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Measurements of properties of the Higgs-like Particle at 125 GeV by the CMS collaboration

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Abstract. CMS results are presented on the measurement of properties of the Higgs-like particle discovered last summer with a mass in the range of 125-126 GeV, based on the full statistics of about 25 fb^{-1}, collected in 2011 and 2012 at 7 and 8 TeV respectively. Five decay channels are considered for these studies, namely the ZZ, $\gamma\gamma$, WW, $\tau\tau$, and bb modes. The mass of the new boson is measured to be 125.7 ± 0.4 GeV. The event yields measured by the different analyses, targeting specific decay modes and production mechanisms, are consistent with those expected for the standard model (SM) Higgs boson, with an overall best-fit signal strength of 0.80 ± 0.14 at the measured mass. A discussion on the measurement of the couplings and the spin-parity properties of this new particle is presented, using the most recent results.

1 Introduction

Within the Standard Model (SM) of particle physics [1–3], the particle masses arise from the spontaneous breaking of the electroweak symmetry which is implemented through the Higgs mechanism. In its minimal version, this is realized through the introduction of a doublet of complex scalar fields. After breaking of the electroweak symmetry, only one scalar field is present in the theory and the corresponding quantum, the Higgs boson, should be experimentally observable [4–9]. The masses of the fermions in the SM are generated via the Yukawa couplings between the fermions and the Higgs field. Understanding the mechanism for electroweak symmetry breaking is one of the primary goals of the physics program at the Large Hadron Collider (LHC). On July 4^{th} 2012, the CMS [10] and ATLAS [11] experiments have announced the discovery of a new boson at a mass around 125 GeV, with properties compatible with the SM Higgs boson. The reported excess is most significant in the $\mathrm{ZZ}^{(*)} \rightarrow 4\mathrm{l}$ and $\gamma\gamma$ final states. In what follows, an updated mass measurement and a set of tests on the properties of the new resonance with the CMS detector [12] are reported. The comprehensive results on the new boson property measurements at CMS can be found in Ref. [13].

2 The combination methodology

2.1 Characterizing an excess of events

To quantify the presence of an excess of events over what is expected for the background, we use the test statistic for the background-only hypothesis $q_0 = -2\ln\frac{\mathcal{L}(\mathrm{data}|b,\hat{\theta}_0)}{\mathcal{L}(\mathrm{data}|\hat{\mu}\cdot s+b,\hat{\theta})}$, where s stands for the signal expected under the SM Higgs hypothesis, μ is a signal strength modifier introduced to accommodate deviations from SM predictions for signal, b stands for backgrounds, and θ are nuisance parameters describing systematic uncertainties. The probability p_0, henceforth referred to as the local p-value, is defined as the probability to obtain a value q_0 at least as large as the one observed in data, q_0^{obs}, under the background-only hypothesis, i.e. $p_0 = P(q_0 \geq q_0^{\mathrm{obs}}|b)$. Such a probability, in the case of a signal-like excess, is then converted into a significance (σ) using the one-sided Gaussian tail convention [14, 15].

2.2 Extracting signal-model parameters

In a similar way, a signal-model parameter a (the signal strength modifier μ is an example) is evaluated from a scan of the profile likelihood ratio $q(a) = -2\ln\frac{\mathcal{L}(\mathrm{data}|s(a)+b,\hat{\theta}_a)}{\mathcal{L}(\mathrm{data}|s(\hat{a})+b,\hat{\theta})}$.

3 The significance of the observed excess

The Higgs boson search in CMS is performed considering five exclusive decay modes. The $\mathrm{H} \rightarrow \mathrm{ZZ}^{(*)} \rightarrow 4\mathrm{l}$ ($\mathrm{l} = \mathrm{e},\mu$) and $\mathrm{H} \rightarrow \gamma\gamma$ channels have a large sensitivity and play a special role due to the excellent mass resolution of the reconstructed di-photon and four-lepton final states. The $\mathrm{H} \rightarrow \mathrm{WW}^{(*)} \rightarrow 2\mathrm{l}2\nu$ channel provides a large sensitivity but has a poor mass resolution due to the presence of neutrinos in the final state. The bb and $\tau\tau$ decay modes have relatively poor mass resolution and large backgrounds reducing their sensitivities. Table 1 summarizes the median expected and observed local significance from the individual decay modes for a SM Higgs boson mass hypothesis of 125.7 GeV (see Sect. 4 for details on

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decay channel	expected (σ)	observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
$\tau\tau$	2.6	2.8
bb	2.2	2.0
$\tau\tau$ + bb	3.4	3.4

Table 1. The median expected and observed significances of the excesses in the individual decay modes and the combination of the leptonic modes ($\tau\tau$ and bb). Values are computed for a SM Higgs boson of mass 125.7 GeV.

the mass measurements). The excesses of events observed in the ZZ, $\gamma\gamma$, and WW decay modes confirm the observation of a new boson. The $\tau\tau$ and bb channels show a combined significance of 3.4σ, representing the first single-experiment evidence of coupling to fermions.

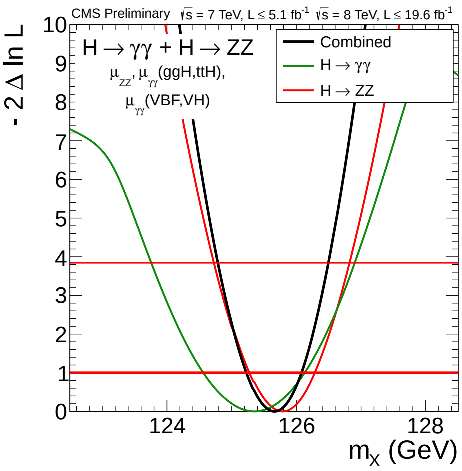

Figure 1. One-dimensional scan of the test statistic $q(m_X) = -2\Delta \ln \mathcal{L}$ versus the boson mass m_X for the $ZZ^{(*)} \to 4l$ and $\gamma\gamma$ final states separately (red and green line respectively) and for their combination (black line).

4 Mass measurement of the observed state

Only the high-resolution $ZZ^{(*)} \to 4l$ and $\gamma\gamma$ final states are considered in the measurement of the mass of this newly discovered particle. The signal in both channels is assumed to be due to a state with a unique mass, m_X. The mass m_X and its uncertainty are extracted from a scan of the combined test statistic $q(m_X)$. In order to extract the value of m_X in a model-independent way, the signal strength modifiers for the different processes are assumed to be independent and, thus, not tied to the SM expectation. Three signal strength modifiers are then introduced and profiled in the same way as all other nuisance parameters (two $\mu_{ZZ,\gamma\gamma}$ for ggH + ttH and one $\mu_{\gamma\gamma}$ for VBF + VH production mechanisms). The likelihood scan is shown in Fig. 1 for the $ZZ^{(*)} \to 4l$ and $\gamma\gamma$ final states separately and for their combination. The two channels are well in agreement and a mass of 125.7 ± 0.4 GeV is measured from the combination, with the overall uncertainty of 0.4 GeV corresponding to the 68% CL interval. The statistic and systematic components equally contribute about 0.3 GeV to the total uncertainty.

5 Compatibility tests

With the intent of characterizing this new particle and assessing its compatibility with the SM prediction for a Higgs boson, a number of tests has been performed. These are presented in the following sub-sections.

5.1 The size of the observed excess

The first compatibility test is provided by the best-fit value for the signal strength modifier $\hat{\mu} = \hat{\sigma}/\sigma_{SM}$. The combination of all search channels yields an observed $\hat{\mu}$ value of 0.80 ± 0.14 for a Higgs boson mass of 125.7 GeV, consistent with the SM prediction $\mu = 1$. Figure 2 shows $\hat{\mu}$ values obtained for different search channels and production modes separately. None of the sub-combinations is found to be in disagreement with SM expectations, given the current individual sensitivities. Note that this result cannot be interpreted as a measurement for pure production mechanisms since tagged samples targeting a specific production mode are often contaminated by other modes. Cross contaminations are evaluated from the simulation and taken into account in the fits. Associating each one of the four Higgs boson production mechanisms to either a fermion coupling (gluon-gluon fusion and ttH) or a boson coupling (VBF and VH associated production), two signal strength modifiers $\mu_{ggH+ttH}$ and μ_{VBF+VH} are introduced. A 2-dimensional likelihood scan as a function of these two signal strength modifier can then be performed for each one of the five decay modes, as shown in Fig. 3. The SM Higgs boson expectation (1,1) is within the 68% CL regions for each of these channels.

5.2 Compatibility of the observed state with the SM Higgs boson couplings

To test for possible deviations from the SM-predicted rate of events in the different channels, modified couplings are introduced (indicated as κ_i in the following), with cross sections and branching fractions being proportional to the second power of these κ_i factors. The possibility of Higgs boson decays into Beyond-Standard-Model (BSM) particles is accommodated by introducing a partial decay width Γ_{BSM} and writing the total Higgs boson decay width $\Gamma_{tot} = \Sigma_i \Gamma_{ii} + \Gamma_{BSM}$, where i runs over all the known SM particles a SM Higgs boson can decay into. Data are then fitted to these new parameters: significant deviations of any of these κ_i from unity or Γ_{BSM} from zero would imply new physics beyond the Standard Model. As agreed within the LHC Higgs Cross Section Working Group [16], eight independent such parameters completely characterize the Higgs boson production and decay rates, but the size of the

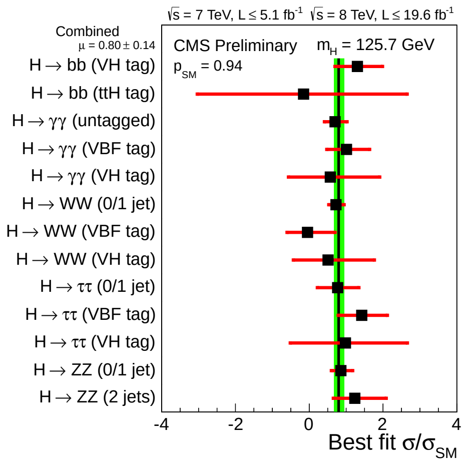

Figure 2. Values of $\hat{\mu} = \hat{\sigma}/\sigma_{\text{SM}}$ for the combination (solid vertical line) and for individual decay modes and additional tags targeting a particular production mechanism (black markers). The vertical band shows the overall μ uncertainty. The horizontal bars indicate the ± 1 standard deviation uncertainties in μ values for the individual modes, including both statistical and systematic uncertainties.

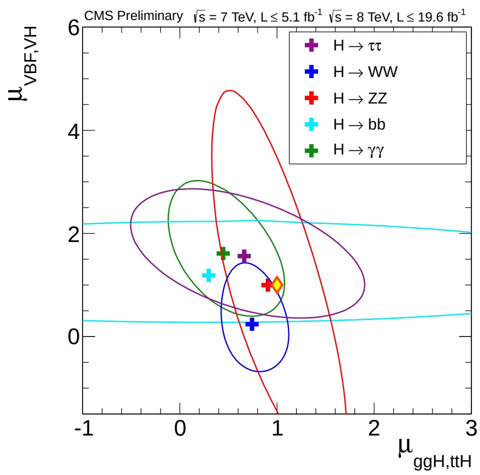

Figure 3. The 68% CL regions (solid lines) for the signal strength in the gluon-gluon-fusion-plus-ttH associated production ($\mu_{\text{ggH+ttH}}$) and in the VBF-plus-VH associated production mechanisms ($\mu_{\text{VBF+VH}}$). The different colors represent the five different decay modes analyzed. The crosses indicate the best-fit values. The diamond at (1,1) indicates the expected value for the SM Higgs boson.

current dataset is too limited to estimate all of them simultaneously. Therefore, only subsets of these parameters are quantified at a time.

As a first test, the Higgs boson couplings to W and Z bosons is probed by introducing two scaling factors κ_{W} and κ_{Z}. To assess the consistency of the ratio $\lambda_{\text{WZ}} = \kappa_{\text{W}}/\kappa_{\text{Z}}$ with unity, as predicted by the custodial symmetry, a likelihood scan of the test statistic $q(\lambda_{\text{WZ}})$ is performed on the combination of all channels, profiling κ_{Z} and κ_{f} together with the other nuisance parameters (κ_{f} modifies the Higgs boson coupling to the fermions). At 95% CL, λ_{WZ} is found within the [0.62,1.19] range, thus in agreement with the Standard Model.

Assuming $\lambda_{\text{WZ}} = 1$ and a common κ_{V} for both W and Z couplings in the following, we can perform a 2D likelihood scan over the $(\kappa_{\text{V}}, \kappa_{\text{f}})$ space to test the couplings to the vector bosons and the fermions. All partial widths scale as κ_{V}^2 or κ_{f}^2, except for $\Gamma_{\gamma\gamma}$, which is induced by W and top loops and scales as $|\alpha\kappa_{\text{V}} + \beta\kappa_{\text{f}}|^2$, making it the only channel sensitive to the relative sign of the vector boson and fermion couplings. The result is shown in Fig. 4 for the combination of all search channels. From 1D likelihood scans, 95% CL intervals for κ_{V} and κ_{f} are found to be [0.74,1.06] and [0.61,1.33] respectively.

The presence of BSM particles can be probed fitting the data for the scale factors of gluon and photon couplings κ_{g} and κ_{γ} (assuming $\Gamma_{\text{BSM}} = 0$), since loop-induced process are particularly susceptible to the presence of new particles, or performing a likelihood scan versus $\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}}/\Gamma_{\text{tot}}$, with κ_{g} and κ_{γ} profiled as nuisances. From all of these tests, no indications of deviations from the SM predictions are derived (the 95% CL confidence intervals for κ_{g}, κ_{γ} and BR_{BSM} are [0.59,1.30], [0.63,1.05] and [0.00,0.52] respectively).

Finally, asymmetries in the coupling of this new particle to up-type and down-type fermions ($\lambda_{\text{du}} = \kappa_{\text{d}}/\kappa_{\text{u}}$) or to lepton and quarks ($\lambda_{\text{lq}} = \kappa_{\text{l}}/\kappa_{\text{q}}$) could indicate the presence of new Physics beyond a pure SM description (such behaviours appear, e.g., in models with two Higgs doublets). Again, the data are not in favour of such models, with the SM expectation well contained within the 95% CL intervals for λ_{du} and λ_{lq} ([0.74,1.95] and [0.57,2.05] respectively).

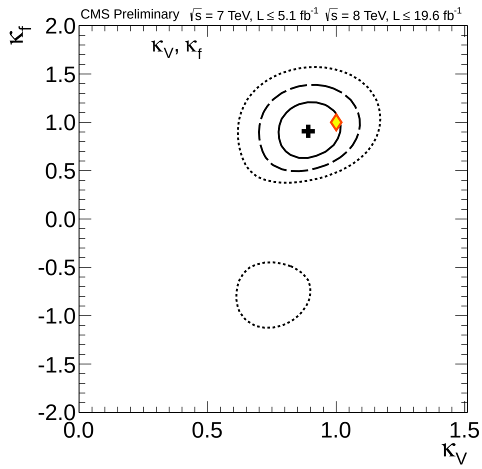

Figure 4. The 2D likelihood of the κ_{V} and κ_{f} parameters. The cross indicates the best-fit values. The solid, dashed and dotted contours show the 68%, 95% and 99.7% CL regions, respectively. The yellow diamond shows the SM point, which is within the 68% CL region defined by the data.

5.3 Test of different spin-parity hypotheses

In order to determine the identity of the new boson, it is crucial to measure its quantum numbers. The observation

J^P	expected ($\mu = 1$)	observed	CL$_s$
0^-	2.6σ (2.8σ)	3.3σ	0.16%
0_h^+	1.7σ (1.8σ)	1.7σ	8.1%
2_m^+(gg)	1.8σ (1.9σ)	2.7σ	1.5%
2_m^+(q$\bar{\text{q}}$)	1.7σ (1.9σ)	4.0σ	<0.1%
1^-	2.8σ (3.1σ)	$> 4.0\sigma$	<0.1%
1^+	2.3σ (2.6σ)	$> 4.0\sigma$	<0.1%

Table 2. List of models used in the analysis of spin-parity hypotheses using the $\text{H} \to \text{ZZ}^{(*)} \to 4\text{l}$ channel. The expected separation is quoted for the two scenarios where the signal strength for each hypothesis is determined from a fit to the data (post-fit model) or where events are generated with SM expectation for the signal yield $\mu = 1$ (pre-fit model). The observed separation quotes the consistency of the observation with the respective J^P model, and corresponds to the post-fit model case. The last column quotes the CL$_s$ criterion.

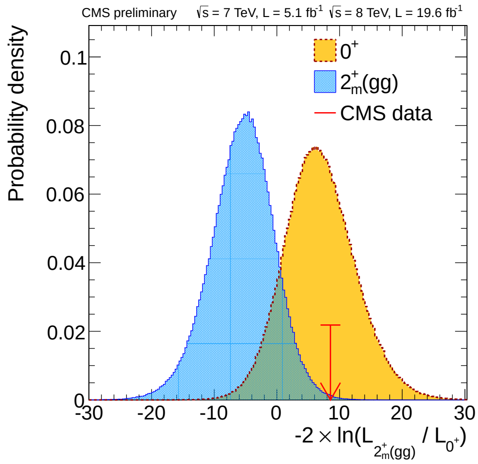

Figure 5. Post-fit model distributions of the test statistic comparing the signal J^P hypotheses 0^+ and 2_m^+(gg) in the combination of $\text{H} \to \text{ZZ}^{(*)} \to 4\text{l}$ and $\text{H} \to \text{WW}^{(*)} \to 2\text{l}2\nu$ analyses. The arrow indicates the value of the test statistic observed in data and disfavours the 2_m^+(gg) signal hypothesis with a CL$_\text{s}$ value of 0.60%.

of decays of this particle in a $\gamma\gamma$ final state already allows to conclude that its spin is different from unity [17, 18]. A comprehensive set of hypothesis tests has been recently carried out in the $\text{H} \to \text{ZZ}^{(*)} \to 4\text{l}$ channel [19], considering as alternative signals the $J^P = 0^-$, 0_h^+, 2_m^+(gg), 2_m^+(q$\bar{\text{q}}$), 1^-, and 1^+ hypotheses. The results of the separation of the SM Higgs boson model and the different J^P hypotheses are summarized in Tab. 2. Further details on the definition of the coupling structure of the alternative spin-parity states can be found in Ref [20].

What is reported here below is the combination of the $\text{H} \to \text{ZZ}^{(*)} \to 4\text{l}$ and $\text{H} \to \text{WW}^{(*)} \to 2\text{l}2\nu$ analyses to improve the sensitivity to separate the $J^P = 0^+$ (scalar boson) from the $J^P = 2_m^+$(gg) (graviton-like boson) hypotheses. The test statistic used is defined as $q = -2\ln(\mathcal{L}_{2_m^+(\text{gg})+\text{bkg.}}/\mathcal{L}_{0^+ + \text{bkg.}})$. The pdf of q for the two different signal hypotheses is modeled by generating pseudo-experiments, assuming $m_H = 125.7$ GeV, under two different models: a pre-fit model, where all nuisance parameters are set to their default values and signal strength modifiers are set to 1, and a post-fit model, where all nuisances (μ included) are set to their best-fit values, as shown in Figure 5. Defining a CL$_\text{s}$ criterion to separate the two hypotheses, namely $\text{CL}_\text{s}^{\text{obs.}} = P(q \geq q^{\text{obs.}}|2_m^+(\text{gg}))/P(q \geq q^{\text{obs.}}|0^+)$, we can conclude that the data disfavour the graviton-like hypothesis with a CL$_\text{s}$ value of 0.60%, which is worse than the expectation of 0.23% in the pre-fit model mostly due to an downward fluctuation observed in the WW channel (best-fit signal strength $\mu_{\text{WW}} < 1$).

6 Conclusions

The properties of the recently discovered boson have been measured with the CMS experiment at the LHC using the full 2011 and 2012 dataset, consisting of up to 5.1 fb^{-1} collected at 7 TeV and up to 19.6 fb^{-1} at 8 TeV center-of-mass energy respectively. Five exclusive decay modes are combined in the measurement, namely the $\text{ZZ}^{(*)} \to 4\text{l}$, $\gamma\gamma$, $\text{WW}^{(*)} \to 2\text{l}2\nu$, $\tau\tau$, and bb final states. The mass of the new boson has been measured from the $\text{ZZ}^{(*)} \to 4\text{l}$ and $\gamma\gamma$ channels to be $125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.})$ GeV.

The event yields obtained by the different analyses are consistent with those expected for the SM Higgs boson, with the best-fit signal strength across all channels measured 0.80 ± 0.14 at the measured mass. Several tests have been performed to test the consistency of the couplings of the observed particle with those predicted by the Standard Model for a Higgs boson, finding no significant deviation. Finally, under the assumption that the observed boson has positive parity, the data disfavour the hypothesis of a graviton-like boson with minimal couplings produced in gluon fusion with a CL$_\text{s}$ value of 0.60%.

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