing. Target is $m_H$ measurement with full Run II dataset

- It has been the leading ingredient of the searches of high-mass resonances in the di-photon and di-electron resonances

- Looking forward for physics beyond SM searches and / or precise SM measurements, including the Higgs boson ones
backup
Simulation

**Noise model:**

- realistic noise with sample-correlations and channel-to-channel variations
- increase of the **APD dark current** (expected with irradiation)
- transparency variations for realistic light-yield

**Material budget in front of ECAL:**

- **tracker material description**, including in-homogeneities in $\varphi$ of services in front of the endcaps implemented in simulation in Run 2
Longitudinal non-uniformity

- Target: adequate uniformity of longitudinal light yield
  - one face of each barrel crystal depolished
  - Simulation: rear non-uniformity of 0.15%, front part assumed uniform
  - Ionizing radiation found to induce additional NUF of 30% of its initial value (worst case scenario) at the end of Run1

- simulation modified to account for these effects

- Result: 0.07% effect on the energy scale, anti-correlated between converted and un-converted photons
ECAL @ 0T

Di-Photon analyses are possible with data at B=0T (0.6 fb-1 of 2015 data).

No information on track momenta:
- weakens isolation power
- more difficult to identify correct vertex

But energy spread for conversions / brem reduced
- better energy resolution, easier e/γ extrapolation
- shower shape discrimination more powerful
- need dedicated channel IC, need absolute scale re-calibration
- especially in EE, where VPT gain changes wrt 3.8T value as a function of η

**0T**: no energy loss in reconstruction due to bremsstrahlung (e.g. in barrel at |η|>1 where material upstream ECAL is higher) → better resolution
Resolution improves after 2015 calibration:

- For $|\eta|<1$, precision at the level of Run I
- elsewhere, limited by electron-sample statistics