Role of the CMS electromagnetic calorimeter in the measurement of the Higgs boson properties and search for new physics

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- Introduction ......................................................... what you already know
- Understanding the detector ................................. what you already heard
- Performance and its evolution ............................. what you would like to see
- Some detail on systematics effects ..................... what you wonder about
- Conclusions ......................................................... 12 min over, more at coffees
Preamble

- 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, $\approx 80\%$ of scintillating light in $\approx 25$ ns, refractive index 2.2, light yield spread among crystals $\approx 10\%$

- **Barrel**: 61200 crystals in 36 super-modules, $|\eta| < 1.48$, Avalanche Photo-Diode (APD) readout

- **Endcaps**: 14648 crystals in 4-Dees, $1.48 < |\eta| < 3.0$, Vacuum Photo-Triode (VPT) readout

- **Preshower** (endcaps only): 3$X_0$ of Pb/Si strips, $1.65 < |\eta| < 2.6$

- Solenoidal magnetic field: 3.8 T

  ECAL fully contained in the coil

  CMS tracker coverage: $|\eta| < 2.5$

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Physics with the ECAL

- Design emphasis: energy resolution and granularity
- Byproduct: time resolution
- Successful examples so far:

$H \rightarrow \gamma\gamma$
energy resolution, position reconstruction, granularity for photon identification

$H \rightarrow ZZ \rightarrow 2e2\mu(4e)$
good reconstruction of electrons with very low $E_T$

Long-lived neutralino physics reach significantly extended by using the ECAL timing information
ECAL performance at Test Beams

- Perfect calibration, no magnetic field, no material upstream, negligible irradiation

Energy resolution

central impact, $3 \times 3$ barrel crystals [2]:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E\,(GeV)} \oplus 0.3\%$$

- constant term to be kept $\ll 1\%$
- stochastic term also affected by the material upstream

Time resolution: constant term $\approx 20$ ps

- from time difference of crystals in the same $e\gamma$ shower
Challenges of *in situ* operations

**Light yield variations:**
- **scintillation light** → *temperature* dependence: $\Delta S/S \sim -2\%/\degree C @ 18\degree C$
- **crystal transparency** → *radiation dose-rate* dependence

**Photo-detector response:**
- **gain** *temperature* dependence: $\Delta G/G \sim -2\%/\degree C$
- **APD** → **gain** *High-Voltage* dependence: $\Delta G/G \sim 3%/V$
- **direct ionization** effects, a.k.a. “spikes”
- **VPT** → *response* dependence on the incremental charge at the cathode

**Tracker material in front of ECAL:**
- **photon** conversions
- **bremsstrahlung** losses for electrons

**3.8 T solenoidal magnetic field:**
- **spread** of the $e, \gamma$ energy along $\varphi$, at $\approx$ constant $\eta$

→ **Excellent environmental stability** ($\times 2$ to $\times 3$ better than required) [3]
→ **Dedicated monitoring system and calibration techniques** [4, 5]
→ **Specific energy reconstruction algorithms and corrections**
Ingredients for precision physics

Electrons and photons deposit energy over several crystals (70% in one 97% in a $3 \times 3$ array), spread in $\varphi$, collected by “clustering” algorithms

$$E_{e,\gamma} = G \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) A_i$$

$A_i$: single channel amplitude, optimal filter in the time domain
$s_i(t)$: single-channel time-dependent response corrections, via a dedicated laser monitoring system
$c_i$: inter-calibration of the single channel response, using physics: $\varphi$- and time-invariance of the energy flow in minimum-bias events, $\pi^0, \eta \rightarrow \gamma \gamma$ and $Z \rightarrow ee$ invariant mass peak, electron $E/p$

$\mathcal{F}_{e,\gamma}$: particle energy correction (geometry, clustering, ...)
$G$: global scale calibration, with $Z \rightarrow ee$ events

Resolution, efficiency and particle ID: $Z \rightarrow ee$
Monitoring and calibration signals

Laser monitoring measurements

Inter-calibration precision

Validation of the corrections with $E/p$

EB RMS: 0.09%
EE RMS: 0.3%

F. De Guio’s talk

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Performance: time resolution

- Better than $O(1 \text{ ns})$ stability required for precise energy determination → regular calibrations
- Fast scintillation response ($\approx 80\%$ of light within 25 ns), shaping time ($\approx 40 \text{ ns}$), and sampling rate (40 MHz) allows for excellent time-resolution

- From the time difference between the highest energy crystal of each of the two electrons from a $Z \rightarrow ee$
- Noise term consistent with Test-Beam
- Constant term of $\approx 150 \text{ ps}$, much better than design, uniform and stable in time
  - residual differences with Test-Beam qualifications ascribed to the clock distribution system

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Performance: energy resolution

With electrons from $Z$

\[ \text{Fit to } Z \to ee \text{ of a Breit-Wigner convolved with a Gaussian function [4]} \]

\[ \text{Simulation tuned to match performance observed in situ with } Z \to ee \text{ events} \]
Accurate simulation

**Noise model:**
- realistic noise with **sample-correlations** and **channel-to-channel variations**
- increase of the **APD dark current** (expected)
- **transparency variations** for realistic light-yield (and corresponding photo-statistics)

**Material description:**
- including **in-homogeneities in** $\phi$ **of services in front of the endcaps**
- for systematic uncertainties, being implemented in current simulation

**Light propagation** effects in the crystals (only relevant for upgrade studies)

**Varying conditions used for a “run-dependent” simulation** [N. Marinelli’s talk]
Performance evolution

- The energy resolution measured in data with $Z \rightarrow ee$ is used to model the expected $H \rightarrow \gamma\gamma$ signal in the simulation
- Steady progress and excellent results

### PROMPT
reconstruction within 48h from data taking

### RECONSTRUCTION
with improved conditions

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**LP 2011**

- $m_\gamma$ (GeV/c^2)
- $\text{FWHM} = 4.35 \text{ GeV/c}^2$
- FWHM = 2.35
- $\text{FWHM} = 1.54\%$

**MORIOND 2013**

- $m_\gamma$ (GeV/c^2)
- $\text{FWHM} = 3.86 \text{ GeV}$
- FWHM = 2.35
- $\text{FWHM} = 1.31\%$

**ICHEP 2012**

- $m_\gamma$ (GeV/c^2)
- $\text{FWHM} = 3.18 \text{ GeV/c}^2$
- FWHM = 2.35
- $\text{FWHM} = 1.12\%$

**2014**

- $m_\gamma$ (GeV/c^2)
- $\text{FWHM} = 3.05 \text{ GeV}$
- FWHM = 2.35
- $\text{FWHM} = 1.04\%$
ECAL-related systematic uncertainties on $m_H$

From $H \rightarrow \gamma\gamma$:

$$m_H = 124.70 \pm 0.31\text{(stat)} \pm 0.15\text{(syst)} \text{ GeV}$$

- Electron/photon differences in the simulation: 0.10 GeV
  - material distribution: 0.07 GeV
  - **longitudinal light-yield non-uniformity**: 0.02 GeV
  - Geant4: 0.06 GeV
  - uncertainty on the single contribution: $\approx 10$ MeV

N.B.: the detector response to electrons and photons shows differences at the level of 0.5%. What matters is the difference of these differences between data and simulation.

- **Residual non-linearity in scale**: 0.10 GeV
- Photon energy scale corrections: 0.05 GeV
- $Z$ line shape: 0.01 GeV
- Checked and negligible contribution: gain switch of the electronics
More detail: residual non-linearity in scale

Residual non-linearity of the energy response in data relative to simulation, relevant in the extrapolation from the energy scale measured at the Z peak (≈ 90 GeV) to the Higgs boson mass (≈ 125 GeV)

1. electron $E/p$ vs. $E_T$ with electrons from $Z$ and $W$ decays
2. di-electron invariant mass vs. $H_T = E^1_T + E^2_T$ in $Z \rightarrow ee$ events

- 0.08% effect on the Higgs boson mass

**CMS Unpublished**

**19.7 fb^{-1} (8 TeV)**

- EB-EB high R9
- EB-EB low R9
- EE-EE high R9
- EE-EE low R9
More detail: longitudinal non-uniformity (NUF)

- **R&D achievements:** 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 [6]
  → simulation modified to account for these effects

- at most **0.06% effect on the energy scale**, anti-correlated between converted and un-converted photons → **0.015% effect on the mass**
Conclusions

- The CMS ECAL has been deeply understood and performance optimized, thanks to an endless effort towards improvement and a careful scrutiny of all the details.


- The concepts that have driven the design of the detector more than 20 years ago have proven to be successful.
  - and the meticulous characterization of all the crystals in laboratory has paid back with reduced systematic uncertainties.

- Looking forward to start Run2 to exploit the excellent discovery potential for physics beyond the Standard Model.
  - with new challenging conditions: increase of collision energy and pile-up, different machine parameters...
Bibliography


