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Measuring the Properties of the Higgs Boson at CMS

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Abstract

After the announcement of a 125 GeV particle by the ATLAS and CMS collaborations on July 4$^{\text{th}}$, 2012, it became very important to study all the properties of this new particle, later identified as a Higgs boson. Measurements of the properties of the Higgs boson with a mass near 125 GeV will be presented. The results are based on data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and up to 19.6 fb^{-1} at 8 TeV in proton-proton collisions at the LHC. The combined result for the measured mass, the best-fit signal for all the channels and different fits for couplings, using all the studied Higgs boson decay modes, will be described.

Keywords: CMS, SM, Higgs Boson, properties

1. Introduction

The Standard Model (SM) is the most successful theory which describes many of the experimental results and predicts all the properties of the interactions of the known elementary particles. The Higgs boson is one of the predicted corner stones in the SM theory and is responsible for giving mass to all the fundamental particles. The Higgs boson has been searched for few decades with different experiments like Large Electron Positron Collider, Tevatron, but success came with Large Hadron Collider (LHC). The spectacular observation of a scalar particle with a mass ~125 GeV by both CMS [1] and ATLAS [2] Collaborations, opens a crucial chapter of properties measurement. The measurement of the properties of the 125 GeV boson is important not only to confirm whether this is the SM Higgs boson but also to look for hints of beyond SM physics. The combination of the different decay modes of this boson i.e. WW [3], ZZ [4], $\gamma\gamma$ [5], $\tau\tau$ [6] and $b\bar{b}$ [7], as well as measurements of the $\mathrm{t\bar{t}H}$ production mode [8, 9, 10], are exploited to measure its properties. To reconstruct the mass of the Higgs boson, high resolution channels i.e. H $\rightarrow ZZ \rightarrow 4l$ (with $l = e, \mu$) and H $\rightarrow \gamma\gamma$, are considered. The statistical methodology used for the combination of all the Higgs analysis was developed by the ATLAS and CMS Collaborations in the context of the LHC Higgs Combination Group [11]. Systematic uncertainties and their correlations are modelled by the introduction of nuisance parameters with their expected distributions.

2. Higgs Boson Mass Measurement

The accurate measurement of the mass of the boson is done using the invariant mass distribution of two decay modes namely, H $\rightarrow \gamma\gamma$ and H $\rightarrow ZZ \rightarrow 4l$ that are the two high resolution channels. A fit to the data is performed separately profiling independent signal strengths in three final states i.e. H $\rightarrow ZZ \rightarrow 4l$, H$\rightarrow \gamma\gamma$ without VBF tag and H $\rightarrow \gamma\gamma$ with VBF tag. The three signal strength are left free to reduce the model dependency of the mass determinations. Figure 1 (top) shows the likelihood scan as function of the mass of the H $\rightarrow ZZ$ and H $\rightarrow \gamma\gamma$ channels and of their combination. The horizontal lines at 1.0 and 3.84 depicts the 68% and 95 % CL intervals. The mass is measured to be $m_H = 125.03^{+0.26}_{-0.27}(stat.)^{+0.13}_{-0.15}(syst.)$ GeV from the combination of the two high resolution channels.

To quantify the compatibility of the two individual measurements, a scan of the test statistics $q(m_H^{\gamma\gamma} - m_H^{4l})$

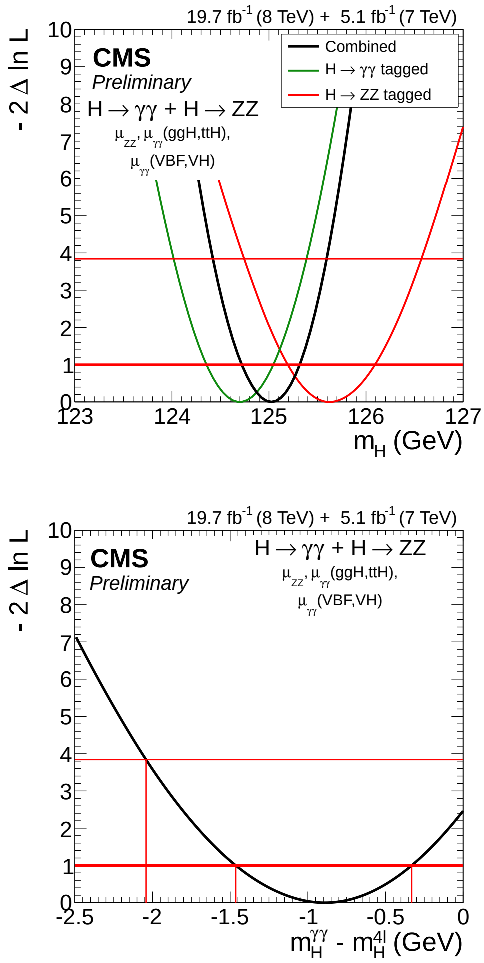

Figure 1: (Top) 1D test statistics $q(m_H)$ scan vs hypothesized Higgs boson mass m_H for the $\gamma\gamma$ (green) and $4l$ (red) final states separately and for their combination (black). (Bottom) Scan of the test statistic $q(m_H^{\gamma\gamma} - m_H^{4l})$ versus the difference between two individual mass measurements.

Decay Channel	Expected (σ)	Observed(σ)
H → WW	5.4	4.3
H → ZZ	6.3	6.5
H → $\gamma\gamma$	5.3	5.6
H → $\tau\tau$	3.9	3.9
H → bb	2.3	2.1

Table 1: Expected and observed significances of the excess for m_H = 125.0 GeV for different decay channels.

versus the difference between two individual mass measurements from $\gamma\gamma$ and $4l$ final states is performed, Fig 1 (bottom). The result comes out to be $m_H^{\gamma\gamma}$-m_H^{4l} = $-0.87^{+0.54}_{-0.57}$ GeV and the two measurements agree at the 1.6σ level. Table 1, summarizes the expected and observed significance for individual channel for a SM Higgs boson mass of 125.0 GeV. We have used the combination of these five dominant decay channels for different compatibility tests of the Higgs boson.

3. Compatibility Tests

After the precise measurement of mass of the Higgs boson, the best fit value of the signal strength modifier, $\mu = \sigma/\sigma_{SM}$ is calculated which quantifies the compatibility of an excess with the expectations from a SM Higgs boson. Evaluation of the signal strength by combining channels with respect to decay mode, Fig 2 (top), or by combining with different production tags, Fig 2 (bottom), has been done. A slight excess in the t$\bar{\text{t}}$H-tagged sub-combination is due to the excesses in the t$\bar{\text{t}}$H-tagged H→ $\gamma\gamma$ and H→leptons analyses. The combined best-fit signal strength for m_H = 125 GeV is found to be 1.00 $\pm$ 0.09(*stat.*) $^{+0.08}_{-0.07}$ (*theo.*) $\pm$ 0.07(*syst.*).

We map the vectorial and fermionic couplings into two scale factors, κ_V and κ_f, respectively. Figure 3 (left) shows the likelihood scan as a function of κ_V, κ_f with the cross indicating the best-fit values (1.01, 0.89) with respective uncertainties. The fit is compatible with the SM at the one sigma level with κ_f value being smaller than unity due to an excess in the VBF H → $\gamma\gamma$ channel and deficit in the fermionic channels. The same (κ_V, κ_f) analysis is also performed separately for each Higgs boson decay mode to better visualize the contribution of individual channels, Fig 3 (right).

To test the custodial symmetry, we introduce two scaling factors κ_W and κ_Z that modify the SM Higgs boson couplings to the W and Z bosons and perform combination in two channels i.e. untagged pp→H→WW and pp→H→ZZ, to assess the consistency of the ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$ with unity. The result is $\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$

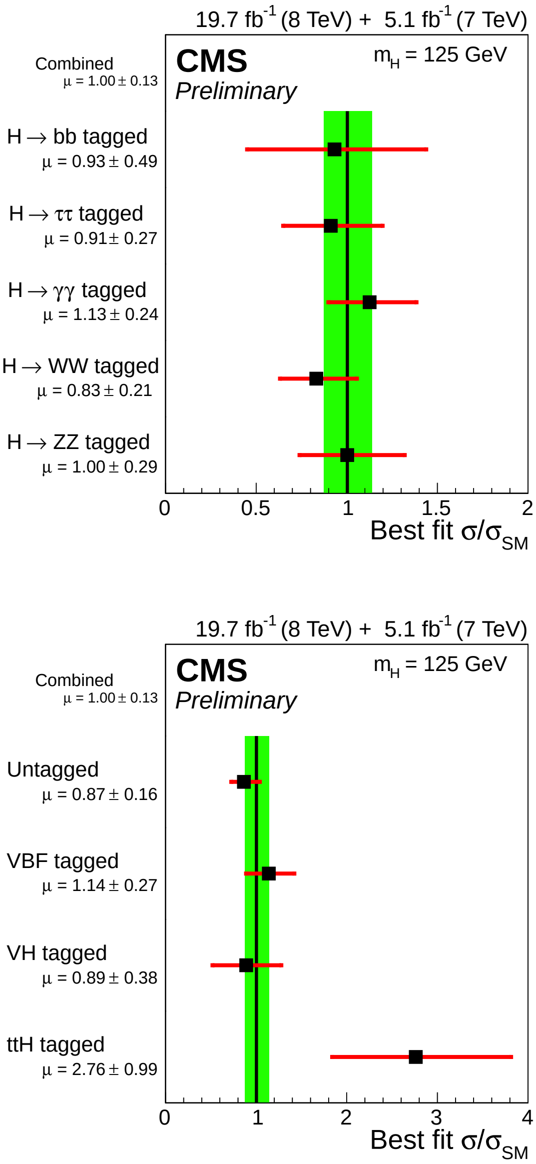

Figure 2: Values of the best-fit $\sigma_{/}\sigma_{SM}$ for sub-combinations by (Top) predominant decay channels and (Bottom) individual production modes. The vertical band shows the overall $\sigma_{/}\sigma_{SM}$ uncertainty while the horizontal bars indicate the ± 1 standard deviation uncertainties in the best-fit $\sigma_{/}\sigma_{SM}$ values for the individual modes; they include both statistical and systematic uncertainties.

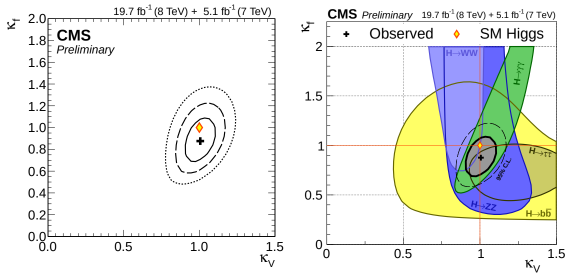

Figure 3: 2D test statistics $q(\kappa_V,\kappa_F)$ likelihood scan constrained to the (+,+) quadrant. The yellow diamond shows the SM point $(\kappa_V, \kappa_f) = (1, 1)$. (Left) The cross indicates the global best-fit values with the solid, dashed, and dotted contours showing the 68%, 95%, and 99.7% CL regions, respectively. (Right) The 68% CL contours for individual channels (colored swaths) and for the overall combination (thick curve) for the (κ_V, κ_f) parameters.

while assuming SM couplings to fermions, $\kappa_f = 1$; which implies that the data are consistent with the SM expectation.

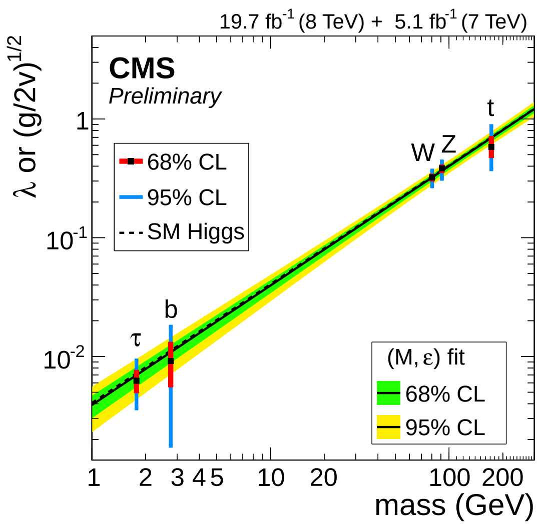

Figure 4: Summary of the fits for deviations in the coupling for the generic five-parameter model assuming SM structure for loops, expressed as function of the particle mass. The solid black line with 68% and 95% CL bands are taken from the fit to data with the model (M, ε)

The asymmetry of couplings to fermions is checked by performing two combinations in which we allow for different ratios of the couplings to down/up fermions ($\lambda_{du} = \kappa_d/\kappa_u$) or different ratios of the couplings to leptons and quarks ($\lambda_{lq} = \kappa_l/\kappa_q$) assuming $\Gamma_{BSM} = 0$. Both λ_{du} and λ_{lq} are found to be constrained within [0.66,1.43] and [0.61,1.49] respectively, at 95% CL.

We also explore a generic five-parameter model by making the following assumptions:

- The couplings to W and Z bosons are scaled by $\kappa_{\rm W}$ and $\kappa_{\rm Z}$, respectively;
- $\kappa_{\rm t}$ denotes the scale factor for couplings of up-type quarks;
- $\kappa_{\rm b}$ denotes the scale factor for couplings of down-type quarks; and
- κ_τ denotes the scale factor for all the charged leptons.

The result of a model with five independent coupling scaling factors, assuming SM structure for loops is shown in Fig 4.

Many other compatibility tests were also performed for checking beyond the SM physics scenarios [12].

4. Results

The excellent performance of the LHC machine and the CMS detector during Run I made the experiment able to collect data corresponding to an integrated luminosity of about 5 fb^{-1} at a collision energy of 7 TeV in 2011 and about 20 fb^{-1} at 8 TeV in 2012 and led to the discovery of a scalar particle. This discovery brought to the Nobel prize awarded in October 2013 to the theorists P. Higgs and F. Englert that elaborated the BEH mechanism to give masses to fermions and gauge bosons and predicted the existence of a scalar particle. It was then required to understand its various properties and to check whether they are consistent with the Higgs boson predicted by SM. It was possible to measure the mass of the Higgs boson that resulted $m_H = 125.03^{+0.26}_{-0.27}(stat.)^{+0.13}_{-0.15}(syst.)$ GeV using the CMS detector, at this value the Higgs boson is allowed to decay in many different modes.

For the mass measured at 125 GeV, the event yields obtained in the different analyses for specific decay modes and production mechanisms are consistent with those expected for the SM Higgs boson. The combined best-fit signal strength was also found compatible with the SM expectation. Searches for deviations of the couplings of the Higgs boson along with some other compatibility tests were performed and no significant deviations were found. Run II of LHC may shed some more light with precision measurement of the above mentioned quantities while having more statistics in hand at higher energy and higher integrated luminosity.

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