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Higgs boson couplings and properties with CMS

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Many different production and decay modes of the 126 GeV mass Higgs boson have been studied by the CMS collaboration at the LHC collider. The analysis is based on pp collision data collected at center-of-mass energies of 7 and 8 TeV corresponding to integrated luminosities of 5/fb and 20/fb respectively. The measurement of the Higgs boson couplings and of the study of its properties are presented.

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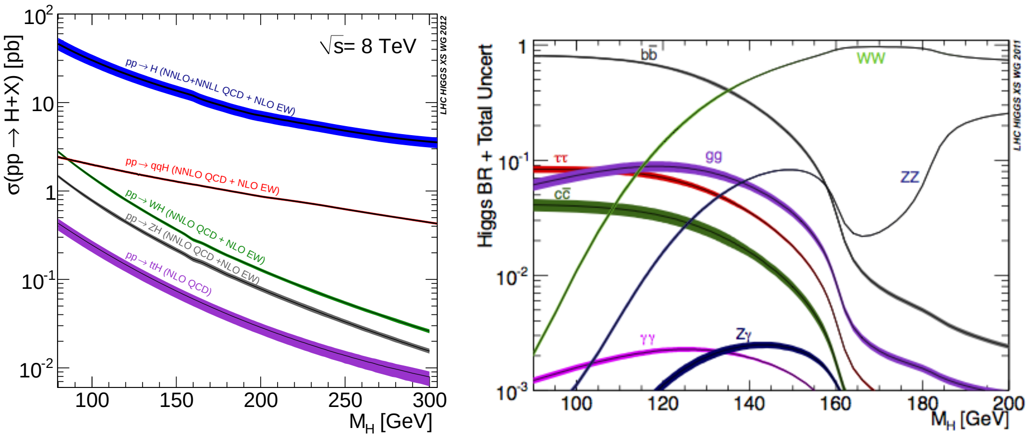

Figure 1: Standard Model Higgs boson production cross sections at $\sqrt{s} = 8$ TeV (left). Standard Model Higgs boson decay branching ratios (right).

This article summarizes the Higgs boson [1] properties and couplings, measured by the Compact Muon Solenoid Experiment (CMS). The proton-proton collision data used in this analysis were recorded by the CMS detector at the Large Hadron Collider (LHC) and correspond to integrated luminosities of 5.1 f^{-1} at $\sqrt{s} = 7$ TeV and 19.6 f^{-1} at $\sqrt{s} = 8$ TeV. After a brief overview on the production and decay modes, the Higgs boson properties (i.e. mass, spin-parity quantum numbers and width) are examined and the Higgs boson couplings with the other particles are analyzed, testing the validity of the Standard Model (SM) [2].

There are four main Higgs boson production modes in pp collisions at $\sqrt{s} = 7-8$ TeV: the gluon-gluon fusion (which has the largest cross section), followed in turn by the vector boson fusion, the associated production with a W or Z boson and with a top quark pair (Fig 1, left). In the low mass range, five main decay channels are exploited: $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, $H \to WW \to \ell\nu\ell\nu$, $H \to \tau\tau$ and $H \to b\bar{b}$ (Fig 1, right).

1. The Mass

The mass is the most important property of the examined particle: its value is not determined by the SM, but once it is known, all the other characteristics are precisely predicted by the theory. The channels with the highest sensitivity for discovering the SM Higgs boson with the mass near to 125 GeV are the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels, thanks to their excellent mass resolution. The former is characterized by a modest branching fraction, a clear signature with two isolated and energetic leptons and a large background from QCD. The $H \to \gamma\gamma$ analysis [3] 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 photon. The search is performed using MVA techniques, both for photon identification and event classification, and the signal is extracted from the background using a fit to the diphoton mass spectrum.
The $H \to ZZ \to 4\ell$ channel [4] is characterized by a very small branching fraction and a very clean signature, represented by two pairs of high p_T and isolated leptons, and its products are

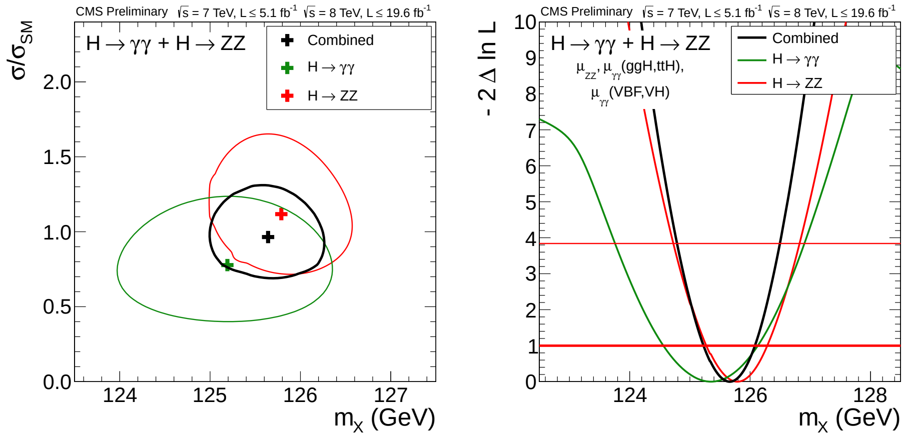

Figure 2: 2D 68% CL contours for a hypothesized Higgs boson mass m_X and signal strength σ/σ_{SM} for the $\gamma\gamma$ and 4ℓ states separately and for their combination (left). 1D test statistics scan versus hypothesized Higgs boson mass m_X for the $\gamma\gamma$ and 4ℓ states separately and for their combination (right).

all visible in the detector, allowing a fine reconstruction of the event topology, thanks also to the small background contribution. Events are categorized according to the lepton flavor and the mass measurement is performed using a 3D fit with the mass of the four-lepton system, the uncertainty estimated on a per-event basis and a kinematic discriminant that depends on the kinematic information from the production and decay.
Measurements obtained in the diphoton and four-lepton channels can be combined (Fig 2), leading to a value of $m_H = 125.7 \pm 0.3(stat.) \pm 0.3(syst.)$ GeV.

2. The Spin and Parity

The measurement of spin and parity quantum numbers is a very good test of SM compatibility, since theoretic predictions are very clear and foresee a 0^+ boson. Alternative hypotheses can be excluded using test statistics and the exploited channels for this measurement are $H \to ZZ \to 4\ell$ and $H \to WW \to \ell\nu\ell\nu$. The former is the most sensitive channel. This analysis uses a 2D fit, depending on two kinematic discriminants based on angular information: one separates the SM Higgs boson from the background, while the other distinguishes between two alternative hypotheses. Twelve models are tested and the summary of the expected and observed values for the test statistic distributions is represented in Fig 3.
The characteristics of $H \to WW \to \ell\nu\ell\nu$ decay mode [5] are the distinct signature represented by two high p_T and isolated leptons with a small opening angle and missing transverse energy due to undetected neutrinos, a very poor mass resolution and a large background. In the spin-parity analysis, categories with different lepton flavor and 0 or 1 jet in the event are used to distinguish between the SM and the 2^+ boson (produced in both gg and $q\bar{q}$ processes) or the pseudoscalar hypothesis (produced in gg fusion only). Two discriminant variables are used (transverse mass and dilepton mass) to separate spin hypotheses. In Fig. 4, distributions of the test statistic for the 0^+ and 2^+ hypothesis are reported, shown for the case in which the 2^+ particle is produced via gg fusion (left)

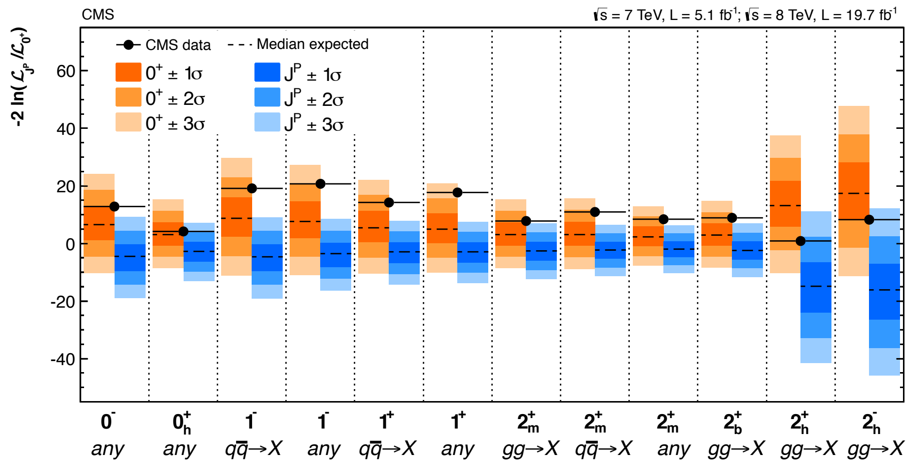

Figure 3: Summary of the expected and observed values for the test-statistic distributions for the twelve alternative hypotheses tested with respect to the SM Higgs boson, obtained using the $H \to ZZ \to 4\ell$ analysis.

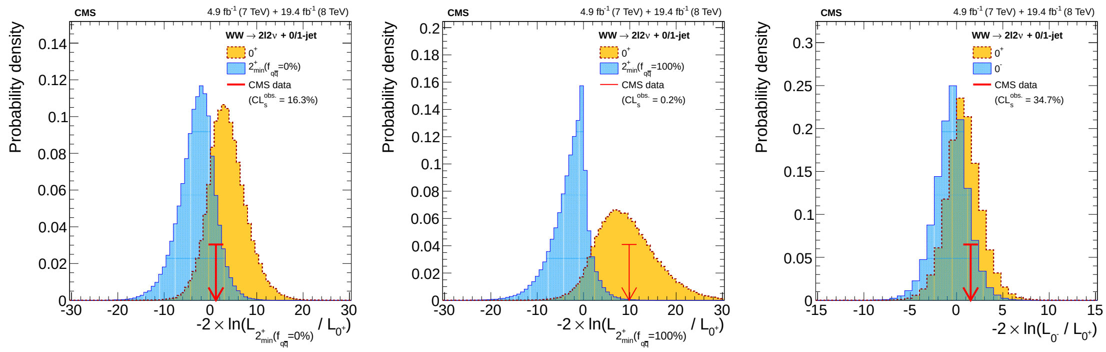

Figure 4: Distributions of the test statistic for the 0^+ vs 2^+ case, produced via gg fusion (left) or $q\bar{q}$ annihilation (center) and distribution of the test statistic for the 0^+ vs 0^- case (right), obtained using the $H \to WW \to \ell\nu\ell\nu$ analysis.

or $q\bar{q}$ annihilation (center), while in Fig. 4 (right) the same distributions are reported for the 0^+ versus 0^- case. The red arrow represents the observed value, that favors the SM hypothesis.

3. The Width

The Higgs width measurement is the most recent result of the CMS collaboration on the Higgs properties [6]. At 125.6 GeV the SM predicts a width of about 4 MeV and therefore a direct measurement is strongly limited by the experimental resolution. Indeed, up to now, constraints of 3.4 (6.9) GeV in the $H \to ZZ \to 4\ell$ ($H \to \gamma\gamma$) channel have been reported. The idea is thus to measure the Higgs boson width using the Higgs boson production and decay away from the resonance, in the 4ℓ and $2\ell 2\nu$ final states. From the theory one can see that the resonant cross section depends on the signal strength μ, while the off-shell cross section depends on the product of μ and r, the ratio of the observed width and the width predicted by the SM. Once the signal

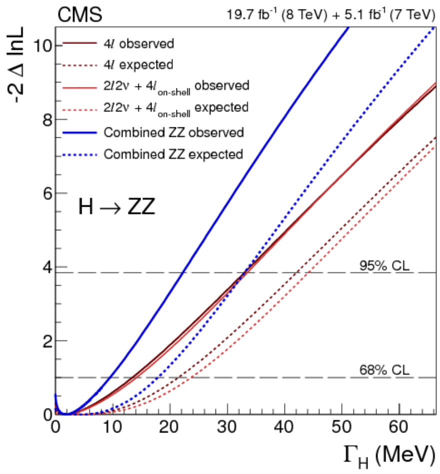

Figure 5: Scan of the negative log-likelihood, as a function of Γ_H for the combined fit of the 4ℓ and $2\ell 2\nu$ channels (blue thick lines), for the 4ℓ channel alone in the off-shell and on-shell regions (dark red lines), and for the $2\ell 2\nu$ channel in the off-shell region and 4ℓ channel in the on-shell region (light red lines). The solid lines represent the observed values, the dotted lines the expected values.

strength is fixed using the value obtained from the data, r value can be extracted by the ratio of the two cross sections, paying attention to the destructive interference with the continuum $gg \to ZZ$, which is not negligible at high masses. A likelihood is defined according to the final state and upper limits are obtained. In Fig. 5 the scan of the likelihood as a function of Γ_H for the 4ℓ and $2\ell 2\nu$ final states is reported and the combination of the two channels leads to an observed constraint of 4.2 times the SM, corresponding to $\Gamma_H < 17.4$ MeV at 95% CL.

4. The Couplings

The event yield in any production times decay mode is assumed to be related to the production cross section (σ_{ii}) and the partial (Γ_{ff}) and total (Γ_{tot}) Higgs boson decay width through the following equation

$$\sigma \times BR(ii \to H \to ff) = \frac{\sigma_{ii}\Gamma_{ff}}{\Gamma_{tot}}.$$

The production cross section and the partial width are proportional to the square of the effective Higgs couplings to the corresponding particles. To test for possible deviations in the data from the rates expected in the different channels, modified couplings are introduced, denoted by scale factors k_i, and the data are fitted to these parameters [2]. Significant deviations of any k_i from unity would imply new physics. One can thus compare the observation with the expectation, by fitting for two parameters (k_V and k_f), modifiers for all Higgs boson couplings to vector bosons and fermions. At leading order all partial widths, except for $\Gamma_{\gamma\gamma}$, scale either as k_V^2 or k_f^2. On the other hand, $\Gamma_{\gamma\gamma}$ is induced through W and top loop diagrams and it scales as $|\alpha k_V + \beta k_f|^2$: $H \to \gamma\gamma$ is thus the only channel sensitive to the relative sign of k_V and k_f. In Fig. 6 (left), the 68% CL contours for individual channels and for the overall combination is shown for the (k_V, k_f) parameters.
Processes induced by loop diagrams can be particularly susceptible to the presence of new physics,

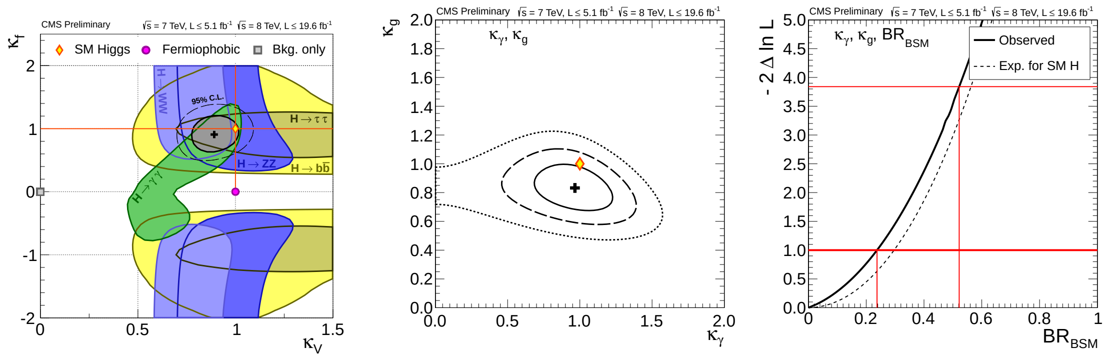

Figure 6: 68% CL contours for individual channels (colored swaths) and for the overall combination (solid line) for the (k_V, k_f) parameters. The cross indicates the global best-fit value and the yellow diamond shows the SM expectation (left). 2D likelihood scan for the k_g and k_γ parameters (center). The solid, dashed and dotted contours show the 68%, 95% and 99.7% CL regions, respectively. Likelihood scan versus $BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$ (right).

thus data can be combined and fitted for the scale factors k_γ and k_g. Results are reported in Fig 6 (center) and they are compatible with the SM prediction. Moreover, the Higgs boson could also decay into invisible particles or particles not detectable at the LHC. A modified total Higgs boson width is thus defined, containing also the branching ratio of not-detectable processes, and left free to float in the fit. Results are shown in Fig 6 (right) and they are compatible with the SM.

In summary, the mass of the analyzed resonance is measured with high precision. The particle is compatible within uncertainties with a SM Higgs boson and alternative spin-parity hypotheses are disfavored by the data. The experimental constraint on Higgs total width is determined using off-shell production and decay, improving by more than two orders of magnitude the previous experimental result. A comprehensive set of Higgs coupling fits is reported and no significant deviation from SM predictions is observed within the uncertainties.

References

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