Measuresments 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

The ATLAS Collaboration

Abstract

Combined analyses of the Higgs boson production and decay rates as well as its coupling strengths to vector bosons and fermions are presented. Included in the combinations are the results of the decay modes $H \rightarrow \gamma\gamma$, $ZZ^*$, $WW^*$, $Z\gamma$, $b\bar{b}$, $\tau\tau$ and $\mu\mu$, and the constraints on the associated production with a pair of top quarks and on the off-shell coupling strengths of the Higgs boson. The results are based on the LHC proton-proton collision datasets, with integrated luminosities of up to 4.7 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV, recorded by the ATLAS detector in 2011 and 2012. Combining all production modes and decay channels, the measured signal yield, normalised to the Standard Model expectation, is $1.18 \pm 0.10 \pm 0.07^{+0.08}_{-0.07}$, where the first error reflects the statistical uncertainty and the second and third errors reflect respectively the experimental and theoretical systematic uncertainties. Strong evidence is found for the vector boson fusion process with a significance of $4.3\sigma$. The observed Higgs boson production and decay rates are interpreted in a leading order coupling framework, exploring a wide range of benchmark coupling models both with and without assumptions on the Higgs boson width and assumption on the SM particle content in loop processes. With the assumption of unified couplings to up-type fermions, down-type fermions and the $W/Z$ boson respectively, strong evidence for Higgs boson couplings to down-type fermions is found with a significance of $4.5\sigma$. Generic Higgs boson coupling models that allow to measure coupling strengths to $\mu$, $\tau$ leptons, $b$, $t$ quarks and $W$, $Z$ bosons, or ratios of these coupling strengths, are presented. The observed data are found to be compatible with the SM expectations for a Higgs boson at a mass of 125.36 GeV for all models considered.

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1. Introduction

In 2012, the ATLAS and CMS Collaborations at the Large Hadron Collider (LHC) reported the observation of a new particle at a mass of approximately 125 GeV [1, 2]. The discovery made in the search of the Standard Model (SM) Higgs boson ($H$), is a milestone in the quest to understand electroweak symmetry breaking (EWSB). Within the SM, EWSB is achieved through the Brout-Englert-Higgs mechanism [3–8] which predicts the existence of a neutral scalar particle, commonly known as the Higgs boson [5]. While the SM does not predict the value of its mass ($m_H$), the production cross sections and decay branching ratios (BR) of the Higgs boson can be precisely calculated once the mass is known. Therefore, precision measurements of the properties of the new particle are critical in ascertaining whether the newly discovered particle is fully responsible for EWSB and whether there are potential deviations from SM predictions.

In the SM, Higgs boson production at the LHC is dominated by the gluon fusion process $gg \to H$ (ggF), followed by the vector boson fusion process $q q' \to q q' H$ (VBF). Associated productions with a $W$ boson $q q' \to W H (WH)$, a $Z$ boson $q q / g g \to Z H (ZH)$ or with a pair of top quarks $q q / g g \to t \bar{t} H (t t H)$ have sizable contributions as well. The $W H$ and $Z H$ productions are collectively referred to as the $V H$ process. Contributions are also expected from $b \bar{b} \to H (b \bar{b} H)$ and the production in association with a single top quark ($t H$). The latter proceeds through either the $q b \to t H q'$ or $g b \to W t H$ process. With the present dataset, the LHC is expected to be mostly sensitive to Higgs boson decays of $H \to \gamma \gamma$, $ZZ^*$, $WW^*$, $\tau \tau$ and $b \bar{b}$. Together they account for approximately 88% of all decays of a Higgs boson at $m_H \sim 125$ GeV in the SM. The state-of-the-art theoretical calculations of the Higgs boson production cross sections and its decay branching ratios have been compiled in Refs. [9–11] and are summarised in Table 1.

The discovery was made through the analyses of the bosonic decay modes of the Higgs boson in $H \to \gamma \gamma$, $H \to ZZ^* \rightarrow 4 \ell$ and $H \to WW^* \rightarrow \ell \nu \ell \nu$ ($\ell = e, \mu$) events. Since the discovery, these analyses have been improved and updated with more data [12–14]. The $H \to WW^* \rightarrow \ell \nu \ell \nu$ analysis has been supplemented with a dedicated $VH$ analysis targeting $H \to WW^*$ [15]. The ATLAS Collaboration has measured the Higgs boson mass from the $H \to \gamma \gamma$ and $H \to ZZ^* \rightarrow 4 \ell$ decays to be $m_H = 125.36 \pm 0.41$ GeV [16], reported results in the $H \to \tau \tau$ [17] and $H \to b \bar{b}$ [18] fermionic decay modes, and published upper limits on the rare decays of $H \to Z \gamma$ [19] and $H \to \mu \mu$ [20]. Furthermore, constraints have been set on the $t t H$ production rate [21–23] and on the off-shell coupling strengths of the Higgs boson [24]. These results are based on the full proton-proton collision data with integrated luminosities of up to 4.7 fb$^{-1}$ at a centre-of-mass energy ($\sqrt{s}$) of 7 TeV recorded in 2011 and 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV recorded in 2012 by the ATLAS detector at the LHC. A detailed description of the ATLAS detector can be found in Ref. [25].

This paper presents the combined results of the analyses mentioned above. These analyses are designed for maximum sensitivities to the Higgs boson production from different processes, exploiting in particular the differences in kinematics through categorisation of the selected events. Thus the yields of different Higgs boson production processes and decays can be extracted. The Higgs boson coupling strengths to SM vector bosons and fermions in different benchmark models are probed for the measured Higgs boson mass of $m_H = 125.36$ GeV. The ATLAS Collaboration has previously published combined studies of Higgs boson production and decay rates [27] and of spin-parity properties [28] using diboson final states. The results are found to be consistent with expectations from the SM Higgs boson. Compared with the previous publication, the current results are based on the improved analysis sensitivities and the addition of information on other decay modes. Similar combination has been published by the CMS Collaboration [29].
The paper is organised as follows. Section 2 briefly summarises the individual analyses that are included in the combinations and Section 3 outlines the statistical method and the treatment of systematic uncertainties used in the combinations. In Section 4, the measured Higgs boson yields are compared with the SM predictions for different production processes and decay modes. In Section 5, the coupling strengths of the Higgs boson are tested through fits to the observed data. These studies probe possible deviations from the SM predictions under various assumptions, motivated in many cases by beyond the SM (BSM) physics scenarios. An upper limit on the branching ratio to invisible or undetected decay modes of the Higgs boson is also set. Finally, a brief summary is presented in Section 6.

2. Input analyses to the combinations

The combinations take inputs from the analyses of $H \rightarrow \gamma\gamma$, $ZZ^*$, $WW^*$, $\tau\tau$, $b\bar{b}$, $\mu\mu$ and $Z\gamma$ Higgs boson decay modes, and of the constraints on the $ttH$ and off-shell Higgs boson productions. These analyses and changes made for the combinations are briefly discussed in this section. Table 2 gives an overview of the analyses and their main results, as published. An essential feature of these analyses is the extensive application of exclusive categorisation, i.e., classifying candidate events based on the expected kinematics of the different Higgs boson production processes. The categorisation not only improves the analysis sensitivity, but also allows for the discrimination among different production processes. Figure 1 summarises the signal-strength measurements of different production processes that are used as inputs to the combinations. The ATLAS Collaboration has also performed a search for the rare $H \rightarrow J/\psi\gamma$ decay [30] which has the potential to constrain the Higgs boson coupling strength to the charm quark. However, the current result does not add sensitivity and is therefore omitted from the combinations. Furthermore, the inclusion of the results from direct searches for Higgs boson decays to invisible particles, such as that reported in Ref. [31], is beyond the scope of the combinations presented in this paper.

Throughout this paper, the signal-strength parameter $\mu$ is defined as the ratio between the measured Higgs

Table 1: SM predictions of the Higgs boson production cross sections and decay branching ratios and their uncertainties for $m_H = 125.36$ GeV, obtained by linear interpolations from those at 125.3 and 125.4 GeV from Ref. [11] except for the $tH$ production cross section which is obtained from Ref. [26]. The uncertainties on the cross sections are the quadratic sum of the uncertainties on the QCD scales, parton distribution functions and $\alpha_s$. The uncertainty on the $tH$ cross section is calculated following the procedure of Ref. [11].

<table>
<thead>
<tr>
<th>Production process</th>
<th>Cross section (pb) $\sqrt{s} = 7$ TeV</th>
<th>Cross section (pb) $\sqrt{s} = 8$ TeV</th>
<th>Decay channel</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>15.0 ± 1.6</td>
<td>19.2 ± 2.0</td>
<td>$H \rightarrow bb$</td>
<td>57.1 ± 1.9</td>
</tr>
<tr>
<td>$VBF$</td>
<td>1.22 ± 0.03</td>
<td>1.57 ± 0.04</td>
<td>$H \rightarrow gg$</td>
<td>8.53 ± 0.85</td>
</tr>
<tr>
<td>$WH$</td>
<td>0.573 ± 0.016</td>
<td>0.698 ± 0.018</td>
<td>$H \rightarrow \tau\tau$</td>
<td>6.26 ± 0.35</td>
</tr>
<tr>
<td>$ZH$</td>
<td>0.332 ± 0.013</td>
<td>0.412 ± 0.013</td>
<td>$H \rightarrow c\bar{c}$</td>
<td>2.88 ± 0.35</td>
</tr>
<tr>
<td>$bbH$</td>
<td>0.155 ± 0.021</td>
<td>0.202 ± 0.028</td>
<td>$H \rightarrow ZZ^*$</td>
<td>2.73 ± 0.11</td>
</tr>
<tr>
<td>$ttH$</td>
<td>0.086 ± 0.009</td>
<td>0.128 ± 0.014</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.228 ± 0.011</td>
</tr>
<tr>
<td>$tH$</td>
<td>0.012 ± 0.001</td>
<td>0.018 ± 0.001</td>
<td>$H \rightarrow Z\gamma$</td>
<td>0.157 ± 0.014</td>
</tr>
<tr>
<td>Total</td>
<td>17.4 ± 1.6</td>
<td>22.3 ± 2.0</td>
<td>$H \rightarrow \mu\mu$</td>
<td>0.022 ± 0.001</td>
</tr>
</tbody>
</table>
Table 2: Overview of the individual analyses that are included in the combinations described in this paper. The signal strengths, the statistical significances of a Higgs boson signal, or the 95% CL upper limits on the Higgs boson production rates or properties are also shown wherever appropriate. A range is quoted for the upper limit on the off-shell signal strength, depending on the assumption of the continuum $gg \to WW/ZZ$ cross section. These results are taken directly from individual publications. Results of the on-shell analyses are quoted for $m_H = 125.36$ GeV except that $m_H = 125.5$ GeV is assumed for the $H \to Z\gamma$ and $H \to \mu\mu$ analyses and that $m_H = 125$ GeV is used for the $ttH$ searches with $H \to b\bar{b}$ and $ttH \to$ multileptons. The luminosity used for the $\sqrt{s} = 7$ TeV $VH \to Vb\bar{b}$ analysis differs slightly from the other analyses because a previous version of the luminosity calibration was applied.

The significance is given in units of standard deviations ($\sigma$). The numbers in parentheses are the expected values from the SM Higgs boson. The $ttH$ analysis in the $H \to \gamma\gamma$ decay is part of the $H \to \gamma\gamma$ analysis and is also included separately under the $ttH$ production for completeness. The checkmark (✓) indicates whether the analysis is performed for the respective $\sqrt{s} = 7$ and 8 TeV dataset.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Categorisation or final states</th>
<th>Strength</th>
<th>Significance [$\sigma$]</th>
<th>$\int L dt$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$ [12]</td>
<td>1.17 ± 0.27</td>
<td>5.2 (4.6)</td>
<td>✓ ✓</td>
<td>4.5 20.3</td>
</tr>
<tr>
<td>$ttH$: lepton, hadronic</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$VH$: one-lepton, dilepton, $E_{T}^{miss}$, hadronic</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>VBF: tight, loose</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>ggF: 4 $p_T$ categories</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$H \to ZZ^* \to 4\ell$ [13]</td>
<td>1.44$^{+0.40}_{-0.33}$</td>
<td>8.1 (6.2)</td>
<td>✓ ✓</td>
<td>4.5 20.3</td>
</tr>
<tr>
<td>VBF</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$VH$: hadronic, lepton</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>ggF</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$H \to WW^*$ [14, 15]</td>
<td>1.16$^{+0.24}_{-0.21}$</td>
<td>6.5 (5.9)</td>
<td>✓ ✓</td>
<td>4.5 20.3</td>
</tr>
<tr>
<td>ggF: (0-jet, 1-jet) $\otimes (ee + \mu\mu, e\mu)$</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>VBF: $\geq$ 2-jet and $e\mu$</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$VH$: opposite-charge dilepton, three-lepton, four-lepton</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$VH$: same-charge dilepton</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$H \to \tau\tau$ [17]</td>
<td>1.43$^{+0.43}_{-0.37}$</td>
<td>4.5 (3.4)</td>
<td>✓ ✓</td>
<td>4.5 20.3</td>
</tr>
<tr>
<td>Boosted: $T_{lepT_{lep}}, T_{lepT_{had}}, T_{hadT_{had}}$</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>VBF: $T_{lepT_{lep}}, T_{lepT_{had}}, T_{hadT_{had}}$</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$VH \to Vb\bar{b}$ [18]</td>
<td>0.52 ± 0.40</td>
<td>1.4 (2.6)</td>
<td>✓ ✓</td>
<td>4.7 20.3</td>
</tr>
<tr>
<td>0$\ell$ ($ZH \to vvbb$): $N_{jet} = 2, 3, N_{btag} = 1, 2, p_T^\gamma &gt;$ and $&lt; 120$ GeV</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>1$\ell$ ($WH \to tvbb$): $N'<em>{jet} = 2, 3, N</em>{btag} = 1, 2, p_T^\gamma &gt;$ and $&lt; 120$ GeV</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>2$\ell$ ($ZH \to t\bar{t}bb$): $N_{jet} = 2, 3, N_{btag} = 1, 2, p_T^\gamma &gt;$ and $&lt; 120$ GeV</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
</tbody>
</table>

95% CL limit

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Categorisation or final states</th>
<th>Strength</th>
<th>Significance [$\sigma$]</th>
<th>$\int L dt$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to Z\gamma$ [19]</td>
<td>$\mu &lt; 11$ (9)</td>
<td>4.5 20.3</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>10 categories based on $\Delta_{T}Z\gamma$ and $p_T$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \to \mu\mu$ [20]</td>
<td>$\mu &lt; 7.0$ (7.2)</td>
<td>4.5 20.3</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>VBF and 6 other categories based on $\eta_\mu$ and $p_T^{\mu\mu}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ttH$ production [21–23]</td>
<td>4.5 20.3</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$H \to bb$: single-lepton, dilepton</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$ttH \to$ multileptons: categories on lepton multiplicity</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
<tr>
<td>$H \to \gamma\gamma$: leptonic, hadronic</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
<td></td>
</tr>
</tbody>
</table>

Off-shell $H^*$ production [24] $\mu < 5.1 - 8.6$ (6.7 - 11.0) 20.3

$H^* \to ZZ \to 4\ell$
$H^* \to ZZ \to 2\ell 2\nu$
$H^* \to WW \to e\nu\mu

4
### Input measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Overall</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.17^{+0.20}_{-0.13}$</td>
<td>$\mu = 1.32^{+1.00}_{-0.76}$</td>
<td>$\mu = 1.0^{+1.20}_{-0.76}$</td>
<td>$\mu = 0.1^{+0.40}_{-0.0}$</td>
<td>$\mu = 0.33^{+0.40}_{-0.30}$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\mu = 1.44^{+1.00}_{-0.76}$</td>
<td>$\mu = 0.98^{+0.40}_{-0.30}$</td>
<td>$\mu = 1.23^{+0.40}_{-0.30}$</td>
<td>$\mu = 0.21^{+0.24}_{-0.16}$</td>
<td>$\mu = 0.21^{+0.24}_{-0.16}$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$\mu = 1.16^{+0.60}_{-0.40}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 3.0^{+3.0}_{-3.0}$</td>
<td>$\mu = 0.37^{+0.43}_{-0.37}$</td>
<td>$\mu = 1.2^{+1.2}_{-1.2}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>$\mu = 1.43^{+1.00}_{-0.76}$</td>
<td>$\mu = 0.98^{+0.40}_{-0.30}$</td>
<td>$\mu = 1.23^{+0.40}_{-0.30}$</td>
<td>$\mu = 0.37^{+0.43}_{-0.37}$</td>
<td>$\mu = 1.2^{+1.2}_{-1.2}$</td>
</tr>
<tr>
<td>$H \rightarrow VV$</td>
<td>$\mu = -0.7^{+0.7}_{-0.7}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 0.6^{+0.0}_{-0.0}$</td>
<td>$\mu = 0.40^{+0.40}_{-0.40}$</td>
<td>$\mu = 0.40^{+0.40}_{-0.40}$</td>
</tr>
<tr>
<td>$H \rightarrow t\bar{t}$</td>
<td>$\mu = 2.7^{+1.7}_{-1.7}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 2.1^{+0.1}_{-0.1}$</td>
<td>$\mu = 1.3^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$\mu = 1.5^{+1.5}_{-1.5}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 1^{+1}_{-1}$</td>
<td>$\mu = 2.1^{+0.1}_{-0.1}$</td>
<td>$\mu = 1.3^{+0.3}_{-0.3}$</td>
</tr>
</tbody>
</table>

#### Figure 1: Summary of the signal-strength measurements, as published, from individual analyses that are inputs to the combinations. The Higgs boson mass column indicates the $m_H$ value at which the result is quoted. The overall signal strength of each analysis (black) is the combined result of the measurements for different production processes (blue). The error bars represent $\pm 1\sigma$ total uncertainties, combining statistical and systematic contributions. The green shaded bands indicate the uncertainty of the overall signal strength of its respective analysis. The combined signal strength of the $H \rightarrow \gamma\gamma$ analysis also includes the $ttH$ contribution which is listed separately under the $ttH$ production.

The boson yield and its SM expectation:

$$\mu = \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}}.$$  \hspace{1cm} (1)

For a specific production process $i$ and decay channel $f$, i.e., $i \rightarrow H \rightarrow f$, the signal-strength parameter is labelled as $\mu_i^f$.

Leptons ($\ell$) refer to electrons or muons unless specified otherwise; the symbols $\tau_{\text{lep}}$ and $\tau_{\text{had}}$ refer to tau leptons identified through their decays to leptons or hadrons; and variables $p_T$, $E_T$ and $E_T^{\text{miss}}$ refer...
to transverse momentum, transverse energy and missing transverse momentum, respectively. Notation
indicating particle charges or antiparticles are generally omitted.

The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction
point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP
to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in
the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in
terms of the polar angle \(\theta\) as \(\eta = -\ln \tan(\theta/2)\).

2.1. \(H \to \gamma\gamma\)

In the \(H \to \gamma\gamma\) analysis, described in detail in Ref. [12], the Higgs boson signal is measured in events with
at least two isolated and well identified photon candidates. The leading and subleading photon candidates
are required to have \(E_T/m_{\gamma\gamma} > 0.35\) and 0.25, respectively, where \(m_{\gamma\gamma}\) is the invariant mass of the two
selected photons. The diphoton candidate events are grouped into twelve exclusive categories separately
for the \(\sqrt{s} = 7\) and 8 TeV datasets: the order of categorisation is chosen to give precedence to production
modes with the most distinct signatures. Each category is optimised by adjusting the event selection
criteria to minimise the expected uncertainty on the signal yield of the targeted production mode.

The first two categories are designed for \(ttH\) production based on the topology of leptonic and hadronic
decays of the associated \(t\bar{t}\) pair. They are described in Section 2.8 on the \(ttH\) production. The next
four categories are optimised for \(VH\) production, targeting one-lepton, dilepton, \(E^{\text{miss}}_T\), and hadronic
signatures of both \(W\) and \(Z\) boson decays. Events from VBF production are identified by requiring
two well-separated and high \(p_T\) jets and little hadronic activity between them. A boosted decision tree
(BDT) [32,33] is employed to maximise the signal and background separation in this category. Events are
sorted into two categories with different VBF purities according to the output value of the BDT. Finally,
the remaining events are separated into four categories based on the pseudorapidities of the photons and
the \(p_T\) of the diphoton system [12], the diphoton momentum transverse to its thrust axis in the transverse
plane.

For most of the categories, the background is composed of a mixture of \(\gamma\gamma\), \(\gamma\)-jet and jet-jet events where
one or two jets are misidentified as photons. In particular the \(\gamma\gamma\) background is dominant and irreducible.
The Higgs boson signal is extracted from maximum likelihood fits of a narrow resonance plus continuum
background models to unbinned diphoton invariant mass distributions observed in the different event
categories. In the fit, the signal is modelled by the sum of a Crystal Ball function [34] and a smaller
but wider Gaussian component while the backgrounds are modelled by category-dependent exponential
functions of first- or second-order polynomials.

2.2. \(H \to ZZ^* \to 4\ell\)

The \(H \to ZZ^* \to 4\ell\) analysis, described in detail in Ref. [13], has a high signal-to-background ratio,
which is about two for each of the four final states considered: \(4\mu, 2e2\mu, 2\mu2e\), and \(4e\), where the
first lepton pair has an invariant mass closest to the \(Z\) boson mass. The analysis selects Higgs boson
candidates by requiring two pairs of isolated, same flavour and opposite charge leptons with one of the
two pairs having a dilepton invariant mass in the range of 50 and 106 GeV.
To measure the rates of different production mechanisms, each $H \rightarrow ZZ^* \rightarrow 4\ell$ candidate is assigned to one of four categories depending on event characteristics beyond the four lepton selection. The VBF category consists of candidates with two additional jets of dijet mass $m_{jj} > 130$ GeV. The events failing this selection are considered for the $VH$-hadronic category, where the dijet mass is required to be $40 < m_{jj} < 130$ GeV. Events failing the $VH$-hadronic category criteria are considered for the $VH$-leptonic category with the requirement of an additional lepton. Finally, the remaining events are assigned to the $ggF$ category. The separation of VBF and $VH$ production from the dominant $ggF$ production mode is improved by exploiting two BDT discriminants trained on the jet kinematics, one for the VBF and the other for the $VH$-hadronic categories. A third BDT discriminant based on the four lepton kinematics is used to improve the separation between the $ggF$ signal and the main background.

The largest background comes from continuum $ZZ^*$ production and is estimated using simulation normalised to the SM next-to-leading-order cross-section calculation. For the four-lepton events with an invariant mass, $m_{4\ell}$, below about 160 GeV, there are also important background contributions from $Z+\text{jets}$ and $t\bar{t}$ production with two prompt leptons, where the additional charged lepton candidates arise from decays of hadrons with $b$- or $c$-quark content, from photon conversions or from misidentified jets. The $Z+\text{jets}$ and $t\bar{t}$ backgrounds are reduced by requirements on the lepton identification, isolation in the inner tracking detector and electromagnetic calorimeter, and on the impact parameter in the transverse plane. The residual $Z+\text{jets}$ and $t\bar{t}$ background is estimated with data-driven methods.

For each category, the signal is extracted from a maximum likelihood fit to either the 1D $m_{4\ell}$ distribution ($VH$ categories) or the combined 2D distributions of $m_{4\ell}$ and a BDT discriminant ($ggF$ and VBF categories). The four-lepton mass range of $110 < m_{4\ell} < 140$ GeV is included in the fits.

### 2.3. $H \rightarrow WW^*$

Analyses targeting the $ggF$, VBF, and $VH$ production modes [14, 15] are performed for the $H \rightarrow WW^*$ decay channel. The $ggF$ and VBF production processes are explored through the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay while the $VH$ process is studied in final states with two or more leptons.

The analysis of the $ggF$ and VBF production processes [14] selects the signal candidate events by requiring two oppositely charged leptons. Candidates are categorised according to the number of jets ($N_{\text{jet}}$) and lepton flavours. The $N_{\text{jet}}$ categorisation separates the large background of the top-quark production from the $ggF$ signal while the categorisation by lepton flavours isolates the most challenging Drell-Yan background in the same flavour categories. The categories targeting the $ggF$ production include $N_{\text{jet}} = 0$, 1 and $\geq 2$ and are further divided into the same- and different-flavour leptons for $N_{\text{jet}} = 0$, 1. Only the different-flavour leptons are considered for $N_{\text{jet}} \geq 2$. The category targeting the VBF analysis requires $N_{\text{jet}} \geq 2$ with same- or different-flavour leptons. The primary background processes are $WW$, top quark ($t\bar{t}$ and $Wt$), $W+\text{jets}$, Drell-Yan, and diboson ($WZ$, $W\gamma$, $W\gamma^*$, and $ZZ$) production. Most of the background contributions are estimated using data. For the $ggF$ categories, the final signal region is selected by $m_{\ell\ell} < 55$ GeV and $\Delta\phi_{\ell\ell} < 1.8$ and the signal is extracted through a combined fit to the transverse mass distributions of the dilepton plus $E_T^{\text{miss}}$ system. For the VBF categories, a BDT combining information such as rapidity separation and mass of the two leading jets and the dilepton angular separation, is used as the final discriminant, from which the signal is extracted.

The $VH$ analysis [15] is optimised for four final states of different lepton multiplicities: opposite-charge dileptons, same-charge dileptons, three- and four-leptons. Most final states are required to have $E_T^{\text{miss}}$ and events with a $b$-tagged jet are vetoed. Dilepton final states target $VH \rightarrow VWW^*$ production with
two bosons decaying leptonically and the other hadronically. The opposite-charge dilepton final state
selects events with two or more jets, with the value of $m_{jj}$ required to be close to the $W$ and $Z$ boson
masses. Similar to the ggF $N_{jet} \geq 2$ category, the dominant background is from top quark production.
The same-charge dilepton category accepts events with either one or two jets. The dominant backgrounds
are from $WZ$, $W\gamma^{(*)}$, and $W+\text{jets}$ production. The three-lepton final state targets $WH \rightarrow WWW^{*}$ and has
the highest sensitivity of the four final states. The three leptons are required to have a net charge of $\pm 1$
and the event can have at most one jet. The dominant background process is the $WZ$ production and is
reduced with a $Z \rightarrow \ell\ell$ veto. The four-lepton category is designed to accept events from $ZH$ production.
The net charge of the leptons is required to be zero and at least one pair of leptons is required to have
the same flavour, opposite sign, and an invariant mass close to $m_{Z}$. The dominant background is SM
$ZZ^{*}$ production. In the three-lepton category, the signal yield is extracted through fits to distributions of
a BDT or the minimum $\Delta R$ between opposite-charged leptons depending on lepton flavours. For other
categories, the event yields are used, without exploiting information on the shapes of distributions.

2.4. $H \rightarrow \tau\tau$

In the $H \rightarrow \tau\tau$ analysis [17] both leptonic ($\tau_{lep}$) and hadronic ($\tau_{had}$) decays of the tau lepton are con-
sidered. Three sub-channels ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) are defined by orthogonal requirements on the
number of reconstructed hadronic tau decays and leptons (electrons or muons) in the event$^1$.

Candidate events are divided into two categories, for a total of six signal regions for $\sqrt{s} = 7$ and 8 TeV
data separately. The boosted category targets signal events where the Higgs boson has been produced
with a large boost, primarily from the gluon fusion process, and requires the transverse momentum of the
reconstructed Higgs boson candidate to be greater than 100 GeV. The VBF category contains events with
two jets separated in pseudorapidity and targets signal events produced through the vector boson fusion
process. A separate BDT is then employed in each category and sub-channel to discriminate signal from
background, utilising between five and nine input variables, chosen in order to exploit discriminating
features such as Higgs boson decay properties, event activity, and the VBF topology in the corresponding
category. One of the most important input variables is the mass of the ditau system, which is quite challen-
ging to reconstruct due to the presence of at least two neutrinos in the final state; the Missing Mass
Calculator [35] is used for this purpose.

In all three sub-channels, the most important backgrounds are irreducible $Z \rightarrow \tau\tau$ events, and events
with one or two jets misidentified as tau lepton decay products (primarily from multijet and $W+\text{jets}$
production). To estimate the former, the embedding technique [17] is used, where $Z \rightarrow \mu\mu$ events are
selected in data and the reconstructed muons are replaced by simulated tau lepton decays. Fully data-
driven techniques are used for the estimation of backgrounds from misidentified tau decay products,
while Monte Carlo corrected to data is used for other backgrounds, such as the top quark and $Z \rightarrow \ell\ell$
production.

The signal is extracted by fitting the shape of the BDT discriminant with signal and background templates
simultaneously in all signal regions. The fit also includes dedicated control regions enriched with top
quark, $Z \rightarrow \ell\ell$ and multijet events. These control regions are used to constrain normalisations of the
corresponding backgrounds.

$^1$ For events with two leptons, a requirement on the invariant mass of the ditau system reconstructed via the collinear approx-
imation also ensures orthogonality with the $H \rightarrow WW^{*} \rightarrow \ell\ell\nu\nu$ analysis.
2.5. \( VH \) with \( H \to b\bar{b} \)

The \( H \to b\bar{b} \) decay mode is predicted in the SM to have the largest branching ratio (see Table 1). In spite of this large branching ratio, an inclusive search for \( H \to b\bar{b} \) is not feasible because of the overwhelming background from multijet production. Associated production of a Higgs boson with a vector boson \( V \) (\( W \) or \( Z \)), offers a viable alternative because leptonic decays of the vector boson, \( W \to \ell \nu \), \( Z \to \ell \ell \), and \( Z \to \nu \nu \), can be efficiently used for triggering and background reduction.

The search for associated \( VH \) production with \( H \to b\bar{b} \) \([18]\) is performed for events containing zero, one, or two charged leptons. Contributions from \( W \to \tau \nu \) and \( Z \to \tau \tau \) decays are also included. A \( b \)-tagging algorithm is used to identify jets from \( H \to b\bar{b} \) decays. To improve the sensitivity, the three channels are each split according to the vector-boson transverse momentum, \( p_T^V \), the number of jets, and the number and quality of \( b \)-tagged jets. Topological and kinematic selection criteria are applied within each of the resulting categories. The categories providing most of the sensitivity are those requiring two jets \( b \)-tagged at the 50\% efficiency operating point, and large \( p_T^V \). The categories with low sensitivity are used to constrain the contributions of the dominant background processes.

A binned profile maximum likelihood fit to all categories simultaneously is used to extract the signal yield and the background normalisations. The most significant background sources are \( V+\text{heavy-flavour-jet} \) production and \( t\bar{t} \) production. The normalisations of these backgrounds are fully determined by the likelihood fit. Other significant background sources are single-top-quark and diboson (\( WZ \) and \( ZZ \)) production, with normalisations from theory, as well as multijet events. The shapes of all backgrounds are estimated from simulation, except for the multijet background for which the shape and normalisation are obtained using multijet-enriched control samples.

Two versions of the analysis are performed. In the dijet-mass analysis, the mass of the dijet system of \( b \)-tagged jets is the final discriminating variable used in the statistical analysis. In the multivariate analysis (MVA), which incorporates various kinematic variables in addition to the dijet mass as well as \( b \)-tagging information, the outputs of boosted decision trees provide the final discriminating variable. Since the MVA has higher expected sensitivity, it is chosen as the nominal analysis for the \( \sqrt{s} = 8 \text{ TeV} \) dataset to extract the final results. For the \( \sqrt{s} = 7 \text{ TeV} \) dataset, only a dijet-mass analysis is performed.

2.6. \( H \to Z\gamma \)

The \( H \to Z\gamma \) analysis \([19]\) with \( Z \to \ell\ell \) searches for a narrow peak in the reconstructed \( \ell\ell\gamma \) invariant-mass distribution around 125 GeV over a smooth background. The \( Z+\gamma \) production, \( Z \to \ell\ell\gamma \) radiative decays and \( Z+jets \) events where a jet is misidentified as a photon dominate the background contributions.

The analysis selects two isolated leptons of same flavour and opposite charge and one isolated photon. Due to the kinematics of the decay, low-\( p_T \) thresholds are applied to the leptons and the photon. The invariant mass of the dilepton system should satisfy \( m_{\ell\ell} > m_Z - 10 \text{ GeV} \) and the three-body invariant mass should be consistent with the mass of the Higgs boson. To enhance the sensitivity of the analysis, events are classified into categories with different signal-to-background ratios and invariant-mass resolutions, based on the pseudorapidity difference \( \Delta\eta_{Z\gamma} \) between the photon and the \( Z \) boson and \( p_T \), the component of the Higgs boson candidate \( p_T \) that is orthogonal to the \( Z\gamma \) thrust axis in the transverse plane.
The final discrimination between signal and background events is based on a simultaneous likelihood fit to the $m_{\ell\ell\gamma}$ spectra in each category, separately for the $\sqrt{s} = 7$ and 8 TeV datasets. Similar to the $H \to \gamma\gamma$ analysis (Section 2.1), the signal is modelled with the sum of a Crystal Ball function and a smaller but wider Gaussian component while the backgrounds are modelled with polynomials, or exponentiated polynomials depending on categories.

2.7. $H \to \mu\mu$

The $H \to \mu\mu$ analysis [20] searches for a narrow peak in the dimuon invariant mass $m_{\mu\mu}$ distribution over a smooth background, where the width of the signal is dominated by the experimental resolution. The mass spectrum is dominated by the continuously falling background due to the $Z/\gamma^*$ production, with smaller contributions from top quark and diboson production.

The selected events containing a pair of oppositely charged muons are separated into seven mutually exclusive categories based on the VBF dijet signature, the muon pseudorapidity $\eta_\mu$, and the transverse momentum of the dimuon system $p_{T\mu\mu}$. The events with two or more jets that match selections designed for the VBF process are accepted in the VBF signal region. All other selected events are split up into six categories based on $\eta_\mu$ and $p_{T\mu\mu}$. This categorisation takes advantage of the higher momentum resolution of muons reconstructed in the central part of the detector, and high $p_{T\mu\mu}$ for the expected SM signal.

The $m_{\mu\mu}$ distribution in the 110–160 GeV region is fitted with an analytic signal plus background model separately for the $\sqrt{s} = 7$ and 8 TeV datasets, setting a limit on the dimuon decay of the SM Higgs boson with a mass of 125.5 GeV. In the fit, the signal is modelled as the sum of a Crystal Ball and a Gaussian function in all regions while the backgrounds are modelled using exponentials or polynomials.

2.8. $ttH$ production

Searches for $q\bar{q}/gg \to t\bar{t}H$ production have been performed with three analyses targeting the Higgs boson decays of $H \to b\bar{b}$; $H \to (WW^*, \tau\tau, ZZ^*) \to$ leptons; and $H \to \gamma\gamma$. The search in the $H \to \gamma\gamma$ decay mode uses both $\sqrt{s} = 7$ and 8 TeV data, while the other two use only the $\sqrt{s} = 8$ TeV data.

The search for $ttH$ production with $H \to b\bar{b}$ [21] considers two separate selections optimised for single-lepton and dilepton final states of $t\bar{t}$ decays. In the single-lepton channel, events are required to have one isolated electron or muon and at least four jets. In the dilepton channel, events are required to have two opposite-charged leptons (ee, $\mu\mu$ or $e\mu$) and at least two jets; events consistent with originating from a $Z \to \ell\ell$ decay are rejected. In both cases at least two $b$-tagged jets are required. Candidate events are categorised according to the jet and $b$-jet multiplicities with a total of 9 (6) categories for the single-lepton (dilepton) final states. The background is dominated by $t\bar{t}+\text{jets}$ events, with increasing fractions of $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$ at the higher $b$-jet multiplicities characteristic of signal events. The analysis uses a neural network to discriminate signal from background in the most signal-like categories. Simpler kinematic discriminants are used in background-like categories.

The $ttH$ search with $H \to WW^*, \tau\tau$ and $ZZ^*$ decays [22] exploits several multilepton signatures resulting from leptonic decays of vector bosons and/or the presence of tau leptons. The events are categorised by the number of reconstructed electrons or muons and hadronic tau candidates. The five channels used in this combination are: one lepton with two hadronic tau candidates, two same-charge leptons with zero or one hadronic tau candidates, three leptons, and four leptons. The largest backgrounds to the analysis are
non-prompt leptons, primarily arising from semileptonic $B$-hadron decays in $t\bar{t}$ events; electron charge misreconstruction in events where opposite-sign leptons are produced and the production of $t\bar{t}W$ and $t\bar{t}Z$ ($t\bar{t}V$). The potential signal is determined from the numbers of observed events in data and of the estimated background events.

The $ttH$ search in the $H \to \gamma\gamma$ channel [23] is part of the $H \to \gamma\gamma$ analysis (see Section 2.1) and employs the same diphoton selection. The leptonic as well as fully-hadronic decay signatures of the $t\bar{t}$ system are considered. The leptonic selection requires at least one lepton and one $b$-tagged jet as well as $E_T^{miss}$. In the hadronic selection, different combinations of jet and $b$-tagging multiplicities are applied to improve the signal sensitivity. The small contribution from ggF, VBF and $VH$ productions is estimated from Monte Carlo simulation. The $ttH$ signal is extracted from a fit to the observed diphoton mass distribution.

2.9. Off-shell Higgs boson production

Measurements of the $H^* \to ZZ$ and $H^* \to WW$ final states in the mass range above the $2m_Z$ and $2m_W$ thresholds (off-shell region) provide a unique opportunity to measure the off-shell coupling strengths of the observed Higgs boson, as discussed in Refs. [36–39]. The $ZZ \to 4\ell$, $ZZ \to 2\ell2\nu$ and $WW \to e\nu\mu\nu$ final states of the $\sqrt{s} = 8$ TeV dataset are used in these measurements, detailed in Ref. [24]. Assuming the relevant Higgs boson coupling strengths are independent of the energy scale of the Higgs boson production, a combination with the on-shell measurements can be interpreted as a constraint on the total width of the Higgs boson.

The analysis in the $ZZ \to 4\ell$ final state follows closely the Higgs boson measurements in the same final state, described in Section 2.2, with the same object definitions, event selections and background estimation methods. The off-peak region is defined to include the range $220 < m_{4\ell} < 1000$ GeV. Like the $H \to ZZ^* \to 4\ell$ analysis, the background is dominated by the $q\bar{q}/gg \to ZZ$ production. A matrix element based discriminant [24] is constructed to enhance the $gg \to H^* \to ZZ$ signal and is used in a binned maximum likelihood fit for the final result.

The analysis in the $ZZ \to 2\ell2\nu$ channel follows closely the invisible Higgs boson search in the $ZH$ channel [31], with the same object definitions. As the analysis is performed inclusively in the number of jets in the final states, kinematic cuts are optimised accordingly. SM $ZZ$ and $WZ$ productions are the major backgrounds. The transverse mass ($m_{TZ}$) [24], reconstructed from the momentum of the dilepton system and the missing transverse momentum, is chosen as the discriminating variable. Events in the range of $380 < m_{TZ} < 1000$ GeV are used in a binned maximum likelihood fit for the final result.

The analysis in the $WW \to e\nu\mu\nu$ channel follows closely the Higgs boson measurements in the oppositely charged electron-muon pair final state, described in Section 2.3, with the same object definitions. The analysis is performed inclusively in the number of jets in the final state, and selections are optimised for the off-shell region with revised background estimation methods. Top quark pairs and $WW$ events constitute the major backgrounds. In order to isolate the off-shell Higgs boson production while minimising sensitivity to higher-order QCD effects on $gg \to WW$ kinematics, a new variable $R_8$ [15], defined as the weighted combination of the dilepton mass and the transverse mass of the dilepton and $E_T^{miss}$ system, is constructed to select the signal region. Events in the signal region, $R_8 > 450$ GeV, are used in a counting experiment for the final results.
2.10. Modifications of analyses

To ensure a consistent interpretation of all inputs in terms of Higgs boson coupling strengths, several minor modifications were made to the inputs of these combinations with respect to their previously published versions:

- The upper limits on the $H \to Z\gamma$ and $H \to \mu\mu$ decays and the results of the $ttH$ searches in $H \to b\bar{b}$ and $ttH \to$ multileptons have been updated to assume a Higgs boson mass of 125.36 GeV.

- In some individual analyses, cross-feed of other Higgs boson decays occurs: in the $VH \to WW^*$ selection cross-feed of $H \to \tau\tau$ and $H \to ZZ^*$ occurs (whereas this cross-feed is negligible in the ggF and VBF $H \to WW^*$ analyses where a veto on the reconstructed $\tau\tau$ mass has been applied). Similarly, there is cross-feed from $H \to WW^*$ in the $H \to \tau\tau$ analysis. In such cases, this cross-feed was treated as background in the relevant individual channel analyses. For the coupling strength combination, such events are interpreted as signal from the corresponding Higgs boson decay.

- The rate of $gg \to ZH$ events in the $VH$ channels has been parameterised in terms of Higgs boson coupling strengths to $Z$ bosons and top quarks, following the calculations of Ref. [40] for $\sqrt{s} = 7$ and 8 TeV.

- The rate of $tH$ events in all the $ttH$ channels has been parameterised in terms of Higgs boson coupling strengths to $W$ bosons and top quarks.

- Theoretical uncertainties on QCD scales in Higgs boson signal processes have consistently been updated to the latest recommendations [11] for $H \to WW^*$, $b\bar{b}$, $\tau\tau$ and $Z\gamma$. No modifications were needed for the $H \to \gamma\gamma$ and $H \to ZZ^*$ channels.

- In channels where $bbH$ production was not explicitly modelled, the signal strength of ggF is re-defined to include this process. In channels where $bbH$ was modelled explicitly ($H \to \gamma\gamma$, $ZZ^*$), ggF and $bbH$ production are correlated with their ratio fixed to the SM value, allowing a consistent treatment of $bbH$ production across all channels. The impact of this average scaling on the results is negligible since, as can be seen in Table 2, the $bbH$ production process has a cross section which is only 1% of the ggF production in the SM.

- The off-shell analysis depends on the unknown K-factor, $R_{H^*}^B$, for the $gg \to H^* \to VV$ background process. In the case of the very similar Higgs boson signal production process, a K-factor between 0.5 and 2 is expected, as discussed in Ref. [24], and the full range from these calculations is used as a systematic uncertainty on $R_{H^*}^B$.

3. Statistical procedure

The statistical treatment of the data is described in Refs. [41–45]. Hypothesis testing and confidence intervals are based on the $\Lambda(\alpha)$ profile likelihood ratio [46] test statistic. The test statistic depends on one or more parameters of interest $\alpha$, such as the Higgs boson signal strength $\mu$ normalised to the SM
expectation (Eq. 1), Higgs boson mass $m_H$, coupling strength scale factors $\kappa$ and their ratios $\lambda$, as well as on additional parameters $\theta$ that are not of interest,

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}. \quad (2)$$

The likelihood functions in the numerator and denominator of the above equation are built using sums of signal and background probability density functions (pdfs) of the discriminating variables, introduced in Section 2. The pdfs are derived from MC simulation for the signal and from both data and simulation for the background. Likelihood fits to the observed data are done for the parameters of interest. The single circumflex in Eq. 2 denotes the unconditional maximum likelihood estimate of a parameter, i.e. both the parameters of interest and the nuisance parameters are jointly minimised. The double circumflex denotes a conditional maximum likelihood estimate, i.e. an estimate for given fixed values of the parameters of interest $\alpha$.

Systematic uncertainties and their correlations [41] are modelled by introducing nuisance parameters $\theta$ described by likelihood functions associated with the estimate of the corresponding effect. Systematic uncertainties that affect multiple measurements are modeled with common nuisance parameters to propagate the effect of these uncertainties coherently to all measurement. Most experimental systematic uncertainties are modeled independently for the $\sqrt{s} = 7$ and 8 TeV data samples, reflecting independent assessments of these uncertainties, but a subset of these uncertainties, e.g. material effects and some components of the jet energy scale, are considered common between the two data taking periods and are correspondingly described by a common set of nuisance parameters. Components of theoretical uncertainties, scale uncertainties on Higgs boson production as well as PDF induced uncertainties, that affect inclusive signal rates are described with common nuisance parameters in all channels, whereas components of theory uncertainties that affect the acceptance of individual channels can be modeled with separate nuisance parameters for each decay channel.

The choice of the parameters of interest depends on the test under consideration, with the remaining parameters being “profiled”, i.e., similarly to nuisance parameters they are set to the values that maximise the likelihood function for the given fixed values of the parameters of interest.

Asymptotically, a test statistic $-2 \ln \Lambda(\alpha)$ of several parameters of interest $\alpha$ is distributed as a $\chi^2$ distribution with $n$ degrees of freedom, where $n$ is the dimensionality of the vector $\alpha$. In particular, the $100(1 - \beta)$% confidence level (CL) contours are defined by $-2 \ln \Lambda(\alpha) < k_\beta$, where $k_\beta$ satisfies $P(\chi^2_n > k_\beta) = \beta$. For one degree of freedom the 68% and 95% CL intervals are given by $-2 \ln \Lambda(\alpha) = 1.0$ and 4.0, respectively. For two degrees of freedom the 68% and 95% CL contours are given by $-2 \ln \Lambda(\alpha) = 2.3$ and 6.0, respectively. All results presented in the following sections are based on likelihood evaluations and therefore give only approximate CL intervals.

For the measurements in the following sections the compatibility with the Standard Model, $p_{SM}$, is quantified using the $p$-value obtained from the profile likelihood ratio $\Lambda(\alpha = \alpha_{SM})$, where $\alpha$ is the set of parameters of interest and $\alpha_{SM}$ are their Standard Model values. For a given coupling benchmark model, $\alpha$ is the set of Higgs boson coupling scale factors $\kappa_i$ and ratios of coupling scale factors $\lambda_{ij}$ probed by that model, where the indices $i, j$ refer to the parameters of interest of the model (see Section 5). All other parameters are treated as independent nuisance parameters.

2 Whenever probabilities are translated into the number of Gaussian standard deviations the two-sided convention is chosen.  
3 The $p$-value is defined as the probability to obtain a value of the test statistic that is at least as high as the observed value, under the hypothesis that is being tested.
4. Signal strength measurements

This section discusses the measurements of the signal-strength parameter $\mu$ of different production modes and decay channels as well as their ratios for a fixed Higgs boson mass hypothesis of $m_H = 125.36$ GeV [27]. The signal-strength parameter is a measure of potential deviations from the SM prediction under the assumption that the Higgs boson production and decay kinematics do not change appreciably from the SM expectations. In particular, the transverse momentum and rapidity distributions of the Higgs boson are assumed to be those predicted for the SM Higgs boson by state-of-the-art event generators and calculations of each production process. This assumption is corroborated by studies such as the measurements of differential production cross sections [47, 48] and tests of spin and CP properties of the Higgs boson [28, 49].

For the signal-strength discussion below, $bbH$ is included in ggF, $tH$ in $ttH$ and $gg \rightarrow ZH$ in $VH$ unless noted otherwise. The ggF and $bbH$ processes lead to similar event signatures and no attempt is made to separate them in the analyses. The $ttH$ and $tH$ events have similar topologies. The $gg \rightarrow ZH$ process leads to the same final state as the $q\bar{q} \rightarrow ZH$ process via $VH$ production.

4.1. Global signal strength

In Section 2, the published ATLAS measurements on Higgs boson production and decay modes as well as the changes since their publications are summarised. Figure 2 shows the updated measurements of the signal-strength parameter $\mu$ from a simultaneous fit to all decay channels analysed. Most of these results are similar to the separate measurements shown in Fig. 1. A few noticeable changes can be attributed to the assignment of the Higgs boson yield of the $ttH$ searches to appropriate Higgs boson decay channels. For example, the result of the $ttH$ search in $H \rightarrow b\bar{b}$ is combined with that of the $VH$ analysis of the $H \rightarrow b\bar{b}$ decay. The measurements are consistent and compatible with a single value with a $p$-value of 76%. Assuming a common multiplier to all signal yields, they can be combined to result in a global, more precise measurement of the signal-strength parameter, providing the simplest consistency test with the SM expectation. Combining all measurements using the profile likelihood ratio $\Lambda(\mu)$ results in a global signal-strength value of

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (expt.)}^{+0.08}_{-0.07} \text{ (theo.)}^4,$$

consistent with the SM expectation of $\mu = 1$ with a $p$-value of 18%. The uncertainty of the combination has comparable statistical and systematic components and is notably reduced compared with individual measurements as illustrated in Fig. 2. Here the theoretical uncertainty includes contributions from those on SM cross sections and branching ratios as well as on the modellings of the production and decays of the Higgs boson. The theoretical uncertainties on background processes are included in the uncertainty labelled as experimental systematic uncertainty. The relative theoretical uncertainty of the measured $\mu$ value is smaller than that of the total SM cross section (Table 1) as $\mu$ is effectively a weighted average of the signal strength measurements in all categories: the contributions from VBF and $VH$ production, which have comparatively small theoretical uncertainties, have a larger weight in this average than in the total cross section. Combinations of measurements at $\sqrt{s} = 7$ and 8 TeV independently lead to signal-strength

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4 In this paper, stat., expt. and theo. refer to statistical, experimental and theoretical systematic uncertainties.
values of

\[ \mu(7 \text{ TeV}) = 0.75 \pm 0.32^{+0.28}_{-0.26} \text{ (stat.)}^{+0.13}_{-0.11} \text{ (expt.)}^{+0.08}_{-0.05} \text{ (theo.), and} \]

\[ \mu(8 \text{ TeV}) = 1.28 \pm 0.17^{+0.08}_{-0.07} \text{ (stat.)}^{+0.10}_{-0.08} \text{ (theo.)} \]

at these two energies.

A significant component of the theoretical uncertainty is associated with the SM predictions of the Higgs boson production cross sections and decay branching ratios. Advances in theoretical calculations are required to improve the precision of future measurements.

**Figure 2:** The observed signal strengths and uncertainties for different Higgs boson decay channels and their combination for \( m_H = 125.36 \text{ GeV} \). Higgs boson signals corresponding to the same decay channel are combined together for all analyses. The best-fit values are shown by the solid vertical lines. The total \( \pm 1\sigma \) uncertainties are indicated by green shaded bands, with the individual contributions from the statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the theory systematic uncertainty (bottom) on the signal strength shown as horizontal error bars.
4.2. Boson and fermion-mediated production processes

The measurements of the signal strengths described above assume the SM predictions of the relative contributions of different Higgs boson production processes and/or decay channels. Thus they may conceal differences between data and theoretical predictions. Therefore, in addition to the signal strengths of different decay channels, the signal strengths of different production modes are determined, exploiting the sensitivity offered by the use of event categories in the analyses of all channels.

The Higgs boson production processes can be categorised into two groups according to the Higgs boson couplings to fermions (ggF and ttH) or vector bosons (VBF and VH). Potential deviations from the SM can be tested with two signal-strength parameters, \( \mu_{\text{ggF+ttH}}^f = \mu_{\text{ggF}}^f + \mu_{\text{ttH}}^f \) and \( \mu_{\text{VBF+VH}}^f = \mu_{\text{VBF}}^f + \mu_{\text{VH}}^f \) for each decay channel \( f \). The 68% and 95% CL two-dimensional contours of \( \mu_{\text{ggF+ttH}}^f \) and \( \mu_{\text{VBF+VH}}^f \) of the five main decay channels are shown in Fig. 3. The cutoff in the contours of the \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \) decays is caused by the expected sum of signal and backgrounds yield in one of the contributing measurements going below zero in selected regions of the parameter space shown in Fig. 3. The SM expectation of \( \mu_{\text{ggF+ttH}}^f = 1 \) and \( \mu_{\text{VBF+VH}}^f = 1 \) is within the 68% CL contour of most of these measurements.

![Figure 3: Likelihood contours in the \( (\mu_{\text{ggF+ttH}}^f, \mu_{\text{VBF+VH}}^f) \) plane for a Higgs boson mass \( m_H = 125.36 \text{ GeV} \) measured separately for \( H \rightarrow WW^*, ZZ^*, b\bar{b}, \gamma\gamma \) and \( \tau\tau \) decays. The sharp lower edges of the \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \rightarrow 4\ell \) contours are due to the small numbers of events in these channels and the requirement of a positive probability density function. The best-fit values to the data (+) and the 68% (full) and 95% (dashed) CL contours are indicated, as well as the SM expectation (•).](image)

The relative production cross sections of the vector boson and fermion-mediated processes can be tested using the ratio of \( \mu_{\text{VBF+VH}}^f / \mu_{\text{ggF+ttH}}^f \). When measured separately for each decay channel, this ratio (shown in Fig. 4) reduces to the ratio of production cross sections as the Higgs boson decay branching...
ratios cancel, \textit{i.e.,}

\[
\mu^f_{VBF+VH}/\mu^f_{ggF+ttH} = \left( \frac{\sigma_{VBF+VH}/\sigma_{ggF+ttH}}{\sigma_{VBF+VH}/\sigma_{ggF+ttH}} \right)_{SM} \equiv R_{ff}.
\]

The combination of these measurements yields an overall value of the cross-section ratio between the boson- and fermion-mediated processes (relative to its SM prediction):

\[
R_{\text{Combined}} = 0.96^{+0.43}_{-0.31} = 0.96^{+0.34}_{-0.26} \text{(stat.)}^{+0.19}_{-0.13} \text{(expt.)}^{+0.18}_{-0.10} \text{(theo.).}
\]

consistent with the SM expectation of one.

Figure 4: The cross-section ratios between vector boson and fermion-mediated processes relative to their SM values at \(m_H = 125.36\text{ GeV}\), measured in the individual Higgs boson decay final states and their combination, \(R_{\text{Combined}}\) (see text). The inner and outer error bars represent 68\% CL and 95\% CL intervals, combining statistical and systematic uncertainties. These measurements are independent on the assumptions of Higgs boson decays.

### 4.3. Individual production processes

The Higgs boson production modes can be probed with four signal-strength parameters: \(\mu_{ggF}\), \(\mu_{VBF}\), \(\mu_{VH}\) and \(\mu_{ttH}\), one for each main production mode, assuming the SM values of the Higgs boson decay branching ratios. The SM predictions of the signal yields are scaled by these four production-dependent parameters. The best-fit values of these parameters for the \(\sqrt{s} = 8\text{ TeV}\) data separately and the combination with the \(\sqrt{s} = 7\text{ TeV}\) data are shown in Table 3. Uncertainties are broken down into statistical,
experimental and theoretical systematic components. The theoretical components include both theory uncertainties on the SM cross sections and branching ratios and on the signal modelling. The $\sqrt{s} = 7$ and 8 TeV combined values with their total uncertainties are also illustrated in Fig. 5. The $\sqrt{s} = 7$ TeV data are included in the combinations only as they have limited statistical power to distinguish between different production modes. The signal-strength measurements are in reasonable agreement with the SM predictions of unity. Though the results indicate evidence for $ttH$ production (see Section 4.4), this production process remains to be firmly established in future LHC runs. Thus, a 95% upper limit on its signal strengths is also derived. Combining the results from various analyses with sensitivity to $ttH$ production, the observed and expected limits are $\mu_{ttH} < 3.2$ and 1.4, respectively.

Table 3: Measured signal strengths $\mu$ at $m_H = 125.36$ GeV and their total $\pm 1\sigma$ uncertainties for different production modes for the $\sqrt{s} = 8$ TeV data and the combination with the $\sqrt{s} = 7$ TeV data. The $\sqrt{s} = 7$ TeV data do not have sufficient statistical power to yield meaningful measurements for individual production modes, but are included in the combination. Shown in the square brackets are uncertainty components: statistical (first), experimental (second) and theoretical (third) systematic uncertainties. These results are derived using the SM values of the Higgs boson decay branching ratios.

<table>
<thead>
<tr>
<th>Production process</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>Combined $\sqrt{s} = 7$ and 8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>$1.23 \pm 0.25$</td>
<td>$1.23 \pm 0.23$</td>
</tr>
<tr>
<td></td>
<td>$[+0.16 +0.10 +0.16]$</td>
<td>$[+0.14 +0.09 +0.16]$</td>
</tr>
<tr>
<td></td>
<td>$[-0.16 -0.08 -0.11]$</td>
<td>$[-0.14 -0.08 -0.12]$</td>
</tr>
<tr>
<td>VBF</td>
<td>$1.55 \pm 0.39$</td>
<td>$1.23 \pm 0.32$</td>
</tr>
<tr>
<td></td>
<td>$[+0.32 +0.17 +0.13]$</td>
<td>$[+0.28 +0.13 +0.11]$</td>
</tr>
<tr>
<td></td>
<td>$[-0.31 -0.13 -0.11]$</td>
<td>$[-0.27 -0.12 -0.09]$</td>
</tr>
<tr>
<td>VH</td>
<td>$0.93 \pm 0.39$</td>
<td>$0.80 \pm 0.36$</td>
</tr>
<tr>
<td></td>
<td>$[+0.37 +0.20 +0.12]$</td>
<td>$[+0.31 +0.17 +0.10]$</td>
</tr>
<tr>
<td></td>
<td>$[-0.33 -0.18 -0.06]$</td>
<td>$[-0.30 -0.17 -0.05]$</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$1.62 \pm 0.78$</td>
<td>$1.81 \pm 0.80$</td>
</tr>
<tr>
<td></td>
<td>$[+0.51 +0.58 +0.28]$</td>
<td>$[+0.52 +0.58 +0.31]$</td>
</tr>
<tr>
<td></td>
<td>$[-0.50 -0.54 -0.10]$</td>
<td>$[-0.50 -0.55 -0.12]$</td>
</tr>
</tbody>
</table>

Table 4: Measured cross sections of different Higgs boson production modes at $\sqrt{s} = 8$ TeV for $m_H = 125.36$ GeV obtained from the signal-strength values of Table 3. Uncertainty breakdowns are shown in the square brackets. These results are derived using the SM values of the Higgs boson decay branching ratios.

<table>
<thead>
<tr>
<th>Production process</th>
<th>Cross section (pb) at $\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>$23.9 \pm 3.6$</td>
</tr>
<tr>
<td>VBF</td>
<td>$2.43 \pm 0.58$</td>
</tr>
<tr>
<td>VH</td>
<td>$1.03 \pm 0.53$</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$0.24 \pm 0.11$</td>
</tr>
</tbody>
</table>

The signal-strength measurements shown in Table 3 are extrapolated to total cross-section measurements for each production process, as shown in Table 4 for $\sqrt{s} = 8$ TeV. The theoretical uncertainties on the SM Higgs production cross sections are thereby removed, but significant theoretical uncertainties remain, related in particular to the modelling of the Higgs boson production and of the limited acceptance of the event selection in some analyses. One can sum the different cross sections to obtain an overall extrapolated cross section for Higgs boson production. Despite its limited statistical power, the $\sqrt{s} = 7$ TeV data
Figure 5: The best-fit signal-strength values of different production modes determined from the combined fit to the $\sqrt{s} = 7$ and 8 TeV data. The inner and outer error bars correspond to 68% CL and 95% CL intervals. Total uncertainties combining statistical, experimental and theoretical systematic uncertainties are shown. The fit assumes the SM values of the Higgs boson decay branching ratios for $m_H = 125.36$ GeV.

nevertheless yield a reasonable measurement for the total cross section. The resulting total Higgs boson production cross sections at the two energies are

$$\sigma_H(7 \text{ TeV}) = 22.1^{+7.4}_{-6.0} \text{ pb} = 22.1^{+6.7}_{-5.3} \text{ (stat)}^{+2.7}_{-2.3} \text{ (expt.)}^{+1.9}_{-1.4} \text{ (theo.) pb} \text{ and}$$

$$\sigma_H(8 \text{ TeV}) = 27.7 \pm 3.7 \text{ pb} = 27.7 \pm 3.0 \text{ (stat.)}^{+2.0}_{-1.7} \text{ (expt.)}^{+1.2}_{-0.9} \text{ (theo.) pb},$$

to be compared with the theoretical predictions of $(17.4 \pm 1.6)$ pb at $\sqrt{s} = 7$ TeV and $(22.3 \pm 2.0)$ pb at $\sqrt{s} = 8$ TeV, as shown in Table 1.

These cross sections are different from what one would naively expect from the global signal-strength values discussed in Section 4.1, particularly for $\sqrt{s} = 7$ TeV. The differences are largely the result of analysis categorisation. Categories often explore production processes or phase space regions with distinct signal-event topologies. The resulting good signal-to-background ratios can significantly improve the precision of the signal-strength measurements. However, these categories often account for small fractions of the production cross section and thus have limited impact on the total cross-section measurement which is dominated by processes with larger expected cross sections. One good example is the VBF category. It contributes significantly to the global signal-strength measurement, but has a relatively minor impact on the total cross-section measurement.
4.4. Ratios of production cross sections and decay branching ratios

At the LHC, the Higgs boson production cross sections and decay branching ratios cannot be separately determined in a model-independent way as only their products are measured. However, the ratios of cross sections and ratios of branching ratios can be factorised model-independently and thus the decays can be decoupled from the production. A parameterisation using these ratios also benefits from cancellations of many theoretical and experimental systematic uncertainties.

By normalising the production yields to the signal strength of the $gg \to H \to WW^*$ production, $\mu^W_{ggF}$, the yields of other Higgs boson production modes and decay channels can be parameterised using the ratios of cross sections and ratios of branching ratios. The $gg \to H \to WW^*$ process is chosen as reference as it has the largest rate after event selection and is well measured (see for example Fig. 3). For example, for the production and decay $i \to H \to f$, the yield is then

$$\sigma_i \cdot BR_f = \mu_f^i \times \left[ \sigma_i \cdot BR_f \right]_{SM} = \left( \mu^W_{ggF} \cdot R_{i/\ggF} \cdot \rho_{f/WW^*} \right) \times \left[ \sigma_i \cdot BR_f \right]_{SM}.$$  \hspace{1cm} (3)

Here $R$ and $\rho$ are ratios of cross sections and branching ratios, respectively:

$$R_{i/\ggF} = \frac{\sigma_i/\sigma_{ggF}}{\sigma_{i}/\sigma_{ggF}}_{SM} \quad \text{and} \quad \rho_{f/WW^*} = \frac{BR_f/BR_{WW^*}}{BR_f/BR_{WW^*}}_{SM}. \hspace{1cm} (4)$$

Table 5: Best-fit values of $gg \to H \to WW^*$ signal strength $\mu^W_{ggF}$, ratios of cross sections $R_{i/\ggF}$ and of branching ratios $\rho_{f/WW^*}$. All $R_{i/\ggF}$ and $\rho_{f/WW^*}$ are measured relative to their SM values for $m_H = 125.36$ GeV from the combined analysis of the $\sqrt{s} = 7$ and 8 TeV data. The observed and expected significances of the VBF, VH and $ttH$ production with respect to the background-only hypothesis are also shown.

<table>
<thead>
<tr>
<th>Ratio of cross sections</th>
<th>Best-fit value</th>
<th>1.15+0.28−0.24</th>
<th>Ratio of branching ratios</th>
<th>Best-fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{VBF/\ggF}$</td>
<td>1.00+0.04−0.04</td>
<td>4.3</td>
<td>$\rho_{\gamma\gamma/WW^*}$</td>
<td>0.95+0.31−0.24</td>
</tr>
<tr>
<td>$R_{VH/\ggF}$</td>
<td>1.33+0.04−0.04</td>
<td>2.6</td>
<td>$\rho_{ZZ^<em>/WW^</em>}$</td>
<td>1.23+0.41−0.31</td>
</tr>
<tr>
<td>$R_{ttH/\ggF}$</td>
<td>1.90+1.12−0.86</td>
<td>2.4</td>
<td>$\rho_{\tau\tau/WW^*}$</td>
<td>1.19+0.51−0.37</td>
</tr>
</tbody>
</table>

The data are fitted with $\mu^W_{ggF}$, three cross-section ratios and one ratio of branching ratios for each decay channel other than the $H \to WW^*$ decay. The results are shown in Table 5 and illustrated in Fig. 6. Results from the searches of $H \to \mu\mu$ and $H \to ZZ$ decays are included in the fit, but the current datasets do not result in sensitive measurements of $\rho_{\mu\mu/WW^*}$ and $\rho_{Z/WW^*}$. Therefore only 95% CL upper limits are derived for these two ratios. The respective upper limit is 5.9 for $\rho_{\mu\mu/WW^*}$ and 11.0 for $\rho_{Z/WW^*}$.

The results exhibit a few noticeable features. As a common multiplicative factor to all rates in this parameterisation, the $gg \to H \to WW^*$ signal strength $\mu^W_{ggF}$ is pulled up from 0.98+0.29−0.26 of its standalone measurement in the $H \to WW^*$ decay (see Fig. 1) to 1.15+0.28−0.24 to accommodate the observed large global signal-strength value (Section 4.1). Another important feature is the anticorrelation between $R_{i/\ggF}$ and $\rho_{f/WW^*}$, see Eq. 3. One evident case is that the fit yields a $R_{VH/\ggF}$ value above the SM prediction, but
it is compensated by a small value of $\rho_{bb/WW^*}$ to account for the small observed signal strength in the $VH \rightarrow Vbb$ analysis.

Table 5 also includes the observed and expected significances in units of standard deviations ($\sigma$) of the VBF, $VH$ and $t\bar{t}H$ processes for the background-only hypothesis. The significance for each process is calculated from a likelihood scan while contributions from other processes are profiled. The result provides strong evidence at the $4.3\sigma$ level of the vector boson fusion production of the Higgs boson and
supports the SM assumptions of production in association with vector bosons or a pair of top quarks.

5. Coupling strength fits

In the previous section signal strength scale factors $\mu_i^f$ for given Higgs boson production or decay modes are discussed. However, for a measurement of Higgs boson coupling strengths, production and decay modes cannot be treated independently, as each observed process involves at least two Higgs boson coupling strengths.

Scenarios with a consistent treatment of coupling strengths in production and decay modes are studied in this section. All uncertainties on the best-fit values shown take into account both experimental and theoretical systematic uncertainties.

5.1. Framework for coupling strength measurements

Following the leading order (LO) tree level motivated framework and benchmark models recommended in Ref. [11], measurements of coupling strength scale factors $\kappa_j$ are implemented for the combination of all analyses and channels summarised in Table 2.

5.1.1. Assumptions of the framework for benchmark models

The framework is based on the following assumptions:

- The signals observed in the different channels originate from a single narrow resonance with a mass near 125.36 GeV. The case of several, possibly overlapping, resonances in this mass region is not considered.

- Unless otherwise noted, the Higgs boson production and decay kinematics are assumed to be compatible with those expected for a SM Higgs boson, similar to what was assumed for the signal strength measurements of Section 4.

- The width of the assumed Higgs boson near 125.36 GeV is neglected, i.e. the zero-width approximation is used. Due to the zero-width assumption in the Higgs boson propagator, the product $[\sigma \times \text{BR}(i \rightarrow H \rightarrow f)$ for on-shell measurements can always be decomposed in the following way for all channels:

$$
\sigma(i \rightarrow H \rightarrow f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}
$$

(5)

where $\sigma_i$ is the production cross section through the initial state $i$, $\Gamma_f$ the partial decay width into the final state $f$ and $\Gamma_H$ the total width of the Higgs boson. The components of $\sigma_i$, $\Gamma_f$, and $\Gamma_H$ of Eq. 5 are expressed in terms of LO-motivated scale factors $\kappa_j$ of the Higgs boson coupling strengths to other particles $j$, where a value of $\kappa_j = 1$ corresponds to the SM expectation. In particular, the total width $\Gamma_H$ relates to the Higgs boson coupling strengths as

$$
\Gamma_H(\kappa_j, \text{BR}_{i,u}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \text{BR}_{i,u})} \Gamma_{\text{SM}}^H ,
$$

(6)
where \( \kappa_H^2(\kappa_j) \) is the sum of the \( \kappa_j^2 \) weighted by the corresponding SM branching ratios, \( \Gamma_H^{\text{SM}} \) is the SM width of the Higgs boson, and \( \text{BR}_{i,u} \) is the Higgs boson branching ratio to invisible or undetected decays\(^5\).

Only modifications of coupling strengths, i.e. of absolute values of coupling strengths, are taken into account, while the tensor structure of the couplings is assumed to be the same as in the SM. This means in particular that the observed state is assumed to be a CP-even scalar as in the SM (this assumption was tested by both the ATLAS\(^{[28]}\) and CMS\(^{[49]}\) Collaborations).

- The signal strength of off-shell measurements is assumed to only depend on the coupling strengths and not on the total width \( [36, 37] \), i.e.

\[
\sigma^{\text{off}}(i \rightarrow H^* \rightarrow f) \sim \kappa_{i,\text{off}}^2 \cdot \kappa_{f,\text{off}}^2
\]

(7)

where the additional assumption of non-running coupling strengths

\[
\kappa_{j,\text{off}} = \kappa_{j,\text{on}}
\]

(8)

allows to constrain \( \Gamma_H \) from a simultaneous measurement of on-shell and off-shell measurements. While this assumption of non-running coupling strengths cannot hold universally for the \( gg \rightarrow H \) and \( qq' \rightarrow qq'H \) production without violating unitarity, it is assumed to hold in the region of phase space of the off-shell \( H^* \rightarrow WW \) and \( H^* \rightarrow ZZ \) measurements described in Section 2.9 that is relatively close to the on-shell regime.

5.1.2. Characterisation of the input measurements in terms of coupling strengths

The combined input channels described in Table 2 probe eight different production processes: \( \sigma(ggF) \), \( \sigma(VBF) \), \( \sigma(WH) \), \( \sigma(q\bar{q} \rightarrow ZH) \), \( \sigma(gg \rightarrow ZH) \), \( \sigma(bbH) \), \( \sigma(ttH) \), and \( \sigma(tH) \) whose SM cross sections are listed in Table 1. Table 6 summarises the Higgs boson coupling strength characteristics of all production processes and lists the rate scaling behavior in terms of Higgs boson coupling strength scale factors.

The ggF production process involves a loop process at lowest order, with contributions from top-quark and \( b \)-quark loops and a small interference between them. The VBF production process probes a combination of \( \kappa_W \) and \( \kappa_Z \) coupling strengths, with a negligible amount (\( \ll 0.1\% \)) of interference between these tree-level contributions.

The \( WH \) and \( q\bar{q} \rightarrow ZH \) processes each probe a single coupling strength, \( \kappa_W \) and \( \kappa_Z \), respectively. The gluon-initiated associated production of a Higgs boson with a \( Z \) boson, \( \sigma(gg \rightarrow ZH) \), is characterised by gluon-fusion-style production involving \( t, b \)-quark loops where the \( Z \) boson is radiated off the fermion loop and the Higgs boson is either also radiated directly off the fermion loop or is radiated off the outgoing \( Z \) boson. The cross section of \( gg \rightarrow ZH \) production is sensitive to the relative sign between \( \kappa_t \) and \( \kappa_Z \) due to interference between these contributions and depends on the kinematics of the process.

The \( ttH \) production process directly probes the Higgs boson coupling strength to \( t \)-quarks, \( \kappa_t \). The tree-level \( tH \) production process is included as background to events in all reconstructed \( ttH \) categories, and has for SM Higgs boson coupling strengths a large destructive interference between contributions where

\(^5\) Invisible final states can be directly searched for through the \( E_T^{\text{miss}} \) signature\(^{[31]}\). An example of an undetected mode would be a decay mode to multiple light jets, which presently cannot be distinguished from multijet backgrounds.
the Higgs boson is radiated from the W boson and from the top quark. Its SM cross section is consequently small, about 14% of the \( t\bar{t}H \) cross section. However, for negative \( \kappa_t \) the interference becomes constructive and, following Table 6, the cross section increases by a factor of 6(13) for \( |\kappa_t| = |\kappa_W| = 1 \) for the \( gb \rightarrow WtH(qb \rightarrow tHq' \) process, making the \( tH \) process a sensitive probe to the relative sign of the W and top-quark coupling strength, despite its small SM cross section.

The \( bbH \) production process directly probes the Higgs boson coupling strength to \( b \)-quarks, \( \kappa_b \). As no MC simulation is available to model the small \( bbH \) contribution in various input channels, and it is in most kinematic regions experimentally indistinguishable from ggF production, the \( bbH \) production mode is modeled using simulated ggF events (see Section 2.10).

The combined input channels probe seven Higgs boson decay modes. Each of the first five of these decay modes \( \Gamma_{b\bar{b}}, \Gamma_{WW}, \Gamma_{ZZ}, \Gamma_{\tau\tau}, \) and \( \Gamma_{\mu\mu} \) probes a single coupling strength scale factor. The remaining two decay modes, \( \Gamma_{\gamma\gamma} \) and \( \Gamma_{Z\gamma} \) are characterised by the interference between W boson or top-quark loop diagrams and probe the W and t coupling strengths and their relative sign through interference effects.

For completeness it should be noted also that the \( gg \rightarrow H, tH \) and \( gg \rightarrow ZH \) cross sections expressed in Higgs boson coupling strengths depend on the kinematic selection criteria used. The \( b-t \) interference expression quoted in Table 6 for \( gg \rightarrow H \) is valid for the inclusive cross section, but in events with additional jets the top-quark loop dominates, and the observed interference is somewhat smaller. Neither this \( gg \rightarrow H \) phase-space dependence, nor that of \( gg \rightarrow ZH \) are considered in this paper. For the \( tH \) process on the other hand, which features a comparatively large \( W-t \) interference term, the effect of phase-space dependence is taken into account, even though Table 6 only lists the inclusive expression.

5.1.3. Effective coupling strength scale factors

In some of the fits, effective scale factors \( \kappa_g, \kappa_\gamma, \kappa_{Z\gamma} \) are introduced to describe the processes \( gg \rightarrow H, H \rightarrow \gamma\gamma, \) and \( H \rightarrow Z\gamma \), which are loop-induced in the SM. In other fits they are treated as a function of the more fundamental coupling strength scale factors \( \kappa_t, \kappa_b, \kappa_W, \) and similarly for all other particles that contribute to these SM loop processes. In these cases, the loop contributions are expressed in terms of the fundamental coupling strengths, including all interference effects, as listed for the SM in Table 6. The loop process \( gg \rightarrow ZH \) is never treated as an effective scale factor, as unlike in the other loop processes, tree-level contributions from new physics are expected to be highly suppressed [40]. What then remains are BSM contributions to \( \kappa_{Z\gamma} \) and \( \kappa_t \), which are best taken into account within the limitation of the framework by resolving the loop.

5.1.4. Strategies for measurements of absolute coupling strengths

As all observed Higgs boson cross sections in the LO framework are inversely proportional to the Higgs boson width (Eq. 5), which is not experimentally constrained to a meaningful precision at the LHC, only ratios of coupling strengths can be measured at the LHC without assumptions on the Higgs boson width. To make measurements of absolute coupling strengths, an assumption on the Higgs boson width must be introduced.

The simplest assumption is that there are no invisible or undetected Higgs boson decay, i.e. \( BR_{i\rightarrow u} = 0 \) is assumed in Eq. 6. An alternative, less strong assumption, is that \( \kappa_W \leq 1 \) and \( \kappa_{Z\gamma} \leq 1 \) [11]. This assumption is theoretically motivated by the premise that the Higgs boson should solve the unitarity problem in vector
Table 6: Overview of Higgs boson production cross sections $\sigma_i$ and Higgs boson partial decay widths $\Gamma_i$. For each production or decay mode the scaling of the corresponding rate in terms of Higgs boson coupling strength scale factors is given. For processes where multiple amplitudes contribute, the rate may depend on multiple Higgs boson coupling strength scale factors, and interference terms may give rise to scalar product terms $\kappa_i \kappa_j$ that allow to determine the relative sign of the coupling strengths $\kappa_i$ and $\kappa_j$. Expressions originate from Ref. [11], except for $\sigma(gg \to ZH)$ (from Ref. [40]) and $\sigma(gb \to WtH)$ and $\sigma(qb \to tHq')$ (calculated using Ref. [26]). The expressions are given for $\sqrt{s} = 8$ TeV and $m_H = 125.36$ GeV and are similar for $\sqrt{s} = 7$ TeV. Interference contributions with negligible magnitudes have been been omitted in this table.

<table>
<thead>
<tr>
<th>Production</th>
<th>Loops</th>
<th>Interference</th>
<th>Expression in terms of fundamental coupling strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(ggF)$</td>
<td>✓</td>
<td>$b - t$</td>
<td>$\kappa_2^2 \sim 1.06 \cdot \kappa_1^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_b \kappa_t$</td>
</tr>
<tr>
<td>$\sigma(VBF)$</td>
<td></td>
<td></td>
<td>$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$</td>
</tr>
<tr>
<td>$\sigma(WH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_W^2$</td>
</tr>
<tr>
<td>$\sigma(q\bar{q} \to ZH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_Z^2$</td>
</tr>
<tr>
<td>$\sigma(gg \to ZH)$</td>
<td>✓</td>
<td>$Z - t$</td>
<td>$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_1^2 - 1.64 \cdot \kappa_Z \kappa_t$</td>
</tr>
<tr>
<td>$\sigma(bbH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_b^2$</td>
</tr>
<tr>
<td>$\sigma(ttH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_t^2$</td>
</tr>
<tr>
<td>$\sigma(gb \to WtH)$</td>
<td></td>
<td>$W - t$</td>
<td>$\sim 1.84 \cdot \kappa_1^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$</td>
</tr>
<tr>
<td>$\sigma(qb \to tHq')$</td>
<td></td>
<td>$W - t$</td>
<td>$\sim 3.4 \cdot \kappa_1^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$</td>
</tr>
</tbody>
</table>

Partial decay width

| $\Gamma_{bb}$ | - | - | $\sim \kappa_b^2$ |
| $\Gamma_{WW}$ | - | - | $\sim \kappa_W^2$ |
| $\Gamma_{ZZ}$ | - | - | $\sim \kappa_Z^2$ |
| $\Gamma_{t\tau}$ | - | - | $\sim \kappa_t^2$ |
| $\Gamma_{\mu\mu}$ | - | - | $\sim \kappa_\mu^2$ |
| $\Gamma_{Y\gamma}$ | ✓ | $W - t$ | $\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_1^2 - 0.66 \cdot \kappa_W \kappa_t$ |
| $\Gamma_{Z\gamma}$ | ✓ | $W - t$ | $\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_1^2 - 0.12 \cdot \kappa_W \kappa_t$ |

Total decay width

| $\Gamma_H$ | ✓ | $W - t$ | $\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_1^2 + 0.0023 \cdot \kappa_1^2 + 0.0016 \cdot \kappa_Z^2 + 0.00022 \cdot \kappa_\mu^2$ |

The assumptions made for the various measurements are summarised in Table 7 and discussed in the next sections together with the results.

Higgs boson scattering and also holds in a wide class of BSM models. In particular, it is valid in any model with an arbitrary number of Higgs doublets, with and without additional Higgs singlets. The assumption is also justified in certain classes of composite Higgs boson models. A second alternative is to assume that the coupling strengths in off-shell Higgs boson production are identical to those for on-shell Higgs boson production. Under the assumption that the off-shell signal strength and coupling strength scale factors are independent of the energy scale of the Higgs boson production, the total Higgs boson decay width can be determined from the ratio of off-shell to on-shell signal strengths [24]. The boundary $BR_{i,u} \geq 0$, motivated by the basic assumption that the total width of the Higgs boson must be greater or equal to the sum of the partial widths, always introduces a lower bound on the Higgs boson width. The difference in effect of these assumptions is therefore mostly in the resulting upper limit on the Higgs boson width.
Table 7: Summary of coupling benchmark models considered in this paper, where $\lambda_{ij} \equiv \kappa_i / \kappa_j$, $\kappa_{ij} \equiv \kappa_j / \kappa_i$, and the functional dependence assumptions are: $\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_u$ (and similarly for the other fermions), $\kappa_g = \kappa_b (\kappa_b, \kappa_t)$, $\kappa_Y = \kappa_b (\kappa_b, \kappa_c, \kappa_t, \kappa_W)$, and $\kappa_H = \kappa_l (\kappa_t)$. The tick marks indicate which assumptions are made in each case. The last column shows, as an example, the relative coupling strengths involved in the $gg \rightarrow H \rightarrow \gamma \gamma$ process.

<table>
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<th>Parameters of interest</th>
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<td>$\checkmark$</td>
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<td>43.3</td>
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<tr>
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<td>Vertex loops + $H \rightarrow$ invisible/undetected decays</td>
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<td>$=1$</td>
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<tr>
<td>5.3.2</td>
<td>48.2</td>
<td>Vertex loops + $H \rightarrow$ invisible/undetected decays</td>
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<td>$=1$</td>
<td>$=1$</td>
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<tr>
<td>5.4.1</td>
<td>43.2</td>
<td>Up/-down-type fermions</td>
<td>$\kappa_F, \kappa_V, \kappa_Y, \kappa_1, \kappa_2$</td>
<td>$\leq 1$</td>
<td>$-\checkmark$</td>
</tr>
<tr>
<td>5.4.2</td>
<td>49</td>
<td>Up/-down-type fermions</td>
<td>$\lambda_{V1}, \lambda_{V2}, \lambda_{V3}$</td>
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<td>Generic models with and without assumptions on vertex loops and $\Gamma_H$</td>
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<td>5.5.3</td>
<td>50.3</td>
<td>Generic models with and without assumptions on vertex loops and $\Gamma_H$</td>
<td>$\lambda_{WZ}, \lambda_{kg}, \lambda_{kZ}, \lambda_{Zg}, \lambda_{WZ}, \lambda_{kZ}, \lambda_{kZ}, \lambda_{kZ}$</td>
<td>$-\checkmark$</td>
<td>$-\checkmark$</td>
</tr>
</tbody>
</table>
5.2. Fermion versus vector (gauge) coupling strengths

This benchmark model is an extension of the fit to the single parameter $\mu$, where different strengths for the fermion and vector couplings are allowed. It assumes that only SM particles contribute to the $gg \to H$, $H \to \gamma\gamma$, $H \to Z\gamma$ and $gg \to ZH$ vertex loops, and modifications of the coupling strength factors for fermions and vector bosons are propagated through the loop calculations. The fit is performed in two variants, with and without the assumption that the total width of the Higgs boson is given by the sum of the known SM Higgs boson decay modes (modified in strength by the appropriate fermion and vector coupling strength scale factors, see for example the last column of Table 7).

5.2.1. Only SM contributions to the total width

The fit parameters are the coupling strength scale factors $\kappa_F$ for all fermions and $\kappa_V$ for all vector bosons:

\[
\begin{align*}
\kappa_V &= \kappa_W = \kappa_Z, \\
\kappa_F &= \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu.
\end{align*}
\]

As only SM particles are assumed to contribute to the $gg \to H$ loop in this benchmark model, the gluon fusion process depends directly on the fermion scale factor $\kappa_F^2$. Only the relative sign between $\kappa_F$ and $\kappa_V$ is physical and hence in the following only $\kappa_V > 0$ is considered, without loss of generality. Sensitivity to this relative sign is gained from the negative interference between the loop contributions of the $W$ boson and the $t$ quark in $H \to \gamma\gamma$ and $H \to Z\gamma$ decays and in $gg \to ZH$ production, as well as from the $tH$ processes (see Table 6).

Figure 7 shows the results of the fits for this benchmark model. Figure 7a illustrates how the $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$, $H \to \tau\tau$ and $H \to bb$ channels contribute to the combined measurement. The slight asymmetry in $\kappa_F$ for the $H \to WW^*$ and $H \to bb$ is introduced by the small contributions of the $tH$ and $gg \to ZH$ production processes for these decay modes. The strong constraint on $\kappa_F$ from $H \to WW^*$ decays is related to the 3.2$\sigma$ observation of the $qq' \to qq'H$ production process in this channel. Outside the range shown in Fig. 7a there are two additional minima for $H \to \gamma\gamma$. The long tails in the $H \to bb$ contour towards high values of $\kappa_V$ are the result of an asymptotically disappearing sensitivity of the observed signal strength in the $bb$ final states to $\kappa_V$ at large values of $\kappa_V$.

Figure 7b shows only the combined measurement with the SM-like minimum with a positive relative sign, as the local minimum with negative relative sign is disfavoured at the $\sim 4.0\sigma$ level, which can be seen in the wider scan of $\kappa_F$, where $\kappa_V$ is profiled, shown in Fig. 7c. The likelihood as a function of $\kappa_V$, profiling $\kappa_F$, is given in Fig. 7d. Around $\kappa_V = 0.8$ the sign of the chosen profiled solution for $\kappa_F$ changes, causing a kink in the likelihood. The profile likelihood curves restricting $\kappa_F$ to be either positive or negative are also shown in Fig. 7d as thin curves to illustrate that this sign change in the unrestricted profile likelihood is the origin of the kink.

The best-fit values and uncertainties, when the other parameter is profiled, are:

\[
\begin{align*}
\kappa_V &= 1.09^{+0.07}_{-0.07}, \\
\kappa_F &= 1.11^{+0.17}_{-0.15}.
\end{align*}
\]

The two-dimensional compatibility of the SM hypothesis with the best-fit point is 41%.
Figure 7: Results of fits for the two-parameter benchmark model defined in Section 5.2.1 that probes different coupling strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width:

(a) Results of the two-dimensional fit to $\kappa_F$ and $\kappa_V$, including 68% and 95% CL contours; overlaying the 68% CL contours derived from the individual channels and their combination; profile likelihood ratios as functions of the coupling strength scale factors (b) the same measurement, without the overlays of the individual channels, (c) $\kappa_F$ ($\kappa_V$ is profiled) and (d) $\kappa_V$ ($\kappa_F$ is profiled). The dashed curves in (c) and (d) show the SM expectations. In (d) the sign of the chosen profiled solution for $\kappa_F$ changes at $\kappa_V \approx 0.8$, causing a kink in the likelihood. The profile likelihood curves restricting $\kappa_F$ to be either positive or negative are also shown to illustrate that this sign change in the unrestricted profile likelihood is the origin of the kink. The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.
5.2.2. No assumption on the total width

The assumption on the total width gives a strong constraint on the fermion coupling strength scale factor $\kappa_F$ in the previous benchmark model, as the total width is dominated in the SM by the sum of the fermion-induced $b$, $\tau$ and gluon-decay widths. The fit is therefore repeated without the assumption on the total width.

In this case only ratios of coupling strength scale factors can be measured. Hence there are the following free parameters:

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$
$$\kappa_{VV} = \frac{\kappa_V \cdot \kappa_V}{\kappa_H},$$

where $\lambda_{FV}$ is the ratio of the fermion and vector boson coupling strength scale factors, $\kappa_{VV}$ is an overall scale that includes the total width and applies to all rates, and $\kappa_H$ is defined in Table 6.

Figure 8 shows the results of this fit. The best-fit values and uncertainties, when profiling the other parameter, are:

$$\lambda_{FV} = 1.07^{+0.14}_{-0.13}$$
$$\kappa_{VV} = 1.07^{+0.14}_{-0.13}.$$
5.3. Probing beyond the SM contributions assuming unmodified coupling strengths of SM particles

In this section, contributions from new particles either in loops or in new final states are considered. All coupling strength scale factors of known SM particles are assumed to be as predicted by the SM, i.e. $\kappa_i = 1$. For the $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ and $gg \rightarrow H$ vertices, effective scale factors $\kappa_\gamma$, $\kappa_{Z\gamma}$ and $\kappa_g$ are introduced that allow for extra contributions from new particles. These effective scale factors are defined to be positive as there is no sensitivity to the sign of these coupling strengths. The potential new particles contributing to the $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$, $gg \rightarrowZH$ and $gg \rightarrow H$ loops may or may not contribute to the total width of the observed state through direct invisible decays or decays into final states that cannot be distinguished from the background. In these cases the resulting variation in the total width is parameterised in terms of the additional branching ratio into invisible or undetected particles $BR_{i,u}$ of Eq. 6.

5.3.1. SM coupling strengths to all known particles and no BSM contributions to the total width

In the first benchmark model it is assumed that there are no extra contributions to the total width caused by non-SM particles, but that BSM contributions can modify the loop coupling strengths from their SM prediction. The free parameters are $\kappa_g$, $\kappa_\gamma$, $\kappa_{Z\gamma}$.

Figure 9 shows the results of fits for this benchmark scenario and the best-fit values and uncertainties, when profiling the other parameters. The effective coupling strengths $\kappa_g$ and $\kappa_\gamma$ are measured to be consistent with the SM expectation, whereas a limit is set on the effective coupling strength $\kappa_{Z\gamma}$.

Also shown in Fig. 9 is the uncertainty on the total width that this model allows, expressed as the ratio $\Gamma_H/\Gamma_{H}^{SM}$. The estimate for the width is obtained from an alternative parameterisation of this benchmark model where the effective coupling strength $\kappa_g$ is replaced by the expression that results from solving Eq. 6 for $\kappa_g$, introducing $\Gamma_H/\Gamma_{H}^{SM}$ as a parameter of the model. As the effective loop couplings only contribute a small fraction to the total width of the Higgs boson, the allowed uncertainty in the Higgs boson width in this benchmark model is highly constrained by its model assumptions. The three-dimensional compatibility of the SM hypothesis with the best-fit point is 69%.

5.3.2. SM coupling strengths to all known particles and no assumption on the total width

When all coupling strength scale factors of known SM particles are assumed to be as predicted by the SM, i.e. $\kappa_i = 1$, the total width $\Gamma_H$ as expressed as function of $\kappa_H^2$ in Eq. 6 is sufficiently constrained that it is possible to probe for invisible and undetected Higgs boson decays with the branching ratio $BR_{i,u}$ as free parameter, without further constraints on the total width. The free parameters in this case are $\kappa_g$, $\kappa_\gamma$, $\kappa_{Z\gamma}$ and $BR_{i,u}$. Figure 10 shows the best-fit values and their uncertainties, when profiling the other parameters. Also shown in Fig. 10 is the uncertainty on the total width that this model allows, obtained in the same fashion as for the previous benchmark model. The upward uncertainty on $\Gamma_H/\Gamma_{H}^{SM}$ is notably increased due the released constraint on $BR_{i,u}$, whereas the downward uncertainty is identical to that of the previous benchmark model due to the imposed condition that $BR_{i,u} \geq 0$.

The four-dimensional compatibility of the SM hypothesis with the best-fit point is 74%. By using the physical constraint $BR_{i,u} > 0$, the 95% CL upper limit is $BR_{i,u} < 0.27$ (the expected limit in case of the SM hypothesis is $BR_{i,u} < 0.37$). The 95% confidence interval is based on the profile likelihood ratio.
Figure 9: Results of fits for the benchmark model that probes for contributions from non-SM particles in the $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ and $gg \rightarrow H$ loops, assuming no extra contributions to the total width: (a) overview of fitted parameters, where the inner and outer bars correspond to 68% CL and 95% CL intervals, and (b) results of the two-dimensional fit to $\kappa_\gamma$ and $\kappa_g$, including 68% and 95% CL contours ($\kappa_{Z\gamma}$ is profiled).
Figure 10: Results of fits for benchmark models that probe for contributions from non-SM particles in the $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ and $gg \rightarrow H$ loops, while allowing for potential extra contributions to the total width: (a) overview of fitted parameters. The inner and outer bars correspond to 68% CL and 95% CL intervals. The confidence intervals for $BR_{i,u}$ are estimated with respect to the physical boundary as described in the text. (b) Profile likelihood ratio as function of the branching fraction $BR_{i,u}$ to invisible or undetected decay modes ($\kappa_\gamma$, $\kappa_g$ and $\kappa_{Z\gamma}$ are profiled). The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.
restricted to the allowed region of parameter space; however, the confidence interval is defined by the standard \( \chi^2 \) cutoff, which leads to some over coverage near the boundaries.

As the choice of free parameters in this model gives extra degrees of freedom to the \( gg \rightarrow H \) production and \( H \rightarrow \gamma\gamma \) and \( H \rightarrow Z\gamma \) decays, the most precise measurements based on the \( gg \rightarrow H \) production or the \( H \rightarrow \gamma\gamma \) decays (see Fig. 2) do not give a sizable contribution to the determination of \( BR_{i,u} \).

Instead \( BR_{i,u} \) is mostly constrained from channels sensitive to VBF and \( VH \) production, as the tree level couplings involved in these production modes are fixed to their SM values within this model.

### 5.4. Probing beyond the SM contributions allowing for modified coupling strengths of SM particles

In this section, benchmark models similar to those of Section 5.3 are considered, but now releasing the assumption that \( \kappa_i = 1 \) and allowing couplings to fermions and boson to be modified according to coupling strengths \( \kappa_F \) and \( \kappa_V \). With these additional parameters these benchmark models are underconstrained, and a constraint on the Higgs boson width must be introduced to resolve the degeneracy. All three choices of the total width constraint discussed in the introduction of this section are studied: \( \kappa_V < 1 \), \( \kappa_{on} = \kappa_{off} \), \( BR_{i,u} = 0 \). These choices of constraints complement each other, as the present limit of \( \mu_{off} < 5.1 \) in the combined off-shell measurement in the \( H \rightarrow WW^* \) and \( H \rightarrow ZZ^* \) channels effectively constrains \( \kappa_V \) to be greater than 1 in the combined fit when exploiting the assumption \( \kappa_{on} = \kappa_{off} \).

#### 5.4.1. Probing BSM contributions to the total width assuming SM loop couplings

This benchmark model is a straightforward extension of the model of Section 5.2.1 by introducing the branching fraction of Higgs boson decays to invisible or undetected states \( BR_{i,u} \) as free parameter. The free parameters of model thus are \( \kappa_F \), \( \kappa_V \) and \( BR_{i,u} \). Loop processes are assumed to have only SM content, as was also the case in the model of Section 5.2.1.

Figure 11 shows the results of fits from this benchmark scenario. Also shown in Figure 11 is the uncertainty that this benchmark models allows on the total width ratio \( \Gamma_H/\Gamma^SM_H \), obtained in similar fashion as for the previous benchmark models, now solving Eq. 6 for \( \kappa_F \) instead of \( \kappa_g \). Unlike the benchmark models of Section 5.3, the measured width ratio is now allowed to go substantially below 1 as the free parameters \( \kappa_F \) and \( \kappa_V \) allow the dominant terms in \( \kappa_H \) to be reduced with respect to their SM expectation (see Table 6). For comparison the results of the benchmark model of Section 5.2.1 are included, corresponding to the condition \( BR_{i,u} = 0 \) in this model. Figure 11 shows that the upper bound on the Higgs width from the assumption \( \kappa_{off} = \kappa_{on} \) is substantially weaker than the bound from the assumption \( \kappa_V < 1 \).

The three-dimensional compatibility of the SM hypothesis with the best-fit point is 99% (29%), when applying the \( \kappa_V < 1 \) (off-shell) constraint, respectively. By using the physical constraint \( BR_{i,u} > 0 \), the 95% CL upper limit is \( BR_{i,u} < 0.13 \), when applying \( \kappa_V < 1 \) (the expected limit in case of the SM hypothesis is \( BR_{i,u} < 0.24 \)), and is \( BR_{i,u} < 0.52 \) when applying the off-shell constraint (the expected limit in case of the SM hypothesis is \( BR_{i,u} < 0.71 \)). The 95% confidence interval is based on the profile likelihood ratio restricted to the allowed region of parameter space; the confidence interval is defined by the standard \( \chi^2 \) cutoff, which leads to some over coverage near the boundaries.
Figure 11: Results of fits for benchmark models that probe for potential extra contributions to the total width, but do not allow contributions from non-SM particles in the $H \rightarrow \gamma\gamma$, $gg \rightarrow H$ and $H \rightarrow Z\gamma$ loops, with free gauge and fermion coupling strengths $\kappa_V$, $\kappa_F$. The result for each parameter marked by a full box corresponds to the model with a constraint on the total width from $\mu_{\text{off}}$. The result for each parameter marked by a full circle corresponds to the model with the constraint $\kappa_V < 1$ imposed. The the inner and outer bars correspond to 68% CL and 95% CL intervals. The confidence intervals of $\text{BR}_{i.,u.}$, and, in the benchmark model with the constraint $\kappa_V < 1$, also $\kappa_V$, are estimated with respect to their physical boundaries as described in the text.

5.4.2. Probing BSM contributions in loops and to the total width

This next benchmark model releases the assumption of SM particle content in loop processes of the previous benchmark by introducing the effective loop coupling parameters used in the benchmark models of Section 5.3. The free parameters of this model are thus $\kappa_F$, $\kappa_V$, $\kappa_g$, $\kappa_\gamma$, $\kappa_{Z\gamma}$ and $\text{BR}_{i.,u.}$. Figure 12 shows the best-fit values and their uncertainties.

The six-dimensional compatibility of the SM hypothesis with the best-fit point is 96% (64%) when apply-
Figure 12: Results of fits for benchmark models that probe for contributions from non-SM particles in the $H \rightarrow \gamma\gamma$, $gg \rightarrow H$ and $H \rightarrow Z\gamma$ loops, with free gauge and fermion coupling strengths $\kappa_V$, $\kappa_F$, while allowing for potential extra contributions to the total width. The result for each parameter marked by a full box corresponds to the model with a constraint on the total width from $\mu_{\text{off}}$. The result for each parameter marked by a full circle corresponds to the model with the constraint $\kappa_V < 1$ imposed. The the inner and outer bars correspond to 68% CL and 95% CL intervals. The confidence intervals of $\text{BR}_{i.,u.}$ and, in the benchmark model with the constraint $\kappa_V < 1$, also $\kappa_V$, are estimated with respect to their physical boundaries as described in the text.
ing the $\kappa_V < 1$ (off-shell) constraint, respectively. By using the physical constraint $BR_{i,u} = 0$, the 95% CL upper limit is $BR_{i,u} < 0.27$ when applying $\kappa_V < 1$ (the expected limit in case of the SM hypothesis is $BR_{i,u} < 0.39$), and is $BR_{i,u} < 0.54$, when applying the off-shell constraint (the expected limit in case of the SM hypothesis is $BR_{i,u} < 0.72$).

5.5. Probing relations within the fermion coupling sector

The previous sections assumed universal coupling strength scale factors for all fermions, while many extensions of the SM predict deviations within the fermion sector [11]. The currently accessible channels, in particular $H \rightarrow bb$, $H \rightarrow \tau\tau$, $H \rightarrow \mu\mu$ and $q\bar{q}/gg \rightarrow t\bar{t}H$, allow the relations between the up- and down-type fermions and between the lepton and quark sectors to be probed.

5.5.1. Probing the up- and down-type fermion symmetry

Many extensions of the SM contain different coupling strengths of the Higgs boson to up-type and down-type fermions. This is for instance the case for certain Two-Higgs-Doublet Models [50–52]. In this benchmark model the ratio $\lambda_{du}$ between down- and up-type fermions is probed, while vector boson coupling strengths are assumed to be unified and equal to $\kappa_V$. The indices $u, d$ stand for all up- and down-type fermions, respectively. The free parameters are:

$$\lambda_{du} = \kappa_d / \kappa_u$$
$$\lambda_{Vu} = \kappa_V / \kappa_u$$
$$\kappa_{uu} = \kappa_u \cdot \kappa_u / \kappa_H.$$ 

The up-type quark coupling strength scale factor is mostly indirectly constrained through the $gg \rightarrow H$ production channel, from the Higgs boson to top-quark coupling strength, with an additional weak direct constraint from the $q\bar{q}/gg \rightarrow t\bar{t}H$ production channel, while the down-type coupling strength is constrained through the $H \rightarrow bb$, $H \rightarrow \tau\tau$ and $H \rightarrow \mu\mu$ decays as well as weakly through the $b\bar{b} \rightarrow H$ production mode and the $b$-loop in the $gg \rightarrow H$ production mode.

Figure 13 shows the results of the fits for this benchmark model. The likelihood curve is nearly symmetric around $\lambda_{du} = 0$ as the model is almost insensitive to the relative sign of $\kappa_u$ and $\kappa_d$. The interference of contributions from the $b$ and $t$ loops in the $gg \rightarrow H$ production induces an observed asymmetry of about 0.6σ (no significant asymmetry is expected with the present sensitivity). The fit results for the parameters of interest are:

$$\lambda_{du} \in [-1.08, -0.81] \cup [0.75, 1.04] \, (68\% \, C.L.)$$
$$\lambda_{Vu} = 0.92^{+0.18}_{-0.16}$$
$$\kappa_{uu} = 1.25^{+0.33}_{-0.33}.$$ 

The value of $\lambda_{du}$ around the SM-like minimum at 1 is $\lambda_{du} = 0.90 \pm 0.15$. This fit provides a $\sim 4.5\sigma$ level evidence of the coupling of the Higgs boson to down-type fermions, mostly coming predominantly from the $H \rightarrow \tau\tau$ measurement and to a lesser extent from the $H \rightarrow bb$ measurements. The three-dimensional compatibility of the SM hypothesis with the best-fit point is 51%.
Figure 13: Results of fits for the benchmark model described in Section 5.5.1 that probes the ratio of scale factors between down- and up-type fermions: profile likelihood ratios as functions of the coupling strength scale factor ratios (a) $\lambda_{du}$ ($\lambda_{Vu}$ and $\kappa_{uu}$ are profiled), (b) $\lambda_{Vu}$ ($\lambda_{du}$ and $\kappa_{uu}$ are profiled), and (c) the overall scale factor $\kappa_{uu}$ ($\lambda_{du}$ and $\lambda_{Vu}$ are profiled). The dashed curves show the SM expectations. The red(green) horizontal lines indicate the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.

5.5.2. Probing the quark and lepton symmetry

Here the ratio $\lambda_{lq}$ of coupling strength scale factors to leptons and quarks is probed, while vector boson coupling scale factors are assumed to be unified and equal to $\kappa_V$. The indices $l, q$ stand for all leptons and quarks, respectively. The free parameters are:

$\lambda_{lq} = \kappa_l / \kappa_q$
$\lambda_{Vq} = \kappa_V / \kappa_q$
$\kappa_{qq} = \kappa_q \cdot \kappa_q / \kappa_H$.

The lepton coupling strength is constrained through the $H \rightarrow \tau\tau$ and $H \rightarrow \mu\mu$ decays.

Figure 14 shows the results of the fits for this benchmark. Similar to the case above, the likelihood curve is nearly symmetric around $\lambda_{lq} = 0$. The fit results for the parameters of interest are:

$\lambda_{lq} \in [-1.34, -0.94] \cup [0.94, 1.34]$ (68% C.L.)
$\lambda_{Vq} = 1.03^{+0.18}_{-0.15}$
$\kappa_{qq} = 1.03^{+0.24}_{-0.20}$.

The value of $\lambda_{lq}$ around the SM-like minimum at 1 is $\lambda_{lq} = 1.12^{+0.22}_{-0.18}$. A vanishing coupling strength of the Higgs boson to leptons is excluded at the $\sim 4.4\sigma$ level due to the $H \rightarrow \tau\tau$ measurement. The three-dimensional compatibility of the SM hypothesis with the best-fit point is 53%.
5.6. Generic models

In the benchmark models studied in sections 5.2 to 5.5, specific aspects of the Higgs sector are tested by combining under certain assumptions coupling strength scale factors into a minimum number of parameters, thereby maximizing the sensitivity to the scenarios under study. In the case of the generic models evaluated in this section the coupling strength scale factors to $W$, $Z$, $t$, $b$, $τ$ and $μ$ are treated independently, while for the $gg → H$ production, $H → γγ$ decay, $H → Zγ$ decay and the total width $Γ_H$, either the SM particle content is assumed (Section 5.6.1) or no such assumptions are made (Sections 5.6.2 and 5.6.3).

5.6.1. Generic model 1: only SM particles in loops, no invisible or undetected Higgs boson decays

In this benchmark scenario, all coupling strengths to SM particles, relevant to the measured modes, are fitted independently. The free parameters are: $κ_W$, $κ_Z$, $κ_t$, $κ_b$, $κ_τ$, and $κ_μ$, while the vertex loop factors and the total width are calculated as a function of these parameters, as listed in Table 6. Without loss of generality the $W$ coupling strength scale factor is assumed to be positive. Due to the interference terms, the fit is sensitive to the relative sign between the $W$ and $t$ couplings (through the $tH$, $H → γγ$, $H → Zγ$ processes) and the relative sign between the $Z$ and $t$ coupling (through the $gg → ZH$ process), providing
Figure 15: Overview of best-fit values of parameters with 68% and 95% CL intervals for the generic model 1 (see text). In this model only SM particles are considered in loops and no invisible or undetected Higgs boson decay are allowed. The sign of $\kappa_W$ is assumed to be positive, as indicated by the hatched area, without loss of generality. The inner and outer bars correspond to 68% CL and 95% CL intervals.

indirect sensitivity to the relative sign between the $W$- and $Z$-coupling. Furthermore, the model has some sensitivity to the relative sign between the top- and bottom-coupling ($gg \rightarrow H$).
Figure 16: Results of fits for the generic model 1 (see text): only SM particles in loops, no invisible or undetected Higgs boson decays. Profile likelihood ratio as a function of the coupling strength scale factors (a) $\kappa_t$ (other coupling strengths are profiled), (b) $\kappa_b$, (c) $\kappa_W$, and (d) $\kappa_Z$. For each measurement, the other coupling strength scale factors are profiled. The kinks in the curves of (a) and (c) are caused by transitions in solutions chosen by the profile likelihood for the relative sign between profiled couplings. The dashed curves show the SM expectations. The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.
Figure 15 shows the results of the fits for this benchmark scenario. All measured coupling strengths are found to be compatible with the SM expectation within 1σ. As shown in Figs. 16a and 16b, the negative solution of κ_κ is strongly disfavoured at 3.1σ (2.9σ expected), while the negative minimum of κ_κ is slightly disfavoured at 0.5σ (no sensitivity expected). The six-dimensional compatibility of the SM hypothesis with the best-fit point is 57%. Figure 17 shows the results of the fit for generic model 1 as reduced coupling strength scale factors

$$y_{V,i} = \sqrt{\frac{\kappa_{V,i} g_{V,i}}{2v}} = \frac{\sqrt{\kappa_{V,i} m_{V,i}}}{v}$$

(9)

for weak bosons with a mass $m_V$, where $g_{V,i}$ is the absolute Higgs boson coupling strength, $v$ is the vacuum expectation value of the Higgs field and

$$y_{F,i} = \frac{\kappa_{F,i} g_{F,i}}{\sqrt{2}} = \frac{\kappa_{F,i} m_{F,i}}{v}$$

(10)

for fermions as a function of the particle mass $m_F$, assuming a SM Higgs boson with a mass of 125.36 GeV. For the b quark mass in Fig. 17 the $\overline{MS}$ running mass evaluated at 125.36 GeV is assumed.

For the measurements this generic model, it should be noted that the low fitted value of κ_κ causes a reduction of the total width $\Gamma_H$ by about 30% compared to the SM expectation (see Table 6), which in turn induces a reduction of all other κ-values by about 20%.

Figure 17: Fit results for the reduced coupling strength scale factors $y_{V,i} = \sqrt{\frac{\kappa_{V,i} g_{V,i}}{2v}} = \frac{\sqrt{\kappa_{V,i} m_{V,i}}}{v}$ for weak bosons and $y_{F,i} = \frac{\kappa_{F,i} g_{F,i}}{\sqrt{2}} = \frac{\kappa_{F,i} m_{F,i}}{v}$ for fermions as a function of the particle mass, assuming a SM Higgs boson with a mass of 125.36 GeV. The dashed line indicates the predicted mass dependence for the SM Higgs boson.
5.6.2. Generic model 2: allowing deviations in vertex loop couplings and invisible or undetected Higgs boson decays

In this case the six free parameters from model 1 are retained but the assumptions about which particles contribute to the loops and the total width are dropped. Effective coupling strength scale factors for the $gg \to H, H\to \gamma\gamma$ and $H\to Z\gamma$ vertices are introduced, and optionally also a branching ratio $BR_{i,u}$ to new non-SM decays that might yield invisible or undetected final states, resulting in a total of 9 (10) free parameters. In the variant where $BR_{i,u}$ is not fixed to zero, either the constraint $\kappa_V < 1$ is imposed, or the constraint on the total width from off-shell measurements is included.

Figure 19 illustrates the results of the fits for this benchmark scenario. The numerical results are shown in Table 8. The nine-dimensional compatibility of the SM hypothesis with the best-fit point is 73% when $BR_{i,u}$ is fixed to zero. The compatibilities for the fits with the conditions $\kappa_V < 1$ and $\kappa_{on} = \kappa_{off}$ imposed are 80% and 57%, respectively.

Figure 18 shows profile likelihood ratios as a function of selected coupling strength scale factors. In Fig. 18a, the negative minimum of $\kappa_i$ is disfavoured at 1.0 $\sigma$. The sensitivity to disfavour the negative minimum of $\kappa_i$ is reduced with respect to generic model 1 as the interference in loop couplings can no longer be exploited as effective coupling strength are introduced. The observed residual sensitivity to the sign of $\kappa_i$ is exclusively due to the tree-level interference effect of the $tH$ background of the $ttH$ channel. The minimum corresponding to the positive solution is given by $\kappa_i = 1.28^{+0.32}_{-0.35}$.

Table 8: Numerical results of the fits to generic model 2: effective coupling strengths for loop processes allowing non-SM contributions with various assumptions on the total Higgs boson width. The inner and outer bars correspond to 68% CL and 95% CL intervals. The confidence interval of $BR_{i,u}$ in the benchmark model with the constraints $\kappa_V < 1$ and $|\kappa_Z| < 1$, and the confidence intervals $\kappa_V$ and $\kappa_Z$, are estimated with respect to their physical boundaries as described in the text. These results are also shown in Fig. 19.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\kappa_V &lt; 1$</th>
<th>$\kappa_{off} = \kappa_{on}$</th>
<th>$BR_{i,u} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_w$</td>
<td>$&gt; 0.64$ (95% CL)</td>
<td>$= 0.96^{+0.35}_{-0.16}$</td>
<td>$= 0.92^{+0.14}_{-0.15}$</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>$&gt; 0.71$ (95% CL)</td>
<td>$= 1.05^{+0.38}_{-0.17}$</td>
<td>$\in [-1.08, -0.84] \cup [0.86, 1.14]$</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$= 1.28 \pm 0.35$</td>
<td>$= 1.35^{+0.61}_{-0.39}$</td>
<td>$\in [-1.12, -1.00] \cup [0.93, 1.60]$</td>
</tr>
<tr>
<td>$</td>
<td>\kappa_b</td>
<td>$</td>
<td>$= 0.62 \pm 0.28$</td>
</tr>
<tr>
<td>$</td>
<td>\kappa_{\tau}</td>
<td>$</td>
<td>$= 0.99^{+0.22}_{-0.18}$</td>
</tr>
<tr>
<td>$</td>
<td>\kappa_\mu</td>
<td>$</td>
<td>$&lt; 2.3$ (95% CL)</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$= 0.90^{+0.16}_{-0.14}$</td>
<td>$0.93^{+0.36}_{-0.17}$</td>
<td>$0.90 \pm 0.15$</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>$= 0.92^{+0.23}_{-0.16}$</td>
<td>$1.02^{+0.37}_{-0.19}$</td>
<td>$0.92 \pm 0.17$</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>$&lt; 3.15$ (95% CL)</td>
<td>$4.03$ (95% CL)</td>
<td>$3.18$ (95% CL)</td>
</tr>
<tr>
<td>$BR_{i,u}$</td>
<td>$&lt; 0.49$ (95% CL)</td>
<td>$0.68$ (95% CL)</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_H/\Gamma_{SM}^H$</td>
<td>$= 0.64^{+0.40}_{-0.23}$</td>
<td>$0.74^{+1.57}_{-0.21}$ $&lt; 4.9$ (95% CL)</td>
<td>$0.64^{+0.31}_{-0.25}$</td>
</tr>
</tbody>
</table>

Figure 20 illustrates the influence of individual loop processes on the precision of the $\kappa_i$ measurement as well as their ability to determine the sign of $\kappa_i$ relative to $\kappa_V$. As a starting point the red curve shows
Figure 18: Results of fits for the generic model 2 (see text): effective coupling strengths for loop processes allowing non-SM contributions, but assuming that the total Higgs boson decay width is not modified with respect to the SM (BR_{hid} = 0). Profile likelihood ratios as functions of the coupling strength scale factors (a) κ_{t}, (b) κ_{b}, (c) κ_{W}, and (d) κ_{Z}. For each measurement, the other coupling strength scale factors are profiled. The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic χ^2 distribution for the test statistic.
the sensitivity of generic model 2, as also shown Fig. 18a. In this benchmark the sensitivity to the $W - t$
relative sign originates only from the non-loop $tH$ process and from the resolved $gg \rightarrow ZH$ loop process.
The observed 1σ sensitivity to the sign of $\kappa_t$ is exclusively due to the $tH$ process contribution, as is
demonstrated by a model variant (blue curve) in which $gg \rightarrow ZH$ contribution described with an effective
coupling strength: this results in a nearly identical sensitivity to the sign, in addition to a slightly reduced
sensitivity to reject $\kappa_t = 0$. Adding information to generic model 2 from the $gg \rightarrow H$ loop process,
by resolving it into its SM content, greatly improves the precision on $\kappa_t$ (green curve), but reduces the
sensitivity to relative sign of $\kappa_t$ relative to $\kappa_W$. This reduction happens because on one hand the $gg \rightarrow H$
process yields no new information on this relative sign, as it is dominated by a $t - b$ interference, and on
the other hand because it decreases the observed magnitude of $\kappa_t$ to a more SM-compatible level, thereby
reducing the sensitivity of the $tH$ process to the relative sign. Further resolving the $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$
loop process, which are dominated by a $W - t$ interference result in the configuration of generic model
1 and greatly improves the measurement of the relative sign of $\kappa_W$ and $\kappa_t$ (orange curve), but does not
significantly contribute to the precision of the magnitude of $\kappa_t$.

5.6.3. Generic model 3: allowing deviations in vertex loop coupling strengths, no assumption on
the total width

In this benchmark model, the six absolute coupling strengths and three effective loop coupling strengths
of generic model 2 are retained, and expressed in ratios of scale factor that can be measured independent
of any assumptions on the Higgs boson total width. The free parameters are:

\[
\begin{align*}
\kappa_{gZ} &= \kappa_g \cdot \kappa_Z / \kappa_H \\
\lambda_{Zg} &= \kappa_Z / \kappa_g \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{tg} &= \kappa_t / \kappa_g \\
\lambda_{bZ} &= \kappa_b / \kappa_Z \\
\lambda_{cZ} &= \kappa_c / \kappa_Z \\
\lambda_{\mu Z} &= \kappa_\mu / \kappa_Z \\
\lambda_{tZ} &= \kappa_t / \kappa_Z \\
\lambda_{Z\gamma Z} &= \kappa_{Z\gamma} / \kappa_Z .
\end{align*}
\]

Figure 21 shows the full set of results obtained from the fit to this benchmark. The fitted values and their
uncertainties are also shown in Table 9.

This model allows the custodial symmetry to be probed: identical coupling strength scale factors for the
$W$ and $Z$ boson are required within tight bounds by the SU(2) custodial symmetry and the $\rho$ parameter
measurements at LEP and at the Tevatron [53]. To test this constraint directly in the Higgs sector, the
ratio $\lambda_{WZ} = \kappa_W / \kappa_Z$ is probed.

The ratio $\lambda_{WZ}$ is in part directly constrained by the decays in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ and $H \rightarrow ZZ^* \rightarrow 4\ell$
channels and the $WH$ and $ZH$ production processes. It is also indirectly constrained by the VBF pro-
duction process, which in the SM is 74% $W$ fusion and 26% $Z$ fusion-mediated (see Table 6). Fig. 22a
shows the profile likelihood ratio as a function of the coupling strength scale factor ratio $\lambda_{WZ}$. Due to
the interference terms, the fit is sensitive to the relative sign between the $W$ and top-coupling ($tH$) and
the relative sign between the $Z$ and top-coupling ($gg \rightarrow ZH$), providing indirect sensitivity to the sign of
Figure 19: Results of fits for the generic model 2 (see text): the results indicated by a full box are obtained for a benchmark model with effective coupling strengths for loop processes allowing non-SM contributions, and a floating $BR_{i,u}$ allowing non-SM contributions to the total decay width. The fit results indicated by a full circle represent a benchmark model where the total Higgs boson decay width is not modified with respect to the SM. The hatched area indicates regions that are outside the defined parameter boundaries. The inner and outer bars correspond to 68% CL and 95% CL intervals. The confidence intervals of $BR_{i,u}$ and, in the benchmark model with the constraints $\kappa_W < 1$ and $|\kappa_Z| < 1$, also $\kappa_W$ and $\kappa_Z$, are estimated with respect to their physical boundaries as described in the text. Numerical results are shown in Table 8.
Figure 20: Comparison of measurements of $\kappa_t$ with and without resolved loop processes: shown are models with no loop processes resolved (blue), only $gg \rightarrow ZH$ resolved (red, generic model 2), $gg \rightarrow H$ additionally resolved (green), and $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ additionally resolved (orange, generic model 1). The dashed blue and orange curves correspond to the expected sensitivity for the no-loop and all-loop models. The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.

Table 9: Numerical results of the fits for generic model 3. These results are also shown in Fig. 21.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa^g_Z$</td>
<td>$1.18 \pm 0.16$</td>
</tr>
<tr>
<td>$\lambda^Z_g$</td>
<td>$1.09^{+0.26}_{-0.22}$</td>
</tr>
<tr>
<td>$\lambda^W_Z$</td>
<td>$[-1.04, -0.81] \cup [0.80, 1.06]$</td>
</tr>
<tr>
<td>$\lambda^t_{tg}$</td>
<td>$[-1.70, -1.07] \cup [1.03, 1.73]$</td>
</tr>
<tr>
<td>$\lambda^{bZ}$</td>
<td>$0.60 \pm 0.27$</td>
</tr>
<tr>
<td>$\lambda^Z_\tau$</td>
<td>$0.99^{+0.23}_{-0.19}$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda_{\mu Z}</td>
</tr>
<tr>
<td>$\lambda^{(Z)}_\gamma$</td>
<td>$0.90 \pm 0.15$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda_{(Z)\gamma Z}</td>
</tr>
</tbody>
</table>

$\lambda^W_Z$. The negative solution is disfavoured at 0.5$\sigma$ (0.3$\sigma$ expected). The minimum corresponding to the positive solution is given by $\lambda^W_Z = 0.92^{+0.14}_{-0.12}$. Also shown in Figs. 22b, 22c are the ratios $\lambda^Z_\mu$ and $\lambda^Z_{tg}$. The ratio $\lambda^Z_\mu$ is sensitive to new charged particles contributing to the $H \rightarrow \gamma\gamma$ loop in comparison to $H \rightarrow ZZ^*$ decays. Similarly, the ratio $\lambda_{tg}$ is sensitive to new coloured particles contributing through $gg \rightarrow H$ loop as compared to $ttH$. The minimum corresponding to the positive solution is given by $\lambda_{tg} = 1.38 \pm 0.35$. Both are observed to be compatible with the SM expectation.

As the loop-induced processes are expressed by effective coupling strength scale factors, there is little.
sensitivity to the relative sign between coupling strength scale factor due to $tH$ and $gg \rightarrow ZH$ processes only. Hence only positive values for all $\kappa$-factors except $\kappa_l$ are shown without loss of generality. The nine-dimensional compatibility of the SM hypothesis with the best-fit point is 73%.

The fit in the third generic benchmark model uses only the basic assumptions as stated at the beginning of this section and hence represents the most model-independent determination of coupling strength scale factors that is currently possible.
Figure 21: Results of fits for the generic model 3 (see text): allowing deviations in vertex loop coupling strengths and in the total width. Overview of best-fit values of parameters, where the inner and outer bars correspond to 68% CL and 95% CL intervals. The hatched area indicates regions that are outside the defined parameter boundaries.
Figure 22: Results of fits for the generic model 3 (see text): allowing deviations in vertex loop coupling strengths and in the total width. (a) Profile likelihood ratio as a function of the coupling strength scale factor ratio $\lambda_{WZ}$ (other parameters are profiled). (b) Profile likelihood ratio as a function of the coupling strength scale factor ratio $\lambda_{tg}$ (other parameters are profiled). (c) Profile likelihood ratio as a function of the coupling strength scale factor ratio $\lambda_{\gamma Z}$ (other parameters are profiled). The dashed curves show the SM expectations. The red(green) horizontal lines indicate the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.
6. Conclusion

The Higgs boson production and decay properties are studied using the \( pp \) data collected by the ATLAS experiment at the LHC corresponding to integrated luminosities of up to \( 4.7 \text{ fb}^{-1} \) at \( \sqrt{s} = 7 \text{ TeV} \) and \( 20.3 \text{ fb}^{-1} \) at \( \sqrt{s} = 8 \text{ TeV} \). The study combines specific analyses of the \( H \to \gamma\gamma \), \( ZZ^* \), \( WW^* \), \( Z\gamma \), \( b\bar{b} \), \( \tau\tau \) and \( \mu\mu \) decay channels, as well as searches for \( ttH \) production and measurements of off-shell Higgs boson production. It significantly extends a previous combination of the \( H \to \gamma\gamma \), \( ZZ^* \) and \( WW^* \) decays [27]. In particular, the addition of the fermionic decays of the Higgs boson in the combinations allows for direct tests of the Yukawa interactions of the Higgs boson with fermions.

The measured Higgs boson signal yields are compared with the SM expectations at the fixed Higgs boson mass of \( m_H = 125.36 \text{ GeV} \). The combined yield relative to its SM prediction is determined to be \( 1.18 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (expt.)} \pm 0.08 \text{ (theo.)} \). Advances in theoretical calculations are required to improve the precision of future measurements of the combined relative yield. The combined analysis provides strong evidence for the vector boson fusion production of the Higgs boson with a significance of \( 4.3\sigma \). Furthermore, it supports the SM predictions of the Higgs boson production in association with a vector boson or a pair of top quark. Values for the total cross sections can be extrapolated from the signal strengths of each production process within the uncertainties related to the modelling of Higgs production and decay kinematics and assuming SM decay branching ratios. The total cross sections at \( \sqrt{s} = 7 \) and \( 8 \text{ TeV} \) are \( [22.1^{+6.7}_{-5.3} \text{ (stat.)}^{+2.7}_{-2.3} \text{ (expt.)}^{+1.9}_{-1.4} \text{ (theo.)}] \text{ pb} \) and \( [27.7 \pm 3.0 \text{ (stat.)}^{+2.0}_{-1.7} \text{ (expt.)}^{+1.2}_{-0.9} \text{ (theo.)}] \text{ pb} \), respectively.

The observed Higgs boson production and decay rates are also interpreted in a leading order coupling framework, exploring a wide range of benchmark coupling models both with and without assumptions on the Higgs boson width and on the SM particle content of loop processes. Evidence for Higgs boson couplings to down-type fermions is found with a \( 4.5\sigma \) significance, under the assumption of unified coupling scale factors to the vector bosons.

The Higgs boson coupling strengths to fermions and bosons are measured with a precision of \( \pm 16\% \) and \( \pm 7\% \) respectively, when assuming the SM Higgs boson width, and are observed to be compatible with the SM expectations. Coupling strengths of loop processes are measured with a precision of \( \pm 12\% \) when assuming the SM expectations for non-loop Higgs boson coupling strengths and the Higgs boson total width, increasing to about \( \pm 20\% \) when these assumptions are removed. No significant deviations from the SM expectations of Higgs boson coupling strengths in loop processes are observed.

Generic Higgs boson coupling models that measure coupling strengths to \( \mu, \tau \) leptons, \( b, t \) quarks and \( W, Z \)-bosons, or ratios of these coupling strengths, are presented. They can constrain the ratio of \( W \) and \( Z \) coupling strengths, a probe of custodial symmetry, with a precision of \( \pm 13\% \). For benchmark models that measure absolute coupling strengths, a variety of physics-motivated constraints on the Higgs boson total width has been explored. The measured Higgs boson coupling strengths and their precision are found to be only weakly dependent on the choice of these constraints. The third generic benchmark model of Section 5.6.3 uses only the most basic assumptions of Section 5 and hence represents the most model-independent determination of the coupling strength scale factors that is currently possible. In this model ratios of couplings are constrained with a precision at the \( 15\%-40\% \) level, depending on the ratio considered. For some ratios, only limits can be obtained with the currently available statistical and systematic uncertainties.
For all considered benchmark models, the $p$-values expressing compatibility of the SM hypothesis with the best-fit point under the considered benchmark models ranges between 29% and 99%. The observed data are thus very compatible with the SM expectation under a wide range of assumptions.

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We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

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References

[34] M. Oreglia, SLAC-R-0236 (1980).
[53] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations; LEP and Tevatron Electroweak Working Group; and SLD Electroweak and Heavy Flavour Groups, arXiv:1012.2367 [hep-ex].
Auxiliary material

A. Probing the custodial symmetry of the W and Z couplings

This dedicated model for probing the custodial symmetry is retained for historical comparison. The generic model Section 5.6.2 also tests custodial symmetry with fewer assumptions and a comparable precision and yields consistent results and is considered to be the main result.

Identical coupling scale factors for the W and Z boson are required within tight bounds by the SU(2) custodial symmetry and the $\rho$ parameter measurements at LEP and at the Tevatron [53]. To test this constraint directly in the Higgs sector, the ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$ is probed. For the other parameters the same assumptions as in Section 5.2.1 on $\kappa_F$ are made ($\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$). The free parameters are:

$$
\begin{align*}
\lambda_{WZ} &= \kappa_W/\kappa_Z \\
\lambda_{FZ} &= \kappa_F/\kappa_Z \\
\kappa_{ZZ} &= \kappa_Z \cdot \kappa_Z/\kappa_H.
\end{align*}
$$

The ratio $\lambda_{WZ}$ is in part directly constrained by the decays in the $H \rightarrow WW^* \rightarrow \ell\ell\nu\nu$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels and the $WH$ and $ZH$ production processes. It is also indirectly constrained by the VBF production process, which in the SM is 74% W fusion and 26% Z fusion-mediated (see Table 6). The scale factor $\kappa_W$ is also constrained by the $H \rightarrow \gamma\gamma$ channel since the decay branching ratio receives a dominant contribution from the W loop.

![Figure 23: Results of fits for the benchmark model that probe the custodial symmetry through the ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$ ($\lambda_{FZ}$ and $\kappa_{ZZ}$ are profiled); The dashed curves show the SM expectations. The red(green) horizontal lines indicates the cutoff values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic $\chi^2$ distribution for the test statistic.

The fit prefers the SM-like local minimum with a positive sign for $\lambda_{FZ}$, implying a positive relative sign between the fermion and Z couplings. 

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The fit results for the parameters of interest, when profiling the other parameters, are:

\[
\begin{align*}
\lambda_{WZ} &= 1.00^{+0.15}_{-0.11} \\
\lambda_{FZ} &= 1.03^{+0.21}_{-0.18} \\
\kappa_{ZZ} &= 1.06^{+0.29}_{-0.24} 
\end{align*}
\]

The three-dimensional compatibility of the SM hypothesis with the best-fit point is 62%.

**B. Additional plots**

Figure 24: Likelihood scans of VBF (left), VH (middle) and ttH (right) cross sections relative to that of ggF. See Section 4.4 for details. The dashed horizontal lines at 1(4) indicates the cut-off values on the profile likelihood ratio corresponding to a 68%(95%) confidence interval on the parameter of interest, assuming the asymptotic \( \chi^2 \) distribution for the test statistic.
**ATLAS** Preliminary

$m_H = 125.36$ GeV

<table>
<thead>
<tr>
<th>$H \to \gamma\gamma$</th>
<th>$\mu_{\text{obs}} = 1.17^{+0.28}_{-0.26}$</th>
<th>$\mu_{\text{exp}} = 1.00^{+0.25}_{-0.23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to ZZ^*$</td>
<td>$\mu_{\text{obs}} = 1.46^{+0.40}_{-0.34}$</td>
<td>$\mu_{\text{exp}} = 0.99^{+0.31}_{-0.26}$</td>
</tr>
<tr>
<td>$H \to WW^*$</td>
<td>$\mu_{\text{obs}} = 1.18^{+0.24}_{-0.21}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+0.21}_{-0.19}$</td>
</tr>
<tr>
<td>$H \to b\bar{b}$</td>
<td>$\mu_{\text{obs}} = 0.63^{+0.39}_{-0.37}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+0.41}_{-0.38}$</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$\mu_{\text{obs}} = 1.44^{+0.42}_{-0.37}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+0.38}_{-0.32}$</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>$\mu_{\text{obs}} = -0.7^{+3.4}_{-3.7}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+3.7}_{-3.7}$</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>$\mu_{\text{obs}} = 2.7^{+4.6}_{-4.5}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+4.2}_{-4.2}$</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>$\mu_{\text{obs}} = 1.18^{+0.15}_{-0.14}$</td>
<td>$\mu_{\text{exp}} = 1.00^{+0.13}_{-0.12}$</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV, 4.5-4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Figure 25: The observed and expected signal strengths and uncertainties for different Higgs boson decay channels and their combination for $m_H = 125.36$ GeV. Higgs boson signals of the same decay in all analyses are combined together. The best-fit values are shown by the solid vertical lines. The observed total ±1σ uncertainties are indicated by green shaded bands and blue error bars, whereas the expected ±1σ total uncertainties are indicated by red error bars, centered at the expected signal strength of 1.
Figure 26: Correlation matrix of the coupling strength ratio parameter of Generic Model 3, detailed in Section 5.6.3.