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

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Abstract

The precise determination of the mass, the width and the couplings of the particle discovered in 2012 with a mass around 125 GeV is of capital importance to clarify the nature of such a particle, in particular to establish precisely if it is a Standard Model Higgs boson. In several new physics scenarios, in fact, the Higgs boson may behave differently with respect to the Standard Model one, or may not be unique, i.e. there can be more than one Higgs boson. In order to achieve the precision needed to discriminate between different models, the energy resolution, the scale uncertainty and the position resolution for electrons and photons are required to be as good as possible. The CMS scintillating lead-tungstate electromagnetic calorimeter (ECAL) was built as a precise tool with an exceptional energy resolution and a very good position resolution that improved over the years with the knowledge of the detector. Moreover, thanks to the fact that most of the lead-tungstate scintillation light is emitted in about 25 ns, the ECAL can be used to accurately determine the time of flight of photons. We present the current performance of the CMS ECAL, with a special emphasis on the impact on the measurement of the properties of the Higgs boson and on searches for new physics.

Keywords:
CMS, Higgs Boson, Electromagnetic Calorimetry, Lead Tungstate

1. Introduction

The Compact Muon Solenoid (CMS) detector is a general purpose detector installed at the CERN Large Hadron Collider (LHC). It consists of a silicon pixel and strip tracker surrounded by the crystal electromagnetic calorimeter and a brass/scintillator sampling hadron calorimeter (HCAL), all in an axial 3.8 T magnetic field provided by a superconducting solenoid of 6 m internal diameter. The muon system is composed of gas-ionization detectors embedded in the steel return yoke of the magnet. In addition to the barrel and endcap detectors, CMS has an extensive forward calorimetry system. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [1].

The electromagnetic calorimeter [13] consists of 75848 crystals of lead tungstate (PbWO₄), a material of high density (8.3 g/cm³), short radiation length (0.89 cm) and narrow Molière radius (2.2 cm). More than 80% of its scintillation light is emitted within about 25 ns, enabling excellent time capabilities. The ECAL is divided into a central part (barrel) covering the region $|\eta| < 1.48$ and forward parts (endcaps) extending the coverage up to $|\eta| < 3$ for a particle originating from the nominal interaction point. The crystals are arranged in a quasi-projective geometry with a granularity of 0.0174 in both the $\eta$ and $\phi$ directions in the barrel, and increasing in $|\eta|$ from 0.021 to 0.050 in the endcaps. The scintillation light is read out by avalanche photo-diodes (APDs) in the barrel and vacuum photo-triodes (VPTs) in the endcaps.

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A preshower detector, consisting of two planes of silicon sensors interleaved with 3 radiation lengths of lead, is placed in front of the endcaps to cover the pseudorapidity region $1.65 < \eta < 2.6$.

The conception of the electromagnetic calorimeter has been driven by the search for the Higgs boson via its electromagnetic decay $H \rightarrow \gamma\gamma$. Excellent energy resolution, position reconstruction, and granularity for photon identification have lead to the discovery of the new scalar particle in the two photon decay [2], appearing as a very narrow resonance on a smoothly falling background of events containing a pair of photon candidates (Fig. 1).

The $H \rightarrow \gamma\gamma$ decay has provided the most precise measurement of the mass of the new particle, $124.70 \pm 0.31\text{(stat)} \pm 0.15\text{(syst)} \text{GeV}$ with well controlled and understood systematic uncertainties. The energy resolution, combined with the tracking capabilities of the CMS detector, also provides precise reconstruction of electrons with very low momentum. This has enabled the observation of the Higgs boson also in the decay channel $H \rightarrow ZZ \rightarrow 2\ell 2\mu, 4\ell$ (Fig. 2) as well as the measurement of its mass, tests of its spin-parity properties, and constraints on its width from off-shell production [3, 4].

The ECAL design emphasis on energy resolution and granularity also features as by-product an excellent time resolution of $\approx 150 \text{ps}$ for high energy showers. This has widened the reach for physics beyond the Standard Model by using the photon timing information e.g. in searches for long-lived particles [5].

### 2. ECAL performance

Prior installation in CMS, the limit on the ultimate achievable performance of the electromagnetic calorimeter has been measured with electrons at beam tests. The energy resolution has been parametrized as [6]

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

while the time resolution has shown an asymptotic constant term of $\approx 20 \text{ps}$ [7]. The tests have been carried out with perfectly calibrated crystals, no magnetic field, no material upstream ECAL, and negligible irradiation. On the other hand, in situ operations require to face several challenges. While the stability of environmental conditions such as temperature and high voltage has been a factor of 2 to 3 better than required [8], other expected and unavoidable effects have demanded both a

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**Figure 1:** Diphoton invariant-mass distribution for the 7 and 8 TeV data (points), with each event weighted by the predicted $S/(S+B)$ ratio of its event class. The solid and dotted lines give the results of the signal-plus-background and background-only fit, respectively. The light and dark bands represent the $\pm 1$ and $\pm 2$ standard deviation uncertainties respectively on the background estimate.

**Figure 2:** Distribution of the observed four-lepton invariant mass from the combined 7 and 8 TeV data for the $H \rightarrow ZZ \rightarrow 4\ell$ analysis (points). The prediction for the expected $Z + X$ and $ZZ(Z\gamma^*)$ background are shown by the dark and light histogram, respectively. The open histogram gives the expected distribution for a Higgs boson mass of 125 GeV.
continuous monitoring and the development of specific algorithms to reconstruct the energy of electromagnetic showers. Dominant among such effects are (i) the radiation dose-rate dependence of the crystal transparency (formation and spontaneous annealing of colour centres absorbing light) and VPT response (photo-cathode conditioning), (ii) the presence of a considerable amount of tracker material in front of ECAL (from \( \approx 0.5 \) to \( \approx 1.5 \) radiation lengths depending on \( \eta \)) causing photons to convert and electrons to emit bremsstrahlung, and (iii) the presence of a 3.8 T magnetic field that spreads the initial energy of electrons and photons over several crystals in \( \varphi \).

### 2.1. Reconstruction of electromagnetic showers

Electrons and photons deposit their energy over several ECAL crystals, with a typical figure of 70% in one (average of uniform impact on the crystal surface) and 97% in a 3\times3 array. Special “clustering” algorithms collect the energy spread along \( \varphi \) in order to have the best estimate of the quadri-momentum of the electromagnetic particle at its production point. The energy of an electron or photon is given by

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

where the index \( i \) runs over the crystals in the electromagnetic cluster; \( A_i \) is the single channel amplitude, obtained via an optimal filter in the time domain (Ref. [9]); \( s_i(t) \) is a time-dependent response correction, measured via a dedicated laser monitoring system (Ref. [10]); \( c_i \) is the “inter-calibration” coefficient, to equalize the channel-to-channel response; \( \mathcal{F}_{\text{e,}\gamma} \) is a particle-based energy correction accounting for geometrical effects as well as any other clustering imperfection due to shower losses before reaching the ECAL; \( G \) is a global scale calibration.

### 2.2. Monitoring and Calibration

The time-dependent response \( s_i(t) \) of the ECAL crystals measured by means of a laser-based monitoring system and averaged in \( \varphi \) regions along \( \eta \) is shown in Fig. 3. Frequent cycles of response loss and recovery correlated to the LHC fills are visible together with an average trend starting to reach the expected equilibrium between (fast) creation and (slow) annealing of the colour centres that absorb the light. Measurements of the response of each of the ECAL crystals are available every \( \approx 40 \) minutes and corrections are validated and delivered to the prompt-reconstruction of the CMS events, within 48 h from the data taking. The validation of the response correction is shown in Fig. 4 for the barrel as obtained by the \( E/p \) ratio of electrons (cf. next paragraph): the overall r.m.s. of the corrected point gives an upper limit on the precision of the procedure and is of \( \approx 0.09\% \) for the ECAL barrel and of \( \approx 0.3\% \) for the ECAL endcaps.

Several techniques are used to derive the inter-calibration coefficients \( c_i \) of the ECAL crystals, all of them exploiting physics from the LHC collisions: the \( \varphi \)- and time-invariance of the energy flow in minimum-bias events; the invariant mass peak of \( \pi^0 \) and \( \eta \) decaying into two photons; the ratio \( E/p \) between the energy measured in the ECAL and the momentum measured in the tracker for electrons from \( W \) and \( Z \) bosons; the invariant mass peak of \( Z \) bosons decaying into electrons. The latter process is also used to set the global scale \( G \). The

![Figure 3: Relative response to laser light (440 nm in 2011 and 447 nm in 2012) measured by the ECAL laser monitoring system, normalized to data at the start of 2011. An average is shown for each pseudorapidity range, for the 2011 and 2012 data taking periods. The bottom plot shows the corresponding instantaneous luminosity.](image1)

![Figure 4: Relative energy response variation for the ECAL barrel determined from the \( E/p \) analysis of electrons in \( W \)-boson decays. Left: Response stability during the 2012 data taking-period before (red open circle) and after (green points) response corrections. The dataset corresponds to the reconstruction with the final calibration and alignment conditions (Winter2013 re-reconstruction). Right: Distribution of the projected relative energy scale.](image2)
residual miscalibration obtained with 8 TeV data for the different inter-calibration methods is shown in Fig. 5 for the barrel and in Fig. 6 for the endcaps. The timescale to accumulate sufficient data to derive the inter-calibration with such a residual miscalibration is of the order of few hours for the energy flow, few weeks for the $\pi^0$ and $\eta$, and the whole year for the electron $E/p$. A more comprehensive description of the inter-calibration algorithms can be found in Ref. [11].

### 2.3. Simulation

In order to have the most accurate description of the ECAL performance in Monte Carlo events, a detailed simulation has been developed and improved by regular comparisons with data. The simulation includes the parametrization of the shower development in the PbWO$_4$ crystals as obtained with the GEANT4 package [12]. This is complemented by the emulation of the electronic digitization and by a detailed description of the electronic noise. The latter accounts for sample-to-sample correlation in the digitized pulse as well as channel-to-channel variation of the average noise. Additionally, a “run-dependent” approach to the simulation combines few scenarios to describe varying conditions such as the observed and expected noise evolution due to the radiation-induced increment of the APD dark current in the barrel and the average transparency loss along the year, which translates into a lower light-yield and higher fluctuations in the amount of the collected light.

With the data available at 8 TeV it has been possible to improve the measurement of the amount of material in front of the ECAL, mostly the tracker and its services. Methods use the energy loss of charged tracks, the energy loss of electrons, the comparison between collisions taken with and without magnetic field, and the ratio between the energy deposits in the preshower and the corresponding clusters in the endcaps. The results, part of which is shown in Fig. 7, are as much accurate as to describe in-homogeneities in $\phi$ of the tracker services, and are used to assess the systematic uncertainties in the $H \rightarrow \gamma\gamma$ analysis at 7 and 8 TeV and are already included in the simulation for the incoming 13 TeV data taking.

### 3. ECAL energy resolution

The energy resolution of the ECAL has been measured in data using $Z \rightarrow ee$ decays. The electrons in the events have been reconstructed as photons, using only the information in the ECAL and without using any information from the tracker. The invariant mass distribution of the dielectrons was then made using the vertex position obtained from the electron tracks. The photons were divided in bins of $\eta$ and classified according to whether they convert before reaching the calorimeter or are unconverted. The observable to discriminate conversions is the ratio $R_9$ of the energy sum in the $3 \times 3$ crystals centred on the most energetic crystal of the cluster over the total energy of the cluster. Unconverted photons have a narrower shower shape and therefore higher values of $R_9$.

The resolution in each bin is parametrized as a Gaussian distribution and is shown in Fig. 8 for...
events reconstructed within 48 h from the data taking (prompt reconstruction), events reconstructed after improved inter-calibration and monitoring corrections (re-reconstruction), and events from simulation. The improvement between prompt reconstruction and re-reconstruction is particularly visible in the forward region, where irradiation effects are more significant.

The difference between the performance in data and simulation may have several sources. Partly it is due to more material present in the detector between the interaction point and the ECAL than is simulated, as shown in Sec. 2.3. Moreover, variations in the constructed ECAL geometry from the nominal geometry may cause the energy corrections $F_{\phi,y}$ derived on simulation to perform suboptimally when applied to data. Finally, the uncertainties in the individual crystal calibration may be underestimated, despite the fact that they have been obtained by detailed comparisons between different methods of inter-calibration. Some of these factors result in an increased constant term in the relative energy resolution, while others have an energy dependence. To tune the performance of the simulation to data, corrections to the energy resolution are applied by adding a Gaussian distributed random energy to the reconstructed energy in simulated events (“smearing”). The applied smearing is determined from $Z$ boson events and parametrized as a quadratic sum of a constant term and a term proportional to $1/\sqrt{E_T}$. The relative magnitude of the two components is extracted from fits of the $Z$ boson mass shape in bins of $\eta$ and $R_9$.

The tuned simulation performance is used to accurately estimate the resolution of $H \to \gamma\gamma$ events in data [2]. This is of about 1% for unconverted photons in the central part of the barrel (up to $|\eta| \lesssim 1$) and is around 2.5% in the endcaps. The resolution for converted photons is of about 1.5% in the central part of the barrel up to 3.5% in the transition between barrel and endcap, where the material in front of the ECAL peaks at $\approx 2X_0$, to reach approximately 3% for $2 \lesssim |\eta| < 2.5$.

4. Dominant systematic uncertainties on the ECAL energy scale

The uncertainties in the ECAL energy scale constitute the main contributions to the systematic uncertainty in the measured mass of the Higgs boson in the diphoton decay channel. The largest uncertainties that will be addressed in these Proceedings are those due to (i) differences in detector response to electrons and photons, relevant because the energy scale is derived using electron showers reconstructed as photons, and (ii) energy response linearity.

The most important cause of imperfect modelling of the difference between electrons and photons in the simulation is due to an inexact description of the material between the interaction point and the ECAL. The effect of changes in the amount of tracker material on the relative difference between the electron and photon energy scales has been studied in simulation by conservatively increasing the material uniformly by 10% in the region $|\eta| < 1.0$ and by 20% for $|\eta| > 1.0$. The resulting uncer-
tainty in the photon energy scale ranges from 0.03% in the central ECAL barrel up to 0.3% in the outer endcap.

A further difference in response between electrons and photons which may result from imperfect simulation is related to modelling of the varying fraction of scintillating light reaching the photodetector as a function of the longitudinal depth in the crystal at which it was emitted. One of the major achievements in the development of the crystal calorimeter has been an adequate uniformity of the longitudinal light yield, obtained by depolishing one face of each barrel crystal. However, an uncertainty remains and in addition the uniformity is modified by radiation [14, 15]. The differential effect on the photon and electron energy scales has been studied by modifying the uniformity in simulation and is found to be 0.04% for unconverted photons and 0.06% for converted photons, anticorrelated. The resulting effect on the Higgs boson mass in the $H \rightarrow \gamma \gamma$ analysis is of $\pm 0.015\%$.

An additional source of systematic uncertainties is related to the difference between data and simulation in the residual non-linearity of the energy response, relevant in the extrapolation from the energy scale measured with electron from $Z$ decays to the energy of photons from $H \rightarrow \gamma \gamma$. The effect was measured by studying the difference between data and simulation in the dependence of the $E/p$ of electrons from $W$ and $Z$ decays as a function of $E_T$, and by looking at the invariant mass of dielectrons from $Z$ decays as a function of the scalar sum of the transverse energy of the electrons, $H_T$. The results are shown in Fig. 9 separated in $\eta$ and $R_9$ categories. The differential non-linearity is estimated from a linear fit through the points. The uncertainties on the fit parameters of a linear response model, shown by the bands, is extracted after adding a common systematic uncertainty to all points, such that the $\chi^2$ per degree of freedom of the fits is equal to unity. The uncertainties on the linearity of the energy response have been found to have an effect of 0.08% on the Higgs boson mass in the $H \rightarrow \gamma \gamma$ analysis. In the $H \rightarrow ZZ \rightarrow 4\ell$ analysis the energy of the electron is estimated using the combination of the tracker momentum and the energy from the ECAL, weighted by the precision of the two measurements. The response linearity has been assessed exploiting dielectron resonances at low mass and $Z \rightarrow ee$ events and the effect on the Higgs boson mass measurement has been conservatively estimated to be 0.1% (0.3%) in $H \rightarrow 4\ell (2e2\mu)$.

5. Conclusion

The electromagnetic calorimeter of CMS has proven to be essential first in the search for the Higgs boson and subsequently in the determination of its properties. The excellent timing performance of the calorimeter has also enabled to extend the CMS reach for physics beyond the Standard Model. The concepts that have driven the design of the detector more than twenty years ago as well as its meticulous construction have proven to be successful. The harsh environment of the LHC has required an outstanding effort in the operation, monitoring and calibration, and simulation of the calorimeter. This has been rewarded by the excellent performance, consistent over time, and by well understood and controlled systematic uncertainties. Established procedures and techniques constitute a solid base for the incoming LHC data taking at 13 TeV.

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