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Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration

1. Introduction

The discovery of a new particle of mass about 125 GeV in the search for the Standard Model (SM) Higgs boson at the CERN Large Hadron Collider (LHC) [1], reported in July 2012 by the ATLAS [2] and CMS [3] Collaborations, is a milestone in the quest to understand the origin of electroweak symmetry breaking [4–9].

This Letter presents measurements of several properties of the newly observed particle, including its mass, production strengths and couplings to fermions and bosons, using diboson final states\(^1\): \(H \to \gamma\gamma\), \(H \to ZZ^* \to 4\ell\), and \(H \to WW^* \to \ell\ell\nu\nu\). Spin studies are reported elsewhere [10]. Due to the outstanding performance of the LHC accelerator throughout 2012, the present data sample is a factor of \(\sim\)2.5 larger than that used in Ref. [2]. With these additional data, many aspects of the ATLAS studies have been improved: several experimental uncertainties have been reduced and new exclusive analyses have been included. In particular, event categories targeting specific production modes have been introduced, providing enhanced sensitivity to different Higgs boson couplings.

The results reported here are based on the data samples recorded with the ATLAS detector [11] in 2011 (at \(\sqrt{s} = 7\) TeV) and 2012 (at \(\sqrt{s} = 8\) TeV), corresponding to integrated luminosities of about 4.7 fb\(^{-1}\) and 20.7 fb\(^{-1}\), respectively. Similar studies, including also fermionic decays, have been reported recently by the CMS Collaboration using a smaller dataset [12].

This Letter is organised as follows. Section 2 describes the data sample and the event reconstruction. Section 3 summarises the measurements of Higgs boson production and couplings in diboson final states. Section 4 presents studies of Higgs boson production using the decays into boson pairs, \(H \to \gamma\gamma\), \(H \to ZZ^* \to 4\ell\), and \(H \to WW^* \to \ell\ell\nu\nu\). The results are based on the complete pp collision data sample recorded by the ATLAS experiment at the CERN Large Hadron Collider at centre-of-mass energies of \(\sqrt{s} = 7\) TeV and \(\sqrt{s} = 8\) TeV, corresponding to an integrated luminosity of about 25 fb\(^{-1}\). Evidence for Higgs boson production through vector-boson fusion is reported. Results of combined fits probing Higgs boson couplings to fermions and bosons, as well as anomalous contributions to loop-induced production and decay modes, are presented. All measurements are consistent with expectations for the Standard Model Higgs boson.

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Table 1

<table>
<thead>
<tr>
<th>Source (experimental)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>±1.8 (2011), ±3.6 (2012)</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>±2.5</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>±1.1</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>±2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source (theory)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale</td>
<td>±8 (ggF, ±1 (VBF, VH), ±4 (tHt))</td>
</tr>
<tr>
<td>PDFs + αs</td>
<td>±8 (ggF, tHt), ±4 (VBF, VH)</td>
</tr>
</tbody>
</table>

H → γγ analysis: a different primary vertex definition is used, as described in Section 4.

Muon candidates [17] are formed by matching reconstructed tracks in the inner detector (ID) with either complete tracks or track segments reconstructed in the muon spectrometer (MS). The muon acceptance is extended to the region 2.5 < |η| < 2.7, which is outside the ID coverage, using tracks reconstructed in the forward part of the MS.

Electron candidates [18] must have a well-reconstructed ID track pointing to a cluster of cells with energy depositions in the electromagnetic calorimeter. The cluster should satisfy a set of identification criteria requiring the longitudinal and transverse shower profiles to be consistent with those expected for electromagnetic showers. Tracks associated with electromagnetic clusters are fitted using a Gaussian Sum Filter [19], which allows bremsstrahlung energy losses to be taken into account. The identification criteria described in Ref. [18] have been modified with time to maintain optimal performance as a function of pile-up, in particular for low-PT electrons.

The reconstruction, identification and trigger efficiencies for electrons and muons, as well as their energy and momentum scales and resolutions, are determined using large samples of Z → ℓℓ, W → ℓv and J/ψ → ℓℓ events [18,20]. The resulting uncertainties are smaller than ±1% in most cases, one exception being the uncertainty on the electron selection efficiency which varies between ±2% and ±5% as a function of PT and η.

Photon candidates [21] are reconstructed and identified using shower shapes in the electromagnetic calorimeter, with or without associated conversion tracks, as described in Section 4.

Jets [22,23] are built from topological clusters [24] using the anti-kT algorithm [25] with a distance parameter R = 0.4. They are typically required to have transverse energies greater than 25 GeV (30 GeV) for |η| < 2.4 (2.4 < |η| < 4.5), where the higher threshold in the forward region reduces the contribution from jet candidates produced by pile-up. To reduce this contribution further, jets within the ID acceptance (|η| < 2.47) are required to have more than 25–75% (depending on the pile-up conditions and Higgs boson decay mode) of the summed scalar PT of their associated tracks coming from tracks originating from the event primary vertex. Pile-up corrections based on the average event transverse energy density in the jet area [26] and the number of reconstructed vertices in the data are also applied.

Jets originating from b-quarks [27–29] are identified (“b-tagged”) by combining information from algorithms exploiting the impact parameter of tracks (defined as the distance of closest approach to the primary vertex in the transverse plane), the presence of a displaced vertex, and the reconstruction of D- and B-hadron decays.

The missing transverse momentum, Emiss T, is the magnitude of the negative vector sum of the PT of muons, electrons, photons, jets and clusters of calorimeter cells with |η| < 4.9 not associated with these objects. The uncertainty on the Emiss T energy scale is obtained from the propagation of the uncertainties on the contributing components and thus depends on the considered final state. A track-based missing transverse momentum, PTmiss, is calculated as the negative vector sum of the transverse momenta of tracks associated with the primary vertex.

The main sources of experimental uncertainty common to all the channels considered in this study are summarised in the top part of Table 1.

3. Signal and background simulation

The SM Higgs boson production processes considered in these studies are gluon fusion (gg → H, denoted ggF), vector-boson fusion (qq → qH, denoted VBF), and Higgs-strahlung (qg → WH, denoted VH) or jointly VH. The small contribution from the associated production with a τ pair (gg/qg → tH, denoted tH) is taken into account in the H → γγ and H → ZZ* analyses. Samples of MC-simulated events are employed to model Higgs boson production and compute signal selection efficiencies. The event generators are listed in Table 2. Cross-section normalisations and other corrections (e.g. Higgs boson PT spectrum) are obtained from up-to-date calculations as described in Refs. [2, 14–16,49–77]. Table 3 shows the production cross sections and the branching ratios for the final states considered in this study for a Higgs boson with mass mH = 125 GeV, while Table 1 summarises the theoretical uncertainties on the expected signal common to all channels.

Backgrounds are determined using data alone or a combination of data and MC simulation, as discussed in Sections 4–6. The generators employed in most cases are also listed in Table 2. To generate parton showers and their hadronisation, and to simulate the underlying event [78–80], PYTHIA6 (for 7 TeV samples as well as for 8 TeV samples produced with MadGraph or Acheck) is used. Alternatively, HERWIG is employed, combined with the underlying event simulation provided by JIMMY [81]. When PYTHIA6 or HERWIG is used, PHOTOS [82,83] is employed to describe additional photon radiation from charged leptons. The small contributions from Z* and W* decays to electrons and muons through intermediate τ-leptons are included in the signal and background generation.

The following parton distribution function (PDF) sets are used in most cases: CT10 [84] for the POWHEG, MC@NLO, gg2WW and
The number of events in the diphoton mass region 100–160 GeV, after applying the requirements to the photon candidates, is 23788 in the 7 TeV data and 118893 in the 8 TeV data. The fraction of genuine $\gamma\gamma$ events, as estimated from data [93], is $(75.4\pm1.9)$%.

4.2. Event categorisation

To increase the sensitivity to the overall Higgs boson signal, as well as to the specific VBF and VH production modes, the selected events are separated into 14 mutually exclusive categories for further analysis, following the order of preference listed below.

Lepton category (8 TeV data only): This category targets mainly $W$ and $Z$ bosons decays to charged leptons. An isolated electron ($E_T > 15$ GeV) or muon ($p_T > 10$ GeV) candidate is required. To remove contamination from $Z\ell\ell$ production with $Z \to ee$, electrons forming an invariant mass with either photon in the range $84\text{ GeV} < m_{\gamma\gamma} < 94\text{ GeV}$ are not considered.
Untagged categories: Events not selected in any of the above categories (corresponding to more than 90% of the expected signal, dominated by ggF production) are classified in nine additional categories according to the properties of their diphoton system. Events with both photons unconverted are classified into unconverted central if $|\eta| < 0.75$ for both photons, and unconverted rest otherwise. Events with at least one converted photon are similarly separated into converted central if $|\eta| < 0.75$ for both photons, converted transition if $1.3 < |\eta| < 1.75$ for either photon, and converted rest otherwise. Finally, all untagged categories except converted transition are split into low $p_T^{\gamma}$ and high $p_T^{\gamma}$ sub-categories by a cut at $p_T^{\gamma} = 60$ GeV. This classification is motivated by differences in mass resolution and signal-to-background ratio for the various categories.

The use of the 14 categories improves the sensitivity of the analysis by about 40% compared to the inclusive analysis.

4.3. Background estimation

The background is obtained from fits to the diphoton mass spectrum in the data over the range 100–160 GeV after the full selection. The procedure, the choice of the analytical forms for the background and the determination of the corresponding uncertainties follow the method described in Ref. [2]. Depending on the category, the analytical form is either a fourth-order Bernstein polynomial [96] (used also for the inclusive sample), an exponential of a second-order polynomial, or a single exponential. In these fits, the Higgs boson signal is described by the sum of a Crystal Ball function [97] for the core of the distribution and a Gaussian function for the tails.

4.4. Systematic uncertainties

Systematic uncertainties can affect the signal yield, the signal fractions in the various categories (with possible migrations between them), the signal mass resolution and the mass measurement. The main sources specific to the $H \to \gamma\gamma$ channel are listed in Table 4, while sources in common with other decay channels are summarised in Section 2 and Table 1. The uncertainties described below are those affecting the 8 TeV analysis (see Ref. [2] for the 7 TeV analysis).

Signal yield: Relevant experimental uncertainties on the signal yield come from the knowledge of the luminosity (Table 1) and the photon identification efficiency. The latter is estimated by comparing the efficiencies obtained using MC simulations and several data-driven methods: $Z \to ee$ events with a simulation-based extrapolation from electrons to photons, an isolation sideband technique using an inclusive photon sample, and photons from $Z \to \ell\ell$ radiative decays. Owing to several analysis improvements and the large size of the 8 TeV data sample, the resulting uncertainty is significantly reduced compared to that reported in Ref. [2] and amounts to $\pm 2.4\%$. Smaller experimental uncertainties come from the knowledge of the trigger efficiency, the impact of the photon isolation requirement and the photon energy scale. In addition to the theoretical uncertainties on inclusive Higgs boson production listed in Table 1, the ggF contribution to the two-jet categories is subject to large uncertainties (Table 4) due to missing higher-order corrections; they are estimated using the method described in Ref. [98] and the MCFM [99] generator calculations. Finally, the background modelling contributes an uncertainty between $\pm 2\%$ and $\pm 14\%$ depending on the category.

Event migration: Mis-modelling of the detector material could cause event migration between the unconverted and converted photon categories in the simulation. The uncertainty is obtained from MC samples produced with variations of the material de-
The uncertainty in the population of the $p_T$ categories due to the description of the Higgs boson $p_T$ spectrum is determined by varying the QCD scales and PDFs used in the H_qT program [62]. Uncertainties on the modelling of two-jet variables for the ggF process, in particular $\Delta \phi_{\gamma\gamma,ij}$ and $\eta^*$, affect the contribution of ggF events to the high-mass two-jet categories. They are estimated by comparing the baseline POWHEG generator with SHERPA and MCFM. Uncertainties on the jet energy scale and resolution affect the selection of jets used in some category definitions, thereby causing migration between jet-based and other categories. The uncertainty due to the modelling of the underlying event is estimated by comparing the reconstructed $E_T^{miss}$ with the sum of the jet energy and the missing transverse energy. The uncertainty in the population of the $p_T$ categories is determined by varying the transverse energies of its components (photons, electrons, jets, soft energy deposits) within their respective uncertainties.

**Mass measurement and mass resolution:** The measurement of the Higgs boson mass in the $H \rightarrow \gamma\gamma$ channel is discussed in Section 7.2. Uncertainties on the diphoton mass distribution are determined by varying the energy scale of the detector material, and the knowledge of the energy scale of the presampler detector located in front of the electromagnetic calorimeter. The total uncertainty amounts to $\pm 0.55\%$ (corresponding to $\pm 0.7$ GeV). The mass resolution, obtained from the Crystal Ball function used in the fits described in Section 4.3, ranges from 1.4 GeV to 2.5 GeV depending on the category. The main uncertainties come from the calorimeter energy scale and the extrapolation from the electron to the photon response. Smaller contributions arise from pile-up and the primary vertex selection.

### Table 4

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On signal yield</td>
<td>$\pm 4.2$</td>
</tr>
<tr>
<td>Trigger</td>
<td>$\pm 0.5$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\pm 1.0$</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>$\pm 0.25$</td>
</tr>
<tr>
<td>ggF (theory), tight high-mass two-jet cat.</td>
<td>$\pm 0.48$</td>
</tr>
<tr>
<td>ggF (theory), loose high-mass two-jet cat.</td>
<td>$\pm 0.28$</td>
</tr>
<tr>
<td>ggF (theory), low-mass two-jet cat.</td>
<td>$\pm 0.30$</td>
</tr>
<tr>
<td>Impact of background modelling</td>
<td>$\pm (2-14)$, cat.-dependent</td>
</tr>
<tr>
<td>On category population (migration)</td>
<td>$\pm 4$ (unconv), $+3.5$ (conv)</td>
</tr>
<tr>
<td>$p_T$ modelling</td>
<td>$\pm (9-12)$ (high-$p_T$, jets), $\pm (2-4)$ (lepton, $E_T^{miss}$)</td>
</tr>
<tr>
<td>$\Delta \phi_{\gamma\gamma,ii}, \eta^*$ modelling in ggF</td>
<td>$\pm (9-12), \pm (6-8)$</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>$\pm (7-12)$ (jets), $\pm (0-1)$ (others)</td>
</tr>
<tr>
<td>Underlying event two-jet cat.</td>
<td>$\pm 4$ (high-mass tight), $\pm 8$ (high-mass loose), $\pm 12$ (low-mass)</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>$\pm 4$ (low-mass category)</td>
</tr>
<tr>
<td>On mass scale and resolution</td>
<td>$\pm 0.6$, cat.-dependent</td>
</tr>
<tr>
<td>Signal mass resolution</td>
<td>$\pm (14-23)$, cat.-dependent</td>
</tr>
</tbody>
</table>

### 5. The $H \rightarrow ZZ^* \rightarrow 4\ell$ channel

Despite the small branching ratio, this channel provides good sensitivity to Higgs boson studies, e.g. to the coupling to $Z$ bosons, mainly because of the large signal-to-background ratio.

Events are required to have two pairs of same-flavour, opposite-charge, isolated leptons: $4e$, $2e2\mu$, $2\mu2\mu$, $4\mu$ (where final states with two electrons and two muons are ordered by the flavour of the dilepton pair with mass closest to the $Z$ boson mass). The largest background comes from continuum $(Z^{(*)}/\gamma^*)(Z^{(*)}/\gamma^*)$ production, referred to hereafter as $ZZ^*$. Important contributions arise also from $Z + \text{jets}$ and $t\bar{t}$ production, where two of the charged lepton candidates can come from decays of hadrons with $b$- or $c$-quark content, misidentification of light-quark jets, and photon conversions.

The analysis presented here is largely the same as that described in Ref. [100] with only minor changes. The electron identification is tightened in the 8 TeV data to improve the background rejection for final states with a pair of electrons forming the lower-mass $Z^*$ boson. The mass measurement uses a constrained fit to the $Z$ mass to improve the resolution. The lepton pairing is modified to reduce the mis-pairing in the $4\mu$ and $4e$ final states, and the minimum requirement on the mass of the second $Z^*$ boson is relaxed. Final-state radiation (FSR) is included in the reconstruction of the first $Z^{(*)}$ in events containing muons. Finally, a classification
which separates Higgs boson candidate events into ggF-like, VBF-like and VH-like categories is introduced.

5.1. Event selection

The data are selected using single-lepton or dilepton triggers. The $p_T$ threshold of the single-muon trigger is 24 GeV (18 GeV) in 2012 (2011) and the $E_T$ threshold of the single-electron trigger is 24 GeV (20–22 GeV). The dielectron trigger threshold is $E_T = 12$ GeV and the dimuon trigger threshold is $p_T = 13$ GeV (10 GeV in 2011) for both leptons. In addition, an asymmetric dimuon trigger and electron–muon triggers are used as described in Ref. [100]. The efficiency for events passing the offline analysis cuts is selected by at least one of the above triggers is between 97% and 100%.

Muon and electron candidates are reconstructed as described in Section 2. In the region $|\eta| < 0.1$, which has limited MS coverage, ID tracks with $p_T > 15$ GeV are identified as muons if their calorimetric energy deposits are consistent with a minimum ionising particle. Only one muon per event is allowed to be reconstructed either in the MS alone or without MS information. For the 2012 data, the electron requirements are tightened in the transition region between the barrel and end-cap calorimeters (1.37 < $|\eta|$ < 1.52), and the pixel-hit requirements are stricter to improve the rejection of photon conversions.

Each electron (muon) must satisfy $E_T > 7$ GeV ($p_T > 6$ GeV) and be measured in the pseudorapidity range $|\eta| < 2.47$ ($|\eta| < 2.7$). The highest-$p_T$ lepton in the quadruplet must satisfy $p_T > 20$ GeV, and the second (third) lepton must satisfy $p_T > 15$ GeV ($p_T > 10$ GeV). To reject cosmic rays, muon tracks are required to have a transverse impact parameter of less than 1 mm.

Multiple quadruplets within a single event are possible. For each quadruplet, the same-flavour, opposite-charge lepton pair with invariant mass closest to the Z boson mass ($m_2$) is referred to as the leading lepton pair. Its invariant mass, denoted by $m_{12}$, is required to be between 50 GeV and 106 GeV. The invariant mass of the other (sub-leading) lepton pair, $m_{34}$, is required to be in the range $m_{34} < m_{34} < 115$ GeV. The value of $m_{34}$ is 12 GeV for a reconstructed four-lepton mass $m_{4\ell} < 140$ GeV, rises linearly to 50 GeV at $m_{4\ell} = 190$ GeV, and remains constant for higher masses. If two or more quadruplets satisfy the above requirements, the one with $m_{34}$ closest to the Z boson mass is selected. For further analysis, events are classified in four sub-channels, 4e, 2e2\mu, 2\mu2e, 4\mu.

The $Z +$ jets and $t\bar{t}$ backgrounds are reduced by applying requirements on the lepton transverse impact parameter divided by its uncertainty, $|d_0|/\sigma_d$. This ratio must be smaller than 3.5 for muons and smaller than 6.5 for electrons (the electron impact parameter is affected by bremsstrahlung and thus its distribution has longer tails). In addition, leptons must satisfy isolation requirements based on tracking and calorimetric information, similar to those described in Section 4.1, as discussed in Ref. [2].

The impact of FSR photon emission on the reconstructed invariant mass is modelled using the MC simulation (PHOTOS), which reproduces the rate of collinear photons with $E_T > 1.3$ GeV in $Z \rightarrow \mu\mu$ decays in data to $\pm5\%$ [101]. Leading muon pairs with $66$ GeV < $m_{12}$ < 89 GeV are corrected for FSR by including any reconstructed photon with $E_T$ above 1 GeV lying close (typically within $\Delta R < 0.15$) to the muon tracks, provided that the corrected $m_{12}$ satisfies $m_{12} < 100$ GeV. The MC simulation predicts that about 4% of all $H \rightarrow ZZ^* \rightarrow 4\mu$ candidate events should have this correction.

For the 8 TeV data, the signal reconstruction and selection efficiency for a SM Higgs boson with $m_H = 125$ GeV is 39% for the 4μ sub-channel, 26% for the 2e2μ/2μ2e sub-channels and 19% for the 4e sub-channel.

The final discriminating variable in this analysis is the 4ℓ invariant mass. Its resolution, which is improved by typically 15% by applying a Z-mass constrained kinematic fit to the leading lepton pair, is about 1.6 GeV, 1.9 GeV and 2.4 GeV for the 4μ, 2e2μ/2μ2e and 4e sub-channels, respectively, and for $m_H = 125$ GeV.

5.2. Event categorisation

To enhance the sensitivity to the individual production modes, events passing the above selection are assigned to one of three categories, named VBF-like, VH-like, and ggF-like. Events are VBF-like if the two highest $p_T$ jets are separated by more than three units in pseudorapidity and have an invariant mass greater than 350 GeV. Events that do not qualify as VBF-like are considered for the VH-like category, and about 1.5 for the inclusive analysis.

The expected background yield and composition is estimated using the MC simulation for $ZZ^*$ production, and methods based on control regions (CRs) from data for the $Z +$ jets and $t\bar{t}$ processes [2]. The transfer factors used to extrapolate the background yields from the CRs to the signal region are obtained from the MC simulation and cross-checked with data. Since the background composition depends on the flavour of the sub-leading lepton pair, different approaches are followed for the $\ell\ell + \mu\mu$ and the $\ell\ell + ee$ final states.

Table 5

For the $H \rightarrow \gamma\gamma$ analysis of the $\sqrt{s} = 8$ TeV data, the numbers of events observed in the data ($N_0$), the numbers of background events ($N_b$) estimated from fits to the data, and the expected SM Higgs boson signal ($N_s$) for $m_H = 126.8$ GeV, split by category. All numbers are given in a mass window centred at $m_H = 126.8$ GeV and containing 90% of the expected signal (the size of this window changes from category to category and for the inclusive sample). The predicted numbers of signal events in each of the ggF, VBF, WH and ZH processes are also given.

<table>
<thead>
<tr>
<th>Category</th>
<th>$N_0$</th>
<th>$N_b$</th>
<th>$N_s$</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>tH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged</td>
<td>14248</td>
<td>13582</td>
<td>350</td>
<td>320</td>
<td>19</td>
<td>7</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Loose high-mass two-jet</td>
<td>41</td>
<td>28</td>
<td>5.0</td>
<td>2.3</td>
<td>2.7</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Tight high-mass two-jet</td>
<td>23</td>
<td>13</td>
<td>7.7</td>
<td>1.8</td>
<td>5.9</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Low-mass two-jet</td>
<td>19</td>
<td>21</td>
<td>3.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.92</td>
<td>0.54</td>
<td>0.1</td>
</tr>
<tr>
<td>$E_T^{miss}$ significance</td>
<td>8</td>
<td>4</td>
<td>1.2</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.43</td>
<td>0.57</td>
<td>0.14</td>
</tr>
<tr>
<td>Lepton</td>
<td>20</td>
<td>12</td>
<td>2.7</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>1.7</td>
<td>0.41</td>
<td>0.50</td>
</tr>
<tr>
<td>All categories (inclusive)</td>
<td>13931</td>
<td>13205</td>
<td>370</td>
<td>330</td>
<td>27</td>
<td>10</td>
<td>5.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>
5.4. Systematic uncertainties

The dominant sources of systematic uncertainty affecting the $H \to ZZ^* \to 4\ell$ 8 TeV analysis are listed in Table 6 (see Ref. [2] for the 7 TeV analysis). Lepton reconstruction, identification and selection efficiencies, as well as energy and momentum resolutions and scales, are determined using large control samples from the data, as described in Section 2. Only the electron uncertainty contributes significantly to the uncertainty on the signal yield.

The background uncertainty is dominated by the uncertainty on the transfer factors from the CRs to the signal region and the available number of events in the control regions.

The uncertainty on the population of the various categories (migration) comes mainly from the knowledge of the theoretical cross sections for the various production processes, the modelling of the underlying event and the knowledge of the jet energy scale.

The $H \to ZZ^* \to 4\ell$ mass measurement is discussed in Section 7.2. The main sources contributing to the electron energy scale uncertainty are described in Section 4.4; the largest impact ($\pm 0.4\%$) is on the $4\ell$ final state. Systematic uncertainties from the knowledge of the muon momentum scale (discussed in detail in Ref. [100]) are smaller. Mass scale uncertainties related to FSR and background contamination are below $\pm 0.1\%$.

5.5. Results

The reconstructed four-lepton mass spectrum after all selections of the inclusive analysis is shown in Fig. 3. The data are compared to the (scaled) expected Higgs boson signal for $m_H = 124.3$ GeV and to the estimated backgrounds. At the maximum deviation from the background-only expectation (occurring at $m_H \sim 90$ GeV), the significance of the observed peak is $6.4\sigma$ for the combined 7 TeV and 8 TeV data, to be compared with $4.4\sigma$ expected from SM Higgs boson production at this mass. This result establishes a discovery-level signal in the $4\ell$ channel alone.

Additional interpretation of these results is presented in Section 7.

6. The $H \to WW^* \to t\bar{t}\ell\nu$ channel

This decay mode provides direct access to the Higgs boson couplings to W bosons. Its rate is large, but a narrow mass peak cannot be reconstructed due to the presence of two neutrinos in the

Table 6

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yield</td>
<td>$4\mu$ $2\mu2e$ $2e2\mu$ $4e$</td>
</tr>
<tr>
<td>Muon reconstruction and identification</td>
<td>$\pm 0.8$ $\pm 0.4$ $\pm 0.4$ $-$</td>
</tr>
<tr>
<td>Electron reconstruction and identification</td>
<td>$\pm 8.7$ $\pm 2.4$ $\pm 9.4$</td>
</tr>
<tr>
<td>Reducible background (inclusive analysis)</td>
<td>$\pm 24$ $\pm 10$ $\pm 23$ $\pm 13$</td>
</tr>
<tr>
<td>Migration between categories</td>
<td>$\pm 32/11/11$ $\pm 36$ $\pm 15/5/6$ $\pm 30$</td>
</tr>
<tr>
<td>Mass measurement</td>
<td>$4\mu$ $2\mu2e$ $2e2\mu$ $4e$</td>
</tr>
<tr>
<td>Lepton energy and momentum scale</td>
<td>$\pm 0.2$ $\pm 0.2$ $\pm 0.3$ $\pm 0.4$</td>
</tr>
</tbody>
</table>

Fig. 3. The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates in the data. The estimated background, as well as the expected SM Higgs boson signal for $m_H = 124.3$ GeV, for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data.
The reconstructed topology consists of two opposite-charge leptons and a large momentum imbalance from the neutrinos. The dominant SM backgrounds are $WW$ (which includes $WW^*$), $t\bar{t}$ and $Wt$, all of which produce two $W$ bosons. The classification of events by jet multiplicity ($N_{\text{jet}}$) allows the control of the background from top quarks, which contains $b$-quark jets, as well as the extraction of the signal strengths for the ggF and VBF production processes. For the hypothesis of a SM Higgs boson, the spin-zero initial state and the $V-A$ structure of the $W$ boson decays imply a correlation between the directions of the charged leptons, which can be exploited to reject the $WW$ background. These correlations lead to the use of quantities such as the dilepton invariant mass $m_{\ell\ell}$ and angular separation $\Delta\phi_{\ell\ell}$ in the selection criteria described below. Drell–Yan (DY) events ($pp \rightarrow Z/\gamma^* \rightarrow \ell\ell$) may be reconstructed with significant missing transverse momentum because of leptonic $\tau$ decays or the degradation of the $E_T^{\text{miss}}$ measurement in the high pile-up environment of the 2012 run. Finally, $W+\text{jets}$ production in which a jet is reconstructed as a lepton, and the diboson processes $WZ$, $WW$, and $Z^*Z^*$, are also significant backgrounds after all event selection.

The studies presented here are a significant update of those reported in Ref. [2]. The signal regions considered include $ee$, $e\mu$, and $\mu\mu$ final states with zero, one, or at least two reconstructed jets. The $N_{\text{jet}} > 2$ analysis has been re-optimised to increase the sensitivity to Higgs boson production through VBF for $m_H = 125$ GeV. Improved DY rejection and estimation techniques have allowed the inclusion of $ee$ and $e\mu\mu$ events from the 8 TeV data. The analysis of the 7 TeV data, most recently documented in Ref. [103], has been updated to apply improvements from the 8 TeV analysis, including more stringent lepton isolation requirements, which reduce the $W+\text{jets}$ background by 40%.

6.1. Event selection

Events are required to have two opposite-charge leptons ($e$ or $\mu$) and to pass the same single-lepton triggers as described in Section 5 for the $H \rightarrow ZZ^*$ channel. The leading lepton must satisfy $p_T > 25$ GeV and the sub-leading lepton $p_T > 15$ GeV. Electron and muon identification and isolation requirements (see Ref. [2]) are more restrictive than those used in the $H \rightarrow ZZ^*$ analysis in order to suppress the $W+\text{jets}$ background.

In the $ee/\mu\mu$ channels, $Z \rightarrow \ell\ell$ and low-mass $\gamma^* \rightarrow \ell\ell$ events, including $J/\psi$ and $\Upsilon$ production, are rejected by requiring $m_{\ell\ell} = m_Z > 15$ GeV and $m_{\ell\ell} > 12$ GeV, respectively. In the $e\mu\mu$ channels, low-mass $\gamma^* \rightarrow \tau\tau \rightarrow e\nu\nu\mu\nu\nu$ production is rejected by imposing $m_{\ell\ell} > 10$ GeV.

Drell–Yan and multi-jet backgrounds are suppressed by requiring large missing transverse momentum. For $N_{\text{jet}} \leq 1$, a requirement is made on $E_T^{\text{miss}} = E_T^{\text{miss}} \cdot \sin |\Delta\phi_{\ell\ell}^{\text{closest}}|$, where $\Delta\phi_{\ell\ell}^{\text{closest}}$ is the smallest azimuthal angle between the $E_T^{\text{miss}}$ vector and any jet or high-$p_T$ charged lepton in the event; if $|\Delta\phi_{\ell\ell}^{\text{closest}}| \geq \pi/2$, then $E_T^{\text{miss}} = E_T^{\text{rel}}$ is taken. For additional rejection of the DY background in the $ee/\mu\mu$ channels with $N_{\text{jet}} \leq 1$, the track-based $p_T^{\text{miss}}$ described in Section 2 is used, modified to $E_T^{\text{miss}}$ in a similar way as $E_T^{\text{rel}}$. For these channels, requirements are also made on $p_T^{\text{recoll}}$, an estimate of the magnitude of the soft hadronic recoil opposite to the system consisting of the leptons and any accompanying jet, normalised to the momentum of the system itself. The $E_T^{\text{recoll}}$ value in DY events is on average larger than that of non-DY events, where the high-$p_T$ system is balanced at least in part by recoiling neutrinos.

The $N_{\text{jet}} > 2$ analysis uses $E_T^{\text{miss}}$ instead of $E_T^{\text{rel}}$ because the larger number of jets in the final states reduces the signal efficiency of the $E_T^{\text{miss}}$ criterion. For the $ee/\mu\mu$ channels with $N_{\text{jet}} \geq 2$, an $E_T^{\text{miss}}$ variant called “$E_T^{\text{miss}}$” is also employed. In the calculation of $E_T^{\text{miss}}$, the energies of (soft) calorimeter deposits unassociated with high-$p_T$ leptons, photons, or jets are scaled by the ratio of the summed scalar $p_T$ of tracks from the primary vertex unmatched with such objects to the summed scalar $p_T$ of all tracks from any vertex in the event which are also unmatched with objects [104].

For all jet multiplicities, selections exploiting the kinematic features of $H \rightarrow WW^* \rightarrow \ell\ell\nu\nu\ell\ell$ events are applied. The dilepton invariant mass is required to be small, $m_{\ell\ell} < 50$ GeV for $N_{\text{jet}} \leq 1$ and $m_{\ell\ell} < 60$ GeV for $N_{\text{jet}} \geq 2$; the azimuthal separation of the leptons is also required to be small, $\Delta\phi_{\ell\ell} < 1.8$.

6.2. Event categorisation

The analysis is divided into categories with $N_{\text{jet}} = 0, N_{\text{jet}} = 1$, and $N_{\text{jet}} \geq 2$. In the $N_{\text{jet}} = 0$ analysis, $E_T^{\text{miss}} > 25$ GeV ($E_T^{\text{miss}} > 45$ GeV and $p_T^{\text{miss}} > 45$ GeV) is required for $e\mu$ ($e\mu\mu$) final states. The transverse momentum of the dilepton system is required to be large, $p_T^{\ell\ell} > 30$ GeV. For $e\mu/\mu\mu$ events, the hadronic recoil is required to be typical of events with neutrinos in the final state. $E_T^{\text{recoll}} < 0.05$. Finally, the azimuthal separation between the $p_T^{\ell\ell}$ and $E_T^{\text{miss}}$ vectors must satisfy $|\Delta\phi_{\ell\ell,E_T^{\text{miss}}} | \geq \pi/2$, in order to remove potentially poorly reconstructed events.

In the $N_{\text{jet}} = 1$ analysis, the $E_T^{\text{miss}}$ and $p_T^{\text{miss}}$ requirements are the same as for $N_{\text{jet}} = 0$, but the hadronic recoil threshold is looser, $E_T^{\text{recoll}} < 0.2$. The top-quark background is suppressed by rejecting events with a $b$-tagged jet. The $b$-tagging algorithm described in Section 2 is used, at an operating point with 85% efficiency for $b$-quark jets and a mis-tag rate of 11% for light-quark and gluon jets, as measured in a sample of simulated $tt$ events. The $Z \rightarrow \tau\tau$ background in $e\mu$ final states is suppressed using an invariant mass $m_{\tau\tau}$ computed assuming that the neutrinos from $\tau$ decays are collinear with the charged leptons [105] and that they are the only source of $E_T^{\text{miss}}$. The requirement $m_{\tau\tau} - m_Z > 25$ GeV is applied.

The $N_{\text{jet}} \geq 2$ analysis is optimised for the selection of the VBF production process. The two leading jets, referred to as “tagging jets”, are required to have a large rapidity separation, $|\Delta y_{jj}| > 2.8$, and a high invariant mass, $m_{jj} > 500$ GeV. To reduce the contribution from ggF, events containing any jet with $p_T > 20$ GeV in the rapidity gap between the two tagging jets are rejected. Both leptons are required to be in the rapidity gap. The DY background is suppressed by imposing $E_T^{\text{miss}} > 20$ GeV for $e\mu$, and $E_T^{\text{miss}} > 45$ GeV and $E_T^{\text{miss}} > 35$ GeV for $ee/\mu\mu$. The same $Z \rightarrow \tau\tau$ veto and $b$-jet veto are applied as in the $N_{\text{jet}} = 1$ analysis. The $\tau$ background is further reduced by requiring a small total transverse momentum, $|p_T^{\text{miss}}| < 45$ GeV, where $p_T^{\text{miss}} = p_T^{\ell\ell} + p_T^{\text{jets}} + E_T^{\text{miss}}$, and $p_T^{\text{jets}}$ is the vectorial sum of all jets in the event with $p_T > 25$ GeV.

The total signal selection efficiency for $H \rightarrow WW^* \rightarrow \ell\ell\nu\nu\ell\ell$ events produced with $\ell = e, \mu$, including all the final state topologies considered, is about 5.3% at 8 TeV for a Higgs boson mass of 125 GeV.

The dilepton transverse mass $m_T$ is the discriminating variable used in the fit to the data to extract the signal strength. It is defined as $m_T = ((E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |p_T^{\ell\ell} - E_T^{\text{miss}}|^2)^{1/2}$ with $E_T^{\ell\ell} = (|p_T^{\ell\ell}|^2 + m_{\ell\ell}^2)^{1/2}$. For the $e\mu$ channels with $N_{\text{jet}} \leq 1$, the fit is performed separately for events with $10$ GeV $< m_{\ell\ell} < 30$ GeV and events with $30$ GeV $< m_{\ell\ell} < 50$ GeV, since the signal-to-background ratio varies across the $m_{\ell\ell}$ distribution, as shown in Fig. 4.
from MCFM [106], except for the NLO cross sections normalised to the NLO cross sections exclusively indicated in the following as

\begin{align*}
\ell\bar{\ell} & \rightarrow \ell\bar{\ell} \nu\bar{\nu}
\end{align*}

and opposite-charge lepton pairs, as does \(W + \text{jets}\). The number and kinematic features of same-charge events which would otherwise pass the full event selection are compared to the above-mentioned predictions for these backgrounds, and good agreement is observed.

6.3.1. \(W + \text{jets}\)

The \(W + \text{jets}\) background is estimated using a CR in the data in which one of the two leptons satisfies the identification and isolation criteria, and the other lepton (denoted here as “anti-identified”) fails these criteria but satisfies looser requirements. All other analysis selections are applied. The contribution to the signal region is then obtained by scaling the number of events in the CR by transfer factors, defined as the ratio of the number of fully identified lepton candidates passing all selections to the number of anti-identified leptons. The transfer factors are obtained from a dijet sample as a function of the \(p_T\) and \(\eta\) of the anti-identified lepton.

6.3.2. \(Z/\gamma^*\)

The \(Z/\gamma^*\) yield in the \(ee/\mu\mu\) channels for \(N_{\text{jet}} \leq 1\) is estimated using the \(E_{\text{miss}}\) requirement efficiency in data for DY and non-DY processes. The former is measured in \(ee/\mu\mu\) events in the \(Z\) boson peak region. The latter is measured in the \(ee\) signal region, taking advantage of the fact that the \(E_{\text{miss}}\) distribution is nearly identical for all non-DY processes including the signal, as well as for \(ee\) and \(ee/\mu\mu\) final states. The DY normalisation in the \(ee/\mu\mu\) signal region can then be extracted, given the two measured efficiencies and the total number of events in the \(ee/\mu\mu\) signal region before and after the \(E_{\text{miss}}\) requirement. For the \(ee/\mu\mu\) channels with \(N_{\text{jet}} \geq 2\), the two-dimensional distribution \(E_{\text{miss}}^{\text{mass}}, \ell\bar{\ell}\) in the data is used to estimate the total \(Z/\gamma^*\) yield, as in Ref. [103].

The \(Z \rightarrow \tau\tau\) background is normalised to the data using an \(ee\) CR defined by the back-to-back configuration of the leptons, \(\Delta \phi_{\ell\bar{\ell}} > 2.8\). For the corresponding CR with \(N_{\text{jet}} \geq 2\), no \(b\)-tagged jets are allowed, and \(p_T^{\text{jet}} < 45\) GeV is required in addition, in order to reduce the contamination from top-quark production. A separate CR in the \(Z \rightarrow \ell\ell\) peak region is used to correct the modelling of the VBF-related event selection.

6.3.3. \(t\bar{t}\) and single top-quark

The top-quark background for the \(N_{\text{jet}} = 0\) category is estimated using the procedure described in Ref. [2], namely from the number of events in data with any number of reconstructed jets passing the \(E_{\text{miss}}^{\text{miss}}\) requirement (a sample dominated by top-quark production), multiplied by the fraction of top-quark events with no reconstructed jets obtained from simulation. This estimate is corrected using a CR containing \(b\)-tagged jets. The top-quark background in the \(N_{\text{jet}} \geq 1\) channels is normalised to the data in a CR defined by requiring exactly one \(b\)-tagged jet and all other signal selections except for the requirements on \(\Delta \phi_{\ell\ell}\) and \(m_{\ell\ell}\).

6.3.4. \(WW\)

The \(WW\) background for \(N_{\text{jet}} \leq 1\) is normalised using CRs in data defined with the same selection as the signal region except that the \(\Delta \phi_{\ell\ell}\) requirement is removed and the \(m_{\ell\ell}\) bound is modified: for \(N_{\text{jet}} = 0\) \(50\) GeV \(\leq m_{\ell\ell} < 100\) GeV is required, while for \(N_{\text{jet}} = 1\) \(m_{\ell\ell} > 80\) GeV is used to define the CR. Fig. 4 shows the \(m_{\ell\ell}\) distribution of \(ee\) events with \(N_{\text{jet}} = 0\) in the 8 TeV data. The level of agreement between the predicted background and the data for \(m_{\ell\ell} > 100\) GeV, a region with negligible signal contribution, validates the \(WW\) background normalisation and the extrapolation procedure based on the simulation. The \(N_{\text{jet}} \geq 2\) prediction is taken from simulation because of the difficulty of isolating a kinematic region with enough events and small contamination from the top-quark background.
For $m_H = 125$ GeV, the leading systematic uncertainties on the total signal and background yields for the 8 TeV $H \rightarrow WW^* \rightarrow e\mu\nu\nu$ analysis. All numbers are summed over lepton flavours. Sources contributing less than 4% are omitted, and individual entries below 1% are indicated with a ‘−’. Relative signs indicate correlation and anticorrelation (migration) between the $N_{\text{jet}}$ categories represented by adjacent columns, and a ‘±’ indicates an uncorrelated uncertainty. The exception is the jet energy scale and resolution, which includes multiple sources of uncertainty treated as correlated across categories but uncorrelated with each other. All rows are uncorrelated.

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{\text{jet}} = 0$</th>
<th>$N_{\text{jet}} = 1$</th>
<th>$N_{\text{jet}} \geq 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical uncertainties on total signal yield (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD scale for ggF, $N_{\text{jet}} \geq 0$</td>
<td>+13</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>QCD scale for ggF, $N_{\text{jet}} \geq 1$</td>
<td>+10</td>
<td>−27</td>
<td>−</td>
</tr>
<tr>
<td>QCD scale for ggF, $N_{\text{jet}} \geq 2$</td>
<td>−</td>
<td>−15</td>
<td>+4</td>
</tr>
<tr>
<td>QCD scale for ggF, $N_{\text{jet}} \geq 3$</td>
<td>−</td>
<td>−</td>
<td>+4</td>
</tr>
<tr>
<td>Paron shower and underlying event</td>
<td>+3</td>
<td>−10</td>
<td>±5</td>
</tr>
<tr>
<td>QCD scale (acceptance)</td>
<td>+4</td>
<td>+4</td>
<td>±3</td>
</tr>
<tr>
<td>Experimental uncertainties on total signal yield (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Uncertainties on total background yield (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>WW + jet transfer factors (theory)</td>
<td>±1</td>
<td>±2</td>
<td>±4</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>−</td>
<td>+7</td>
<td>+2</td>
</tr>
<tr>
<td>$f_{\text{recoll}}$ efficiency</td>
<td>±4</td>
<td>±2</td>
<td>−</td>
</tr>
</tbody>
</table>

6.4. Systematic uncertainties

The systematic uncertainties affecting this analysis are summarized here and described in detail in Ref. [107]. The leading sources, i.e., those resulting in at least 4% uncertainty on the total signal or background yield in at least one $N_{\text{jet}}$ category, are reported in Table 8.

Theoretical uncertainties on the inclusive signal production cross sections are given in Section 2. Additional, larger uncertainties from the QCD renormalisation and factorisation scales affect the predicted distribution of the ggF signal among the exclusive jet bins and can produce migration between categories. These uncertainties are estimated using the HNN program [108, 109] and the method reported in Ref. [110]. Their impact on the signal yield is summarised in Table 8, in addition to other non-negligible contributions (parton shower and underlying event modelling, as well as acceptance uncertainties due to QCD scale variations).

The experimental uncertainties affecting the expected signal and background yields are associated primarily with the reconstruction and identification efficiency, and with the energy and momentum scale and resolution, of the final-state objects (leptons, jets, and $E_T^{\text{miss}}$), as described in Section 2. The largest impact on the signal expectation comes from the knowledge of the jet energy scale and resolution (up to 6% in the $N_{\text{jet}} \geq 2$ channel).

For the $W$ and $W$ background in the $N_{\text{jet}} \leq 1$ final states, the theoretical uncertainties on the transfer factors (evaluated according to the prescription of Ref. [15]) include the impact of missing higher-order QCD corrections, PDF variations, and MC modelling choices. They amount to ±2% and ±4–6% relative to the predicted $WW$ background in the $N_{\text{jet}} = 0$ and $N_{\text{jet}} = 1$ final states, respectively. For the $WW$ yield in the $N_{\text{jet}} \geq 2$ channel, which is obtained from simulation, the total uncertainty is 42% for QCD production with gluon emission, and 11% for the smaller but non-negligible contribution from purely electroweak processes; the latter includes the size of possible interference with Higgs boson production through VBF. The resulting uncertainties on the total background yield for all $N_{\text{jet}}$ are quoted in Table 8.

The leading uncertainties on the top-quark background are experimental. The b-tagging efficiency is the most important of these, and it appears in Table 8 primarily through its effect on this background. Theoretical uncertainties on the top-quark background have the greatest relative importance, ±2% on the total background yield, for $N_{\text{jet}} \geq 2$, and therefore do not appear in Table 8.

The $W + \mu$ jets transfer factor uncertainty (±(40–45)%%) is dominated by differences in the jet composition between dijet and $W + \mu$ samples as observed in the MC simulation. The uncertainties on the muon and electron transfer factors are treated as correlated among the $N_{\text{jet}}$ categories but uncorrelated with each other. The impact on the total background uncertainty is at most ±2.5%.

The main uncertainty on the DY contribution in the $N_{\text{jet}} \leq 1$ channel comes from the use of the $f_{\text{recoll}}$ efficiency evaluated at the peak of the $Z$ boson mass distribution for the estimation of the DY contamination in the low-$m_T$ region.

The uncertainty on the $m_T$ shape for the total background, which is used in the fit to extract the signal yield, is dominated by the uncertainties on the normalisations of the individual components. The only explicit $m_T$ shape uncertainty is applied to the $WW$ background, and is determined by comparing several generators and showering algorithms.

The estimated background contributions with their uncertainties are listed in Table 9.

6.5. Results

Fig. 5 shows the transverse mass distributions after the full selection for $N_{\text{jet}} \leq 1$ and $N_{\text{jet}} \geq 2$ final states. The regions with $m_T > 150$ GeV are depleted of signal contribution; the level of agreement of the data with the expectation in these regions, which are different from those used to normalise the backgrounds, illustrates the quality of the background estimates. The expected numbers of signal and background events at 8 TeV are presented in Table 9. The VBF process contributes 2%, 12% and 81% of the predicted signal yield, for $N_{\text{jet}} \leq 1$ and $N_{\text{jet}} \geq 2$, respectively. The total number of observed events in the same $m_T$ windows as in Table 9 is 218 in the 7 TeV data and 1195 in the 8 TeV data.

An excess of events relative to the background-only expectation is observed in the data, with the maximum deviation (4.1σ) occurring at $m_T = 140$ GeV. For $m_T = 125.5$ GeV, a significance of 3.8σ is observed, compared with an expected value of 3.8σ for a SM Higgs boson.

Additional interpretation of these results is presented in Section 7.

7. Higgs boson property measurements

The results from the individual channels described in the previous sections are combined here to extract information about the Higgs boson mass, production properties and couplings.

7.1. Statistical method

The statistical treatment of the data is described in Refs. [111–115]. Hypothesis testing and confidence intervals are based on the profile likelihood ratio [116] $\Delta(\alpha)$. The latter depends on one or more parameters of interest $\alpha$, such as the Higgs boson production strength $\mu$ normalised to the SM expectation (so that $\mu = 1$ corresponds to the SM Higgs boson hypothesis and $\mu = 0$ to the background-only hypothesis), mass $m_H$, coupling strengths $k$, ratios of coupling strengths $\lambda$, as well as on nuisance parameters $\theta$.
with ground probability density functions (pdfs) in the discriminating of the above equation are built using sums of signal and back-

Fig. 5. The transverse mass distributions for events passing the full selection of the $H \to WW^* \to ℓνℓν$ analysis: (a) summed over all lepton flavours for final states with $N_{νν} \leq 1$; (b) different-flavour final states with $N_{νν} \geq 2$. The signal is stacked on top of the background, and in (b) is shown separately for the ggF and VBF production processes. The hatched area represents the total uncertainty on the sum of the signal and background yields from statistical, experimental, and theoretical sources. In the lower part of (a), the residuals of the data with respect to the estimated background are shown, compared to the expected $m_ℓ$ distribution of a SM Higgs boson.

$$\Lambda(α) = \frac{L(α, \hat{θ}(α))}{L(α, \hat{θ})}.$$  

The likelihood functions in the numerator and denominator of the above equation are built using sums of signal and background probability density functions (pdfs) in the discriminating variables (chosen to be the $γγ$ and $4ℓ$ mass spectra for $H \to γγ$ and $H \to ZZ^* \to 4ℓ$, respectively, and the $m_T$ distribution for the $H \to WW^* \to ℓνℓν$ channel). The pdfs are derived from MC simulation for the signal and from both data and simulation for the background, as described in Sections 4–6. Likelihood fits to the observed data are done for the parameters of interest. The single circumflex in Eq. (1) denotes the unconditional maximum likelihood estimate for given fixed values of the parameters of interest $α$. Systematic uncertainties and their correlations [111] are modelled by introducing nuisance parameters $θ$ described by likelihood functions associated with the estimate of the corresponding effect. 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 at the values that maximise the likelihood function for the given fixed values of the parameters of interest.

Table 9

<table>
<thead>
<tr>
<th>$N_{νν}$</th>
<th>Observed</th>
<th>Signal</th>
<th>Total background</th>
<th>$WW$</th>
<th>Other $VV$</th>
<th>Top-quark</th>
<th>Z+jets</th>
<th>W+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>831</td>
<td>100 ± 21</td>
<td>739 ± 39</td>
<td>551 ± 41</td>
<td>108 ± 40</td>
<td>58 ± 8</td>
<td>30 ± 10</td>
<td>61 ± 21</td>
</tr>
<tr>
<td>1</td>
<td>309</td>
<td>41 ± 14</td>
<td>261 ± 28</td>
<td>108 ± 40</td>
<td>27 ± 6</td>
<td>27 ± 6</td>
<td>12 ± 6</td>
<td>20 ± 5</td>
</tr>
<tr>
<td>≥ 2</td>
<td>55</td>
<td>10.9 ± 1.4</td>
<td>36 ± 4</td>
<td>41 ± 1.5</td>
<td>1.9 ± 0.4</td>
<td>5.4 ± 2.1</td>
<td>22 ± 3</td>
<td>0.7 ± 0.2</td>
</tr>
</tbody>
</table>

$H \to WW^* \to ℓνℓν$ channel.

$7.2. Mass and production strength$

The mass of the new particle is measured from the data using the two channels with the best mass resolution, $H \to γγ$ and $H \to ZZ^* \to 4ℓ$. In the two cases, $m_{H} = 126.8 ± 0.2(\text{stat}) ± 0.7(\text{sys})$ GeV and $m_{H} = 124.3^{+0.6}_{−0.5}(\text{stat})–0.5(\text{sys})$ GeV are obtained from fits to the mass spectra.

To derive a combined mass measurement, the profile likelihood ratio $Λ(m_0)$ is used; the signal production strengths $μ^{γγ}$ and $μ^{4ℓ}$, giving the signal yields measured in the two individual channels, are normalised to the SM expectation, are treated as independent nuisance parameters in order to allow for the possibility of different deviations from the SM prediction in the two decay modes. The ratios of the cross sections for the various production modes for each channel are fixed to the SM values. It was verified that this restriction does not cause any bias in the results. The combined mass is measured to be:

$$m_{H} = 125.5 ± 0.2(\text{stat})^{+0.5}_{−0.6}(\text{sys})\text{ GeV.}$$

As discussed in Sections 4.4 and 5.4, the main sources of systematic uncertainty are the photon and lepton energy and momentum scales. In the combination, the consistency between the muon and electron final states in the $H \to γγ$ channel causes a $0.8σ$ adjustment of the overall $e/γ$ energy scale, which translates into a $350$ MeV downward shift of the fitted $m_{H}^{γγ}$ value with respect to the value measured from the $H \to γγ$ channel alone.

To quantify the consistency between the fitted $m_{H}^{γγ}$ and $m_{H}^{4ℓ}$ masses, the data are fitted with the profile likelihood ratio $Λ(Δm_0)$, where the parameter of interest is the mass difference $Δm_0 = m_{H}^{γγ} − m_{H}^{4ℓ}$. The average mass $m_{H}$ and the signal strengths...
To give a value of \( \Lambda(\Delta_{1}\sigma) \) is more strongly than observed in the data is found to be at the energy scale of the presampler detector) the consistency between the material upstream of the electromagnetic calorimeter and the \( \Lambda(\mu) \) is determined from a fit to the data using the profile likelihood at 0. The measured production strengths for a Higgs boson of mass \( m_H = 125.5 \text{ GeV} \), normalised to the SM expectations, for the individual diboson final states and their combination. Results are also given for the main categories of each analysis (described in Sections 4.2, 5.2, and 6.2). The best-fit values are shown by the solid vertical lines, with the total \( \pm 1\sigma \) uncertainty indicated by the shaded band, and the statistical uncertainty by the superimposed horizontal error bars. The numbers in the second column specify the contributions of the (symmetrised) statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the theory uncertainty (bottom) on the signal cross section (from QCD scale, PDF, and branching ratios) alone; for the individual categories only the statistical uncertainty is given.

\[
\sigma_{\text{stat}} + \sigma_{\text{sys}} = \sigma_{\text{theo}} \pm 1\sigma \text{ on } \mu 
\]

where the production strengths measured in the three channels and in their main analysis categories are presented. The signal production strength normalised to the SM expectation, obtained by combining the three channels, is:

\[
\mu = 1.33 \pm 0.14(\text{stat}) \pm 0.15(\text{sys}) \tag{4}
\]

where the systematic uncertainty receives similar contributions from the theoretical uncertainty on the signal cross section (ggF QCD scale and PDF, see Table 1) and all other, mainly experimental, sources. The uncertainty on the mass measurement reported in Eq. (2) produces a \( \pm 3\% \) variation of \( \mu \). The consistency between this measurement and the SM Higgs boson expectation (\( \mu = 1 \)) is about 7%; the use of a flat likelihood for the ggF QCD scale systematic uncertainty in the quoted \( \pm 1\sigma \) interval yields a similar level of consistency with the \( \mu = 1 \) hypothesis. The overall compatibility between the signal strengths measured in the three final states and the SM predictions is about 14%, with the largest deviation (\( \sim 1.9\sigma \)) observed in the \( H \rightarrow \gamma\gamma \) channel. Good consistency between the measured and expected signal strengths is also found for the various categories of the \( H \rightarrow \gamma\gamma \), \( H \rightarrow ZZ \rightarrow 4\ell \) and \( H \rightarrow WW \rightarrow \ell\ell\ell\ell \) analyses, which are the primary experimental inputs to the fit discussed in this section. If the preliminary \( H \rightarrow \tau\tau \) \([117]\) and \( H \rightarrow b\bar{b} \) \([118]\) results, for which only part of the 8 TeV dataset is used (13 fb\(^{-1}\)), were included, the combined signal strength would be \( \mu = 1.23 \pm 0.18 \).

7.3. Evidence for production via vector-boson fusion

The measurements of the signal strengths described in the previous section do not give direct information on the relative contributions of the different production mechanisms. Furthermore, fixing the ratios of the production cross sections for the various processes to the values predicted by the Standard Model may conceal tensions between the data and the theory. Therefore, in addition to the signal strengths for different decay modes, the signal strengths of different production processes contributing to the same decay mode\(^4\) are determined, exploiting the sensitivity offered by the use of event categories in the analyses of the three channels.

The data are fitted separating vector-boson-mediated processes, VBF and VH, from gluon-mediated processes, ggF and t\(t\)\(\bar{t}\), involving fermion (mainly top-quark) loops or legs.\(^5\) Two signal strength parameters, \( \mu_{\text{ggF+ttH}} = \mu_{\text{ggF}} + \mu_{\text{ttH}} \) and \( \mu_{\text{VBF+VH}} = \mu_{\text{VBF}} + \mu_{\text{VH}} \), which scale the SM-predicted rates to those observed, are introduced for each of the considered final states (\( f = H \rightarrow \gamma\gamma, H \rightarrow ZZ \rightarrow 4\ell, H \rightarrow WW \rightarrow \ell\ell\ell\ell \)). The results are shown in Fig. 7. The 95\% CL contours of the measurements are consistent with the SM expectation. A combination of all three channels would provide a higher-sensitivity test of the theory. This can be done in a model-independent way (i.e. without assumptions on the Higgs boson branching ratios) by measuring the ratios \( \mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}} \) for the individual final states and their combination. The results of this fit to the data with the likelihood \( \mathcal{L}(\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}}) \) are shown in Fig. 8. Good agreement with the SM expectation is observed for the individual final states and their combination.

To test the sensitivity to VBF production alone, the data are also fitted with the ratio \( \mu_{\text{VBF}}/\mu_{\text{ggF+ttH}} \). A value

\[
\mu_{\text{VBF}}/\mu_{\text{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{sys}) \tag{5}
\]

\(^4\) Such an approach avoids model assumptions needed for a consistent parameterisation of production and decay modes in terms of Higgs boson couplings.\(^5\) Such a separation is possible under the assumption that the kinematic properties of these production modes agree with the SM predictions within uncertainties.
Fig. 7. Likelihood contours in the \((\mu_{\text{ggF}+ttH}^f, \mu_{\text{VBF}+VH}^f)\) plane for the final states \(f = H \to \gamma\gamma, H \to ZZ' \to 4l\), \(H \to WW' \to 4\ell\) and a Higgs boson mass \(m_H = 125.5\) GeV. The sharp lower edge of the \(H \to ZZ' \to 4l\) contours is due to the small number of events in this channel and the requirement of a positive pdf. The best fits to the data (×) and the 68% (full) and 95% (dashed) CL contours are indicated, as well as the SM expectation (+).

Fig. 8. Measurements of the \(\mu_{\text{VBF}+VH}/\mu_{\text{ggF}+ttH}\) ratios for the individual diboson final states and their combination, for a Higgs boson mass \(m_H = 125.5\) GeV. The best-fit values are represented by the solid vertical lines, with the total \(\pm 1\sigma\) and \(\pm 2\sigma\) uncertainties indicated by the dark- and light-shaded band, respectively, and the statistical uncertainties by the superimposed horizontal error bars. The numbers in the second column specify the contributions of the statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the theoretical uncertainty (bottom) on the signal cross section (from QCD scale, PDF, and branching ratios) alone. For a more complete illustration, the distributions of the likelihood ratios from which the total uncertainties are extracted are overlaid.

is obtained from the combination of the three channels (Fig. 9), where the main components of the systematic uncertainty come from the theoretical predictions for the ggF contributions to the various categories and jet multiplicities and the knowledge of the jet energy scale and resolution. This result provides evidence at the 3.3\(\sigma\) level that a fraction of Higgs boson production occurs through VBF (as Fig. 9 shows, the probability for a vanishing value of \(\mu_{\text{VBF}}/\mu_{\text{ggF}+ttH}\), given the observation in the data, is 0.04%). The inclusion of preliminary \(H \to \tau\tau\) results [117], which also provide some sensitivity to this ratio, would give a significance of 3.1\(\sigma\).

7.4. Couplings measurements

Following the approach and benchmarks recommended in Ref. [119], measurements of couplings are implemented using a leading-order tree-level motivated framework. This framework is based on the following assumptions:

- The signals observed in the different search channels originate from a single resonance. A mass of 125.5 GeV is assumed here; the impact of the uncertainty reported in Eq. (2) on the results discussed in this section is negligible.
- The width of the Higgs boson is narrow, justifying the use of the zero-width approximation. Hence the predicted rate for a given channel can be decomposed in the following way:
  \[
  \sigma \cdot B (i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \quad (6)
  \]
  where \(\sigma_i\) is the production cross section through the initial state \(i\), \(\Gamma_f\) and \(\Gamma_H\) are the branching ratio and partial decay width into the final state \(f\), respectively, and \(\Gamma_H\) the total width of the Higgs boson.
- Only modifications of coupling strengths are considered, while the tensor structure of the Lagrangian is assumed to be the same as in the Standard Model. This implies in particular that the observed state is a CP-even scalar.\(^6\)

The coupling scale factors \(\kappa_j\) are defined in such a way that the cross sections \(\sigma_j\) and the partial decay widths \(\Gamma_j\) associated

\(^6\) The spin-CP hypothesis is addressed in Ref. [10].
with the SM particle $j$ scale with $\kappa_j^2$ compared to the SM prediction [119]. With this notation, and with $\kappa_j^2$ being the scale factor for the total Higgs boson width $\Gamma_H$, the cross section for the $gg \to H \to \gamma\gamma$ process, for example, can be expressed as:

$$\frac{\sigma \cdot B (gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \kappa_H^2 \cdot \kappa_{\gamma\gamma}^2.$$  \hspace{1cm} (7)

In some of the fits, $\kappa_H$ and the effective scale factors $\kappa_{\gamma\gamma}$ and $\kappa_g$ for the loop-induced $H \to \gamma\gamma$ and $gg \to H$ processes are expressed as a function of the more fundamental factors $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$ and $\kappa_\tau$ (only the dominant fermion contributions are indicated here for simplicity). The relevant relationships are:

$$\kappa_H^2 (\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH} + \kappa_b^2 \cdot \sigma_{bbH} + \kappa_t \kappa_b \cdot \sigma_{t\bar{t}H}}{\sigma_{ggH}^2 + \sigma_{bbH}^2 + \sigma_{t\bar{t}H}^2},$$

$$\kappa_{\gamma\gamma}^2 (\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{ij}^{\gamma\gamma},$$

$$\kappa_{\gamma\gamma}^2 = \sum_{j=WW, ZZ} \Gamma_{jj}^{\gamma\gamma} + \Gamma_{SM}^{\gamma\gamma},$$  \hspace{1cm} (8)

where $\sigma_{ij}^{ggH}$, $\Gamma_{ij}^{\gamma\gamma}$ and $\Gamma_{SM}^{\gamma\gamma}$ are obtained from theory [14,119].

Results are extracted from fits to the data using the profile likelihood ratio $\Lambda(k)$, where the $\kappa_i$ couplings are treated either as parameters of interest or as nuisance parameters, depending on the measurement.

The assumptions made for the various measurements are summarised in Table 10 and discussed in the next sections together with the results.

### 7.4.1. Couplings to fermions and bosons

The first benchmark considered here (indicated as model 1 in Table 10) assumes one coupling scale factor for fermions, $\kappa_F$, and one for bosons, $\kappa_V$; in this scenario, the $H \to \gamma\gamma$ and $gg \to H$ loops and the total Higgs boson width depend only on $\kappa_F$ and $\kappa_V$, with no contributions from physics beyond the Standard Model (BSM). The strongest constraint on $\kappa_F$ comes indirectly from the $gg \to H$ production loop.

Fig. 10 shows the results of the fit to the data for the three channels and their combination. Since only the relative sign of $\kappa_F$ and $\kappa_V$ is physical, in the following $\kappa_V > 0$ is assumed. Some sensitivity to this relative sign is provided by the negative interference between the $W$ boson loop and $t$-quark loop in the $H \to \gamma\gamma$ decay. The data prefer the minimum with positive relative sign, which is consistent with the SM prediction, but the local minimum with negative sign is also compatible with the observation (at the $\sim 2\sigma$ level). The two-dimensional compatibility of the SM prediction with the best-fit value is $12\%$. The 68% CL intervals of $\kappa_F$ and $\kappa_V$, obtained by profiling over the other parameter, are:

$\kappa_F \in [0.76, 1.18], \quad \kappa_V \in [1.05, 1.22]$  \hspace{1cm} (9, 10)

with similar considerations from the statistical and systematic uncertainties.

In this benchmark model, the assumption of no contributions from new particles to the Higgs boson width provides strong constraints on the fermion coupling $\kappa_F$, as about 75% of the total SM width comes from decays to fermions or involving fermions. If this assumption is relaxed, only the ratio $\lambda_{FV} = \kappa_F/\kappa_V$ can be measured (benchmark model 2 in Table 10), which still provides useful information on the relationship between Yukawa and gauge couplings.

Fits to the data give the following 68% CL intervals for $\lambda_{FV}$ and $\kappa_{VV}/\kappa_H$ (when profiling over the other parameter):

$\lambda_{FV} \in [0.70, 1.01], \quad \kappa_{VV} \in [1.13, 1.45]$  \hspace{1cm} (11, 12)

The two-dimensional compatibility of the SM prediction with the best-fit value is $12\%$. These results also exclude vanishing couplings of the Higgs boson to fermions (indirectly, mainly through the $gg \to H$ production loop) by more than $5\sigma$.

### 7.4.2. Ratio of couplings to the W and Z bosons

In the Standard Model, custodial symmetry imposes the constraint that the $W$ and $Z$ bosons have related couplings to the
Higgs boson, \( g_{VV} \sim m_V^2/v \) (where \( v \) is the vacuum expectation value of the Higgs field), and that \( \rho = m_W^2/(m_Z^2 \cdot \cos^2 \theta_W) \) (where \( \theta_W \) is the weak Weinberg angle) is equal to unity (as measured at LEP [120]). The former constraint is tested here by measuring the ratio \( \lambda_{WZ} = \kappa_W/\kappa_Z \).

The simplest and most model-independent approach is to extract the ratio of branching ratios normalised to their SM expectation, \( \lambda_{WZ} = B(H \to W^+W^-)/B(H \to ZZ^*) \). The measured inclusive rates of the \( H \to ZZ^* \) channel, from the measured inclusive rates of the \( H \to WW^* \) and \( H \to ZZ^* \) channels. A fit to the data with the likelihood function \( \Lambda(\lambda_{WZ}) \), where \( \mu_{\text{BF}} \) is the SM expectation, is performed, giving \( \lambda_{WZ} = 0.81^{+0.16}_{-0.15} \) at 68% CL. The two-dimensional compatibility of the SM prediction with the best-fit value is 14%.

Potential contributions from BSM physics affecting the \( H \to \gamma\gamma \) channel could produce apparent deviations of the ratio \( \lambda_{WZ} \) from unity even if custodial symmetry is not broken. It is therefore desirable to decouple the observed \( H \to \gamma\gamma \) event rate from the measurement of \( \lambda_{WZ} \). This is done with an extended fit for the ratio \( \lambda_{WZ} \), where one extra degree of freedom (\( \lambda_{WZ} = \kappa_Y/\kappa_Z \)) absorbs possible BSM effects in the \( H \to \gamma\gamma \) channel (benchmark model 4 in Table 10). This measurement yields:

\[
\lambda_{WZ} = 0.82 \pm 0.15 \quad (13)
\]

and a four-dimensional compatibility of the SM prediction with the best-fit value of 20%.

### 7.4. Constraints on production and decay loops

Many BSM physics scenarios predict the existence of new heavy particles, which can contribute to loop-induced processes such as \( gg \to H \) production and \( H \to \gamma\gamma \) decay. In the approach used here (benchmark model 5 in Table 10), it is assumed that the new particles do not contribute to the Higgs boson width and that the couplings of the known particles to the Higgs boson have SM strength (i.e., \( \kappa_i = 1 \)). Effective scale factors \( \kappa_g \) and \( \kappa_Y \) are introduced to parameterise the \( gg \to H \) and \( H \to \gamma\gamma \) loops. The results of their measurements from a fit to the data are shown in Fig. 12. The best-fit values when profiling over the other parameters are:

\[
\kappa_g = 1.04 \pm 0.14, \quad (14)
\]

\[
\kappa_Y = 1.20 \pm 0.15. \quad (15)
\]

The two-dimensional compatibility of the SM prediction with the best-fit value is 14%.

### 7.4.4. Summary

The results of the measurements of the coupling scale factors discussed in the previous sections, obtained under the assumptions detailed in Section 7.4 and Table 10, are summarised in Fig. 13. The measurements in the various benchmark models are strongly correlated, as they are obtained from fits to the same experimental data. A simple \( \chi^2 \)-like compatibility test with the SM is therefore not meaningful.

The coupling of the new particle to gauge bosons \( \kappa_Y \) is constrained by several channels, directly and indirectly, at the ±10% level. Couplings to fermions with a significance larger than 5\( \sigma \) are indirectly observed mainly through the gluon-fusion production process, assuming the loop is dominated by fermion exchange. The ratio of the relative couplings of the Higgs boson to the \( W \) and \( Z \) bosons, \( \kappa_W/\kappa_Z \), is measured to be consistent with unity, as predicted by custodial symmetry. Under the hypothesis that all couplings of the Higgs boson to the known particles are fixed to their SM values, and assuming no BSM contributions to the Higgs boson width, no significant anomalous contributions to the \( gg \to H \) and \( H \to \gamma\gamma \) loops are observed.

### 8. Conclusions

Data recorded by the ATLAS experiment at the CERN Large Hadron Collider in 2011 and 2012, corresponding to an integrated luminosity of up to 25 fb\(^{-1} \), at \( \sqrt{s} = 7 \) TeV and \( \sqrt{s} = 8 \) TeV, have been analysed to determine several properties of the recently discovered Higgs boson using the \( H \to \gamma\gamma \), \( H \to ZZ^* \to 4\ell \) and \( H \to WW^* \to \ell\ell v\bar{v} \) decay modes. The reported results include measurements of the mass and signal strength, evidence for production through vector-boson fusion, and constraints on couplings to bosons and fermions as well as on anomalous contributions to loop-induced processes. The precision exceeds previously published results in several cases. All measurements are consistent with expectations for the Standard Model Higgs boson.
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