Role of the CMS Electromagnetic Calorimeter in the hunt for the Higgs boson in the two-gamma channel

T. Tabarelli de Fatis (on behalf of the CMS Collaboration)

Dipartimento di Fisica, Università di Milano Bicocca and INFN Milano Bicocca, Piazza della Scienza 3, I-20126, Milano, Italy

E-mail: tommaso.tabarelli@cern.ch

Abstract. The distinctive signature of the two-photon decay mode of a low-mass Higgs boson $(H \rightarrow \gamma \gamma)$ would be a narrow resonance, smeared by the photon energy and direction resolution, over a non-resonant background of diphotons or spurious events. The sensitivity to this decay mode greatly benefits from the energy and position resolution and photon identification capabilities of the electromagnetic calorimeters at the LHC. In this context, the performance of the electromagnetic calorimeter (ECAL) of the CMS experiment - a hermetic, fine grained and homogeneous calorimeter made of lead-tungstate (PbWO₄) crystals, completed by a silicon/lead preshower installed in front of the endcaps - is presented.

1. Introduction

The Compact Muon Solenoid (CMS) experiment [1] at the LHC has a broad physics programme [2], including the investigation of electroweak symmetry breaking through the direct search of the postulated standard model (SM) Higgs boson. The two-photon decay mode $(H \rightarrow \gamma \gamma)$ is one of the most sensitive channels in the search for a low-mass SM Higgs boson $(m_H < 150 \text{ GeV})$ [3]. Its distinctive experimental signature would be a narrow peak – of width determined by the instrumental resolution – in the invariant mass distribution of two isolated photons of high transverse momentum to the beam axis, on a large irreducible background from QCD production of two photons. Events where at least one of the photon candidates originates from misidentification of jet fragments contribute to an additional, reducible background. The electromagnetic calorimeter (ECAL) [4] of CMS has been specifically designed to provide excellent invariant mass – via energy and position – resolution, and fine transverse granularity for photon identification purposes, to enhance the sensitivity to the $H \rightarrow \gamma \gamma$ decay mode.

In this report, we discuss the instrumental and operational aspects of the CMS ECAL relevant in the 'hunt' for the $H \to \gamma \gamma$ decay channel. Emphasis is given to single channel response stability and uniformity within ECAL, and to the calibration of the energy of electrons and photons in CMS, as these effects directly contribute to the overall energy resolution. The energy resolution is estimated from the analysis of $Z \to e^+e^-$ events collected during the 2011 LHC run at a centre of mass energy $\sqrt{s} = 7$ TeV and for an integrated luminosity of 4.98 fb⁻¹, and compared to Monte Carlo (MC) simulation. Implications for the $H \to \gamma \gamma$ analysis are presented. CMS results on the search for the $H \to \gamma \gamma$ decay mode have been published elsewhere¹ [5, 6].

¹ At the time of writing of these Proceedings, the observation of a new boson, with a two-photon decay mode, compatible with a ~ 125 GeV SM Higgs, has been reported by the CMS [7] and the ATLAS [8] collaborations.

2. The electromagnetic calorimeter of CMS

The CMS ECAL is a compact, hermetic, fine-grain and homogeneous calorimeter made of 75848 lead-tungstate (PbWO₄) scintillating crystals, arranged in a quasi-projective geometry and distributed in a barrel region (EB), with pseudorapidity coverage up to $|\eta| = 1.48$, closed by two endcaps (EE) that extend up to $|\eta| < 3.0$. The scintillation light is readout with avalanche photodiodes (APDs) in EB and with vacuum phototriodes (VPTs) in EE. To facilitate photon identification, the crystals have transverse size comparable to the typical shower size in PbWO₄ (Molière radius 21 mm). The front-face cross section of the crystals is $22 \times 22 \text{ mm}^2$ in EB and $28.6 \times 28.6 \text{ mm}^2$ in EE, with crystal depths of about 26 and 25 radiation lengths, respectively. Preshower detectors (ES) comprising two planes of silicon sensors interleaved with lead absorber for a total of three radiation lengths are located in front of each endcap, at $1.65 < |\eta| < 2.6$, to help in π^0/γ separation. Electron/photon separation is limited to the region covered by the silicon tracker ($|\eta| < 2.5$), which defines the acceptance region for photons in the $H \to \gamma\gamma$ search.

The performance of the components of the calorimeter has been extensively tested with electron beams: the stochastic and the electronic noise contributions to the energy resolution of ECAL have been shown to match the design requirements; the overall resolution was proven excellent and well below 1% at high energies, with an irreducible constant term of about 0.3% for particles impinging on the centre of the crystals [9].

In contrast to the test beam setup, in CMS additional contributions to the energy resolution are caused by residual miscalibrations of the channel-to-channel response within ECAL and by channel response changes with time, due to radiation damage of the crystals and environmental instability. These effects are dominant for photons that do not interact in the material upstream of ECAL ('unconverted photons'), and have to be calibrated-out to a fraction of a percent not to spoil the excellent intrinsic resolution of ECAL. The energy resolution is further degraded for electrons and photons that interact in the tracker material in front of ECAL, for which specific reconstruction algorithms and additional calibration factors are needed.

3. ECAL operation and stability

ECAL has been efficiently operating since installation, with a small fraction (about 1% in EB and EE and 4% in ES) of non-operational channels. Triggers for e/γ candidates are provided through the two-level trigger system of CMS. At level-1 (L1), electromagnetic candidates are formed from the sum of the transverse energy (E_T) in two adjacent trigger towers [10] (e.g. arrays of 5x5 crystals in EB). Coarse information on the lateral extent of the energy deposit inside each trigger tower elaborated by the front-end trigger electronics is exploited to suppress spurious triggers, such as those originated by direct ionization in the APD sensitive region [11]. This feature has allowed the single-photon L1-trigger to be operated unprescaled at a low threshold $(E_T = 15 \text{ GeV during 2011 LHC run})$. From offline data analysis, this trigger has been verified to be efficient (> 99%) for $E_T > 20 \text{ GeV}$ [12], causing no inefficiencies to the $H \rightarrow \gamma \gamma$ analysis, where events are retained for $E_T > 35 \text{ GeV}$ of the leading photon [6].

Fluctuations in temperature directly affect the light yield of the crystals $(-2\%/^{\circ}C)$ and the gain of the APDs $(-2.3\%/^{\circ}C)$. Throughout operations, a cooling system utilising water flow [13] has maintained the temperature stable within about $0.02^{\circ}C$ rms in EB and $0.05^{\circ}C$ rms in EE, ensuring a contribution below 0.1% to the energy resolution. The stability of the bias voltage supply has also matched specifications [14, 15].

The ECAL response varies under irradiation due to formation of colour centres that reduce the transparency of the lead tungstate. A monitoring system, based on the injection of laser light at 440 nm, close to the emission peak of scintillation light from PbWO₄, into each crystal, is used to track and correct for these variations during LHC operation [16]. It provides one monitoring point per crystal every 40 minutes with single point precision better than 0.1% and long-term instabilities of about 0.2%, related to maintenance interventions on the laser. Upon



Figure 1. Relative response variation measured by the laser monitoring system in 2011. The response is averaged over the pseudorapidity ranges listed in the legend. Technical stops without monitoring data are shaded. The LHC luminosity varied from 10^{33} cm⁻²s⁻¹ in April to 3.5×10^{33} cm⁻²s⁻¹ in October. Heavy ion collisions took place in November.

quasi-online processing of the monitoring data, response variation corrections are delivered in less than 48 h for prompt reconstruction of CMS data. To strengthen the monitoring system, a new less maintenance intensive laser (447 nm) has been installed for the 2012 run [17].

Response variations to laser light during 2011 are shown in Fig.1 for several $|\eta|$ intervals corresponding to increasing levels of irradiation. Damage and recovery cycles are noteworthy, as well as steady recovery periods during LHC stops due to thermal annealing of the colour centres. The smooth recovery in the last period occurred during heavy ion collisions at low luminosity. The observed losses are consistent with expectations and reach 3% in the barrel and about 15% at the end of the CMS acceptance region for e/γ ($|\eta| < 2.5$). Crystals with radiation tolerance insufficient to stand a dose rate of 0.15 Gy/h with a response loss below 6% were rejected at construction [18]. At the peak luminosity of the LHC in 2011 (3.5×10^{33} cm⁻²s⁻¹), this dose rate is not exceeded up to $|\eta| \simeq 2.0$. In EE, a contribution to the observed response variations is also expected from photocathode aging of the VPTs [19]. The two effects are not disentangled by the current monitoring system.

4. Electromagnetic shower reconstruction and energy calibration

Electromagnetic particles deposit their energy over several ECAL crystals and the energy estimate implies a sum over the corresponding channels. At test beams, the best energy estimate is obtained by summing the energy deposited in fixed arrays of crystals. In CMS, dynamic 'clustering' algorithms are used: clusters of energy deposits due to secondary emission in the tracker material by bremsstrahlung or photon conversions, and spread azimuthally by the intense magnetic field of CMS, are merged into superclusters [20]. After clusterisation, the energy of the e/γ candidate is estimated from the sum of the signal amplitudes (A_i) [21] of the individual channels in the cluster, weighted with channel dependent coefficients to correct for time response variation $(S_i(t))$, to equalize the channel response C_i (hereafter referred to as



Figure 2. Reconstructed invariant mass of electron pairs from $Z \rightarrow ee$ events, using the energy reconstructed in fixed arrays of 5x5 crystals (blue shaded), in the raw supercluster (red shaded) and in the supercluster with algorithmic corrections. For EE the effect of the addition of the preshower energy is also shown.

intercalibration coefficients), to calibrate the ADC-to-energy conversion (G) and to correct for imperfect clustering and geometry effects $(F_{e/\gamma})$. For endcap clusters the preshower energy E_{ES} is also added:

$$E_{e,\gamma} = F_{e,\gamma} \cdot \left[G \cdot \sum_{i} S_i(t) \cdot C_i \cdot A_i + E_{ES} \right]$$
(1)

As an illustration of the clusterisation process, the invariant mass of electron pairs in $Z \rightarrow ee$ decays is shown in Fig.2 at different levels of the energy reconstruction, using fixed arrays of 5×5 crystals, the raw supercluster energy, and the supercluster energy including algorithmic corrections (F_e). The figure also suggests that the ratio of the energy in a fixed array of crystals over the energy in the supercluster is a convenient way to identify electrons with little radiation in the tracker or unconverted photons, for which a better energy resolution is expected. To this purpose the variable $R_9 = E_{3\times3}/E_{raw}$, defined as the ratio of the energy in a 3×3 array to the energy in the supercluster before algorithmic corrections, is introduced. According to MC, about 70% of the photons with $R_9>0.94$ are truly unconverted photons, while all the photons with $R_9<0.94$ interact upstream of ECAL [22].

In the calibration schema of Eq.(1), single channel calibration and e/γ corrections are factorised. In situ calibration, designed in conformity to this factorisation, exploits different event samples to intercalibrate, and to verify and tune monitoring and algorithmic corrections.

4.1. Corrections for channel response variation

According to test beam results [16, 23], transparency variations can be corrected for by a simple power law relating the relative response to laser light $L(t)/L_0$ to relative response to scintillation light generated by electromagnetic showers $S(t)/S_0$:

$$S(t)/S_0 = (L(t)/L_0)^{\alpha}$$
. (2)

The spectral index α , related to the optical path of the light in the crystal, has been determined empirically only on a few tens of crystals from different production batches and



Figure 3. Stability of the energy response (top) and mass resolution (bottom) during the 2011 LHC run for electrons in the ECAL barrel (left) and endcaps (right), upon application of laser monitoring (LM) corrections (green dots). Uncorrected data are also shown (red dots).

manufacturers. Mean values of $\langle \alpha \rangle = 1.52$ and 1.00 have been measured for BTCP², the vast majority in ECAL, and SIC³ crystals respectively, with a 10% rms spread within the crystals from the same manufacturer [24]. Given this reproducibility, a common value is currently adopted for all the crystals from the same manufacturer. With the observed losses, a 10% spread on α would result in a spread of the single channel corrections of the order of 0.1% in EB and 1% in EE. Verification of the response stability *in situ* using reference physics signatures led to a better determination of the value of α , 1.16, for the BTCP crystals in EE, where deviations from Eq.(2) are expected at large values of transparency loss, or as a consequence of VPT response losses.

In Fig.3-top, the evolution of the ECAL response monitored from the energy-to-momentum ratio E/p of isolated electrons is shown. The overall relative response stability throughout the year is about 0.12% and 0.35% in in EB and EE respectively. Additional information is gathered studying the resolution stability, through the analysis of the instrumental contribution to the Z width, reconstructed from the invariant mass of e^+e^- pairs (see Fig.3-bottom). The resolution in EB is stable within the measurement accuracy. In EE, a worsening of about 1.5% in quadrature is observed. This is not inconsistent with the observed losses and the uncertainty on α estimated from test beam results, although part of the effect might be associated to the increased number of collisions per beam crossing (*pileup interactions*) during the run. For further optimization of the corrections, studies are being carried out to measure α for each crystal with *in situ* events.

² Bogoroditsk Plant of Technochemical Products, 43, per. Vyazovsky, Bogoroditsk, Tula region, 301801, Russia

³ Shanghai Institute of Ceramics, Chinese Academy of Sciences 1295 Dingxi Road Shanghai, 200050, P.R.China

4.2. Intercalibrations



Figure 4. Precision of the various calibration sets used in 2011 in EB (left) and EE (right).

The spread of the channel response affects the constant term of the energy resolution of ECAL with little dilution, as electromagnetic showers involve only a small number of crystals: unconverted photons deposit on average about 70% of their energy in a single crystal. The main sources of channel-to-channel response variation are the crystal light yield variation in EB, about 15% at construction, and the gain spread of the photodetectors in EE, about 25%. To reduce these spreads and provide an acceptable performance at startup, calibration procedures with different levels of accuracy have been adopted during the construction and commissioning phase of ECAL [25]. Refined intercalibration has been derived in situ with several techniques exploiting the properties of collision events [26]. These include the invariance around the beam axis of the energy flow in minimum bias events, the π^0/η mass constraint on the energy of the two photons from the $\pi^0/\eta \to \gamma\gamma$ decays, and the momentum constraint on the energy of isolated electrons from W decays. For fast calibration purposes, special calibration streams have been deployed for the former two methods: designated high-level trigger (HLT) modules unpack, select online, and log data only in restricted regions of ECAL upon specific L1 triggers, while all the rest of the event is dropped. With this sagacity, calibration data can be logged at high rate (~ 5 kHz) with little impact on the total CMS bandwidth.

The precision of each method has been estimated through the cross-comparison of the individual results, and cross-checked against precalibration constants. Results obtained in the 2011 run are shown in Fig.4 as a function of pseudorapidity for EB (left) and EE (right). The intercalibration precision upon combination of the different methods and of the precalibration constants is also displayed. Further progress is anticipated for the intercalibration precision with isolated electrons, still statistically limited at variance with the other methods. The residual miscalibration of the channel response already ensures a contribution to the energy resolution below 0.5% in the central part of the barrel ($|\eta| < 1$), and below 2% in the endcaps.

4.3. Algorithmic corrections to electron and photon energies

Dynamic clustering algorithms are used in the energy reconstruction to mitigate the impact of the material upstream of ECAL. However, not all the energy is clustered, due to algorithm inefficiencies, and part of the energy, lost in the tracker and swept by the magnetic field, never reaches ECAL. Thus, algorithmic corrections must be applied. These corrections are particle,



Figure 5. Average energy correction factors for $W \rightarrow e\nu$ electrons with $R_9 > 0.94$ and $R_9 < 0.94$ (left) and amount of radiation lengths upstream of ECAL (right) as a function of η .



Figure 6. Dependence of the electron E/p on the supercluster centre along η referred to a local coordinate system where crystal edges are at -0.5 and 0.5. Results for EB crystals are shown in the η ranges: [0, 0.43], [0.43, 0.79], [0.79, 1.10] and [1.10, 1.48] from left to right.

energy and position dependent due to the different interaction mechanisms of e/γ upstream of ECAL and to the CMS geometry. Corrections have been optimized separately for electrons and photons on MC events with a multivariate analysis (MVA). Input variables include shower shape information on the azimuthal spread of the energy deposit, shower position in ECAL local and CMS global coordinates, and global event variables sensitive to pileup effects. Corrections closely follow the distribution of the material budget upstream of ECAL (see Fig.5), and are sizable at $1 < |\eta| < 2$, where the tracker material is up to two radiation lengths thick. Local structures are related to the ECAL geometry.

Due to unavoidable imperfections of the MC model, algorithmic corrections must be tested and tuned on collision data. To this end, the stability of the E/p ratio of electrons is studied as a function of the MVA input variables. An identified case of imperfect corrections is shown in Fig.6, displaying the variation of the E/p ratio versus the impact point of the electron on the crystal for four different $|\eta|$ intervals in EB. MC-driven corrections do not fully compensate for the energy leakage in the inter-crystal gaps, yielding a residual response variation of 0.3-0.5% rms. This indicates that the shower width in MC is not exactly matched to data.

5. Energy resolution

In order to study the energy resolution, in situ data are compared to the predictions of a full MC simulation of the CMS detector based on Geant4 [27]. The simulation of the ECAL standalone response has been tuned to match test beam results, and includes a detailed description of the single channel noise, a spread of the single channel response corresponding to the estimated residual miscalibration, and a constant term of 0.3% matched to test beam results. Moreover, the few non-operational channels are also simulated. Response instabilities are not simulated. Pileup interactions are simulated for beam crossings up to ± 50 ns, which might result in an underestimate of the out-of-time pileup contribution to the noise term.



Figure 7. Relative energy resolution for $Z \rightarrow ee$ electrons in data and MC unfolded in η bins for EB (left) and EE (right). The resolution is shown separately for pairs with two $R_9 > 0.94$ electrons (top) and for the inclusive sample (bottom).

The energy and mass resolutions are studied with $Z \rightarrow ee$ events. The instrumental contribution to the Z width is extracted from a fit to the invariant mass distribution of a Breit-Wigner convoluted with a Crystal-Ball response function [28]. The electron energy resolution is derived from an unbinned maximum likelihood fit to the invariant mass distribution of e^+e^- pairs, where the energy resolution of each electron is floated as a function of $|\eta|$. The inclusive energy resolution in data varies between 1.5% in central EB, to 3-4% in the outer EB and 4% in EE (see Fig.7). For the $R_9 > 0.94$ sample the resolution is better than 1.5% in the central barrel. The corresponding mass resolutions are given in Table 1 for different categories of events.

The impact on the resolution from the material upstream of ECAL, in particular at $|\eta| > 1$, is noteworthy, and it is the main limitation to the resolution in the barrel. Effects not included in the simulation or not perfectly simulated may explain the data/MC difference. In the EE, likely contributions to the discrepancy come from the single channel calibration. In this region

Category:	Both EB & $R_9 > 0.94$	Both EB	Both EE
σ_{CB} (Data)	$(0.97 \pm 0.01) { m ~GeV}$	$(1.51 \pm 0.01) { m GeV}$	$(2.36 \pm 0.02) \text{ GeV}$
σ_{CB} (MC)	$(0.83\pm0.02)~{\rm GeV}$	$(1.29\pm0.02)~{\rm GeV}$	$(1.78 \pm 0.02) \text{ GeV}$

Table 1. Mass resolution of the Crystal-Ball component in $Z \rightarrow ee$ events.

the impact of the material in front of ECAL is also large. As we discuss below, in the $H \rightarrow \gamma \gamma$ analysis the MC is tuned to match the resolution in data.

6. ECAL position reconstruction and photon direction

In diphoton events, an additional contribution to the invariant mass resolution comes from the knowledge of the opening angle between the two photons, determined from the positions of the showers and of the interaction vertex. The precision of the shower position measurement in ECAL [29], including residual ECAL/Tracker misalignment effects, matches the performance of a MC with aligned geometry and meets resolution goals for $H \rightarrow \gamma \gamma$ reconstruction [30]. In 2011 LHC conditions, about 10 interaction vertices are reconstructed for each event with an rms spread of 6 cm along the beam direction. The diphoton vertex must be located to better than about 1 cm to make a negligible contribution to the mass resolution, as compared to the ECAL energy resolution. The vertex assignment relies on the kinematic properties of the tracks associated with that vertex and on their correlation with the diphoton kinematics. The efficiency of correct assignment (within 1 cm of the true vertex) has been estimated with simulation and control data samples to be about 83% for $H \rightarrow \gamma \gamma$ events [5].

7. Photon identification

Photon identification is tuned for the same signal to background ratio in four different categories of 'unconverted' ($R_9 > 0.94$) and 'converted' ($R_9 < 0.94$) photons in EB and EE.

In addition to R_9 , used to classify photons of high or low resolution, a key calorimetric variable for π^0/γ separation is the measure of the lateral extent of the ECAL cluster along η $(\sigma_{i\eta i\eta})$: a projection orthogonal to the bending direction of the magnetic field and thus relatively insensitive to conversions upstream of ECAL. The shower shape of photon canidates in $Z \to \mu \mu \gamma$ decays are well described by simulation (see Fig.8), upon a small reweighting of MC based on the shower shapes observed in $Z \to ee$ events. In addition, isolation variables based on tracker, ECAL and the hadron calorimeter are used to separate photons from electromagnetic deposits associated with jet fragments [31].

Photon selection efficiencies have been verified with data mainly by means of $Z \rightarrow ee$ events, with electrons reconstructed as if they were photons. A 'tag & probe' technique is adopted, where the topology of the event is used to tag the presence of a supercluster to be probed as a photon candidate. Efficiencies are somewhat smaller in EE, plagued by a larger background, than in EB (Fig.9 left). Simulation studies indicate that the background in the selected sample for $H \rightarrow \gamma \gamma$ analysis is dominated by the irreducible background of diphotons from QCD production and that fewer than 30% of the events contains one or more misidentified photons, mainly from γ + jet production (Fig.9 right). The MC background composition and shape are not used in the search of the $H \rightarrow \gamma \gamma$, but only to tune photon identification selections.

8. Implications for the $H \rightarrow \gamma \gamma$ hunt

The $H \to \gamma \gamma$ analysis is designed to exploit optimally the dependence of the resolution on the properties of the reconstructed photons and on their location within ECAL. To enhance the sensitivity of the analysis, events with two photon candidates satisfying p_T requirements and



Figure 8. Distribution of $\sigma_{i\eta i\eta}$ in data and MC for photons in $Z \to \mu \mu \gamma$ decays



Figure 9. Left: Photon identification efficiency as a function of $|\eta|$ for high and low R_9 candidates. Right: Di-photon spectrum in 2011 data and its composition estimated from MC.

"loose" photon identification criteria are classified into mutually exclusive categories of different mass resolution and signal-to-background ratios. The $H \rightarrow \gamma \gamma$ search is performed in each category independently and results are combined.

A simple categorisation separates candidates with both photons in EB from those with at least one photon in EE, and then splits these two sets into candidates with both photons 'unconverted' $(R_9>0.94)$ or with at least one converted photon $(R_9<0.94)$ [5]. In an improved version of the analysis events are categorized by means of a multivariate (MVA) technique using photon, vertex and global event variables to estimate the expected mass resolution and signal likelihood of the diphoton candidates, with category boundaries optimized for sensitivity to an SM Higgs boson [6]. The analysis also includes a category of dijet-tagged events with inclusive diphoton selection. This latter sample has enhanced sensitivity to the Higgs search in the vector boson fusion production (VBF) channel, where two forward jets are associated to the Higgs production. The MVA analysis has a higher efficiency to the signal and a larger background rejection factor than the analysis with simple categorisation, resulting in a sensitivity enhancement of 15%.

In each category, the background is estimated from data with a parametric fit to the invariant mass spectrum of the diphoton candidates on a range wider than the signal search window. The signal model is derived from the MC simulation of the $H \to \gamma \gamma$ decay. The constant term of the energy resolution in the MC is tuned in different regions of ECAL and for the different R_9 categories to match the observed resolution in $Z \to ee$ data, with electrons reconstructed



Figure 10. Invariant mass distribution for a Higgs of $m_H = 120$ GeV decaying into two photons for the category of second-best resolution (25% of the sample) and for the inclusive sample.

	0	1	2	3	Dijet tag
SM signal expected	3.4(4.4%)	19.3(25.0%)	18.7(24.2%)	33.0(42.8%)	2.8~(3.6%)
Data $(events/GeV)$	4.5~(1.2%)	55.1(14.8%)	81.3~(21.8%)	229.1~(61.6%)	2.1~(0.6%)
FWHM/2.35 (GeV)	1.09	1.09	1.43	2.08	1.32

Table 2. Expected SM $H \to \gamma \gamma$ signal for $m_H = 120$ GeV, selected events and mass resolutions in the different analysis categories. Numbers in parentheses give the percentages of events in each category. Results are given for 4.8 fb⁻¹ at $\sqrt{s} = 7$ TeV.

as photons, except for the vertex. The shape of the expected signal at 120 GeV is shown in Fig.10, for the inclusive sample of $H \rightarrow \gamma \gamma$ events and for the category of second-best resolution, which includes 25% of the expected signal. A breakdown of the expected signal, the observed candidates and the expected resolutions is given in Table 2 for the five categories of the MVA analysis. Due to the optimization of the category boundaries, the expected signal significances are rather similar in the different categories ⁴. Given the variation of the energy resolution and of the photon reconstruction properties within ECAL, the overall significance is, however, driven by events with both photons in the ECAL barrel: diphoton candidates with at least one photon in EE only contribute to less than about 50% of the events of the category of lowest resolution.

The results of the $H \to \gamma \gamma$ search based on 4.8 fb⁻¹ of data collected at $\sqrt{s}=7$ TeV in 2011 are summarized in Fig.11, where the exclusion curve normalised to the SM $H \to \gamma \gamma$ production cross section is shown as a function of the mass interval probed by the analysis. On the right panel, the (*p*-value) plot shows the probability for the background to deviate from expectation by at least the observed amount. The exclusion limit is weaker than expected at mass of about 125 GeV, due to a 2.9 σ excess of events with contributions from both dijet-tagged and non dijettagged events. Additional 10 fb⁻¹ of integrated luminosity are deemed sufficient to ascertain the origin of the excess and discover at 5σ significance or exclude the SM Higgs boson.

⁴ An approximate estimator of the significance is given by the $S/\sqrt{S+B}$ ratio in a FWHM-wide mass window, with S given by the second row of the table and (S+B) proportional to the product of the third and fourth rows.



Figure 11. Left: Exclusion limit at 95% of the confidence level for the SM Higgs boson in the $H \rightarrow \gamma \gamma$ search mode. The expected exclusion limit for the MVA analysis (red) and the simple categorisation analysis (blue) are also shown. Right: Local probability of the background only hypothesis (*p*-value) as a function of the Higgs mass.

9. Summary and outlook

The hunt for the SM $H \rightarrow \gamma \gamma$ decay placed stringent requirements on the energy resolution and photon identification capabilities of electromagnetic calorimeters at the LHC. In CMS these requirements have been translated into the first incarnation of a crystal calorimeter at a hadron collider. Notwithstanding the harsh radiation environment, the calorimeter has been successfully operated and calibrated.

In the ECAL barrel, the achieved resolution and photon identification performance put CMS in an excellent position to be able to observe or exclude the postulated SM Higgs boson through the $H \rightarrow \gamma \gamma$ decay with the data sample being collected in 2012 at $\sqrt{s} = 8$ TeV. Limitations to the resolution come predominantly from the impact of the material in front of ECAL, and from imperfect algorithmic corrections, for which further tuning is in progress. The ECAL endcaps, with lower acceptance to $H \rightarrow \gamma \gamma$ photons, contribute less to this search because of the lower photon identification efficiency, and non optimal resolution. Further progress in the precision of the single channel calibrations is needed.

At the time of writing of these Proceedings, the observation of a new boson with a mass of 125 GeV, with a local significance of 4.1 σ in the two photon decay mode alone, has been reported by CMS after the analysis of a data sample of 5.1 fb⁻¹ at $\sqrt{s} = 7$ TeV (2011) and 5.4 fb⁻¹ at 8 TeV (2012) [7]. Similar results have been reported by ATLAS [8].

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