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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Higgs boson properties and tests of the Standard Model at CMS

Johannes Brandstetter for the CMS Collaboration

Abstract

The measurements of the Higgs boson properties, mass, spin/CP, couplings, off-shell cross sections and constraints on invisible width, as well as other Standard model measurements at CMS will be presented. The analysis is based on pp collision data collected at centre-of-mass energies of 7 and 8 TeV by the CMS experiment at the LHC, corresponding to integrated luminosities of 5/fb and 20/fb, respectively.

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Higgs boson properties and tests of the Standard Model at CMS *

Johannes Brandstetter

*On behalf of the CMS Collaboration
Institute of High Energy Physics Vienna, Austria*

Abstract

The measurements of Higgs boson properties, mass, spin/CP, couplings, off-shell cross sections and constraints on invisible width are summarized and compared with standard model expectations. The analysis is based on pp collision data collected at centre-of-mass energies of 7 and 8 TeV by the CMS experiment at the LHC, corresponding to integrated luminosities of 5 fb^{-1} and 20 fb^{-1} , respectively.

1. Introduction

During LHC run 1 a Higgs boson of mass around 125 GeV has been discovered by the ATLAS and CMS collaborations at LHC [1, 2]. CMS collected data at a centre-of-mass energy of 7 TeV in 2010 and 2011 and 8 TeV in 2012, corresponding to integrated luminosities of approximately 5 fb^{-1} and 20 fb^{-1} , respectively. The four dominant production modes of the Higgs boson are gluon-gluon fusion (ggH), vector-boson fusion (VBF) with two associated jets, vector-boson production (VH) with an associated vector-boson and $t\bar{t}$ fusion with an associated $t\bar{t}$ pair (ttH). This article summarizes the CMS results of the searches for the standard model (SM) Higgs boson in the decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$. Furthermore, measurements of important quantities, i.e. mass and total width, signal strengths and couplings, spin and parity are presented and compared with standard model expectations.

2. Decay channels

The results of 5 decay channels are presented. All of them are important for studies of Higgs boson properties.

2.1. $H \rightarrow \gamma\gamma$

The $H \rightarrow \gamma\gamma$ channel has a small branching ratio of 0.0023 at a Higgs boson mass of 125 GeV, but a very clean signature. The selected events are split into different categories depending on the signal purity and the mass resolution. The underlying background is a large continuum diphoton background which is estimated from a fit to the observed diphoton mass distribution. A peak is observed at $124.70 \pm 0.34 \text{ GeV}$ with a local significance of 5.7σ [3] (Fig. 1).

2.2. $H \rightarrow ZZ$

The $H \rightarrow ZZ$ channel has a branching ratio of 0.0266 at a Higgs boson mass of 125 GeV. The four-lepton mass peak is measured over a small continuum background, further signal-background discriminants are built depending on the masses of the dilepton pairs and the 5 angles of four leptons in the center-of-mass frame. The dominant irreducible background arises from nonresonant ZZ production where both Z bosons decay to a pair of leptons. A signal is observed at $125.59 \pm 0.45 \text{ GeV}$ with a local significance of 6.8σ

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Email address: johannes.brandstetter@cern.ch
(Johannes Brandstetter)

Figure 1: Diphoton invariant mass distribution (upper plot), diphoton invariant mass distribution after background subtraction (lower plot) [3].

[4] (Fig. 2). An additional SM like Higgs boson with SM like cross-sections is excluded at 95% confidence level in a mass range of $145 \text{ GeV} < m_H < 1000 \text{ GeV}$ [5].

2.3. $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$

In addition to the discovery channels ($H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$) a local significance with more than 3σ is also observed in the $H \rightarrow WW$ and $H \rightarrow \tau\tau$ channels [6, 7]. For $H \rightarrow WW$ the event signatures are either two opposite-signed leptons or three leptons with a charge sum of ± 1 . An excess of events over the background-only hypothesis is observed with a local significance of 4.3σ . The observed signal cross section times the branching fraction to WW is $0.72^{+0.2}_{-0.18}$ times the SM expectation. Similar to the $H \rightarrow ZZ$ channel an additional SM like Higgs boson with SM like cross sections is excluded at 95% confidence level in a mass range of $145 < m_H < 1000 \text{ GeV}$ [5]. The $H \rightarrow \tau\tau$ channel allows the most accurate measurements of a fermion Yukawa coupling. The final states consist of either hadronically or leptonically (e, μ and missing energy) decaying taus and the cleanest signature is found in VBF events. The search is statistically limited but already reaches a local significance of $> 3\sigma$ over the background-only hypothesis. The $H \rightarrow b\bar{b}$ channel has the largest branching ratio of 0.577 at a Higgs boson mass of 125 GeV, but has a overwhelming large QCD background. The search

Figure 2: Distribution of the 4-lepton channels reconstructed mass for the sum of the 4 lepton channels [4].

is performed for VH events and a local significance of 2.1σ is observed for $115 < m_H < 130 \text{ GeV}$ [8].

3. Mass and total width

3.1. Mass

A well known Higgs boson mass is required to predict other properties of the SM Higgs boson. A joint measurement of the ATLAS and CMS collaborations with combined $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ data samples yields a combined Higgs boson mass of $125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.}) \text{ GeV}$ (Fig. 3). To obtain the results a simultaneous fit is applied to the reconstructed invariant mass peaks of the two channels and for both experiments. The resulting masses from the individual channels and both experiments are found to be consistent among themselves.

3.2. Total width

To measuring the total width (Γ) of the Higgs boson CMS uses $H \rightarrow ZZ \rightarrow 4l$ events [10]. In contrast to Γ_Z and $\Gamma_{\pm W}$ ($\Gamma \sim O(\text{GeV})$), Γ_H is expected to be small ($\Gamma_H^{\text{SM}} \sim 4 \text{ MeV}$). Direct measurements allow to constrain $\Lambda_H < O(\text{GeV})$. Another possibility is to study the ratio of off-shell and on-shell Higgs boson production cross sections

Figure 3: Higgs boson mass measurements at the ATLAS and CMS experiments [9].

$$\left. \begin{aligned} \sigma_{i \rightarrow H \rightarrow f}^{\text{on}} &\propto \frac{g_i^2 g_f^2}{\Gamma_H} \\ \sigma_{i \rightarrow H \rightarrow f}^{\text{off}} &\propto g_i^2 g_f^2 \end{aligned} \right\} \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}} = \Gamma_H, \quad (1)$$

where g_i is the coupling to the initial and g_f the coupling to the final state. Off-shell contributions mostly arise due to the proximity of the ZZ threshold (Fig. 4). For this analysis the assumption that no beyond the standard model particles decay to ZZ is made. The analysis allows to constrain $\Gamma_H / \Gamma_{\text{SM}} < 5.4$ (8.0) observed (expected).

Figure 4: On-shell and off-shell contributions of $H \rightarrow ZZ \rightarrow 4l$ events [10].

4. Signal strength and couplings

4.1. Signal strength

A simple compatibility test for the SM Higgs boson is the best-fit value of the signal strength modifier μ_i which is obtained from the combined analysis of all channels [11]

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}}, \quad (2)$$

where σ_i is the production cross section for production mode i and σ_i^{SM} is the SM production cross section. μ can become negative if the number of observed events is smaller than the background-only hypothesis. Results for sixteen individual combinations grouped by production tag and predominant decay mode show good agreement with the SM expectations. A 2σ excess shows up in the $t\bar{t}H$ -tagged $H \rightarrow \gamma\gamma$ and $H \rightarrow WW$ channels w.r.t the SM predictions. The ratio of bosonic ($\mu_{\text{VBF,VH}}$) and fermionic $\mu_{\text{ggH,tH}}$ production modes provides another important check of the SM. The confidence regions for bosonic and fermionic production modes are shown in Fig. 5. The best-fit $\mu_{\text{VBF,VH}}/\mu_{\text{ggH,tH}}$ is observed to be $1.25^{+0.62}_{-0.44}$ and compatible with the SM expectations.

Figure 5: 68% CL confidence regions for the signal strength of the ggH and $t\bar{t}H$ and of the VBF and VH production mechanisms [11].

4.2. Higgs boson couplings

The event yield for a production mode x and a final state yy can be written as

$$(\sigma\mathcal{B})(x \rightarrow H \rightarrow yy) = \frac{\sigma_x \Gamma_{yy}}{\Gamma_{\text{tot}}}, \quad (3)$$

where $\mathcal{B}$ is the branching ratio, Γ_{yy} the partial decay width into the final state and Γ_{tot} the total decay width of the Higgs boson. The coupling strength modifiers κ_i are introduced as

$$\kappa_i^2 = \frac{\Gamma_{ii}}{\Gamma_{ii}^{\text{SM}}} = \frac{\sigma_i}{\sigma_i^{\text{SM}}}. \quad (4)$$

Custodial symmetry predicts that both the ratio of the W and Z boson masses as well as the ratio of their couplings are stable against large radiative corrections. In a combined analysis a likelihood scan of $\lambda_{WZ} = \kappa_W/\kappa_Z$ and κ_Z is performed where the latter is treated as nuisance parameter [11]. The assumptions that $\Gamma_{\text{tot}} = \Gamma_{\text{H}}^{\text{SM}}$ and $\kappa_f = 1$ are made where κ_f describes the coupling to fermions. The result of $\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$ (Fig. 6) agrees with the SM expectation $\lambda_{WZ} = 1$. Another SM compatibility test is a 2D likelihood scan over the (κ_f, κ_V) parameter space with the assumption of no contributions beyond the SM. The couplings to bosons and fermions are based on two different mechanisms: electroweak symmetry breaking and fermion-Yukawa coupling. Any significant deviations from $(\kappa_f, \kappa_V) = (1, 1)$ would indicate a discrepancy with respect to the SM. $(\kappa_f, \kappa_V) = (1, 1)$ is within a 68% CL region defined by data of five different decay channels ($\gamma\gamma$, ZZ, WW, $\tau\tau$, $b\bar{b}$) as well as combined data.

Figure 6: Likelihood scan versus λ_{WZ} assuming $\kappa_f = 1$ [11].

5. Spin and parity

The study of the spin-parity structure of the Higgs boson is performed using the $H \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$, and $H \rightarrow \gamma\gamma$ decay modes [12, 13]. The test statistic $q = -2 \cdot \ln\left(\frac{L_{J^P}}{L_{0^+}}\right)$ for different J^P hypotheses is tested against the SM Higgs boson with spin 0 and positive parity. The spin-parity 0^+ hypothesis is consistent with data (Fig. 7). A wide range of spin-two models is excluded at a 99% CL or higher and at a 99.87% CL for the minimal graviton-like couplings, respectively. Any mixed-parity spin-one state is excluded in the ZZ and WW modes at a greater than 99.999% CL.

Figure 7: Distribution of the test statistic $q = L_{0^-}/L_{0^+}$ of the 0^- Higgs boson hypothesis tested against the SM Higgs boson hypothesis [12].

All observations are consistent with a SM Higgs boson with zero spin and positive parity, but there is e.g. still a chance of mixtures of anomalous 0^+ and 0^- contributions. To further investigate these models more data is needed.

6. Conclusions

The Higgs boson discovery was made in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels, further observations with a local significance larger than 3σ are made in the $H \rightarrow WW$ and $H \rightarrow \tau\tau$ channels. The Higgs boson mass is close to 125 GeV. Using the ratio of on-shell and off-shell Higgs boson productions allows to constrain the

upper limit of the decay width to the MeV scale. Signal-strengths and couplings are consistent with SM predictions. The SM spin-parity 0^+ model is consistent with data. Many run 1 measurements are statistically limited. LHC run 2 will provide both more statistics and higher luminosities. The dominant production cross sections of the Higgs boson are ggH, VBF, VH and ttH. All of them will increase with increasing center-of-mass energy where the largest increase will be seen in the ttH channel for a center of mass energy of 13 TeV.

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