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 4th, 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 \(\sim 125\) 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 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 \(m_H = 125.03^{+0.22}_{-0.23}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})\) 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 \(q(m_H^\gamma - m_H^4l)\)
Table 1: Expected and observed significances of the excess for $m_H = 125.0$ GeV for different decay channels.

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Expected ($\sigma$)</th>
<th>Observed($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to WW$</td>
<td>5.4</td>
<td>4.3</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>6.3</td>
<td>6.5</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>5.3</td>
<td>5.6</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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 1.6$\sigma$ 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, $\mu = \sigma_{\text{fit}}/\sigma_{\text{SM}}$ 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 $t\bar{t}H$-tagged sub-combination is due to the excesses in the $t\bar{t}H$-tagged $H \to \gamma\gamma$ and $H \to$ leptons analyses. The combined best-fit signal strength for $m_H = 125$ GeV is found to be $1.00 \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})$.

We map the vectorial and fermionic couplings into two scale factors, $\kappa_V$ and $\kappa_f$, respectively. Figure 3 (left) shows the likelihood scan as a function of $\kappa_V$, $\kappa_f$ 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 $\kappa_f$ value being smaller than unity due to an excess in the VBF $H \to \gamma\gamma$ channel and deficit in the fermionic channels. The same ($\kappa_V, \kappa_f$) 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 $\kappa_W$ and $\kappa_Z$ that modify the SM Higgs boson couplings to the W and Z bosons and perform combination in two channels i.e. untagged pp$\to H\to WW$ and pp$\to H\to ZZ$, to assess the consistency of the ratio $A_{WZ} = \kappa_W/\kappa_Z$ with unity. The result is $A_{WZ} = 0.94^{+0.22}_{-0.18}$.
while assuming SM couplings to fermions, $\kappa_f = 1$; which implies that the data are consistent with the SM expectation.

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 ($\lambda_{d_u} = \kappa_d/\kappa_u$) or different ratios of the couplings to leptons and quarks ($\lambda_{l_q} = \kappa_l/\kappa_q$) assuming $\Gamma_{BSM} = 0$. Both $\lambda_{d_u}$ and $\lambda_{l_q}$ 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 $\kappa_W$ and $\kappa_Z$, respectively;
- $\kappa_t$ denotes the scale factor for couplings of up-type quarks;
- $\kappa_b$ denotes the scale factor for couplings of down-type quarks; and
- $\kappa_\tau$ 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].

5. Acknowledgments

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References

[12] CMS Collaboration, “Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model”, CMS PAS HIG-14-009.