Performance of the CMS electromagnetic calorimeter at the LHC and role in the hunt for the Higgs boson

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on behalf of
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Compact Muon Solenoid

Multipurpose experiment at the Large Hadron Collider.

~5+5 fb\(^{-1}\) of p-p data collected at 7 TeV (2011) and 8 TeV (2012) centre of mass energy with a peak lumi of 7\(\cdot\)10\(^{33}\) cm\(^{-2}\) s\(^{-1}\)

Outline:
- The Electromagnetic Calorimeter
- ECAL calibration
- \(e/\gamma\) energy resolution
CMS Electromagnetic Calorimeter

- Excellent energy (and position) resolution for photons and electrons ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4e$)
- Lead Tungstate (PbWO$_4$) homogenous crystal calorimeter
- Barrel (EB):
  - 36 Supermodules (SM), each 1700 crystals
  - $|\eta| < 1.48$
  - APD photodetectors
- Endcaps (EE):
  - 2 Endcap sides, each 7324 crystals
  - $1.48 < |\eta| < 3.0$
  - VPT photodetectors
- Preshower (ES):
  - sampling calorimeter (lead, silicon strips)
  - $1.65 < |\eta| < 2.6$
- Fraction of working channels stable in the last three years:
  EB 99.2%, EE 98.5%, ES 96.9%
Electromagnetic trigger

- Electron and photon selection in CMS starts with the online selection.
- The plot shows the Level-1 $e/\gamma$ trigger efficiency (nominal 15 GeV threshold) for electrons from $Z$ decay estimated with Tag & probe method.
- Transparency corrections not applied at trigger level in 2011 data-taking (applied since the beginning of 2012).

| EG15  | EB    | EE       |
|-------|-------|----------|
| 50%   | $16.06^{+0.01}_{-0.01}$ GeV | $19.05^{+0.05}_{-0.06}$ GeV |
| 95%   | $22.46^{+0.04}_{-0.05}$ GeV | $27.06^{+0.58}_{-0.43}$ GeV |
| 99%   | $28.04^{+0.07}_{-0.10}$ GeV | $34.57^{+1.48}_{-1.10}$ GeV |
| 100 GeV | $99.95^{+0.01}_{-0.88}$ %   | $99.84^{+0.10}_{-0.28}$ %   |
Energy resolution challenge

- ECAL «standalone» energy resolution measured at the test beam: (3x3 arrays of barrel crystals in the absence of magnetic field, with no material in front of the calorimeter and negligible inter-calibration contribution in the constant term)

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

- Results used to tune MC simulation.
- In-situ, for unconverted photons with energies in the range of interest for physics analyses, ~100 GeV, the in-situ constant term dominates.
- Constant term in-situ strongly depends on the quality of the stability, calibration and monitoring.
- Asymptotically to be kept at ~0.5%
Measurement of electron/photon energy:

\[ E_{e,\gamma} = F_{e,\gamma} \cdot \sum_{xtal} (G \cdot C_{xtal} \cdot L_{xtal}(t) \cdot A_{xtal}) \]

- \( A_{xtal} \) [ADC counts] → signal channel amplitude
- \( L_{xtal} \) → laser monitoring correction (time dependent)
- \( C_{xtal} \) → crystal inter-calibration (\(<C_{xtal}> = 1\))
- \( G \) [GeV/ADC] → ECAL energy scale
- \( \Sigma \) → e.m. shower, energy deposited over several crystals clustered with dynamic algorithms
- \( F \) → cluster energy corrections
  - particle dependent
  - compensate shower leakage and bremsstrahlung losses for electrons)
ECAL response monitoring

Radiation → Wavelength-dependent loss of light transmission (w/o changes in scintillation)

Crystal Transparency *drops* within a run by a few percent but *recovers* in the inter-fill periods

- Inject fixed amount of light to monitor transparency loss
- Response loss up to 5% in EB and 30%-50% in EE (20% in the electron acceptance region |\(\eta|\) < 2.5)

![Diagram of ECAL response monitoring](image)

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CMS Preliminary 2011-2012

| | 01/11 | 03/11 | 05/11 | 07/11 | 09/11 | 11/11 | 01/12 | 03/12 | 05/12 | 07/12 |
|---|---|---|---|---|---|---|---|---|---|---|
| Luminosity ~ | 10^{33} | 2\times10^{33} | 3\times10^{33} | | | | | | | |
| 1.5 < |\(\eta|\) < 1.4 | | | | | | | | | |
| 1.8 < |\(\eta|\) < 1.8 | | | | | | | | | |
| 2.1 < |\(\eta|\) < 2.1 | | | | | | | | | |
| 2.4 < |\(\eta|\) < 2.4 | | | | | | | | | |
| 2.7 < |\(\eta|\) < 2.7 | | | | | | | | | |
| technical stop | | | | | | | | | |

Cycle of response loss during irradiation and recovery in beam-off periods evident
ECAL response stability

Stability of the energy scale after monitoring corrections with $W\nu$ events.

- **Barrel**: average signal loss $\sim$2.5% 
  RMS stability $\sim$0.12%
- **Endcaps**: average signal loss $\sim$10% 
  RMS stability $\sim$0.45%
- **2012 prompt reco**: 
  Barrel RMS stability $\sim$0.19%

Stability of the ECAL resolution from Zee invariant mass peak.

- **Barrel**: resolution stable within errors.
- **Endcaps**: worsening of $\sim$1.5% in quad. 
  (residual PU effect)
Crystal Inter-calibration

Several methods to calibrate (and follow-up) in-situ:

- \(\phi\)-symmetry calibration: invariance around the beam axis of energy flow in minimum bias events. Intercalibrate crystals at the same pseudorapidity.
- \(\pi^0\) and \(\eta\) calibration: mass constraint on photon energy, use unconverted \(\gamma\)’s reconstructed in 3x3 matrices of crystals.
- High energy electron from W and Z decays (E/p with single electrons and invariant mass with double electrons).

The precision (not yet asymptotic at \(|\eta|>1\)) is strongly related to the material in front of ECAL.
ECAL Calibration

- Zee invariant mass distribution applying:
  - channel Inter-Calibration
  - IC and Laser Monitoring corrections
Cluster Energy Corrections

Cluster Energy corrections vs pseudo-rapidity for non-showering and showering electrons.

- compensate for unclustered energy and energy not reaching the calorimeter: strongly related to the amount of material in front of ECAL.
- energy lost inside gaps: intermodule boundary visible in the Barrel

Reconstructed energy as a function of the local position of the most energetic crystal in the cluster, with E/p method.

- MC driven corrections not sufficient to correct the data
- crystal staggering variation along $\eta$ (bigger in module 4)
Energy scale and resolution with $Z\rightarrow ee$ events

- Fit of the $Z$ invariant mass shape with convolution of Breit-Wigner (fixed PDG mass and width) and Crystal Ball (CB).
- Energy scale and resolution estimated with CB parameters.
- Cross-check of energy scale with radiative $Z\mu\mu$ events.
- An extra energy smearing is applied to the MC to match the observed resolution of the $Z\rightarrow ee$ peak in data (additional contribution in the constant term).

Golden category (both electrons in EB and low-brem):
$\sigma_{CB} = 1.01$ GeV

Both electrons in EB:
$\sigma_{CB} = 1.56$ GeV

Both electrons in EE:
$\sigma_{CB} = 2.57$ GeV
Double effort continuously ongoing to:

1. Improve the energy resolution both in Data and MC: inter-calibration precision, optimization of cluster corrections.
2. Reduce/nullify the difference between data and MC due to contributions possibly not fully simulated (improvement observed in laser correction stability, tuning of the material simulation, etc).
Evolution of CMS $H \rightarrow \gamma \gamma$ invariant mass resolution

- Inclusive $H_{gg}$ invariant mass distribution after the MC energy smearing

**July 2011**
- **EPS**
- 2011 Zee data (re-reconstructed with improving conditions)
  - FWHM/2.35 = 1.80 GeV (1.50%)

**March 2012**
- **Moriond**
- FWHM/2.35 = 1.40 GeV (1.17%)

**July 2012**
- **ICHEP**
- 2012 data (prompt reco)
  - FWHM/2.35 = 1.35 GeV (1.13%)
  - FWHM/2.35 = 1.57 GeV (1.31%)

Golden category (both photons in EB and unconverted) FWHM/2.35 = 1.04 GeV (0.87%)
The excellent ECAL performance of the last two years is visibly demonstrated by this historic plot from the CMS 4th July Higgs search presentation.
References

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No time for...
ECAL stability

- Fraction of working channels stable in the last three years: EB 99.2%, EE 98.5%, ES 96.9%

- Temperature stability:
  - crystal light yield and APD gain are temperature dependent.
  - negligible contribution to the energy resolution constant term if temperature of the Barrel/Endcap stable within 0.05 °C/0.1 °C (VPT are stable in temperature).

- High Voltage stability (EB):
  - APD gain very sensitive to the bias voltage: 3%/Volt
  - Stability < 60 mV is required to provide a negligible contribution to the constant term of the energy resolution.
  - High Voltage stability well within allowed limits
Alignment (in time and space)

- Timing fundamental in exotic long lived particle searches and in anomalous signal rejection.
- Time difference between the seed crystals for the two Z electrons.
- The time resolution for a single ECAL crystal, for the energy range of electrons from Z decays, is 0.19/0.28 ns in EB/EE.
- No longitudinal segmentation of ECAL → Photon direction from shower position and identification of the interaction vertex
- Relative alignment of the ECAL crystals and the CMS tracker measured using electrons from Z→ee and W→ev events.
- Position resolution ≤ 1 mm
A very intense 10 years long pre-calibration campaign. Several orders of magnitude in energy: from 1 MeV of Co$^{60}$ source to 120 GeV electron beam.

**Laboratory measurements**
during crystal qualification phase.  
(2000-2006)

**Test Beam:**  
Cern electron beams.  
From 15 GeV to 250 GeV.  
(2004-2007)

**Beam Splash:**  
In September 2008 and November 2009, beam was circulated in LHC, stopped in collimators 150m away from CMS.

**Channel intercalibration**
with cosmic muons (only Barrel SMs)  
(2006-2007)
Optimal clustering

- Zee invariant mass distribution with optimal ECAL clustering

![Diagram showing Zee invariant mass distribution with optimal ECAL clustering]
2012 ECAL performance

Single electron energy scale (E/p) stability in the ECAL barrel measured using $W\nu$ events in prompt Reco.

- **RMS stability after Laser Monitoring corrections: 0.19%**
  - was 0.12% in the final rereco of 2011 data (0.45% in EE).