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The study of a Higgs decaying into two photons in CMS

Mauro Donega* **ETH Zürich, Switzerland**

E-mail: mauro.donega@cern.ch

The most recent results from a search for the Standard Model (SM) Higgs boson decaying into two photons in the mass range $110 < m_H < 150$ GeV are presented. The results are based on the full dataset recorded by the CMS experiment at the LHC from pp collisions at centre-of-mass energies of 7 and 8 TeV. They show an excess of events at a mass of 125 GeV, with a local significance of 3.2σ, where a local significance of 4.2σ is expected from a standard model Higgs boson. The best-fit signal strength, σ/σ_{SM}, is 0.78 ± 0.27 at $m_H = 125$ GeV, and the mass is fitted to be $125.4 \pm 0.5(stat.) \pm 0.6(syst.)$. A few properties of the excess are reported together with the results of the search for a second excess in the same mass window and the study to resolve the excess as the superposition of two nearly mass degenerate states. The results of the search for a SM Higgs decaying in a Z boson and a photon are also presented.

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*Speaker.

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1. Introduction

Within the Standard Model (SM) of particle physics, the masses of the particles arise from the spontaneous breaking of the electroweak symmetry, which is implemented through the Higgs-mechanism. In its minimal version, this is realized through the introduction of a doublet of complex scalar fields. After breaking of the electroweak symmetry, only one scalar field is present in the theory and the corresponding quantum, the Higgs boson, should be experimentally observable. In the mass range $110 < m_H < 150$ GeV, $H \rightarrow \gamma\gamma$ is one of the most promising channels for the Higgs search at the LHC despite its low branching fraction varying between 0.14% and 0.23%. The primary production mechanism of the Higgs boson at the LHC is gluon fusion with additional smaller contributions from vector boson fusion (VBF) and production in association with a W or Z boson, or with a $t\bar{t}$ pair.

The analysis searches for a localized excess of diphoton events over a smoothly falling background due to prompt diphoton production and to events with at least one jet misidentified as a photon. To achieve the best sensitivity to a Standard Model Higgs boson decaying to two photons, the events are separated into classes. The search results are presented for an analysis that uses multivariate analysis (MVA) techniques both for photon identification and event classification, and extracts the signal from the background using a fit to the diphoton mass spectrum. Results from an independent analysis are also presented in which the photon identification and the events classification is cut-based, and in which the background model is derived as before from a fit to the diphoton mass spectrum (referenced as "cut-based"). Additional event classes are defined to identify the events from specific production mechanisms, selecting events based on the presence of additional objects in the final state. The results are presented on the full dataset collected by CMS [1] at the centre-of-mass energies of 7 TeV ($5.1 fb^{-1}$) and 8 TeV ($19.6 fb^{-1}$) in the years 2011 and 2012 [2]. A few properties of the excess are also reported [3] together with the results of the search for a SM Higgs decaying in a Z-boson and a photon [4].

2. Photon reconstruction and identification

Photon candidates are reconstructed from the energy deposits in the electromagnetic calorimeter (ECAL), grouping its channels into superclusters within the fiducial region $|\eta| < 2.5$, excluding the barrel-endcap transition region $1.4442 < |\eta| < 1.566$. About half of the photons convert in the material in front of the ECAL. Conversion track pairs are reconstructed from a combination of Gaussian-Sum-Filter (GSF) electron tracks and ECAL-seeded tracks fit to a common vertex and then matched to the photon candidate. The photon energy is computed starting from the raw crystal energies recorded by the ECAL (in the region covered by the preshower detector, $|\eta| > 1.65$, the energy recorded in that detector is added). In order to obtain the best energy resolution, the crystal signals are calibrated to compensate several detector effects [5] such as the variation of crystal transparency, the different single-channels response, etc. The containment of the shower in the clustered crystals, and the shower losses for photons which convert in the material upstream of the calorimeter are corrected using a multivariate regression technique based on a Boosted Decision Tree (BDT). The absolute energy scale and the residual longterm drifts in the response are corrected using $Z \rightarrow e^+e^-$ decays.

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The dominant backgrounds to $H \rightarrow \gamma\gamma$ consist of an irreducible fraction from the prompt diphoton production and a reducible one from pp $\rightarrow \gamma +$ jet and pp $\rightarrow$ jet + jet where one or more of the objects reconstructed as a photon corresponds to a jet. These reconstructed objects are generally referred to as *fake* photons. A photon identification BDT is used to distinguish prompt photons from the fake ones for the MVA analysis while a cut-based photon identification is used for the cut-based analysis.

The diphoton mass resolution is driven by the photon energy resolution combined with the knowledge about the direction of the photons, which is dominated by the knowledge of the vertex where they originate. The relative contribution from the vertex assignment to the mass resolution becomes negligible with respect to the photon energy resolution when the distance between the chosen vertex and the true one is below 1 cm. Since photons are neutral particles, and therefore do not leave an ionization signal in the tracker, the diphoton vertex is identified indirectly using the kinematic properties of the diphoton system and its correlations with the kinematic properties of the recoiling tracks. If either of the photons converts, the direction of the converted photon tracks can be used to identify the diphoton interaction vertex. Several kinematic variables are input to a BDT to choose the reconstructed vertex to be associated with the diphoton.

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3. Event classes

To achieve the best analysis performance, the events are first separated into classes based on their mass resolution and signal to background ratio, analysed separately and the individual results combined in a simultaneous statistic treatment of all event classes. The first step in the classification of the events extracts those with specific signatures: first the muon tagged events are selected then, from the remainder, the electron events, then the dijet events and lastly the $\not{E}_T$ events. The events remaining untagged are further subdivided into classes based on a BDT classifier in the case of the MVA analysis, and based on the minimum R_9[1] and the maximum pseudorapidity of the two photons for the cut-based analysis.

4. Signal classes and background models

The description of the Higgs boson signal used in the search is obtained from MC simulation at next-to-leading order (NLO). The SM Higgs boson cross sections and branching fractions used are taken from ref. [6]. The gluon fusion process cross-section is reduced by 2.5% for all values of m_H to account for the interference with the QCD diphoton production. The simulated events are reweighted to reproduce the observed distribution of the number of interactions taking place in each bunch crossing.

The background models for the MVA and the cut-based analyses are obtained by fitting the observed diphoton mass distributions in each of the event classes over the range $100 < m_{\gamma\gamma} < 180$ GeV. The choice of background parametrisation in each event class is fully data-driven and starts with considering families of functions that could a priori describe the background distribution.

[1]The R_9 variable is defined as the energy sum of 3×3 crystals centred on the most energetic crystal in the supercluster divided by the energy of the supercluster. Unconverted photons, having a narrow shower shape will tend to have high values of R9, while converted photons, with wide shower shapes will tend to have lower values.

In each family, the number of degrees of freedom is increased until the F-test between N+1 degrees of freedom and N degrees of freedom for the fit to data shows no significant improvement ($p-$value$<$0.05), and the function with N degrees of freedom is retained as representative of that family of functions. These "truth" functions are used to generate sets of toy MC. The same functional families are then used as "fit" functions for the toy MCs. For each pair of "truth-fit" functions a potential bias on the signal estimation is computed. The final background model, for each event class, is chosen to be the one giving a maximum potential bias on the fitted signal strength less than five times the statistical uncertainty on the background. Provided that the potential bias fulfils this condition, the systematic uncertainty on the background shape can be safely neglected. Polynomials of orders from 2 to 5 are found to fulfil the requirements above and are used to model the background distributions in the various categories for both the MVA and the cut-based analyses.

5. Systematics uncertainties

The systematic uncertainties considered cover the effects of energy scale and resolution, photon identification, integrated luminosity, vertex finding efficiency, trigger efficiency, global energy scale, dijet tagging efficiency, lepton identification efficiency, $\not\!\!E_T$ selection efficiency and the theoretical uncertainty on the production cross section. Further details can be found in [2] for the 8 TeV dataset and in [7] for the 7 TeV.

6. Results

For the MVA analysis, the local p-value corresponding to the largest signal-like excess at 125 GeV, has been computed to be 3.2 σ in the asymptotic approximation where a local significance of 4.2σ is expected from a Standard Model Higgs boson (see Fig. 1). For the cut-based analysis, the largest signal-like excess is observed at 124.5 GeV with a corresponding value of 3.9σ (3.5 σ expected). In the same figure the combined best fit signal strength is shown as a function of the Higgs boson mass hypothesis, for the MVA analysis. The best fit signal strength corresponding to the largest signal like fluctuation at 125 GeV is $\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$ for the MVA analysis and $\sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$ at the mass of 124.5 GeV for the cut-based analysis. The two results on the complete 2011 and 2012 datasets are found to be compatible at the 1.5σ level after taking into account the correlations between the two analysis.

The four main Higgs boson production mechanisms can be associated with either top-quark couplings (gluon fusion and $t\bar{t}$H) or vector boson couplings (VBF and VH). The best fit values are found to be $(\mu_{ggH+t\bar{t}H}, \mu_{q\bar{q}H+VH}) = (0.52, 1.48)$ for the MVA analysis.

The best fit to the mass of the observed boson is measured to be $125.4 \pm 0.5(stat.) \pm 0.6(syst.)$ GeV. The natural width of the observed resonance is dominated by resolution effects. A profile likelihood estimator is used to calculate upper limits on the width of the observed boson whilst allowing the fitted Higgs mass to float and it is found to be 6.9 GeV at 95% C.L.

A search for a second excess has been performed in the mass range $110 < m_H < 150$ GeV. In this search the observed state around 125 GeV is considered as part of the background. The background model now becomes the SM analysis signal plus background model, such that the mass and signal strength of the already observed state are allowed to float and an additional independent

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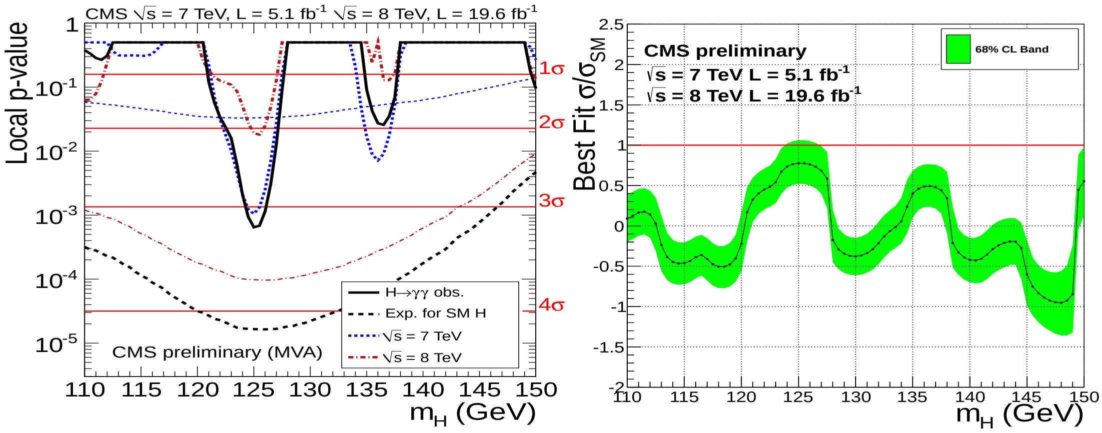

Figure 1: (left) The observed local $p-$values as a function of m_H for the MVA analysis. (right) The observed best-fit signal strength σ/σ_{SM}, in the MVA analysis, as a function of the SM Higgs boson mass.

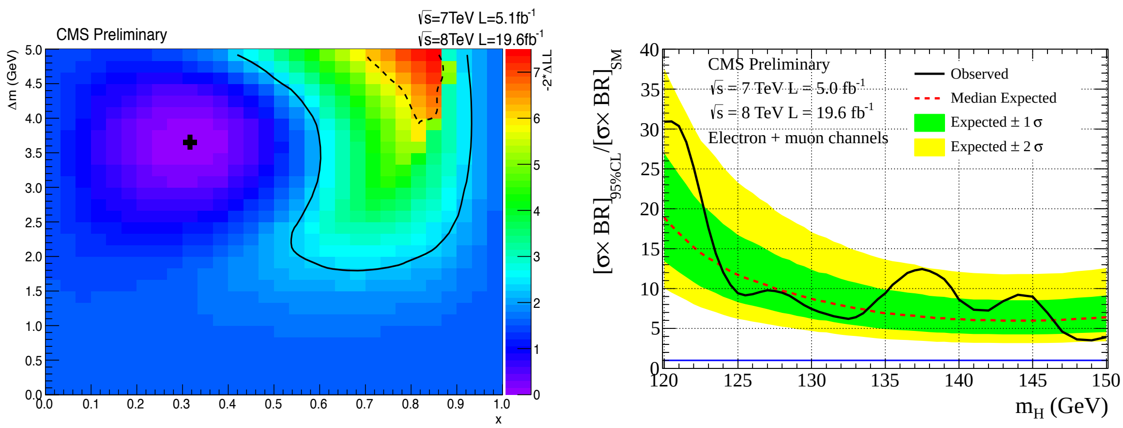

Figure 2: (left) The observed 2D negative-log-likelihood scan for two near mass-degenerate states. (right) The exclusion limit on the cross section times the branching ratio for a Higgs boson decaying into a Z boson and a photon normalized to the SM value.

signal model is introduced as a second Higgs. The p-value at the most significant excess, where $m_H = 136.5$ GeV, is found to be 2.93σ. The area around 125 ± 3 GeV, where the expected sensitivity to a second Higgs boson is degraded due to the presence of the already observed state, is probed using a different strategy. The signal model is re-parametrized such that two mass variables, m_H and $m_{H_2} = m_H + \Delta m$, refer to two similar but independent signals. The relative strength of the two signals, parametrised by the variable x, is allowed to float such that the two signals are modulated by rx and $r(1-x)$ respectively, where r is the total signal strength and x is the fraction of signal contained in the state lower in mass. A 2D scan of Δm and x is obtained by profiling over m_H and r is shown in Fig.2. The data disfavours at 95% C.L. cases for which the signal lower in mass is around 4 times the strength of the signal higher in mass, where the signals are separated by greater than 4 GeV.

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7. $H \to Z\gamma$

A search for a SM Higgs boson decaying into a Z-boson and a photon using the complete 7 and 8 TeV datasets has been performed (see Fig.2). No excess has been found and the observed limits on the Higgs production cross-section times the $H \to Z\gamma$ branching fraction are between 3 and 31 times the standard model cross section in the mass range between 120 and 150 GeV.

8. Conclusions

A search has been performed for the Standard Model Higgs boson decaying into two photons using data obtained from $5.1 fb^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV and $19.6 fb^{-1}$ at $\sqrt{s} = 8$ TeV [2]. For the MVA analysis, the local significance of the excess is 3.2 σ with a corresponding expected value of 4.2 σ and the best fit signal strength is $0.78^{+0.28}_{-0.26}$ times the Standard Model Higgs boson cross section. The best fit value for the signal strength modifiers associated with the gluon-fusion-plus-$t\bar{t}$H and for VBF-plus-VH production mechanisms are found to be $(\mu_{ggH+t\bar{t}H}, \mu_{q\bar{q}H+VH}) = (0.52, 1.48)$ for the MVA analysis. The mass of the observed Higgs boson is measured to be $125.4 \pm 0.5(stat.) \pm 0.6(syst.)$GeV. A few properties of the excess have been reported together with the results of the search for a second excess in the same mass window and the study to resolve the excess as the superposition of two nearly mass degenerate states [3]. The results of the search for a SM Higgs decaying in a Z-boson and a photon were also presented [4].

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