Chapter 16

Higgs Boson Properties

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This chapter presents an overview of the measured properties of the Higgs boson discovered in 2012 by the ATLAS and CMS collaborations at the CERN LHC. Searches for deviations from the properties predicted by the standard theory are also summarised. The present status corresponds to the combined analysis of the full Run 1 data sets of collisions collected at centre-of-mass energies of 7 and 8 TeV.

1. Introduction

The discovery of a Higgs boson at the LHC^{1–3} and the subsequent measurements of its properties have yielded no significant deviations from the standard theory expectations.

This brings the status of the theoretical cornerstone of elementary particle physics from a model to a complete — renormalisable — theory, that seems to be self-consistent to energy scales that can reach the Planck scale.⁴ Large efforts are being poured into direct searches that may point to how the standard theory may be supplemented in order to account for observed phenomena for which it makes no prediction, such as dark matter or neutrino masses.

On the other hand, precision measurements of the Higgs boson properties may reveal indirect evidence for physical phenomena beyond the standard theory. The measurement of the Higgs boson mass constrains a fundamental parameter in the standard theory and the 0.2% precision of the present measurement allows to test the internal consistency of the standard theory, against existing measurements of the W boson and top quark masses, for instance. Furthermore, the standard theory predicts all other properties of the Higgs boson once its mass is specified. Consequently, such a precise measurement of its mass sets the stage for more precise searches for deviations from the standard theory predictions in other Higgs boson properties.

2. Overview of Analyses Used

The ATLAS and CMS collaborations have designed and built the two largest and general-purpose detectors at the LHC.^{5,6} Although their design requirements were similar because of the similar physics goals, the technologies used to fulfil those requirements are very different in all aspects, ranging from the geometry of the detectors to the offline software frameworks used.⁷

From 2010 to 2013, during the LHC Run 1, there were proton–proton collisions at centre-of-mass energies of 7 TeV and 8 TeV. The integrated luminosity available for analysis in each experiment was about 5/fb at 7 TeV and 20/fb at 8 TeV.

The combination of Higgs boson searches and measurements^{8–14} is based on a large number of analyses. Depending on the combinations being performed and properties being probed, different channels and analyses are used. Table 1 provides a schematic overview of which Higgs boson production and decay modes enter in the various combinations.

The Higgs boson searches that lead to the discovery of the Higgs boson^{1–3} were dominated by the gluon fusion production process and the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow llll$, and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ decay modes. Dedicated searches for other production and decay modes, as listed in Table 1, were also included and improved the overall expected sensitivity.

The combined measurement of the Higgs boson mass is based on the two channels where a narrow mass resonance can be observed: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow llll$. The differential measurements of kinematic production properties in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channels are mainly based on events produced via gluon fusion and vector-boson fusion (VBF). The measurements of kinematic decay properties for spin and parity hypothesis tests in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow llll$, and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channels aim to be independent of the production modes. As the selection criteria used are rather inclusive, the gluon fusion process dominates within the standard model (SM). Finally, the combined measurements of signal and coupling strengths make use of almost all channels analysed by the ATLAS and CMS collaboration for the 125 GeV Higgs boson, which cover almost all combinations of Higgs boson production and decay modes accessible at the LHC.

2.1. Rare decays

In addition to the Higgs boson decay modes summarised in Table 1, there are other, rarer, decays predicted by the SM for a 125 GeV Higgs boson. Those searched for include $H \rightarrow \mu\mu$,^{40,41} $H \rightarrow ee$,⁴¹ $H \rightarrow Z\gamma$,^{42,43} $H \rightarrow \gamma^*\gamma$,⁴⁴ and $H \rightarrow V\gamma$ ^{44,45} with $V = J/\psi, \Upsilon$. Even with small expected branching fractions in the SM, effects beyond the SM (BSM) could result in enhanced branching fractions and thus an observable signal. However, no signal from these decay modes was found with the Run 1 dataset, and 95% confidence level (CL) upper limits on the signal

Table 1. Overview of where different Higgs boson production and decay modes enter into the different Higgs combinations. The “ 5σ ” dark grey triangles indicate channels for which dedicated searches were used in the discovery of the Higgs boson.^{1–3} The “ m_H ” light grey triangles indicate channels contributing to the mass measurement.^{8–10} The “ J ” and “ J^{CP} ” grey triangles indicate channels contributing to spin and CP hypothesis tests using kinematic decay properties.^{11–13} The “ $\frac{d\sigma}{dx}$ ” dark grey triangles indicate channels where differential measurements of kinematic production properties were performed.^{15–21} The black check marks indicate channels entering the combined signal and coupling strength measurements.¹⁴ These channels are documented in the references given in the table. References noted with [†] describe analyses not included in the combined analysis of both ATLAS and CMS data.

	$H \rightarrow \gamma\gamma$ Refs. 22, 23	$H \rightarrow ZZ^{(*)}$ Refs. 24, 25	$H \rightarrow WW^{(*)}$ Refs. 26, 27	$H \rightarrow \tau\tau$ Refs. 28, 29	$H \rightarrow b\bar{b}$
$gg \rightarrow H$					
VBF					Refs. 30 [†] , 31 [†]
WH, ZH					
			Ref. 32	Ref. 33 [†]	Refs. 34, 35
$t\bar{t}H$					
			Refs. 36, 37	Refs. 36, 37	Refs. 38 [†] , 37, 39

strength, $\mu = (\sigma \times \text{BR})/(\sigma_{\text{SM}} \times \text{BR}_{\text{SM}})$, were reported by the ATLAS and CMS experiments.

The most notable limit is that on the $H \rightarrow \mu\mu$ decay with the observed (expected) limits $\mu < 7.4$ (6.5) and $\mu < 7.0$ (7.2) for CMS and ATLAS, respectively. For $H \rightarrow ee$, CMS also finds an upper limit for μ of about 3.7×10^5 . Generation-universal couplings of the Higgs boson to leptons would imply a striking signal strength of $\mu \sim 280$ for $H \rightarrow \mu\mu$ and $\mu > 10^6$ for $H \rightarrow ee$. Universal couplings to leptons are therefore strongly excluded, something that is in contrast with the observed decays of the W and Z bosons.

Also of interest is the $H \rightarrow Z\gamma$ decay that is loop-induced in the SM and could be enhanced by the presence of (virtual) BSM particles. The observed (expected) limits from ATLAS and CMS are $\mu < 11$ (9) and $\mu < 9.5$ (10), respectively.

2.2. BSM decays

The ATLAS and CMS experiments have also performed direct searches for some BSM Higgs boson decay modes. Higgs boson decays to weakly interacting particles (*invisible* particles), that leave no signature in the detector, are not expected in the SM beyond a per-mille level contribution from $H \rightarrow ZZ^{(*)} \rightarrow 4\nu$ decays. Decays to invisible particles can be experimentally detected using events featuring large missing transverse momentum. Both experiments searched for such invisible decays in the VBF, WH , and ZH production modes.^{46,47} The observed (expected) 95% CL limits on an invisible branching fraction $\text{BR}_{\text{inv.}}$ are <0.28 (0.31) and <0.58 (0.44), in ATLAS and CMS, respectively. In the future, analyses using boosted gluon-fusion topologies, where a single jet is detected, will increase the overall sensitivity to invisible decays.

Decays of the Higgs boson into lepton-flavour-violating final states are also not expected in the SM. ATLAS and CMS searched for the $H \rightarrow \tau\mu$ and $H \rightarrow \tau e$ decay, and both reported small excesses in $H \rightarrow \tau\mu$ with respect to the background expectations. For a 125 GeV Higgs boson, 95% CL observed (expected) limits on $\text{BR}(H \rightarrow \tau\mu)$ was set to be $<1.51\%$ (0.75%) and $<1.43\%$ (1.01%) by CMS and ATLAS, respectively.^{48,49} For a 125 GeV Higgs boson, the 95% CL observed (expected) limit on $\text{BR}(H \rightarrow \tau e)$ was set to be $<1.04\%$ (1.21%) by ATLAS.⁴⁹

3. Measurements

3.1. Mass

The mass of the Higgs boson, m_H , is a parameter of the standard theory that plays an important role in the stability of the electroweak vacuum, or lack thereof.⁴

Given the precision electroweak data⁵⁰ and the standard theory structure,⁵¹ m_H can be determined indirectly to be 93^{+25}_{-21} GeV.⁵² The large uncertainty reflects the fact that m_H enters (at one loop) only in logarithmic corrections, reducing the ability for the electroweak precision data to constrain it.

A precise measurement of m_H is fundamental in testing the compatibility of the observed properties of the Higgs boson with those predicted by the standard theory, since the standard theory can make precise predictions for all the Higgs boson properties for a given value of m_H .

For all these reasons, it is not surprising that the first combined Higgs result of the ATLAS and CMS collaborations was a measurement of m_H , resulting in a determination with a precision of 0.2%.¹⁰

The decay channels used in measuring the Higgs boson mass were $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow llll$. In both these final states it is possible to perform a precise measurement of all particles in the decay, leading to an expected relative mass resolution for the Higgs boson between 1 and 2%.^{22–25} This is in contrast with other final states where the hadronisation into jets of particles ($H \rightarrow b\bar{b}$ and $H \rightarrow WW^{(*)}$)

or the presence of neutrinos in the final states ($H \rightarrow \tau\tau$ and $H \rightarrow WW^{(*)}$) smears the reconstructed mass, pushing their expected relative mass resolutions to values ranging between 10 and 20%.^{26–29,34,35} An excellent experimental resolution can also be achieved from the measurement of the $H \rightarrow \mu\mu$ decay, once there is enough data to observe that decay.^{40,41}

The precision of the m_H measurement in the $H \rightarrow \gamma\gamma$ decay channel essentially depends on the precision in the measurement of the energy of each photon and of the angle between the two photons. Here, the complementarity of the ATLAS and CMS detectors shines: given their different design, the electromagnetic (EM) calorimeters of ATLAS and CMS have different strengths. For instance, the ATLAS EM calorimeter is able to reconstruct the direction of the EM shower and therefore have a precise measurement of the diphoton opening angle,²² while the CMS EM calorimeter is homogeneous, allowing for a better precision on the individual photon energy measurement.^{53,54} Overall, the precision achieved by both experiments is comparable, the differences providing robustness to the combined measurement.

In the $H \rightarrow ZZ^{(*)} \rightarrow llll$ decay channel, the precision depends on the flavour of the leptons, with the $H \rightarrow ZZ^{(*)} \rightarrow \mu\mu\mu\mu$ final state providing the most precise measurements.

In both ATLAS and CMS, the energy scale is calibrated against the $Z \rightarrow ll$ “standard candle”. In the $H \rightarrow ZZ^{(*)} \rightarrow llll$ decay channel, there are also cross-check measurements performed using the $Z \rightarrow llll$ final state, where one lepton pair is the result of QED radiation. In the $H \rightarrow \gamma\gamma$ decay channel, the energy scale is set from the study of $Z \rightarrow ee$ decays. In this case, some “electron-to-photon” extrapolation is involved, since the two particles are differently affected, for instance, by discrepancies between the simulated and actual material in front of the EM calorimeters.

The mass measurements in the $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow \gamma\gamma$ final states are performed using observables that are not necessarily the same used in the analyses targeting the measurement of yields or cross-sections. For instance, for the measurement of m_H the ATLAS $H \rightarrow \gamma\gamma$ analysis categorises events so as to minimise the experimental systematic uncertainties, and the CMS $H \rightarrow ZZ^{(*)} \rightarrow llll$ analysis uses an event-by-event estimator of the mass resolution. The results of the four individual analysis are shown in the top part of Fig. 1.

In order to reduce the dependence of the measurement on standard theory assumptions, which is used to model the expected yields in each event category, three separate signal strength modifiers are floated simultaneously. The factors separately scale gluon-fusion and $t\bar{t}H$ in $H \rightarrow \gamma\gamma$, VBF and VH in $H \rightarrow \gamma\gamma$, and the overall $H \rightarrow ZZ^{(*)} \rightarrow llll$ signal. Figure 1 also shows the result of the combined analysis of ATLAS and CMS data for the two decay channels. The fully-combined measurement yields $m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (syst) GeV. The breakdown of the systematic uncertainty yields ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV. This shows that the largest contribution to the systematic uncertainty is due to

Fig. 1. Summary of the ATLAS and CMS m_H measurements, partial combinations per decay channel, and the result of the combined analysis. Systematic uncertainties are denoted by the thinner boxes with darker shade, the statistical uncertainties by the thicker boxes with lighter shade, and the total uncertainties by the black bars. (Figure reproduced from Ref. 10.)

the uncertainty on the energy or momentum scales, all other contributions being negligible in comparison.

The compatibility between the four individual measurements with the combined one was estimated from a fit with four separate masses. The asymptotic p -value is found to be 10%, changing to 7% if the production rates are also decorrelated between ATLAS and CMS.

It is worth noting that less precise measurements from other decay channels, such as $H \rightarrow WW^{(*)}$ ^{26,27} or $H \rightarrow \tau\tau$,²⁹ are in agreement with the determination from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$, within their uncertainties, which are comparably larger.

Finally, given how the statistical uncertainty is about twice the systematic uncertainty, the existing results on the Higgs boson mass allow to confidently say that the LHC Run 2 has the potential to reduce the total uncertainty by a significant factor.

3.2. Total width

For $m_H \sim 125$ GeV the SM Higgs boson is predicted to be narrow, with a total width $\Gamma_{\text{SM}} \sim 4$ MeV. From the study of off-shell Higgs boson production and decay into the $ZZ \rightarrow 4\ell$ and $VV \rightarrow 2\ell 2\nu$ final states, ATLAS⁵⁵ and CMS⁵⁶ have set an indirect observed (expected) 95% CL limit on the total width in the range of $\Gamma_{\text{tot}}/\Gamma_{\text{SM}} < 4.5\text{--}7.5$ ($6.5\text{--}11.2$) for ATLAS, and $\Gamma_{\text{tot}} < 13$ (26) MeV for CMS. While that result is about two orders of magnitude better than the experimental mass resolution, it relies on assumptions about the underlying theory, such as the absence of contributions to Higgs boson off-shell production from BSM particles.

In contrast, a direct limit does not rely on such assumptions and is only limited by the experimental resolution.

The best experimental mass resolution, achieved in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ analyses, is typically between 1 and 3 GeV. The resolution depends on the energy, rapidity, and azimuthal angle of the decay products, and on the flavour of the leptons in the case of $H \rightarrow ZZ^{(*)} \rightarrow lll$ decays. If found inconsistent with the expected detector resolution, the total width measured in data could suggest the production of a resonance with a larger intrinsic width or the presence of two quasi-degenerate states.

To perform a measurement of the total width, the signal models in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ analyses are modified to allow for a natural width using the relativistic Breit–Wigner distribution, as described in Refs. 8, 25 and 23. For the $H \rightarrow \gamma\gamma$ channel the observed (expected) upper limit at the 95% CL is 2.4 (3.1) GeV for CMS⁹ and 5.0 (6.2) GeV for ATLAS.⁸ In the $H \rightarrow ZZ^{(*)} \rightarrow lll$ channel the observed (expected) upper limit at the 95% CL is 3.4 (2.8) GeV for CMS⁹ and 2.6 (6.2) GeV for ATLAS.⁸ For the combination of the two CMS analyses, the observed (expected) upper limit at the 95% CL is 1.7 (2.3) GeV.⁹

From the study of the flight distance in $H \rightarrow ZZ^{(*)} \rightarrow lll$ decays, CMS set a 95% CL observed (expected) lower limit on the total width of $\Gamma_{\text{tot}} > 3.5 \times 10^{-9}$ (3.6×10^{-9}) MeV.⁵⁷

3.3. Differential and fiducial cross-sections

The very clean final state signatures of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ decays do not only allow to measure the mass and width of the Higgs boson, but also allow rather model-independent differential measurements of the Higgs boson production kinematic properties. These include the transverse momentum and rapidity of the Higgs boson, and the associated number of jets as well as the transverse momentum distribution of the jets. Comparisons between the measured production properties and predictions for different Higgs boson production modes can be used to draw conclusions about QCD aspects of Higgs boson production and possible contributions from BSM physics in Higgs boson production.

Both experiments measured the production properties in the two decay channels both as inclusive as well as differential fiducial cross sections.^{15,16,18,19} ATLAS also combined the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ channels in a common fiducial volume.¹⁷ Measurements using the $H \rightarrow WW^{(*)}$ decay channel were also performed^{20,21} but not considered in the following examples.

As examples of the observables considered, the measurements of the Higgs boson transverse momentum $p_T(H)$ and the number of jets N_{jets} associated with the Higgs boson are shown in Fig. 2. The measurements are shown together with predictions from the most accurate theory calculations at the time. For ATLAS, the combination of the cross-section-normalised distributions for $p_T(H)$ and N_{jets} are shown,

Fig. 2. Comparison of the predictions of several SM theory calculations with the measured distributions of the Higgs boson transverse momentum, p_T^H (top left and bottom row) and the number of jets produced in association with the Higgs boson, N_{jets} (top right). In the top row, ATLAS measurements combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ channels, normalised to the cross section. In the bottom row, CMS measurements in the $H \rightarrow \gamma\gamma$ (left) and $H \rightarrow ZZ^{(*)} \rightarrow lll$ (right) channels. At the time, HRes⁵⁸ and NNLOPS⁵⁹ provided the most accurate SM predictions for p_T^H and N_{jets} , respectively, and are therefore used as theory references. (Figures reproduced from Refs. 17–19.)

as this combination is independent of assumptions on the Higgs boson branching fractions. For CMS, the p_T^H distribution is shown separately for the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow lll$ channels.

Within the SM, the $gg \rightarrow H$ production mode dominates and these measurements are especially sensitive to the intricate QCD aspects of this process. However, some sensitivity to the VBF production is also reached in the high p_T and

$N_{\text{jets}} = 2$ part of the phase space, where dedicated measurements for VBF-related observables were done in the $H \rightarrow \gamma\gamma$ analyses.^{15,18} With increasing luminosity, the sensitivity to other production modes can be expected to increase.

The overall agreement of the observed distributions and the SM predictions is good within the current uncertainties of the measurements and of the theory predictions. The most noticeable difference with respect to the SM predictions is in the lowest- p_T^H bins in ATLAS analyses and the CMS $H \rightarrow ZZ^{(*)} \rightarrow llll$ channel, where the theory seems to predict larger yields than observed. This is not visible in the p_T^H distribution of the CMS $H \rightarrow \gamma\gamma$ analysis. Besides statistical fluctuations, QCD effects unaccounted for in theory calculations could contribute a deviation. BSM modifications of Higgs boson production are mostly expected to appear in the high p_T and high jet multiplicity part of the phase space, where the agreement with the SM predictions is good within the uncertainties.

The analyses also include model-independent measurements of cross sections in fiducial volumes as well as comparisons with SM theory predictions within the corresponding fiducial regions. Examples are shown in Fig. 3 and more information can be found in Refs. 15–19.

Fig. 3. Fiducial cross section measurements, for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow llll$, and combination at 8 TeV from ATLAS (left) and as a function of $\sqrt{s}$ for $H \rightarrow ZZ^{(*)} \rightarrow llll$ from CMS (right). In both cases a comparison to theory predictions is provided. (Figures reproduced from Refs. 17 and 19.)

4. Searches for Deviations

Measurements of the Higgs boson properties that are almost model independent are so far only possible in the cleanest Higgs boson channels, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow llll$, as discussed in the previous section. The analyses in the $H \rightarrow WW^{(*)} \rightarrow \nu l \nu l$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ channels retain some dependence on the SM, as this is needed for a good separation from background processes. Studies of Higgs boson properties involving these channels are therefore better understood as searches for deviations from the SM.

These searches for deviations in Higgs boson properties from the SM can be broadly grouped in two categories of comparisons to the SM predictions:

- (1) Higgs boson signal yields in different Higgs boson production and decay modes or alternative comparisons of the Higgs boson coupling strength to the SM expectation. These comparisons assume for each Higgs boson production and decay mode the kinematic structure of the SM.
- (2) Kinematic (tensor) structure of Higgs boson decays. While these analyses are designed to be independent of the observed signal yield, they assume production kinematics similar to the SM in some cases.

As the latter justifies — to some degree — the assumptions of the former, the following discussion will start with the kinematic structure of Higgs boson decays.

4.1. Compatibility in decay kinematics

The SM predicts a spin-0 Higgs boson with quantum numbers $J^{CP} = 0^{++}$. This results in characteristic kinematic distributions for Higgs boson decay products and kinematic correlations between them, which can be used to search for deviations from the SM. As the SM Higgs boson has spin 0, in the SM no kinematic correlations are expected between production and decay.

ATLAS^{11,12} and CMS¹³ have used the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{(*)} \rightarrow lll$, and $H \rightarrow WW^{(*)} \rightarrow \nu\nu\nu$ decay channels to search for such deviations from the SM by testing several non-SM hypotheses of spin and parity J^P . This allows to determine J^{CP} assuming that either C or CP is conserved. In addition, non-SM effective Lagrangian operators or non-SM anomalous coupling contributions were explored in the case of a spin-0 Higgs boson.

4.1.1. Hypothesis tests on the spin of the new boson

Hypothesis tests for pure $J^P = 0^-, 1^+, \text{ and } 1^-$ states were performed in the $H \rightarrow ZZ^{(*)} \rightarrow lll$ and $H \rightarrow WW^{(*)} \rightarrow \nu\nu\nu$ channels by analysing kinematic decay properties. The inclusive $H \rightarrow \gamma\gamma$ channel is not sensitive to the parity for a spin-0 particle since the two photons decay back-to-back in the rest frame of the Higgs boson and yield no additional information. The observation of the $H \rightarrow \gamma\gamma$ final state excludes a single spin-1 boson as a consequence of the Landau–Yang theorem.^{60,61} Hypothesis tests for a new spin-2 boson were performed for a large number of models using the $H \rightarrow ZZ^{(*)} \rightarrow lll$, $H \rightarrow WW^{(*)} \rightarrow \nu\nu\nu$ and $H \rightarrow \gamma\gamma$ channels. For spin-2 hypotheses, the angular correlations between the production and the decay of the new boson can also be exploited, as is done in the $H \rightarrow \gamma\gamma$ channel by measuring the θ^* angle between the production and decay system.

In order to be less dependent on the implementations of concrete BSM models in excluding J^P states, the overall observed signal yields were floated in the hypothesis tests. Consequently, the information on total predicted yield is not used. This is

especially motivated in spin-2 models with universal couplings that predict branching fractions otherwise not compatible with the observed signal yields in different final states. This also ensures that conclusions drawn from these studies are valid when deviations from the SM in the Higgs boson signal and coupling strengths are allowed.

For the combined spin hypothesis tests^{12,13} using the three channels, the best-motivated spin-2 model corresponding to a massive graviton-like particle (2_m^+) is taken here as a spin-2 example, even if many others were tested. Table 2 shows that all tested J^P states are excluded with CL_s values⁶² $\ll 1\%$ when compared with the SM hypothesis, $J^P = 0^+$.

Table 2. Observed CL_s values from ATLAS and CMS for different J^P hypotheses tested against the SM Higgs boson hypothesis of $J^P = 0^+$. The loosest limit is given whenever different production mode hypotheses were tested. Smaller values of CL_s disfavour more strongly the non-SM hypotheses.

J^P	ATLAS	CMS
0^-	$<0.026\%$	$<0.01\%$
1^+	0.03%	0.004%
1^-	0.27%	$<0.001\%$
2_m^+	0.011%	0.13%

A model-independent test of all spin-2 structures may eventually become possible with more data. States with a spin larger than 2 were not considered by either experiment, and are even more challenging to motivate for an elementary particle.

4.1.2. Kinematic decay structure of a $J = 0$ boson

Deviations from the SM predictions in kinematic distributions for a scalar boson (with spin 0) can be analysed within different frameworks as extensively discussed in Ref. 63. Among the frameworks, the effective Lagrangian and anomalous coupling approaches are the most common. On the one hand, the most general effective Lagrangian compatible with Lorentz and gauge invariance can be used as a basis for calculations. On the other hand, in the anomalous coupling approach, the most general amplitude compatible with Lorentz and gauge invariance is introduced. As the latter does not assume a hierarchy in scales, the couplings become momentum-dependent form factors. However, no common and agreed-upon approach exists and also the notations differ substantially. ATLAS¹² used an effective Lagrangian approach, but provides results also in an anomalous coupling formulation. CMS¹³ used an anomalous couplings approach, providing also results in terms of an effective Lagrangian.

For a better comparison, the results from both collaborations for the $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channels are therefore translated in terms of the following effective Lagrangian, that describes a spin-0 on-shell scalar boson decaying to $H \rightarrow VV$ ($V = W^\pm, Z$):

$$\begin{aligned} \mathcal{L}_{HVV} \sim & \kappa_Z \frac{m_Z^2}{v} H Z^\mu Z_\mu + \kappa_W \frac{2m_W^2}{v} H W^\mu W_\mu \\ & + \frac{\alpha_Z}{v} H Z^\mu \square Z_\mu + \frac{\alpha_W}{v} (H W^{+\mu} \square W_\mu^- + H W^{-\mu} \square W_\mu^+) \\ & + \frac{\beta_Z}{v} H Z^{\mu\nu} Z_{\mu\nu} + \frac{2\beta_W}{v} H W^{\mu\nu} W_{\mu\nu} \\ & + \frac{\gamma_Z}{v} H Z^{\mu\nu} \tilde{Z}_{\mu\nu} + \frac{2\gamma_W}{v} H W^{\mu\nu} \tilde{W}_{\mu\nu} \end{aligned} \quad (1)$$

where v is the SM Higgs field vacuum expectation value, V_μ represents the V boson field, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ is the field strength tensor, and $\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$ is the dual field-strength tensor. The first two terms are the minimal dimension-3 operator and, with $\kappa_V = 1$, correspond to the SM Higgs boson ($J^P = 0^+$). The six terms in the last three rows of Eq. (1) are dimension-5 operators: the α - and β -terms are parity-even interactions, that can be kinematically distinguished from the SM Higgs boson. The β terms are commonly referred to as 0_h^+ . The γ terms correspond to a pseudo-scalar interaction (0^-). In principle, also SM particles contribute to these last six terms due to higher-order corrections, but at a very small rate.

The Lagrangian in Eq. (1) allows for both CP-even and CP-odd tensor structures in addition to the SM gauge boson interactions. Within the effective Lagrangian calculations, a non-vanishing value of the parameters α_V , β_V , and γ_V leads to changes of the kinematic distributions as well as the overall signal yields, with respect to the SM. The SM tensor structure is scaled by κ_V , which modifies the SM signal yields, and correspond to the κ_W and κ_Z scalar coupling rescaling factors defined for Higgs boson couplings measurements, as discussed in Section 4.3.

As done in the J^P hypothesis tests, the overall observed signal yields are not used in the analysis for the discrimination from the SM. This not only simplifies the analysis, but also allows for a more general interpretation of the results. This implies that only ratios of Lagrangian parameters are probed. The ratios are chosen to be α_V/κ_V , β_V/κ_V , and γ_V/κ_V . Without further assumptions, these ratios of parameters may be different in the HZZ and HWW interaction vertexes. For the combination of measurements from the $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channels, the same values of these ratios are assumed in the HZZ and HWW interactions: $\alpha^{ZZ}/\kappa^{ZZ} = \alpha^{WW}/\kappa^{WW}$, $\beta^{ZZ}/\kappa^{ZZ} = \beta^{WW}/\kappa^{WW}$, and $\gamma^{ZZ}/\kappa^{ZZ} = \gamma^{WW}/\kappa^{WW}$. The allowed 95% CL confidence intervals for these ratios are listed in Table 3 for

Table 3. The expected and observed 95% CL confidence intervals for non-SM spin-0 interactions with gauge bosons, as described in Eq. (1). The results are presented for the combination of the $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ channels. The results obtained by ATLAS and CMS in Refs. 12 and 13 are translated to the notation used in this Section.

		α/κ	β/κ	γ/κ
ATLAS	observed	-	$[-0.63, 0.73]$	$[-0.83, 2.18]$
	expected	-	$[-4.80, 0.55]$	$[-2.30, 2.33]$
CMS	observed	$[-1.66, 1.57]$	$[-0.76, 0.58]$	$[-1.57, 1.54]$
	expected	$[-\infty, 1.24] \cup [9.0, +\infty]$	$[-1.67, 0.45]$	$[-2.65, 2.65]$

the combined $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ analyses of the full LHC Run 1 data. In all cases, very small non-vanishing values for the α/κ , β/κ , and γ/κ ratios are also expected in the SM from higher-order loop contributions, but the sensitivity was not sufficient to be probe such contributions.

The structure of the HVV vertex can also be probed using the VBF and VH production modes. The analyses in Refs. 64 and 65 search directly for anomalous CP-odd tensor structures in addition to the SM gauge boson interactions. In Ref. 66 the differential cross section measurements described in Section 3.3 are used to probe for non-SM CP-even and CP-odd contributions in Higgs boson production modes.

4.2. Compatibility in signal yields

The signal yields for Higgs boson production and decay processes can be measured from experimental analyses optimised for each of the 25 combinations of five production processes and five decay modes briefly illustrated in Table 1. While the selection of the Higgs boson final state decay products allows for a rather clean experimental separation of decay modes, the separation of Higgs boson production modes poses a bigger challenge. In many cases, several Higgs boson production processes are expected to contribute to the different experimental analysis categories. Different Higgs boson production processes can still be separated, if the same acceptance as for the SM processes (within uncertainties) is assumed for each production process and decay mode. This is equivalent to assuming, for each process, the kinematic distributions predicted by the SM. A combined fit can then estimate the contributions from individual production and decay processes from the observed signal yields in different experimental analysis categories with different compositions.

The most general result in this context would be a measurement of all 25 cross section combinations $\sigma_i \times \text{BR}^f$ for the production process i and decay mode f listed in Table 1. Such a measurement is not yet possible in full generality, but 20 combinations were determined, with varying precision, from a combined analysis

Fig. 4. Best-fit values of the combined analysis of ATLAS and CMS for twenty $\sigma_i \times \text{BR}^f$ combinations. The results are expressed in terms of the SM predictions. The uncertainties in the points correspond to all sources of uncertainty, except for the SM prediction uncertainties on the overall signal yields, which are represented as the grey bars around the prediction. As could be expected, the Run 1 dataset did not allow to set precise bounds on some combinations of production processes and decay modes (cross-hatched). (Figure reproduced from Ref. 14.)

of ATLAS and CMS data,¹⁴ as illustrated in Fig. 4. Among the missing combinations are some that could not be meaningfully constrained with the combined ATLAS and CMS Run 1 datasets for lack of statistics.

On the other hand, if it is assumed that all signals originate from a single narrow Higgs boson resonance, one can exploit the fact that different rows and columns in Table 1 and Fig. 4 share either common ratios of production cross sections σ_i or common ratios of branching fractions BR^f . This then allows to choose a reference cross section, such as $\sigma_{\text{ggF}} \times \text{BR}^{ZZ}$ for the $gg \rightarrow H \rightarrow ZZ$ process, and eight ratios, one for each of the other Higgs boson production and decay modes. Figure 5 shows the result for the ATLAS and CMS measurements,¹⁴ and their combination. The results are compared to the SM theory predictions.⁶³ The most notable differences with respect to the SM are $\sigma_{\text{ttH}}/\sigma_{\text{ggF}}$, which is about 3.0σ above the SM expectation, and $\text{BR}^{bb}/\text{BR}^{ZZ}$, which is about 2.5σ below the SM expectation. The p -value of the observed data under the SM hypothesis is 16%.

More sensitive, but less general, tests of the SM hypothesis are possible if additional assumptions are introduced. For instance, if the signal strength in a decay mode f , defined as $\mu_i^f = (\sigma_i \times \text{BR}^f)/(\sigma_{i,\text{SM}} \times \text{BR}_{\text{SM}}^f)$, is assumed to be identical for all vector-boson-mediated Higgs production modes ($\mu_{\text{VBF}+VH}^f = \mu_{\text{VBF}}^f = \mu_{\text{WH}}^f = \mu_{\text{ZH}}^f$) and all fermion-mediated processes ($\mu_{\text{ggF}+ttH}^f = \mu_{\text{ggF}}^f = \mu_{\text{ttH}}^f$), deviations from the SM can be explored in the 2D plane of $\mu_{\text{VBF}+VH}^f$ versus $\mu_{\text{ggF}+ttH}^f$ for each decay mode f . Figure 6 shows the results of the combined analysis of ATLAS and CMS, which agree, within uncertainties, with the SM hypothesis for each decay mode studied.

Fig. 5. Best-fit values for the ATLAS, CMS, and combined analyses of Higgs boson production and decay modes. The results are expressed in terms of ratios and compared to the SM predictions. The uncertainties in the points correspond to all sources of uncertainty, except for the SM prediction uncertainties on the overall signal yields, which are represented as grey bars around the prediction. (Figure from Ref. 14.)

Fig. 6. Confidence regions for signal strength multipliers of the fermion-mediated and vector-boson-mediated productions processes. The regions are determined for each of the five main decay modes studied. Only the combined analysis of the ATLAS and CMS data is shown. (Figure adapted from Ref. 14.)

The most sensitive test, at the cost of the strongest assumptions, is the determination of a common signal strength $\mu = \mu_i^f$ for all Higgs boson production modes i and decay modes f . The combined ATLAS and CMS analysis yields $\mu = 1.09^{+0.11}_{-0.10}$ in agreement with the SM hypothesis. The detailed breakdown of the uncertainty yields ± 0.07 (stat) ± 0.04 (expt) ± 0.03 (thbgd) $^{+0.07}_{-0.06}$ (thsig). This shows that the statistical uncertainty for this test is already at the same level of the systematic uncertainty from theory calculations of the signal (thsig) and background (thbgd), as well as experimental sources of uncertainty (expt). Therefore, improvements in the theory systematic uncertainties will be needed for LHC Run 2, where substantially more data are expected than in Run 1, entailing even smaller statistical uncertainties.

The search for a second, mass-degenerate, state was also performed via a statistical test of the structure of the matrix of the different production and decay mode signal strengths.⁶⁷ The result from the combined analysis of the ATLAS and CMS datasets is compatible with SM prediction of a single particle.

4.3. Compatibility in couplings

In the previous section, the production and decay processes of this Higgs boson were treated as independent. Given that the couplings of the Higgs boson to SM particles are involved both in its production as well as in its decay, a framework was proposed for the simultaneous interpretation of all the information.^{63,68} In this framework, the coupling of the Higgs boson with each of the SM particles is scaled by a multiplicative factor κ_i . These factors represent the ratios of production cross sections and partial decay width to the SM expectation: $\kappa_i^2 = \sigma_i/\sigma_i^{\text{SM}}$ or $\kappa_i^2 = \Gamma_i/\Gamma_i^{\text{SM}}$.

The fundamental assumptions underlying this framework are that there is one single state with $J^P = 0^+$ and a very narrow width, such that production and decay factorise, $\sigma_i \cdot \text{BR}_f = \sigma_i \cdot \Gamma_f/\Gamma_{\text{tot}}$.

In this framework, the loop-induced gluon and photon couplings to the Higgs boson can either be resolved into the SM amplitudes or treated as effective couplings. This allows to search for the effect of new particles “running” in the loops. As an example, the $H \rightarrow \gamma\gamma$ decay modifier can be expressed in a “resolved” way as $\kappa_\gamma^2 \sim 0.07\kappa_t - 0.66\kappa_W \cdot \kappa_t + 1.59\kappa_W^2$, where the (destructive) interference between the loops mediated by W bosons and top quarks can be seen. The effect of this structure can be clearly seen in Fig. 7 that shows the confidence regions allowed by each decay channel for two parameters, $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_F = \kappa_b = \kappa_t = \kappa_\tau$. The interference effects in the tHq ^{69–72} and $gg \rightarrow ZH$ ^{71,73} subdominant production processes lead to the observations in some individual decays channels to prefer very slightly the $\kappa_V\kappa_F < 0$ BSM scenario over the $\kappa_V\kappa_F > 0$ SM-like region (largest deviation is 1.3σ). But because of the interference effect in the $H \rightarrow \gamma\gamma$ decay, the combination of all channels excludes the $\kappa_V\kappa_F < 0$ BSM scenario by almost 5σ .

Fig. 7. Allowed confidence regions for each decay channel for two parameters that collect the scaling factors to massive bosons (κ_V) and fermions (κ_F). While most decay channels exclude regions that are almost symmetric, the interference of the top- and W -amplitudes in the $H \rightarrow \gamma\gamma$ decay make the contour for that channel very asymmetric. For this reason, the combination of channels strongly excludes the possibility that $\kappa_V = -\kappa_F$. (Figure adapted from Ref. 14.)

The results for a general fit with one scaling factor per SM particle as well as the gluon and photon interactions treated with an effective scaling parameter are shown in Fig. 8. In this figure, the two different sets of results correspond to different assumptions on the treatment of the total width.

The lighter points in Fig. 8 correspond to the case when the total width is a dependent function of all the other κ_i that scale the corresponding partial widths: $\Gamma_{\text{tot}}(\kappa_i) = \sum_i (\kappa_i^2 \Gamma_i^{\text{SM}})$. From the result of the fit to data, it can be seen that having separate gluon and top-quark modifiers reveals an excess, due to the results in $t\bar{t}H$ searches. The p -value for the data under the SM hypothesis in this model is 11%.

The assumption on the total width can be relaxed by allowing for the possibility of decays to invisible or undetected particles, whose branching fraction is denoted BR_{BSM} . In this case, the total width scales as $\Gamma_{\text{tot}}(\kappa_i) = \frac{\sum_i (\kappa_i^2 \Gamma_i^{\text{SM}})}{1 - \text{BR}_{\text{BSM}}}$. In this scenario, an additional constraint is assumed, namely $\kappa_V \leq 1$, something that is well-motivated in a large class of BSM models. The results of this fit are represented by the black points in Fig. 8, and yield a 95% CL observed (expected) upper limit $\text{BR}_{\text{BSM}} < 0.34$ (0.35).

Without assumptions on either the total width or the allowed range of any coupling only ratios $\lambda_{ij} = \kappa_i / \kappa_j$ of coupling modifiers can be determined. This is similar to what was done in the measurement of ratios of cross sections and ratios of branching fractions in the previous section. In addition to the λ_{ij} ratios, also one overall scale factor that modifies the rate of all processes by the same amount

Fig. 8. General search for coupling strength deviations, where the gluon and photon couplings to the Higgs boson are scaled with effective coupling modifiers. The light points correspond to a scenario where the total width is scaled according to the κ_i , while for the black points the decay to BSM particles is probed under the assumption that $\kappa_V \leq 1$. (Figure from Ref. 14.)

is determined: $\kappa_{gZ}^2 = \sigma_{ggF}/\sigma_{ggF}^{\text{SM}} \times \text{BR}_{ZZ}/\text{BR}_{ZZ}^{\text{SM}}$, where again the $gg \rightarrow H \rightarrow ZZ$ process is chosen as reference.

The results of this fit are shown in Fig. 9. All other determinations of coupling modifiers can be derived from these results, provided the correct correlations are taken into account.

Assuming the SM structure for the loop amplitudes and no BSM Higgs decays, deviations from the expected tree-level couplings to the SM particles can be probed. In this case the gluon and photon coupling modifiers become functions of the other κ_i and the top coupling deviation is mostly probed by the gluon-fusion cross section measurement. The result is presented as a function of the mass of the SM particles in Fig. 10, where it can be seen that it is very likely that the Higgs boson has non-universal interactions, or else the muon coupling modifier would have been measured to be much larger than observed.

Other results of the tests include the relative strength of the couplings to W and Z bosons, $\lambda_{WZ} = 0.88^{+0.10}_{-0.09}$, as well as tests with fewer parameters that probe the relative up-down and lepton-quark coupling strengths, $\lambda_{du} = 0.92 \pm 0.12$ and $|\lambda_{lq}| = 1.06^{+0.15}_{-0.14}$, which are expected to deviate from unity in models with two Higgs doublets.

Fig. 9. General search for coupling strength deviations, where the gluon and photon couplings to the Higgs boson are scaled as effective coupling modifiers. No assumptions on either the total width or the allowed range of any coupling is made, which then allows to determine only ratios of coupling modifiers $\lambda_{ij} = \kappa_i/\kappa_j$ and one overall rate modifier $\kappa_{gZ}^2 = \sigma_{ggF}/\sigma_{ggF}^{\text{SM}} \times \text{BR}_{ZZ}^{\text{SM}}/\text{BR}_{ZZ}^{\text{SM}}$. (Figure from Ref. 14.)

Fig. 10. Depiction of the result of the fit for deviations in the coupling of the Higgs boson to SM particles, presented as a function of the mass of the given particle. It can be seen that the Higgs boson has non-universal couplings with leptons, a highly distinctive feature of the standard theory Higgs boson. The coupling modifiers to the W and Z bosons were transformed with a square root in order to be plotted together with fermions and on the same (dotted) line, that represents the prediction of the standard theory. That transformation implies halving the uncertainties on κ_W and κ_Z . The solid line and bands indicate the result of the fit using the (M, ϵ) parameterization of Ref. 74. (Figure from Ref. 14.)

5. Summary

The data collected during the LHC Run 1 have allowed both ATLAS and CMS to characterise the observed Higgs boson with a mass of $m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (syst) GeV with enough detail to rule out many non-standard alternatives. Measurements and searches for deviation from the SM in the Higgs boson signal yields, in the Higgs boson couplings as well as in Higgs boson production and decay differential distributions provided results consistent with the SM. These results have also brought intense discussion between the theory and experiment communities, demonstrating the importance of more accurate predictions.

With more data, the LHC experiments will improve on the detailed characterisation of the properties of this Higgs boson. While the ultimate goal remains to find a deviation from the standard theory predictions, every measurement along the way will be a tribute to the resilience of the standard theory.

References

1. G. Aad *et al.* [ATLAS], Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B.* **716**, 1 (2012), [arXiv:1207.7214 \[hep-ex\]](#).
2. S. Chatrchyan *et al.* [CMS], Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B.* **716**, 30 (2012), [arXiv:1207.7235 \[hep-ex\]](#).
3. S. Chatrchyan *et al.* [CMS], Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* **06**, 081 (2013), [arXiv:1303.4571 \[hep-ex\]](#).
4. D. Buttazzo, G. Degrandi, P. P. Giardinio, G. F. Giudice, F. Sala, A. Salvio, and A. Strumia, Investigating the near-criticality of the Higgs boson, *J. High Energy Phys.* **12**, 089 (2013), [arXiv:1307.3536 \[hep-ph\]](#).
5. G. Aad *et al.* [ATLAS], The ATLAS Experiment at the CERN Large Hadron Collider, *JINST* **3**, S08003 (2008).
6. S. Chatrchyan *et al.* [CMS], The CMS experiment at the CERN LHC, *JINST* **3**, S08004 (2008).
7. D. Froidevaux and P. Sphicas, General-purpose detectors for the Large Hadron Collider, *Ann. Rev. Nucl. Part. Sci.* **56**, 375 (2006).
8. G. Aad *et al.* [ATLAS], Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data, *Phys. Rev. D.* **90**, 052004 (2014), [arXiv:1406.3827 \[hep-ex\]](#).
9. V. Khachatryan *et al.* [CMS], Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV, *Eur. Phys. J. C.* **75**, 212 (2015), [arXiv:1412.8662 \[hep-ex\]](#).
10. G. Aad *et al.* [ATLAS, CMS], Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments, *Phys. Rev. Lett.* **114**, 191803 (2015), [arXiv:1503.07589 \[hep-ex\]](#).
11. G. Aad *et al.* [ATLAS], Evidence for the spin-0 nature of the Higgs boson using ATLAS data, *Phys. Lett. B.* **726**, 120 (2013), [arXiv:1307.1432 \[hep-ex\]](#).

12. G. Aad *et al.* [ATLAS], Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector, *Eur. Phys. J. C.* **75**, 476 (2015), [arXiv:1506.05669 \[hep-ex\]](#).
13. V. Khachatryan *et al.* [CMS], Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV, *Phys. Rev. D.* **92**, 012004 (2015), [arXiv:1411.3441 \[hep-ex\]](#).
14. G. Aad *et al.* [ATLAS, CMS], Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, Submitted to J. High Energy Phys. (2016), [arXiv:1606.02266 \[hep-ex\]](#).
15. G. Aad *et al.* [ATLAS], Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV with ATLAS, *J. High Energy Phys.* **09**, 112 (2014), [arXiv:1407.4222 \[hep-ex\]](#).
16. G. Aad *et al.* [ATLAS], Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Lett. B.* **738**, 234 (2014), [arXiv:1408.3226 \[hep-ex\]](#).
17. G. Aad *et al.* [ATLAS], Measurements of the total and differential Higgs boson production cross sections combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels at $\sqrt{s} = 8$ TeV with the ATLAS detectors, *Phys. Rev. Lett.* **115**, 091801 (2015), [arXiv:1504.05833 \[hep-ex\]](#).
18. V. Khachatryan *et al.* [CMS], Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at $\sqrt{s} = 8$ TeV, *Eur. Phys. J. C.* **76**, 13 (2016), [arXiv:1508.07819 \[hep-ex\]](#).
19. V. Khachatryan *et al.* [CMS], Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* **04**, 005 (2016), [arXiv:1512.08377 \[hep-ex\]](#).
20. G. Aad *et al.* [ATLAS], Measurement of fiducial differential cross sections of gluon-fusion production of Higgs bosons decaying to $WW^* \rightarrow e\nu\mu\nu$ with the ATLAS detector at $\sqrt{s} = 8$ TeV, Submitted to J. High Energy Phys. (2016), [arXiv:1604.02997 \[hep-ex\]](#).
21. V. Khachatryan *et al.* [CMS], Measurement of the transverse momentum spectrum of the Higgs boson produced in pp collisions at $\sqrt{s} = 7$ TeV using $H \rightarrow WW$ decays, Submitted to J. High Energy Phys. (2016), [arXiv:1606.01522 \[hep-ex\]](#).
22. G. Aad *et al.* [ATLAS], Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, *Phys. Rev. D.* **90**, 112015 (2014), [arXiv:1408.7084 \[hep-ex\]](#).
23. S. Chatrchyan *et al.* [CMS], Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties, *Eur. Phys. J. C.* **74**, 3076 (2014), [arXiv:1407.0558 \[hep-ex\]](#).
24. G. Aad *et al.* [ATLAS], Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, *Phys. Rev. D.* **91**, 012006 (2015), [arXiv:1408.5191 \[hep-ex\]](#).
25. S. Chatrchyan *et al.* [CMS], Measurement of the properties of a Higgs boson in the four-lepton final state, *Phys. Rev. D.* **89**, 092007 (2014), [arXiv:1312.5353 \[hep-ex\]](#).
26. G. Aad *et al.* [ATLAS], Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector, *Phys. Rev. D.* **92**, 012006 (2015), [arXiv:1412.2641 \[hep-ex\]](#).

27. S. Chatrchyan *et al.* [CMS], Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states, *J. High Energy Phys.* **01**, 096 (2014), [arXiv:1312.1129 \[hep-ex\]](#).
28. G. Aad *et al.* [ATLAS], Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, *J. High Energy Phys.* **04**, 117 (2015), [arXiv:1501.04943 \[hep-ex\]](#).
29. S. Chatrchyan *et al.* [CMS], Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons, *J. High Energy Phys.* **05**, 104 (2014), [arXiv:1401.5041 \[hep-ex\]](#).
30. G. Aad *et al.* [ATLAS], Search for the Standard Model Higgs boson produced by vector-boson fusion in 8 TeV pp collisions and decaying to bottom quarks with the ATLAS detector, Submitted to *J. High Energy Phys.* (2016), [arXiv:1606.02181 \[hep-ex\]](#).
31. V. Khachatryan *et al.* [CMS], Search for the standard model Higgs boson produced through vector boson fusion and decaying to $b\bar{b}$, *Phys. Rev. D.* **92**, 032008 (2015), [arXiv:1506.01010 \[hep-ex\]](#).
32. G. Aad *et al.* [ATLAS], Study of (W/Z)H production and Higgs boson couplings using $H \rightarrow WW^*$ decays with the ATLAS detector, *J. High Energy Phys.* **08**, 137 (2015), [arXiv:1506.06641 \[hep-ex\]](#).
33. G. Aad *et al.* [ATLAS], Search for the Standard Model Higgs boson produced in association with a vector boson and decaying into a tau pair in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Submitted to *Phys. Rev. D* (2015), [arXiv:1511.08352 \[hep-ex\]](#).
34. G. Aad *et al.* [ATLAS], Search for the $b\bar{b}$ decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector, *J. High Energy Phys.* **01**, 069 (2015), [arXiv:1409.6212 \[hep-ex\]](#).
35. S. Chatrchyan *et al.* [CMS], Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks, *Phys. Rev. D.* **89**, 012003 (2014), [arXiv:1310.3687 \[hep-ex\]](#).
36. G. Aad *et al.* [ATLAS], Search for the associated production of the Higgs boson with a top quark pair in multilepton final states with the ATLAS detector, *Phys. Lett. B.* **749**, 519 (2015), [arXiv:1506.05988 \[hep-ex\]](#).
37. V. Khachatryan *et al.* [CMS], Search for the associated production of the Higgs boson with a top-quark pair, *J. High Energy Phys.* **09**, 087 (2014), [arXiv:1408.1682 \[hep-ex\]](#). [Erratum: *ibid.* **10**, 106 (2014)].
38. G. Aad *et al.* [ATLAS], Search for the Standard Model Higgs boson decaying into $b\bar{b}$ produced in association with top quarks decaying hadronically in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Submitted to *J. High Energy Phys.* (2016), [arXiv:1604.03812 \[hep-ex\]](#).
39. G. Aad *et al.* [ATLAS], Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C.* **75**, 349 (2015), [arXiv:1503.05066 \[hep-ex\]](#).
40. G. Aad *et al.* [ATLAS], Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector, *Phys. Lett. B.* **738**, 68 (2014), [arXiv:1406.7663 \[hep-ex\]](#).
41. V. Khachatryan *et al.* [CMS], Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC, *Phys. Lett. B.* **744**, 184 (2015), [arXiv:1410.6679 \[hep-ex\]](#).
42. S. Chatrchyan *et al.* [CMS], Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *Phys. Lett. B.* **726**, 587 (2013), [arXiv:1307.5515 \[hep-ex\]](#).

43. G. Aad *et al.* [ATLAS], Search for Higgs boson decays to a photon and a Z boson in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector, *Phys. Lett. B.* **732**, 8 (2014), [arXiv:1402.3051 \[hep-ex\]](#).
44. V. Khachatryan *et al.* [CMS], Search for a Higgs boson decaying into $\gamma^*\gamma \rightarrow \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Lett. B.* **753**, 341 (2016), [arXiv:1507.03031 \[hep-ex\]](#).
45. G. Aad *et al.* [ATLAS], Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector, *Phys. Rev. Lett.* **114**, 121801 (2015), [arXiv:1501.03276 \[hep-ex\]](#).
46. S. Chatrchyan *et al.* [CMS], Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes, *Eur. Phys. J. C.* **74**, 2980 (2014), [arXiv:1404.1344 \[hep-ex\]](#).
47. G. Aad *et al.* [ATLAS], Search for invisible decays of a Higgs boson using vector-boson fusion in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *J. High Energy Phys.* **01**, 172 (2016), [arXiv:1508.07869 \[hep-ex\]](#).
48. V. Khachatryan *et al.* [CMS], Search for Lepton-Flavour-Violating Decays of the Higgs Boson, *Phys. Lett. B.* **749**, 337 (2015), [arXiv:1502.07400 \[hep-ex\]](#).
49. G. Aad *et al.* [ATLAS], Search for lepton-flavour-violating decays of the Higgs and Z bosons with the ATLAS detector, Submitted to *Eur. Phys. J. C* (2016), [arXiv:1604.07730 \[hep-ex\]](#).
50. LEP Electroweak Working Group, Tevatron Electroweak Working Group, and SLD Electroweak and Heavy Flavour Groups [ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD], Precision electroweak measurements and constraints on the standard model (2010), [arXiv:1012.2367 \[hep-ex\]](#).
51. D. Bardin *et al.*, Electroweak working group report (1997), [arXiv:hep-ph/9709229 \[hep-ph\]](#).
52. M. Baak, J. Cúth, J. Haller, A. Hoecker, R. Kogler, K. Mönig, M. Schott, and J. Stelzer [Gfitter Group], The global electroweak fit at NNLO and prospects for the LHC and ILC, *Eur. Phys. J. C.* **74**, 3046 (2014), [arXiv:1407.3792 \[hep-ph\]](#).
53. V. Khachatryan *et al.* [CMS], Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, *JINST* **10**, P08010 (2015), [arXiv:1502.02702 \[physics.ins-det\]](#).
54. V. Khachatryan *et al.* [CMS], Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, *JINST* **10**, P06005 (2015), [arXiv:1502.02701 \[physics.ins-det\]](#).
55. G. Aad *et al.* [ATLAS], Constraints on the off-shell Higgs boson signal strength in the high-mass ZZ and WW final states with the ATLAS detector, *Eur. Phys. J. C.* **75**, 335 (2015), [arXiv:1503.01060 \[hep-ex\]](#).
56. V. Khachatryan *et al.* [CMS], Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width, (2016), Submitted to *J. High Energy Phys.*, [arXiv:1605.02329 \[hep-ex\]](#).
57. V. Khachatryan *et al.* [CMS], Limits on the Higgs boson lifetime and width from its decay to four charged leptons, *Phys. Rev. D.* **92**, 072010 (2015), [arXiv:1507.06656 \[hep-ex\]](#).
58. D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, Higgs boson production at the LHC: transverse momentum resummation effects in the $H \rightarrow 2\gamma$, $H \rightarrow WW \rightarrow \nu\bar{\nu}\nu$ and $H \rightarrow ZZ \rightarrow 4l$ decay modes, *J. High Energy Phys.* **06**, 132 (2012), [arXiv:1203.6321 \[hep-ph\]](#).
59. K. Hamilton, P. Nason, E. Re, and G. Zanderighi, NNLOPS simulation of Higgs boson production, *J. High Energy Phys.* **10**, 222 (2013), [arXiv:1309.0017 \[hep-ph\]](#).

60. L. Landau, On the angular momentum of a two-photon system, *Dokl. Akad. Nauk Ser. Fiz.* **60**, 207 (1948).
61. C.-N. Yang, Selection rules for the dematerialization of a particle into two photons, *Phys. Rev.* **77**, 242 (1950).
62. A. L. Read, Presentation of search results: The CL(s) technique, *J. Phys. G.* **28**, 2693 (2002).
63. J. R. Andersen *et al.* [LHC Higgs Cross Section Working Group], Handbook of LHC Higgs cross sections: 3. Higgs properties, (2013), [arXiv:1307.1347 \[hep-ph\]](#).
64. G. Aad *et al.* [ATLAS], Test of CP Invariance in vector-boson fusion production of the Higgs boson using the optimal observable method in the ditau decay channel with the ATLAS detector, Submitted to *Eur. Phys. J. C* (2016), [arXiv:1602.04516 \[hep-ex\]](#).
65. V. Khachatryan *et al.* [CMS], Combined search for anomalous pseudoscalar HVV couplings in VH production and H to VV decay, Accepted by *Phys. Lett. B* (2016), [arXiv:1602.04305 \[hep-ex\]](#).
66. G. Aad *et al.* [ATLAS], Constraints on non-Standard Model Higgs boson interactions in an effective Lagrangian using differential cross sections measured in the $H \rightarrow \gamma\gamma$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Lett. B.* **753**, 69 (2016), [arXiv:1508.02507 \[hep-ex\]](#).
67. A. David, J. Heikkilä, and G. Petrucciani, Searching for degenerate Higgs bosons, *Eur. Phys. J. C.* **75**, 49 (2015), [arXiv:1409.6132 \[hep-ph\]](#).
68. A. David, A. Denner, M. Dührssen, M. Grazzini, C. Grojean, G. Passarino, M. Schmacher, M. Spira, G. Weiglein, and M. Zanetti [LHC Higgs Cross Section Working Group], LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle, (2012), [arXiv:1209.0040 \[hep-ph\]](#).
69. M. Farina, C. Grojean, F. Maltoni, E. Salvioni, and A. Thamm, Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson, *J. High Energy Phys.* **05**, 022 (2013), [arXiv:1211.3736 \[hep-ph\]](#).
70. G. Aad *et al.* [ATLAS], Search for $H \rightarrow \gamma\gamma$ produced in association with top quarks and constraints on the Yukawa coupling between the top quark and the Higgs boson using data taken at 7 TeV and 8 TeV with the ATLAS detector, *Phys. Lett. B.* **740**, 222 (2015), [arXiv:1409.3122 \[hep-ex\]](#).
71. G. Aad *et al.* [ATLAS], Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment, *Eur. Phys. J. C.* **76**, 6 (2016), [arXiv:1507.04548 \[hep-ex\]](#).
72. V. Khachatryan *et al.* [CMS], Search for the Associated Production of a Higgs Boson with a Single Top Quark in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV, Submitted to *J. High Energy Phys.* (2015), [arXiv:1509.08159 \[hep-ex\]](#).
73. C. Englert, M. McCullough, and M. Spannowsky, Gluon-initiated associated production boosts Higgs physics, *Phys. Rev. D.* **89**, 013013 (2014), [arXiv:1310.4828 \[hep-ph\]](#).
74. J. Ellis and T. You, Updated global analysis of Higgs couplings, *J. High Energy Phys.* **06**, 103 (2013), [arXiv:1303.3879 \[hep-ph\]](#).