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Measurement of the Higgs properties at CMS

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Summary. — The studies of the properties of the recently found boson performed by CMS are presented. The analyses reported here use the data sample of $5.1\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$ and $12.1\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$ delivered by LHC and collected by the CMS experiment. The background-only hypothesis is excluded with a 6.9σ significance. The mass of the new boson is measured to be $125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})\,\text{GeV}/c^2$, combining the diphoton and four lepton channels. Several spin and intrinsic parity hypotheses are tested. The SM coupling structure is tested combining the measurements in all the considered final states, and a good agreement is found with the Standard Model predictions.

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1. – Introduction

The presence of a new boson with a mass around $125\,\text{GeV}/c^2$ has been announced both by the ATLAS [1] and CMS [2] experiments. Since then, CMS updated the results and the statistical combination for many of the analysis channels. The measurement of the properties of this new state becomes of great importance to determine its compatibility with the Standard Model (SM) Higgs hypothesis.

In most of the channels, CMS performs the analysis both inclusively (*untagged*) and isolating specific production modes: requiring two forward jets (*Vector Boson Fusion* (*VBF*) *tag*), and in association with another vector boson (W or Z, *VH tag*) or two top quarks ($t\bar{t}$ *tag*). Table I summarizes the final states and specific production modes, along with the invariant mass range considered.

For all channels but $H \to \gamma\gamma$ the luminosity used is $5.1\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$ and $12.1\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$. For the $H \to \gamma\gamma$ analysis, $5.7\,\text{fb}^{-1}$ of the 8 TeV sample are used.

TABLE I. – *Final states and specific production modes considered by CMS.*

Final state	untagged	VBF tag	VH tag	$t\bar{t}$ tag	Mass range [GeV/c^2]
$H \to \gamma\gamma$	X	X			110–150
$H \to ZZ \to 4l$	X				110–1000
$H \to b\bar{b}$			X	X	110–135
$H \to \tau\tau$	X	X	X		110–145
$H \to WW \to 2l2\nu$	X	X	X	X	110–600
$H \to WW \to 2\nu qq$	X				170–600

2. – Statistical approach

In the determination of the parameters of interest a for signal, a scan of the profile likelihood ratio is used [3]

$$q(a) = -2\ln\frac{\mathcal{L}(\mathrm{obs}|s(a)+b,\hat{\theta}_a)}{\mathcal{L}(\mathrm{obs}|s(\hat{a})+b,\hat{\theta})}\,, \tag{1}$$

where $\hat{a}$ and $\hat{\theta}$ maximize the likelihood function. The 68% (95%) CL on a given parameter a_i is evaluated from $q(a_i) = 1(3.84)$. All the other unconstrained model parameters are treated as nuisance parameters. The 2D CL contours of pairs of parameters are obtained from $q(a_i, a_j) = 2.3(6)$.

3. – Measurement of the mass

One of the main characteristics of both the $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ $(l = e, \mu)$ channels is the good resolution on the boson mass (m_X). To extract m_X, it is assumed that both final states are originated from the same particle. Firstly, we assume that the two processes are independent, and the signal strength modifiers μ (the scaling of the measured cross section with respect to the SM prediction) of the diphoton and four leptons channels are profiled as nuisance parameters. The result can be seen in fig. 1 (left). The result is $m_X = 125.8 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{syst})$. We also perform a 2D scan of m_X and μ, assuming a common signal strength between the two channels and constraining only the relative branching ratio among them, and find good agreement with the SM.

4. – Measurement of the signal strength

As explained earlier, we define the signal strength modifier parameter μ as the scaling of the measured cross section with respect to the SM prediction. Determining this parameter allows to establish the compatibility among the different channels and between their combination and the SM expectation ($\mu = 1$). The best fit values for μ in the different final states considered is shown in fig. 1 (center). Overall, a good compatibility among the channels is observed. The combined signal strength measured is $\mu = 0.88 \pm 0.21$, well in agreement with the SM. The background-only hypothesis ($\mu = 0$) is excluded with a 6.9σ significance.

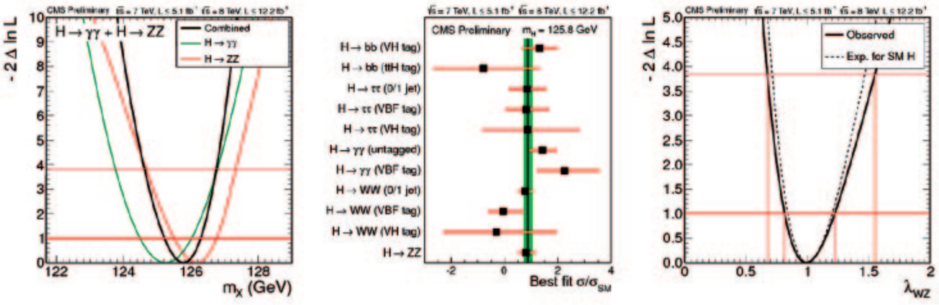

Fig. 1. – Left: likelihood scan for the m_X parameter for the diphoton (green) and the $4l$ (red) final states and for their combination (black). Center: values of μ for the combination (solid vertical line) and for contributing channels (points). The horizontal bars indicate the $\pm\sigma$ uncertainties on the μ values for individual channels. Right: likelihood scan *versus* λ_{WZ}. The solid line represents the scan on data, the dotted line the expected result in the presence of SM Higgs.

5. – Measurement of the Higgs coupling to SM particles

In order to test the compatibility of the new boson with the coupling of the Higgs to SM particles, CMS constructs a framework to combine the contribution to the couplings from all the analyses performed. In general, the number of signal events measured in any given channel is related to the Higgs total and partial widths

$$N(xx \to H \to yy) \sim \sigma(xx \to H) \cdot \mathcal{B}(H \to yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{tot}}\,. \tag{2}$$

Within the current experimental measurements scenario, seven partial widths (Γ_{WW}, Γ_{ZZ}, Γ_{tt}, Γ_{bb}, $\Gamma_{\tau\tau}$, Γ_{gg}, $\Gamma_{\gamma\gamma}$) and the total width Γ_{tot} are considered. Γ_{gg} and $\Gamma_{\gamma\gamma}$ are connected to loop diagrams; this makes them potentially sensitive to physics beyond the SM. Γ_{tot} is generally a free parameter of the fits, to accommodate the possibility that the Higgs may decay into new particles which are not detected. It should be noted that the widths are proportional to the square of the effective Higgs boson coupling, so they are not directly sensitive to its sign unless quantum interference between two different processes is present. To test for SM variations in the couplings, we consider modified couplings (κ), which correspond to the couplings normalized to the SM expectation. Any variation of κ from unity represents a difference with respect to the SM predictions.

With the statistics collected by CMS, it is impossible to determine all eight free parameters simultaneously. Therefore, CMS measures a combination of a smaller number of free parameters that are sensitive to particular new physics scenarios. The other parameters are either fixed to SM expectations or profiled in the likelihood like nuisance parameters.

5˙1. *Test of the custodial symmetry.* – In the SM, the tree level relations between the W and Z masses, and therefore the ratio of their couplings with the Higgs boson g_W/g_Z, are protected from large radiative corrections. This is due to the way in which the Higgs vacuum expectation value breaks the symmetry, and is known as *custodial symmetry*. This property can be violated in several new physics scenarios. In order to test this, we introduce $\lambda_{WZ} = \kappa_W/\kappa_Z$ and verify its consistency with unity.

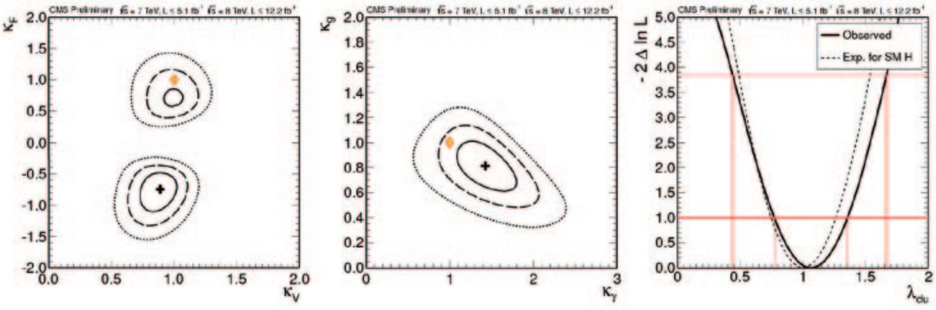

Fig. 2. – Left: 2D scan of κ_f *vs.* κ_V. The 68%, 95% and 99.7% confidence contours are shown with solid, dashed and dotted lines respectively. Center: 2D likelihood scan for κ_γ and κ_g, assuming $\Gamma_{tot} = \Gamma_{SM,tot}$. Right: likelihood scan of Higgs couplings to down/up fermions λ_{du}, with the other couplings profiled together with the nuisance parameters.

The likelihood scan of λ_{WZ} is shown in fig. 1 (right) for the combination of all the channels. The 95% CL on λ_{WZ} is $[0.67, 1.55]$, therefore compatible with the SM. Additionally, λ_{WZ} is extracted considering the $H \to ZZ \to 4l$ and $H \to WW \to 2l2\nu$ channels only, and is found compatible with the result from the full combination.

From now on, we assume $\lambda_{WZ} = 1$ and the modified coupling is assumed to be common between W and Z bosons (κ_V).

5˙2. *Test of couplings to vector bosons and fermions.* – Assuming the custodial symmetry is verified, the next step is to test the coupling of the Higgs boson to fermions and bosons (κ_f and κ_V respectively). As stated above, all the partial widths are proportional to the square of the couplings. The exception is $\Gamma_{\gamma\gamma}$, which is introduced via W and top loop diagrams and is proportional to $|\alpha\kappa_V + \beta\kappa_f|^2$, so it is sensitive to the relative sign between the two modifiers.

The result of the 2D scan is shown in fig. 2 (left). The difference between the global minimum in the fourth quadrant and the local (SM) minimum in the first quadrant is not statistically relevant, and is driven by the excess in the $\gamma\gamma$ decay channel. In fact, if the relative sign between κ_V and κ_f is negative, the destructive interference between W and top loops in the $H \to \gamma\gamma$ decay becomes constructive and increases the branching fraction.

5˙3. *Test of presence of BSM particles.* – All processes that involve loop diagrams ($H \to \gamma\gamma$ and $gg \to H$) are sensitive to the presence of new particles. To test this, we scan the κ_γ and κ_g parameters, assuming that the partial widths associated to tree level processes are not modified. Also, the total width is fixed to the SM value. This is shown in fig. 2 (center). The 1D projections for each of the parameters are $[0.98, 1.92]$ for κ_γ and $[0.55, 1.07]$ for κ_g.

5˙4. *Test of asymmetries in fermion couplings.* – In models where two Higgs doublets are present (2HDM), the couplings of the Higgses to fermions can be modified with respect to the SM. In MSSM, the couplings of neutral Higgses to up-type and down-type fermions are modified. This difference is the same for all families and for both quarks and leptons. If one considers more general 2HDMs, leptons can decouple from Higgs boson while the couplings to vector bosons and quarks are unchanged. To test this, we

TABLE II. – *Summary of the spin and parity hypotheses tested.* 0^+_h *refers to the scalar hypothesis where higher dimension operators (suppressed in SM) are present in the likelihood.* 2^+_{mqq} (2^+_{mgg}) *refers to the term of the spin* 2 *amplitude that couples to two quarks* (*gluons*).

J^P	Production	Comment	Expected	Obs.	CL_s
0^-	$gg \to X$	Pseudoscalar	2.6σ	3.3σ	0.16%
0^+_h	$gg \to X$	Higher dim. op.	1.7σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	Minimal couplings	1.8σ	2.7σ	1.5%
2^+_{mqq}	$qq \to X$	Minimal couplings	1.7σ	4.0σ	$< 0.1\%$
1^-	$qq \to X$	Exotic vector	2.8σ	$> 4.0\sigma$	$< 0.1\%$
1^+	$qq \to X$	Exotic pseudovector	2.3σ	$> 4.0\sigma$	$< 0.1\%$

define $\lambda_{du} = \kappa_d/\kappa_u$ and $\lambda_{lq} = \kappa_l/\kappa q$ to test the MSSM and general 2HDMs respectively. The result for λ_{du} is shown in fig. 2 (right). The 95% CL intervals are $[0.00, 2.11]$ and $[0.45, 1.66]$ for λ_{lq} and λdu respectively.

6. – Test of the spin and parity properties of the boson

The differential cross section of the new boson will depend on its spin and parity. Using the $H \to ZZ \to 4l$ channel, one can construct a kinematic discriminant to separate the different J^P hypotheses using the likelihood ratio $q = -2\ln(\mathcal{L}_{H_1}/\mathcal{L}_{SM})$, where H_1 represents the hypothesis to be tested [4]. Table II reports the results for the different hypotheses tested. One can notice that most of the non-SM scenarios are excluded.

7. – Conclusions

After the discovery of a new boson made by CMS and ATLAS, a detailed study of this boson properties has been performed. The analysis done by CMS, based on $5.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ and $12.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ delivered by LHC measured the mass of the new state to be $125.8 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{GeV}/c^2$. The decay rates in all the studied channels are compatible with the SM expectations within errors. Data disfavor most of the spin and parity hypotheses different from the SM scalar scenario.

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