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Measurement of the properties of a Higgs boson with the CMS detector

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Summary. — A new boson has been discovered using proton–proton collision data recorded by CMS during the first run of the LHC, corresponding to integrated luminosities of $5.1\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ and $19.6\,\mathrm{fb}^{-1}$ at $8\,\mathrm{TeV}$. It has been observed in several decay channels with a best-fit signal strength, expressed in units of standard model Higgs boson cross section, of 0.80 ± 0.14 at the measured mass of $125.7 \pm 0.3\,(\mathrm{stat.}) \pm 0.3\,(\mathrm{syst.})\,\mathrm{GeV}$. Consistency of its couplings with respect to the expectation from a standard model Higgs boson has been tested and no significant deviation has been observed.

PACS `14.80.Bn` – Standard-model Higgs bosons.

Introduction

The discovery of a new boson by ATLAS and CMS in July 2012 [1, 2] opened a new area for the search of additional new physics, through the study of the properties of this new particle. Already with the data recorded during the first run of the LHC it has been possible to observe the new particle in different decay channels, as well as to study both the strengths of its couplings and its spin and parity.

The studies of these properties using decays into $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ and $b\bar{b}$ and based on the CMS [3] data recorded in 2011 and 2012, corresponding to integrated luminosities of $5.1\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ and $19.6\,\mathrm{fb}^{-1}$ at $8\,\mathrm{TeV}$, are summarised here. The characteristics of the observed signal in terms of mass and signal strength are first described. The studies of the couplings and of the spin and parity of the new state are then detailed in two subsequent sections.

1. – Signal observation

The observation of a new state compatible with a Higgs boson is the starting point for the study of its properties. The bosonic channels ($\gamma\gamma$, ZZ, W^+W^-) give the most significant signal, with for instance a standalone discovery in the $ZZ \to 4\ell$ final state [4].

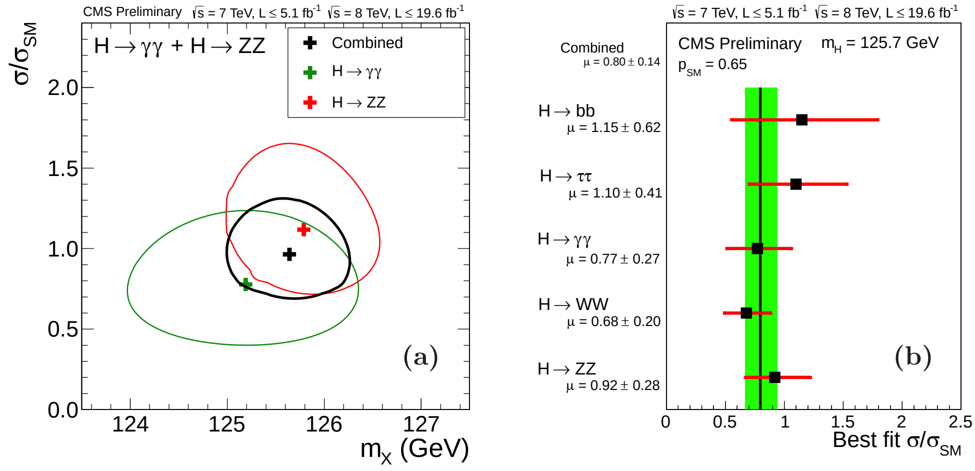

Fig. 1. – (a) The 2D 68% CL contours for a hypothesised Higgs boson mass m_X and signal strength in units of SM Higgs boson cross section $\sigma/\sigma_{\mathrm{SM}}$ for the $\gamma\gamma$ and $ZZ \to 4\ell$ decay channels, and their combination [6]. (b) Values of signal strength for the combination (solid vertical line) and for sub-combinations grouped by decay mode (points) [6].

There are in addition strong evidence of decays into fermions ($\tau^+\tau^-$ and $b\bar{b}$) [5]. The different analyses targeting specific decay modes ($\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$) and production mechanisms have been combined to extract the maximum information on the couplings [6]. Individual measurements ($\gamma\gamma$ [7], ZZ [4] and W^+W^- [8]) have also been used for property studies.

The mass of the new particle has been measured using the two high resolution $ZZ \to 4\ell$ and $\gamma\gamma$ channels with the assumption that the two signals are coming from the same state. Figure 1 (a) shows the 2D 68% CL regions for the two parameters of interest, the signal strength modifier μ and the mass m_X of the new particle, for these two channels. The combined 68% CL contour shown with a black line is calculated assuming the standard model (SM) Higgs boson relative event yield between the two channels, while the overall signal strength is left as a free parameter. To extract the value of m_X in a model-independent way the signal strength modifiers of the different channels entering the combination are profiled in the same way as all other nuisance parameters and a combined mass value of $125.7 \pm 0.3\,(\mathrm{stat.}) \pm 0.3\,(\mathrm{syst.})$ GeV is obtained [6]. It can be noted that this combination uses a preliminary analysis for $H \to ZZ$, which has been updated since. The latest standalone mass measurement based on the $ZZ \to 4\ell$ analysis gives a very compatible result of $125.6 \pm 0.4\,(\mathrm{stat.}) \pm 0.2\,(\mathrm{syst.})$ GeV [4].

The measured yields in all combined channels are found to be compatible with the expectation for a SM Higgs boson, within the currently large uncertainties (see fig. 1 (b)). The best fit value for the common signal strength modifier expressed in units of SM Higgs cross section is 0.80 ± 0.14 for a Higgs boson mass of 125.7 GeV [6].

The invariant mass line shape in the two high resolution channels can also be used to set limits on the Higgs boson total width. Nevertheless this measurement is limited by the detector energy resolution and only limits far from the SM Higgs boson width can be set, of the order of a few GeV. 95% CL limits of 3.4 GeV and 6.9 GeV have been set in the $ZZ \to 4\ell$ [4] and $\gamma\gamma$ [7] decay channels, respectively.

2. – Coupling strengths

The compatibility of the coupling strengths with expectations from a SM Higgs boson are studied using the procedure recommended by the LHC Higgs Cross Section Working Group [9]. It is assumed that the resonance is narrow and therefore the production cross section and decay width factorise in the event yield leading to the following equation:

$$(\sigma \cdot \mathrm{BR})(xx \to H \to yy) = \frac{\sigma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{tot}}}\,, \tag{1}$$

where σ_{xx} is the production cross section through the initial state xx (including gluon-gluon fusion, VBF, WH and ZH, and $t\bar{t}H$), Γ_{yy} is the partial decay width into the final state yy and Γ_{tot} is the total width of the Higgs boson. The σ_{xx} and Γ_{yy} are then parameterised at leading order in terms of multiplicative modifiers κ_i around the state of the art SM prediction. Since the size of the Run-1 dataset is not sufficient to quantify all the meaningful κ_i parameters, several benchmark parameterisations with a reduced number of degrees of freedom are defined, intended to probe specific scenarios beyond the standard model (BSM). Additionally only modifications of the coupling strengths are considered, with the assumption that the tensor structure of the couplings is the SM one, meaning that minimal couplings of a 0^+ state are assumed. Different analyses described in sect. **3** are devoted to test the spin and parity of the new particle.

A first set of benchmarks tests specifically the couplings to the SM particles assuming no contribution from BSM particles in the loop-induced couplings and in the invisible decays of the Higgs boson. Other benchmarks are intended to test these BSM contributions.

2˙1. *Absence of additional particles in decay and loops.* – Some of the benchmarks assume that no additional particles are present in either the decay or in the loops. In that case the modifiers for photon and gluon loop-induced couplings κ_γ and κ_g are derived in terms of tree level couplings to SM particles.

Since the couplings to fermions and to bosons come from two distinct parts of the Higgs sector, one of the simplest way to test it is to introduce two universal modifiers for Higgs couplings to fermions and to bosons (κ_f and κ_V). Given the interference between quark and W loops in the $H\gamma\gamma$ coupling the relative sign of κ_f and κ_V can be assessed from the $\gamma\gamma$ measurement. The 68% CL contours in the (κ_V, κ_f) plane for individual channels and for the combination are shown in fig. 2 (a). The positive couplings are strongly preferred and data are well compatible with the expectation from a SM Higgs boson, inside the 68% confidence region.

In the standard model the custodial symmetry protects the ratio between the W and Z couplings against large radiative corrections. Nevertheless large violations of custodial symmetry are possible in new physics models. It is tested by introducing two coupling modifiers κ_W and κ_Z that modify the SM Higgs couplings to the W and Z bosons, and evaluating the consistency of their ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$ with unity. Two different tests have been performed. The first one is almost a model-independent measurement of λ_{WZ} and is based on the ratio of event yields in categories of $H \to WW$ and $H \to ZZ$ mostly populated by gluon-gluon fusion. The second one is a combination of all the channels: it provides additional information from the VBF and VH production modes as well as from the $H\gamma\gamma$ coupling, but it is model-dependent. The 95% CL intervals for λ_{WZ} obtained with the two methods are $[0.60, 1.40]$ and $[0.62, 1.19]$ [6], and hence consistent with the expectation set by the custodial symmetry.

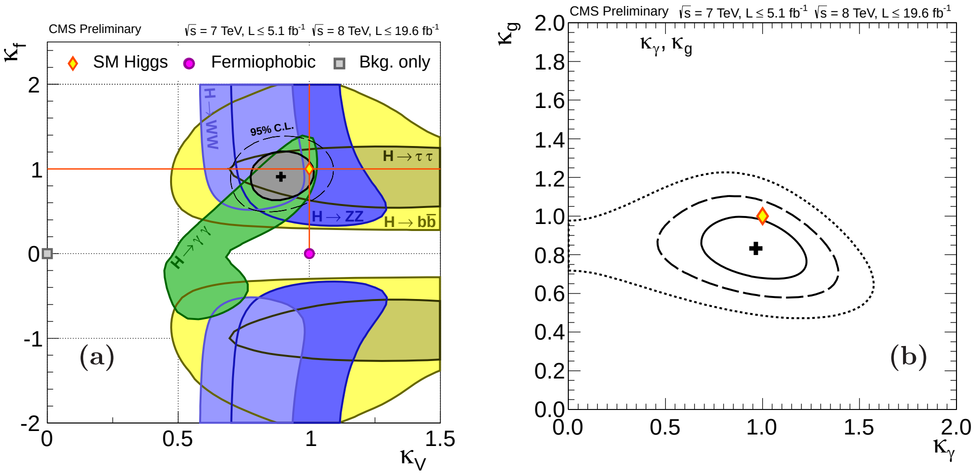

Fig. 2. – (a) The 68% CL contours for individual channels (coloured regions) and for the overall combination (solid line) for the (κ_V, κ_f) parameters. (b) The 2D likelihood scan for the κ_g and κ_γ parameters, assuming that no new Higgs boson decay modes are open. In both figures the cross indicates the global best-fit values.

Models with two Higgs doublets can bring substantial modifications to the couplings of neutral Higgs bosons compared to Yukawa couplings of the SM Higgs boson. For instance couplings to up and down-type fermions, or leptons and quarks can be modified in a different manner. This is tested by measuring ratios of coupling modifiers for down/up fermions $\lambda_{du} = \kappa_d/\kappa_u$, and for leptons/quarks $\lambda_{\ell q} = \kappa_\ell/\kappa_q$, both being constrained to be positive. The 95% CL intervals for these ratios are found to be $[0.74, 1.95]$ and $[0.57, 2.05]$ [6], respectively, well in agreement with the expectation for a SM Higgs boson.

2˙2. *Tests of the presence of BSM particles.* – Effects of new physics can appear in decays to non-SM states, leading to a modified total width. It is parameterised as $\Gamma_{\text{tot}} = \Gamma_{\text{SM}} + \Gamma_{\text{BSM}}$, where Γ_{BSM} takes into account both invisible and undetectable decays into new particles. New physics can also be revealed by modifications of the loop-induced couplings, particularly sensitive to the presence of additional particles, even if the Higgs sector remains unaltered. Gluon-gluon and $\gamma\gamma$ loop-induced coupling modifiers κ_g and κ_γ have been measured together, assuming unmodified tree-level production processes and decay modes, as well as $\Gamma_{\text{BSM}} = 0$. The 2D likelihood scan for the two parameters is shown in fig. 2 (b). The results are compatible with the expectation from a SM Higgs within the 95% CL region.

In addition a limit on $\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}}/\Gamma_{\text{tot}}$ has been set, while profiling together κ_γ and κ_g. It is found to be smaller than 0.52 at 95% CL [6]. It is interesting to compare this result with direct searches of invisible decays, which set limits of 0.69 and 0.75 at 95% CL using the VBF and VH production mechanisms [10, 11], respectively.

2˙3. *Less constrained fits.* – More general fits have also been performed, with 5 or 6 free parameters. In fig. 3 (a) are shown the results corresponding to a generic model with five parameters where couplings to third-generation fermions are scaled independently, as well as W and Z couplings, and only SM particles are considered in the loops. In fig. 3 (b) are shown the results corresponding to a generic model with six parameters

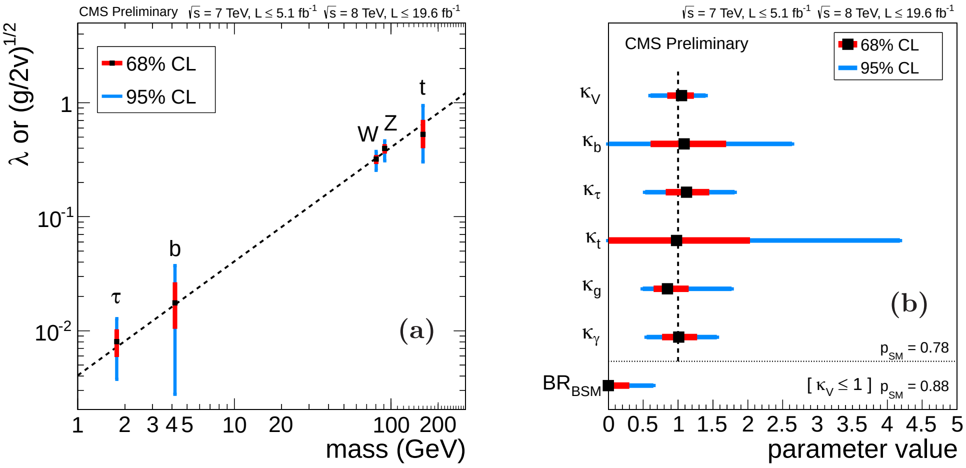

Fig. 3. – (a) Summary of the fits for deviations in the coupling for the generic five-parameter model, without effective loop couplings, expressed as function of the particle mass [6]. (b) Summary of the fits for deviations in the coupling for the generic six-parameter model including effective loop couplings [6].

where custodial symmetry is assumed, effective couplings to gluons and photons are considered, and couplings to third-generation fermions are scaled independently with the coupling modifier for the top κ_t obtained from the associated $t\bar{t}H$ production. In both cases results consistent with the expectation from a SM Higgs boson are obtained.

3. – Spin-parity state and coupling structure

In addition to coupling strength studies, based on yield measurements with analyses targeting different decay channels and different production mechanisms, the spin and parity of the new state have been studied using the kinematic information of the events. In the case of the $H \to \gamma\gamma$ analysis different spin hypotheses are separated using a single discriminating variable: the cosine of the scattering angle in the Collins–Sopper frame, $\cos(\theta^*_{\mathrm{CS}})$. In the case of the $H \to WW \to 2\ell 2\nu$ analysis both the visible dilepton mass and the transverse mass of the dilepton and missing transverse energy system are used. In the case of the $H \to ZZ \to 4\ell$, five angles and two masses are available and can be used to fully reconstruct the Higgs kinematic in the centre-of-mass frame; these information are merged in several discriminants suited for specific tests of spin-parity hypotheses.

3˙1. *Tests of pure state hypotheses.* – The structure of the couplings can first be studied with hypothesis tests aiming at the discrimination between pure spin-parity states. The most powerful channel for this purpose is the $ZZ \to 4\ell$ channel, which has been used to test various hypotheses of spin 0, 1 and 2 states with different parity and coupling structure. Pure gg and $q\bar{q}$ productions have been tested as well as any kind of production (production-independent tests). A summary of the results is shown in fig. 4. All the non-standard tested hypotheses have been excluded at more than 95% CL except the 2^+_h and 0^+_h hypotheses, which correspond to spin-2 and spin-0 models with higher-dimension operators and positive parity.

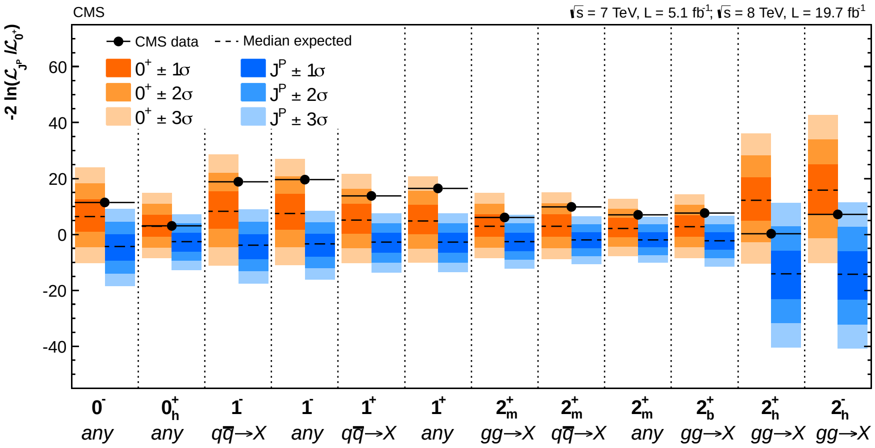

Fig. 4. – Summary of the expected and observed values for the test-statistic $q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{0^+})$ distributions for the twelve alternative hypotheses tested with respect to the SM Higgs boson in the $ZZ \to 4\ell$ decay channel. The orange (blue) band represents the 1σ, 2σ, and 3σ around the median expected value for the SM Higgs boson hypothesis (alternative hypothesis). The black point represents the observed value [4].

In the $H \to WW$ and $H \to \gamma\gamma$ analyses the 2^+ state with minimal couplings (2^+_m) has been tested against the standard model case (0^+) for different fractions of production via $q\bar{q}$ annihilation. The 2^+_m hypothesis has been excluded in the WW decay channel at a 83.7% (99.8%) CL or higher for a fraction of $q\bar{q}$ production of 0% (100%) [8]. On the other hand the separation power between 0^+ and 2^+_m is still too weak in the $H \to \gamma\gamma$ channel to make any statement [7].

3·2. *Spin-0 tensor structure study.* – In addition to pure state hypothesis tests it is already possible to look at possible mixed states with the Run-1 data. Given that spin-0 is strongly favoured by the data, only a possible spin-0 mixture of CP-odd and CP-even contributions has been measured. This is measured in terms of the fraction of CP-odd contribution in the $H \to ZZ$ decay amplitude, denoted as f_{a_3}. A value of f_{a_3} equals to 0 or 1 would correspond to pure 0^+ or 0^- state, while a value between 0 and 1 would mean a mixture of the two contributions in the decay amplitude and therefore an indication of CP violation in the Higgs sector. A limit $f_{a_3} < 0.51$ at 95% CL has been set [4], consistent with the expectation of 0 for a SM Higgs boson.

It is important to stress that such measurements will become more and more important in the next runs of the LHC, now that most of the pure non-standard states have been ruled out by Run-1 data. The present limit is just the first of its kind.

Conclusion

The data recorded by CMS during the first run of the LHC lead to the discovery of a new boson in 2012, compatible with a Higgs boson. They also gave the possibility to perform first studies of its properties. These studies include the measurements of possible deviations from the coupling strengths predicted by the standard model, within well-defined benchmark scenarios, as well as tests of the spin and parity state of the new particle. Based on these data no significant deviation from the standard model predictions has been observed.

But these studies are still limited by the small amount of data recorded so far and a much more precise picture of the Higgs couplings will be available in the next runs of the LHC, thanks to more production and decay modes becoming accessible, as well as more data in already well-established channels.

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