Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at 13 TeV with the ATLAS detector

The ATLAS Collaboration

Inclusive and differential fiducial cross sections of Higgs-boson production in proton-proton collisions are measured in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel. The proton-proton collision data were produced at the Large Hadron Collider at a centre-of-mass energy of 13 TeV and recorded by the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb$^{-1}$. The inclusive fiducial cross section in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel is measured to be $3.62^{+0.53}_{-0.50} \, \text{(stat)}^{+0.25}_{-0.20} \, \text{(sys)}$ fb, in agreement with the Standard Model prediction of $2.91 \pm 0.13$ fb. The cross section is also extrapolated to the total phase space including all Standard Model Higgs-boson decays. Several differential fiducial cross sections are measured for observables sensitive to the Higgs-boson production and decay, including kinematic distributions of the jets produced in association with the Higgs boson. Good agreement is found between data and Standard Model predictions. The results are used to put constraints on anomalous Higgs-boson interactions with Standard Model particles, using the pseudo-observable framework.
1 Introduction

The ATLAS and CMS Collaborations at the Large Hadron Collider (LHC) have performed extensive studies of the Higgs-boson properties in the past few years. The Higgs-boson mass has been measured to be $m_H = 125.09 \pm 0.24$ GeV \cite{1} and no significant deviations from Standard Model (SM) predictions have been found in the cross sections measured per production mode, the branching ratios \cite{2}, or spin and parity quantum numbers \cite{3, 4}. Furthermore, inclusive and differential fiducial cross sections of Higgs-boson production, defined as event yields corrected for the detector response, have been measured by the ATLAS and CMS Collaborations in proton-proton ($pp$) collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, using the $4\ell$ ($\ell = e, \mu$), $\gamma\gamma$, and $e\nu\mu\nu$ final states \cite{5–10}. The measured differential cross sections are also in good agreement with the SM predictions.

This paper presents the first measurements of inclusive and differential fiducial cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel using $pp$ collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector. The combined effect of a higher centre-of-mass energy and an integrated luminosity of $36.1 \text{ fb}^{-1}$ is expected to increase the number of Higgs-boson events by a factor of almost four compared to the previous analysis at $\sqrt{s} = 8$ TeV. Significantly larger gains are expected in the regions of the differential distributions that probe higher momentum scales due to increased parton-parton luminosities. The differential cross sections presented in this paper are measured in a fiducial phase space to avoid model-dependent extrapolations. The observed distributions are corrected for detector inefficiency and resolution.

Fiducial cross sections are presented both inclusively and separately for each of the final states of the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay ($4e, 4\mu, 2e2\mu, 2\mu2e$). Differential fiducial cross sections are presented for various observables that describe Higgs-boson production and decay in $pp$ collisions. They are not split into the
different final states or Higgs-boson production modes, such as gluon fusion (ggF) or vector-boson fusion (VBF). The Higgs-boson transverse momentum \( p_{T,4f} \) can be used to test perturbative QCD calculations, especially when separated into exclusive jet multiplicities. This variable is also sensitive to the Lagrangian structure of the Higgs-boson interactions [11]. The Higgs-boson rapidity distribution \( |y_{4f}| \) is sensitive to the parton distribution functions (PDFs) of the colliding protons. The decay variables \( |\cos \theta^*| \) and \( m_{34} \) test the spin and parity nature of the Higgs boson. The variable \( |\cos \theta^*| \) is defined as the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis. The variables \( m_{12} \) and \( m_{34} \) refer to the invariant masses of the leading and subleading lepton pairs and correspond to the invariant mass of the on-shell and off-shell \( Z \) bosons produced in the Higgs-boson decay. The number of jets \( N_{jets} \) produced in association with the Higgs boson and the transverse momentum of the leading jet \( p_T^{lead,jet} \) both provide sensitivity to the theoretical modelling of high-\( p_T \) quark and gluon emission. The invariant mass \( m_{jj} \) of the two leading jets in the event is sensitive to different production mechanisms. The signed angle between the two leading jets in the transverse plane\(^2\) \( \Delta \phi_{jj} \) is another observable that tests the spin and parity nature of the Higgs boson [12].

Providing fiducial cross sections simplifies the testing of theoretical models with \( H \rightarrow ZZ^* \rightarrow 4\ell \) final states since the response of the ATLAS detector has been removed. As an example, the cross section in the \( m_{12} \) vs \( m_{34} \) parameter plane is interpreted in the framework of pseudo-observables [13], and limits are set on parameters describing anomalous Higgs-boson interactions with leptons and \( Z \) bosons.

2 The ATLAS detector

The ATLAS detector [14] is a multi-purpose detector with a forward-backward symmetric cylindrical geometry. At small radii, the inner detector (ID), immersed in a 2 T magnetic field produced by a thin superconducting solenoid located in front of the calorimeter, is made up of fine-granularity pixel and microstrip detectors. These silicon-based detectors cover the pseudorapidity range \( |\eta| < 2.5 \). A gas-filled straw-tube transition radiation tracker complements the silicon tracker at larger radii up to \( |\eta| < 2 \) and also provides electron identification capabilities based on transition radiation. The electromagnetic (EM) calorimeter is a lead/liquid-argon sampling calorimeter with accordion geometry. The calorimeter is divided into a barrel section covering \( |\eta| < 1.475 \) and two end-cap sections covering \( 1.375 < |\eta| < 3.2 \). For \( |\eta| < 2.5 \) it is divided into three layers in depth, which are finely segmented in \( \eta \) and \( \phi \). A thin presampler layer, covering \( |\eta| < 1.8 \), is used to correct for fluctuations in upstream energy losses. A hadronic calorimeter in the region \( |\eta| < 1.7 \) uses steel absorbers and scintillator tiles as the active medium. A liquid-argon calorimeter with copper absorbers is used in the hadronic end-cap calorimeters, which cover the region \( 1.5 < |\eta| < 3.2 \). A forward calorimeter using copper or tungsten absorbers with liquid argon completes the calorimeter coverage up to \( |\eta| = 4.9 \). The muon spectrometer (MS) measures the deflection of muon tracks within \( |\eta| < 2.7 \), using three stations of precision drift tubes, with cathode strip chambers in the innermost layer for \( |\eta| > 2.0 \). The deflection is provided by a toroidal magnetic field from air-core superconducting magnets, with an integral of approximately 3 T·m and 6 T·m in the central and end-cap regions, respectively. The muon spectrometer is instrumented with trigger chambers covering \( |\eta| < 2.4 \). Events are selected using a first-level trigger implemented in custom electronics, which reduces

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\(^1\) ATLAS 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 \( z \)-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).

\(^2\) \( \Delta \phi_{jj} \) is defined as \( \Delta \phi_{jj} = \phi_{j1} - \phi_{j2} \), if \( \eta_{j1} > \eta_{j2} \), otherwise \( \Delta \phi_{jj} = \phi_{j2} - \phi_{j1} \).
the event rate to a maximum of 100 kHz using a subset of detector information. Software algorithms with access to the full detector information are then used in the high-level trigger to yield a recorded event rate of about 1 kHz.

3 Theoretical predictions and event simulation

The Higgs-boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Refs. [15–18], and are referred to as LHCXSWG. The cross section for Higgs-boson production via ggF is available at next-to-next-to-next-to-leading order (N3LO) in QCD and has next-to-leading order (NLO) electroweak (EW) corrections applied [19–32]. The cross section for the VBF process is calculated with full NLO QCD and EW corrections [33–35], and approximate next-to-next-to-leading-order (NNLO) QCD corrections are applied [36]. The cross sections for the production of a weak boson in association with a Higgs boson, $VH$ ($V = W, Z$), are calculated at NNLO accuracy in QCD [37, 38] and NLO EW radiative corrections [39] are applied. The cross section for the associated production of a Higgs boson with a $t\bar{t}$ pair ($t\bar{t}H$) is calculated up to NLO accuracy in QCD [40–43]. The cross section for the $bbH$ process is calculated by the Santander matching with five-flavour scheme (NNLO in QCD) and four-flavour scheme (NLO in QCD) [44]. The composition of the different production modes in the SM is 87.3% (ggF), 6.8% (VBF), 4.1% ($VH$), 0.9% ($t\bar{t}H$), 0.9% ($bbH$).

The Higgs-boson decay branching ratio to the four-lepton final state ($\ell = e, \mu$) for $m_H = 125$ GeV is predicted to be 0.0124% [45] in the SM using PROPHECY4F [46, 47], which includes the complete NLO QCD and EW corrections, and the interference effects between identical final-state fermions. Due to the latter, the expected branching ratios of the $4e$ and $4\mu$ final states are about 10% higher than the branching ratios to $2e2\mu$ and $2\mu2e$ final states.

The POWHEG-BOX v2 Monte Carlo (MC) event generator [48–50] is used to simulate ggF [51], VBF [52] and $VH$ [53] processes, using the PDF4LHC NLO PDF set [54]. The ggF Higgs-boson production is accurate to NNLO in QCD, using the POWHEG method for merging the NLO Higgs-boson plus jet cross section with the parton shower, and the MiNLO method [55] to simultaneously achieve NLO accuracy for inclusive Higgs-boson production. Furthermore, a reweighting procedure is performed using the HNNLO program [56, 57] to achieve full NNLO accuracy. This sample is referred to as NNLOPS. The VBF and $VH$ samples are produced at NLO accuracy in QCD. For $VH$, the MiNLO method is used to merge 0- and 1-jet events [58]. For Higgs-boson production in association with a heavy quark pair, events are simulated at NLO with MadGraph5_aMC@NLO [59], using the CT10nlo PDF set [60] for $t\bar{t}H$ and the NNPDF23 PDF set [61] for $bbH$. For the ggF, VBF, $VH$, and $bbH$ production mechanisms, PYTHIA 8 [62] is used for the $H \rightarrow ZZ' \rightarrow 4\ell$ decay as well as for parton showering, hadronisation, and multiple partonic interactions using the AZNLO parameter set [63]. For the $t\bar{t}H$ production mechanism, Herwig++ [64] is used with the UEEEE5 parameter set [65].

The measured event yields and the differential fiducial cross-section measurements are compared to a SM prediction constructed from the MC predictions presented above, after normalizing each sample to the corresponding LHCXSWG prediction. All samples are generated for $m_H = 125$ GeV.

An alternative prediction for ggF SM Higgs-boson production is generated using MadGraph5_aMC@NLO at NLO accuracy in QCD for 0, 1, 2 additional jets, merged with the FxFx scheme [59, 66], using the NNPDF30_nlo_as_0118PDF set [67]. This MG5_aMC@NLO_FxFx sample is interfaced to PYTHIA 8 for Higgs-boson decay, parton showering, hadronisation and multiple partonic interactions using the
AZNLO parameter set. The data are also compared to ggF SM Higgs-boson production in the 4ℓ decay channel simulated with HRes v2.3 [68, 69], using the MSTW2008 NNLO PDF set [70]. The HRes program computes fixed-order cross sections for ggF SM Higgs-boson production up to NNLO in QCD and describes the \( p_{T,4\ell} \) distribution at NLO. All-order resummation of soft-gluon effects at small transverse momenta is consistently included up to NNLL (next-to-next-to-leading logarithmic order) in QCD, using dynamic factorisation and resummation scales (the central scales are chosen to be \( m_H/2 \)). The program implements top- and bottom-quark mass dependence up to NLL + NLO in QCD. At NNLL + NNLO accuracy only the top-quark contribution is considered. HRes does not perform showering and QED final-state radiation effects are not included. Both the MG5_AMC@NLO_FxFx and the HRes prediction are normalized to the LHCXSWG cross section.

A ggF sample used to study deviations from the SM predictions within the pseudo-observable framework is generated with MadGraph5 at LO using FeynRules 2 [71] and the NN23PDF PDF set [13, 72]. The sample is interfaced to PYTHIA 8 using the A14 parameter set [73]. It is normalized to the LHCXSWG cross section.

The \( Z\bar{Z} \) continuum background is simulated using Sherpa 2.2 [74–76] for quark-antiquark annihilation, using the NNPDF3.0 NNLO PDF set. NLO accuracy is achieved in the matrix element calculation for 0-, 1- and 1-jet final states and LO accuracy for 2- and 3-jet final states. The merging is performed with the Sherpa parton shower [77] using the ME+PS@NLO prescription [78]. NLO EW corrections are applied as a function of the invariant mass of the \( Z\bar{Z} \) system \( m_{Z\bar{Z}} \). [79, 80]. The gluon-induced \( Z\bar{Z} \) production is modelled with gg2VV [81] at leading order in QCD. The k-factor accounting for missing higher order QCD effects in the calculation of the \( gg \rightarrow Z\bar{Z} \) continuum is taken to be 1.7 ± 1.0 [82–86]. Sherpa 2.2 is also used to generate samples of the \( Z + \text{ jets} \) background at NLO accuracy for 0-, 1- and 2-jet final states and LO accuracy for 3- and 4-jet final states. In this measurement, the \( Z + \text{ jets} \) background is normalized using control samples from data. For comparisons with simulation, the QCD NNLO FEWZ [87, 88] and MCFM cross-section calculations are used for inclusive \( Z \) boson and \( Z + b\bar{b} \) production, respectively. Samples for the \( t\bar{t} \) background are produced with POWHEG interfaced to PYTHIA 6 [89] for parton shower and hadronisation, to PHOTOS [90] for QED radiative corrections, to Tauola [91, 92] for the simulation of \( \tau \) lepton decays and to EVTGEN for the simulation of \( B \)-hadron decays. For this sample, the Perugia 2012 parameter set [93] is used. The WZ background is modelled using POWHEG+PYTHIA 8 and the AZNLO parameter set. The triboson backgrounds \( ZZZ, WZZ, \) and WWZ with four or more leptons originating from the hard scatter, as well as the \( t\bar{t} + W \) process are produced with Sherpa 2.1. MadGraph, interfaced to PYTHIA 8 with the A14 parameter set is used to simulate the all-leptonic \( t\bar{t} + Z \).

The particle-level events produced by each event generator are passed through the Geant4 [94] simulation of the ATLAS detector [95] and reconstructed in the same way as for the data. Additional pp interactions in the same and nearby bunch crossings (pile-up) are simulated using inelastic pp collisions generated using PYTHIA 8 (with the A2 MSTW2008LO parameter set) and overlaid on the simulated events discussed above. The MC events are weighted to reproduce the distribution of the average number of interactions per bunch crossing observed in the data.
4 Event selection

Electrons are reconstructed using tracks in the ID and energy clusters in the EM calorimeter [96]. They are required to satisfy loose identification criteria based on tracking and calorimeter information. Muons are reconstructed as tracks in the ID and the MS [97] if they lie in the region $0.1 < |\eta| < 2.5$. In the region $|\eta| < 0.1$, the MS has reduced coverage, and muons are reconstructed from ID tracks and identified by either a minimal calorimeter deposit or hits in the MS. For $2.5 < |\eta| < 2.7$, only the MS can be used. For events with four muons, at least three muons are required to be reconstructed combining ID and MS tracks. Each muon (electron) must have transverse momentum $p_T > 5$ GeV (transverse energy $E_T > 7$ GeV), within the pseudorapidity range $|\eta| < 2.7$ (2.47) and with a longitudinal impact parameter $|z_0 \sin(\theta)| < 0.5$ mm. Muons originating from cosmic rays are removed with the transverse impact parameter requirement $|d_0| < 1$ mm. Jets are reconstructed from topological clusters of calorimeter cells using the anti-$k_t$ algorithm [98, 99] with the distance parameter $R = 0.4$. Jets are corrected for detector response and pile-up contamination [100, 101] and required to have $p_T > 30$ GeV, and $|\eta| < 4.5$. In order to avoid double counting of electrons also reconstructed as jets, jets are removed if $\Delta R({\text{jet}}, e) = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2$. This overlap removal is also applied to jets close to muons if the jet has less than three tracks and the energy and momentum differences between the muon and the jet are small, or if $\Delta R({\text{jet}}, \mu) < 0.1$.

Events with at least four leptons are selected with single-lepton, dilepton and trilepton triggers. The trigger selections changed with the increase of instantaneous luminosity during data-taking, e.g. the single electron trigger minimum $E_T$ requirement changed from 24 to 26 GeV. The multilepton triggers have lower $E_T$ or $p_T$ requirements. The overall trigger efficiency in this analysis is about 98%. The data are subjected to quality requirements to reject events in which detector components were not operating correctly. Events are required to have at least one vertex with two associated tracks with $|\Delta R| < 0.025$, a requirement on the $\chi^2$ value of a common vertex fit is applied, corresponding to a signal efficiency of 99.5% for all decay channels. If more than one quadruplet passes all requirements, e.g. for $VH$ or $t \bar{t} H$, the channel with the highest expected signal rate is selected, in the order: $4\mu$, $2e2\mu$, $2\mu2e$ and $4e$. The invariant mass distribution of the four leptons of the selected events is shown in Figure 1. Only events with a four-lepton invariant mass in the range $115–130$ GeV are used in the final fit.

The selected events are divided into bins of the variables of interest. The bin boundaries are chosen such that each bin has an expected signal significance greater than $2\sigma$ and that there are minimal migrations.
Figure 1: Four-lepton invariant mass distribution of the selected events before the $m_{4\ell}$ requirement. The error bars on the data points indicate the statistical uncertainty. The SM Higgs signal prediction is obtained from the samples discussed in Section 3. The backgrounds are determined following the description in Section 6. The systematic uncertainty on the prediction is shown by the dashed band, calculated as described in Section 9.

5 Fiducial phase space

The fiducial cross sections are defined at particle-level using the selection requirements outlined in Table 1, which are chosen to closely match those in the detector-level analysis in order to minimize model-dependent acceptance extrapolations.

The fiducial selection is applied to final-state$^3$ electrons and muons that do not originate from hadrons or $\tau$-decays. The leptons are “dressed”, i.e. the transverse momenta of photons within a cone of $\Delta R = 0.1$ are added to each lepton, requiring the photons to not originate from hadron decays. Particle-level jets are reconstructed from final-state particles using the anti-$k_t$ algorithm with radius parameter $R = 0.4$. Electrons, muons, and neutrinos, if they are not from hadron decays, and photons used to dress leptons are excluded from the jet clustering. Jets are removed if they are within a cone of $\Delta R = 0.1$ (0.2) of a selected muon (electron).

$^3$ Final-state particles are defined as particles with a life time $c\tau > 10$ mm.
Table 1: List of event selection requirements which define the fiducial phase space of the cross-section measurement. SFOS lepton pairs are same-flavour opposite-sign lepton pairs.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leptons and jets</strong></td>
<td></td>
</tr>
<tr>
<td>Muons</td>
<td>$p_T &gt; 5$ GeV, $</td>
</tr>
<tr>
<td>Electrons</td>
<td>$p_T &gt; 7$ GeV, $</td>
</tr>
<tr>
<td>Jets</td>
<td>$p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>Jet-lepton overlap removal</td>
<td>$\Delta R (\text{jet, } \ell) &gt; 0.1 \ (0.2)$ for muons (electrons)</td>
</tr>
<tr>
<td><strong>Lepton selection and pairing</strong></td>
<td></td>
</tr>
<tr>
<td>Lepton kinematics</td>
<td>$p_T &gt; 20, 15, 10$ GeV</td>
</tr>
<tr>
<td>Leading pair ($m_{12}$)</td>
<td>SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td>Subleading pair ($m_{34}$)</td>
<td>remaining SFOS lepton pair with smallest $</td>
</tr>
<tr>
<td><strong>Event selection (at most one quadruplet per channel)</strong></td>
<td></td>
</tr>
<tr>
<td>Mass requirements</td>
<td>$50 &lt; m_{12} &lt; 106$ GeV and $12 &lt; m_{34} &lt; 115$ GeV</td>
</tr>
<tr>
<td>Lepton separation</td>
<td>$\Delta R (\ell_i, \ell_j) &gt; 0.1 \ (0.2)$ for same- (different-) flavour leptons</td>
</tr>
<tr>
<td>$J/\psi$ veto</td>
<td>$m(\ell_i, \ell_j) &gt; 5$ GeV for all SFOS lepton pairs</td>
</tr>
<tr>
<td>Mass window</td>
<td>$115$ GeV &lt; $m_{4\ell}$ &lt; 130 GeV</td>
</tr>
</tbody>
</table>

Quadruplets are formed with the selected dressed leptons in the same manner as for the reconstructed events. This allows for mispairing of the Higgs-boson leptons when assigning them to the leading and subleading $Z$ boson and the inclusion of leptons coming from vector bosons produced in association with the Higgs boson. The differential variables are calculated using the dressed leptons in the quadruplets.

The acceptance of the fiducial selection (with respect to the full phase space of $H \to ZZ^* \to 2\ell 2\ell'$, where $\ell, \ell' = e$ or $\mu$) is 42% for a SM Higgs boson with $m_H = 125$ GeV. The ratio of the number of events passing the detector-level event selection to those passing the particle-level selection, is 53%. Due to resolution effects, about 2% of the events which pass the detector-level selection fail the particle-level selection.

6 Background estimates

Non-resonant SM $ZZ^*$ production via $q\bar{q}$ annihilation and gluon-gluon fusion can result in four prompt leptons in the final state and constitutes the largest background for this analysis. It is estimated using the Sherpa and gg2VV simulated samples presented in Section 3. To cross-check the theoretical modelling of this background, a $ZZ^*$-enriched control region is formed using almost the full event selection, but requiring that the four-lepton invariant mass is outside of the region $115 < m_{4\ell} < 130$ GeV. In this control region, good agreement is observed between the simulation and the data for all distributions, as demonstrated for $p_T, N_{\text{jets}}$ in Figure 2.

Other processes that contribute to the background, such as $Z + \text{jets, } t\bar{t}$, and $WZ$, contain at least one object that is misidentified as a prompt lepton. These backgrounds are significantly smaller than the non-resonant $ZZ^*$ background and are estimated using data where possible, following slightly different approaches for the $\ell\ell\mu\mu$ and $\ell\ell\ee$ final states [102].

In the $\ell\ell\mu\mu$ final states, the normalisations for the $Z + \text{jets and } t\bar{t}$ backgrounds are determined using fits to the invariant mass of the leading lepton pair in dedicated data control regions. The control regions are
Figure 2: Reconstructed event yields in bins of $p_T$,4ℓ (a) and $N_{jets}$ (b), in a non-resonant $ZZ^*$-enriched control region, obtained by applying the full event selection except for the $m_{4ℓ}$ window, which here is required to be $m_{4ℓ} < 115$ GeV or $130$ GeV $< m_{4ℓ} < 170$ GeV. The error bars on the data points indicate the statistical uncertainty. The systematic uncertainty on the prediction is shown by the dashed band. The bottom part of the figures shows the ratio of data over expectation.

formed by relaxing the $\chi^2$ requirement on the vertex fit, and by inverting and relaxing isolation and/or impact-parameter requirements on the subleading muon pair. An additional control region ($e\mu\mu\mu$) is used to improve the $t\bar{t}$ background estimate. Transfer factors to extrapolate from the control regions to the signal region are obtained separately for $t\bar{t}$ and $Z$ + jets using simulation. The shapes of the $Z$ + jets and $t\bar{t}$ backgrounds for the differential observables are taken from simulation and normalized using the inclusive data-driven estimate. Comparisons in the control regions show good agreement between data and the simulation for the different observables.

The $\ell\ell ee$ control-region selection requires the electrons in the subleading lepton pair to have the same charge, and relaxes the identification and isolation requirements on the electron candidate with the lowest transverse energy. This electron candidate can be a light-flavour jet, a photon conversion or an electron from heavy-flavour hadron decay. The heavy-flavour background is completely determined from simulation, whereas the light-flavour and photon conversion background is obtained with the sPlot [103] method, based on a fit to the number of hits in the innermost ID layer $n_{IBL}$ in the data control region. Efficiencies for the light-flavour jets and converted photons, obtained from simulated samples, are corrected using $Z$ + X control regions and then used to extrapolate the extracted yields to the signal region. Both the yield extraction and the extrapolation are performed in bins of the transverse momentum of the electron candidate and the jet multiplicity. In order to extract the shape of the backgrounds from light-flavour jets and photon conversions in bins of the differential distributions, a similar method is used, except that the extraction and extrapolation is now performed as a function of the transverse momentum of the electron candidate in each bin of the variable of interest.

The $m_{4ℓ}$ shapes are extracted from simulation for most background components except for the light-flavour jet contribution in the $\ell\ell ee$ final state, which is not well described by the simulation and therefore taken
from the control region and extrapolated using the data-corrected efficiencies. It was observed that the $m_{4\ell}$ shape of the $Z +$ jets and $t\bar{t}$ backgrounds does not change significantly across the differential distributions, and so the inclusive shape is used for all bins.

The $WZ$ production is included in the data-driven estimates for the $\ell\ell ee$ final states, while it is added from simulation for the $\ell\ell \mu\mu$ final states. The contributions from $t\bar{t} + Z$ and triboson processes are very small and taken from simulated samples.

### 7 Measured data yields

The number of events in the four decay channels observed in data after the event selection, as well as the expected signal and background yields, are presented in Table 2. Figure 3 shows the expected and observed event yields after the analysis selection for four of the measured differential spectra. The total observed and predicted event counts agree within 1.3 standard deviations.

Table 2: Number of expected and observed events in the four decay channels after the event selection, in the mass range $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$. The sum of the expected number of SM Higgs-boson events and the estimated background yields is compared to the data. Combined statistical and systematic uncertainties are included for the predictions (see Section 9).

<table>
<thead>
<tr>
<th>Final state</th>
<th>SM Higgs</th>
<th>$ZZ^*$</th>
<th>$Z +$ jets, $t\bar{t}$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$20.1 \pm 2.1$</td>
<td>$9.8 \pm 0.5$</td>
<td>$1.3 \pm 0.3$</td>
<td>$31.2 \pm 2.2$</td>
<td>$33$</td>
</tr>
<tr>
<td>$4e$</td>
<td>$10.6 \pm 1.2$</td>
<td>$4.4 \pm 0.4$</td>
<td>$1.3 \pm 0.2$</td>
<td>$16.3 \pm 1.3$</td>
<td>$16$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$14.2 \pm 1.4$</td>
<td>$7.1 \pm 0.4$</td>
<td>$1.0 \pm 0.2$</td>
<td>$22.3 \pm 1.5$</td>
<td>$32$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$10.8 \pm 1.2$</td>
<td>$4.6 \pm 0.4$</td>
<td>$1.4 \pm 0.2$</td>
<td>$16.8 \pm 1.3$</td>
<td>$21$</td>
</tr>
<tr>
<td>Total</td>
<td>$56 \pm 6$</td>
<td>$25.9 \pm 1.5$</td>
<td>$5.0 \pm 0.6$</td>
<td>$87 \pm 6$</td>
<td>$102$</td>
</tr>
</tbody>
</table>

### 8 Signal extraction and correction for detector effects

To extract the number of signal events, in each bin of a differential distribution (or for each decay channel for the inclusive fiducial cross section), templates for the Higgs-boson production and the background processes are fit to the $m_{4\ell}$ distribution in data. The signal shape is obtained from the simulated samples described in Section 3 at a Higgs-boson mass of 125 GeV. Most of the background shapes are also obtained from the simulated samples described in Section 3, while some of the backgrounds in the $\ell\ell ee$ channel are derived from control regions in data, as discussed in Section 6. The normalisation of the backgrounds is fixed in this fit. Figures 4 and 5 show the data, templates and best fits for the $m_{4\ell}$ distributions in the four decay channels for the extraction of the inclusive fiducial cross section, and in representative bins of the transverse momentum of the four leptons. For the differential distributions, no split into decay channels is performed, and the SM $ZZ^* \rightarrow 4\ell$ decay fractions are assumed.

The fiducial cross section $\sigma_{t,\text{fid}}$ for a given final state or bin of the differential distribution is defined as:
Figure 3: Measured data yields compared to SM Higgs-boson signal and background processes for the transverse momentum of the four leptons $p_{T,4\ell}$ (a), the number of jets $N_{\text{jets}}$ (b), the invariant mass of the subleading lepton pair $m_{34}$ (c), and the invariant mass of the leading vs the subleading pair $m_{12}$ vs $m_{34}$ (d). Subfigure (d) also includes an illustration of the chosen bins, as well as the two-dimensional distributions of data and prediction. The error bars on the data points indicate the statistical uncertainty. The systematic uncertainty on the prediction is shown by the dashed band.
Figure 4: Template fit of Higgs-boson signal and background to the data for the inclusive distributions for the different decay channels. The error bars on the data points indicate the statistical uncertainty. The SM Higgs-boson predictions are normalized to the cross sections discussed in Section 3, while the backgrounds are normalized to the estimates described in Section 6. The systematic uncertainty on the prediction is shown by the dashed band.
Figure 5: Template fit of Higgs-boson signal and background to the data for the first and last bins of the distribution of the transverse momentum of the four leptons $p_T^{\ell\ell}$. The error bars on the data points indicate the statistical uncertainty. The SM Higgs-boson predictions are normalized to the cross sections discussed in Section 3, while the backgrounds are normalized to the estimates described in Section 6. The systematic uncertainty on the prediction is shown by the dashed band. The dotted green line illustrates the best fit.

$$\sigma_{i,\text{fid}} = \sigma_i \times A_i \times \text{BR} = \frac{N_{i,\text{fit}}}{\mathcal{L}} \times C_i = \frac{N_{i,\text{reco}}}{N_{i,\text{part}}}$$

where $A_i$ is the acceptance in the fiducial phase space, BR the branching fraction and $\sigma_i$ is the total cross section in bin $i$. $N_{i,\text{fit}}$ is the number of extracted signal events in data, $\mathcal{L}$ the integrated luminosity and $C_i$ the bin-by-bin correction factor for detector inefficiency and resolution. $N_{i,\text{reco}}$ is the number of reconstructed signal events and $N_{i,\text{part}}$ is the number of events at the particle-level in the fiducial phase-space. The correction factor is calculated from simulated Higgs-boson samples, assuming SM production mode fractions and $ZZ^* \to 4\ell$ decay fractions as discussed in Section 3. The systematic uncertainties on this assumption are described in Section 9. The correction factors for the different Higgs production modes agree within 15%, except for the $t\bar{t}H$ mode, which differs by up to 40%, due to the fact that $t\bar{t}H$ events have more hadronic jets and no isolation requirements are applied to the leptons at the particle-level. The correction factors for the four final states are $0.64 \pm 0.04 (4\mu)$, $0.55 \pm 0.03 (2e2\mu)$, $0.48 \pm 0.05 (2\mu2e)$, $0.43 \pm 0.06 (4e)$. Figure 6 shows the bin-by-bin correction factors including systematic uncertainties for the $p_T^{\ell\ell}$ and $N_{\text{jets}}$ distributions. The same figure also shows the purity, defined as the fraction of events in a bin of the reconstructed distribution that are found in the same bin at particle level. The purity is greater than 0.75 for the Higgs kinematic and decay observables, and typically greater than 0.6 for the jet variables. It can be seen that the narrower bins at low $p_T^{\ell\ell}$ have a slightly reduced purity, as detector resolution effects result in larger bin migrations.

The signal, background, and data $m_{4\ell}$ distributions, as well as the correction factors, are used as input to
Figure 6: Bin-by-bin correction factors and purities for the transverse momentum of the four leptons $p_T, 4\ell$ and the number of jets $N_{jets}$. The bands show the systematic uncertainties on the correction factors, which are discussed in Section 9. No uncertainty is shown for the purity.

A profile likelihood ratio fit [104], taking into account all bins of a given distribution and all final states for the inclusive measurement. The likelihood includes the shape and normalisation uncertainties of the backgrounds and correction factors as nuisance parameters. This allows for correlation of systematic uncertainties between the background estimates and the correction factors, as well as between bins or decay channels. The cross sections are extracted for each bin, or final state, by minimizing twice the negative logarithm of the profile likelihood ratio $-2 \ln \Lambda$. Under the asymptotic assumption, i.e. the large sample limit, $-2 \ln \Lambda$ behaves as a $\chi^2$ distribution with one degree of freedom. The compatibility between a measured cross section and a theoretical prediction is evaluated by computing a $p$-value based on the difference between the value of $-2 \ln \Lambda$ at the best-fit value and the value obtained by fixing the cross sections in all bins to the ones predicted by the theory. These $p$-values do not include the uncertainties on the theoretical predictions, which are significantly smaller than the total data uncertainties. Therefore they are a bit lower than they would be with all uncertainties included. For all measured observables the asymptotic assumption is verified with pseudo-experiments, and if necessary, the uncertainties are corrected to the values obtained with the pseudo-experiments. In the case of zero observed events, 95% confidence level (CL) limits on the fiducial cross sections are set using the CLs modified frequentist formalism [104, 105].

The inclusive fiducial cross section for each channel is calculated from the fit results following Eq. 1. The fiducial cross sections of the four final states can either be summed together to obtain an inclusive fiducial cross section, or they can be combined assuming the SM $ZZ^* \rightarrow 4\ell$ branching fractions. The latter combination is more model dependent, but benefits from a smaller statistical uncertainty.
9 Systematic uncertainties

Experimental systematic uncertainties affecting both the simulation-based background and correction factors arise from uncertainties on the efficiencies, resolutions and energy scales of leptons and jets [96, 97, 100, 106], as well as pile-up modeling. These uncertainties can affect both the shape and the normalization of the distributions. For the background estimate and the conversion of the number of particle-level events to cross sections, the luminosity uncertainty needs to be taken into account. The uncertainty on the combined 2015+2016 integrated luminosity is 3.2%. It is derived, following a methodology similar to that detailed in Ref. [107], from a preliminary calibration of the luminosity scale using x-y beam-separation scans performed in August 2015 and May 2016.

Uncertainties are also considered on the method used for extracting the non-prompt backgrounds. In particular, the composition estimates, which affect the yields in the bins of the differential distributions, have large uncertainties. Further uncertainties are assigned to the efficiencies of the different background components to pass the signal selection.

For the simulated backgrounds and the extrapolation of the inclusive fiducial cross section to the total cross section, theoretical modelling uncertainties associated with PDF, missing QCD higher order corrections (via variations of the factorisation and renormalisation scales), and underlying event/parton showering uncertainties are considered. For the extrapolation to the total cross section, uncertainties are also included on the branching fractions [15].

The effect on the fitted event yields of shifting the $m_{4\ell}$ template by 0.24 GeV [1] has been shown to be smaller than 0.5% and is therefore neglected.

The dependence of the correction for detector effects on the theoretical modeling is assessed in a number of ways. For ggF, VBF and $VH$, the PDF4LHC NLO PDF set is varied according to its eigenvectors, and the envelope of the variations is used as the systematic uncertainty. The renormalisation and factorisation scales are varied by factors of 2 and 0.5. Furthermore, $m_H$ is varied within the measured uncertainties. The relative contribution of each Higgs-boson production mechanism is varied by an amount consistent with the uncertainties obtained in the ATLAS and CMS combined measurement of the Higgs-boson production cross sections [2], except for $t\bar{t}H$ where the allowed variation is inflated to cover the measured value, which is more than 2 standard deviations away from the SM prediction. The correction factor is cross-checked using the alternative Madgraph5 ggF samples (for SM and modified couplings) and the differences with respect to nominal are found to be well within the statistical uncertainties of the samples. Bias studies and cross-checks with other unfolding methods, such as matrix inversion and Bayesian iterative unfolding [108] show results that agree very well with the bin-by-bin correction factor results. Observed differences are much smaller than the statistical uncertainties.

The uncertainties in this analysis are dominated by limited data statistics. The statistical uncertainty on the fiducial inclusive cross section obtained by combining all decay channels is 14%, while the systematic uncertainty is 7% dominated by the lepton uncertainties and the uncertainty on the luminosity. For the differential cross sections, the size of the statistical and systematic uncertainties depends on the variable and is shown in Table 3. The breakdown of the dominant systematic uncertainties is obtained by performing the fits while fixing groups of nuisance parameters to their best fit value. The statistical uncertainties are mostly in the range 20–50%, and can be as high as 150%. For the Higgs-boson kinematic properties, the most important systematic uncertainties are the experimental lepton uncertainties, 1–5%. The signal composition uncertainty grows with the increase of the fraction of $t\bar{t}H$ in some regions of phase space, such as for $N_{\text{jets}} \geq 3$. Therefore, for observables defined by the jet activity produced in association
than the LHCXSWG calculation. The observed fiducial cross sections in the
accurate to NLO in QCD for inclusive ggF production. All generators predict cross sections that are lower
than the MG5_aMC@NLO_FxFx

differences. The measured differential cross sections and their comparisons to SM predictions are presented in Fig-
ures 8 and 9. The measured cross sections for the combined fiducial and total phase space, as shown in the right panel, using the same acceptance as well as the branching
fractions or combining them assuming SM branching fractions. The data are compared to the LHCXSWG prediction after accounting for the fiducial acceptance as determined from the SM Higgs-boson simulated samples (see Section 3). The fiducial cross section is extrapolated to the total phase space, as shown in the right panel, using the same acceptance as well as the branching fractions, with the additional uncertainties described in Section 9. The total cross section is also compared to the cross sections predicted by NNLOPS, HERA, and MG5_aMC@NLO_FxFx (see Section 3). It can be seen that the MG5_aMC@NLO_FxFx cross section is lower than the other predictions, as given by the NLO in QCD for inclusive ggF production. All generators predict cross sections that are lower than the LHCXSWG calculation. The observed fiducial cross sections in the 2e2µ and 2µ2e final states are higher than the expectation, which leads to an overall larger observed cross section. The agreement between the combined fiducial cross section and the prediction is within 1.3 standard deviations. The p-values, calculated as described in Section 8, are also shown in Table 4. They indicate good compatibility with the SM predictions.

The measured differential cross sections and their comparisons to SM predictions are presented in Figures 8-10. The data are compared to SM predictions constructed from the ggF predictions provided by
Table 4: The fiducial and total cross sections of Higgs-boson production measured in the 4ℓ final state. The fiducial cross sections are shown separately for each decay channel, and for same- and opposite-flavour decays. The inclusive fiducial cross section is measured as the sum of all channels, as well as by combining the per-channel measurements assuming SM ZZ’ → 4ℓ branching ratios. The LHCXSWG prediction is accurate to N3LO in QCD for the ggF process. For the fiducial cross section predictions, the LHCXSWG cross sections are multiplied by the acceptances determined using the NNLOPS sample for ggF and the samples discussed in Section 3 for the other production modes. The p-values indicating the compatibility between measurement and SM prediction are shown as well. They do not include the systematic uncertainty on the theoretical predictions.

<table>
<thead>
<tr>
<th>Cross section [fb]</th>
<th>Data (± (stat) ± (sys) )</th>
<th>LHCXSWG prediction</th>
<th>p-value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{4μ}</td>
<td>0.92 ±0.03 +0.07 -0.05</td>
<td>0.880 ± 0.039</td>
<td>88</td>
</tr>
<tr>
<td>σ_{4e}</td>
<td>0.67 ±0.08 +0.08 -0.06</td>
<td>0.688 ± 0.031</td>
<td>96</td>
</tr>
<tr>
<td>σ_{2μ2e}</td>
<td>0.84 ±0.09 +0.08 -0.06</td>
<td>0.625 ± 0.028</td>
<td>39</td>
</tr>
<tr>
<td>σ_{2e2μ}</td>
<td>1.18 ±0.07 +0.08 -0.05</td>
<td>0.717 ± 0.032</td>
<td>7</td>
</tr>
<tr>
<td>σ_{4μ+4e}</td>
<td>1.59 ±0.12 +0.12 -0.033</td>
<td>1.57 ± 0.07</td>
<td>65</td>
</tr>
<tr>
<td>σ_{2μ2e+2e2μ}</td>
<td>2.02 ±0.14 +0.14 -0.36</td>
<td>1.34 ± 0.06</td>
<td>6</td>
</tr>
<tr>
<td>σ_{sum}</td>
<td>3.61 ±0.26 +0.31 -0.30</td>
<td>2.91 ± 0.13</td>
<td>19</td>
</tr>
<tr>
<td>σ_{comb}</td>
<td>3.62 ±0.25 +0.32 -0.50</td>
<td>2.91 ± 0.13</td>
<td>18</td>
</tr>
<tr>
<td>σ_{tot} [pb]</td>
<td>69 +10 -9 ±5</td>
<td>55.6 ± 2.5</td>
<td>19</td>
</tr>
</tbody>
</table>

NNLOPS, MG5_AMC@NLO_FxFx, and, for p_{T, 4ℓ} and |y_{4ℓ}|, by HRes. All ggF samples are normalized to the LHCXSWG cross section. Predictions for all other Higgs-boson production modes normalized as discussed in Section 3. The shaded bands on the expected cross sections indicate the PDF and scale uncertainties. The PDF inputs used for each prediction are varied according to the eigenvectors of each PDF set. The renormalisation and factorisation scales are varied by factors of 2 and 0.5. The figures include the p-values quantifying the compatibility between the measurement and the predictions.

The observed small excess in the measured inclusive cross section is mostly reflected in an overall normalisation offset. Figure 8 shows differential fiducial cross sections as a function of p_{T, 4ℓ}, |y_{4ℓ}|, m_{34}, and |cos θ'|. The measured cross sections at high p_{T, 4ℓ} are slightly higher than the predictions, but the distribution is consistent with the SM predictions within the uncertainties. The good agreement between data and prediction of the cross sections as a function of m_{34} and |cos θ'| is consistent with dedicated measurements that have shown the Higgs boson to have the spin and parity as predicted by the SM [3, 4].

In Figure 9, the differential fiducial cross sections as a function of N_{jets}, p_{T, lead,jet}^j, m_{jj}, and Δφ_{jj} are shown. The agreement between data and theory is still good, but becomes a bit worse for higher jet multiplicities and higher p_{T, lead,jet}^j, similarly to what was observed in the ATLAS analyses at $\sqrt{s} = 8$ TeV [5–7]. MG5_AMC@NLO_FxFx describes the jet multiplicities slightly better than NNLOPS. For large values of m_{jj} and the left bin of the Δφ_{jj} distribution, the measured cross section is more than twice the predicted value (~2 and ~1.5 standard deviations respectively).

Figure 10 presents the differential fiducial cross sections as a function of p_{T, 4ℓ} for different jet multiplicities as well as the cross sections measured in regions of the m_{12} vs m_{34} distribution. The split into different jet multiplicities allows to probe perturbative QCD calculations for different production modes. The 0-jet bin
Figure 7: The fiducial cross sections (left two panels) and total cross section (right panel) of Higgs-boson production measured in the $4\ell$ final state. The fiducial cross sections are shown separately for each decay channel, and for same- and opposite-flavour decays. The inclusive fiducial cross section is measured as the sum of all channels, as well as by combining the per-channel measurements assuming SM $ZZ^* \rightarrow 4\ell$ branching ratios. The LHCXSWG prediction is accurate to N3LO in QCD for the ggF process. For the fiducial cross section predictions, the LHCXSWG cross sections are multiplied by the acceptances determined using the NNLOPS sample for ggF and the samples discussed in Section 3 for the other production modes. For the total cross section, the cross-section predictions by the generators NNLOPS, HRes, and MG5_aMC@NLO_FxFx are also shown, each normalized to its respective predicted cross section. The cross sections for all other Higgs-boson production modes $XH$ are added. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The shaded bands around the expected values indicate the PDF and scale uncertainties.
Figure 8: Differential fiducial cross sections, for the transverse momentum of the Higgs-boson $p_{T,4ℓ}$ (a), the absolute value of the rapidity of the Higgs-boson $|y_{4ℓ}|$ (b), the invariant mass of the subleading lepton pair $m_{34}$ (c), the magnitude of the cosine of the decay angle of the leading lepton pair in the four-lepton rest frame with respect to the beam axis $|\cos θ^*|$ (d). The measured cross sections are compared to ggF predictions by NNLOPS, MG5_aMC@NLO_FxFx, and, for $p_{T,4ℓ}$ and $|y_{4ℓ}|$, by HRs, all normalized to the N3LO cross section with the listed $k$-factors. Predictions for all other Higgs-boson production modes $XH$ are added. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The shaded bands on the expected cross sections indicate the PDF and scale uncertainties. The $p$-values indicating the compatibility between measurement and SM prediction are shown as well. They do not include the systematic uncertainty on the theoretical predictions.
Figure 9: Differential fiducial cross sections, for the number of jets \(N_{\text{jets}}\) (a), the transverse momentum of the leading jet \(p_{T}^{\text{lead jet}}\) (b), the invariant mass of the two leading jets \(m_{jj}\) (c), the angle between the two leading jets in the transverse plane \(\Delta \phi_{jj}\) (d). The measured cross sections are compared to ggF predictions by NNLOPS and MG5_aMC@NLO_FxFx, all normalized to the N3LO cross section with the listed \(k\)-factors. Predictions for all other Higgs-boson production modes \(XH\) are added. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The shaded bands on the expected cross sections indicate the PDF and scale uncertainties. The \(p\)-values indicating the compatibility between measurement and SM prediction are shown as well. They do not include the systematic uncertainty on the theoretical predictions.
Figure 10: Differential fiducial cross sections of the transverse momentum of the Higgs-boson $p_{T,4\ell}$ for different jet multiplicities $N_{\text{jets}}$ (a)-(c) and the invariant mass of the leading lepton pair vs that of the subleading pair, $m_{12}$ vs $m_{34}$ (d). The measured cross sections are compared to ggF predictions by NNLOPS and MG5_aMC@NLO_FxFx, all normalized to the N3LO cross section with the listed $k$-factors. Predictions for all other Higgs-boson production modes $XH$ are added. The error bars on the data points show the total uncertainties, while the systematic uncertainties are indicated by the boxes. The shaded bands on the expected cross sections indicate the PDF and scale uncertainties. For the cross sections as a function of $p_{T,4\ell}$, the $p$-values reflect the agreement for the three jet bins together, treating them as a two-dimensional distribution.
is dominated by Higgs-boson events produced through ggF, while the ≥ 2-jet bin is enriched with VBF events. No significant deviation is seen, as indicated by the $p$-values which reflect the agreement for the three jet bins together, treating them as a two-dimensional distribution. The higher values of the measured cross sections in the ≥ 2-jet bin reflect the observations on Figure 9(a). The $m_{12}$ vs $m_{34}$ kinematic plane is divided into five regions and projected onto a one-dimensional distribution, as shown in Figure 3(d). The agreement between the data and the predictions is good.

Figure 11: Limits on modified Higgs-boson decays within the framework of pseudo-observables [13, 72]. In subfigure (a), the limits are extracted in the plane of $\varepsilon_L$ and $\varepsilon_R$, which modify the contact terms between the Higgs boson and left- and right-handed leptons, assuming lepton-flavour universality. In subfigure (b), the tested parameters are $\varepsilon_L$ and $\kappa$. The latter modifies the coupling of the Higgs boson to Z bosons. The allowed observed area at the 95% CL is surrounded by the red solid line. This can be compared to the SM expectation, which is indicated by the black star and the black dotted line. The coloured scale indicates the values of $-2 \ln \Lambda$.

The differential fiducial cross sections can be interpreted in the context of searches for physics beyond the SM. In the absence of significant deviations from the SM expectations, limits are set on modified Higgs-boson interactions within the framework of pseudo-observables [13, 72]. In this note, the couplings related to the contact-interaction of the Higgs-boson decay are considered, $\varepsilon_L$ and $\varepsilon_R$, which modify the contact terms between the Higgs boson and left- and right-handed leptons, assuming lepton-flavour universality. Since the contact terms have the same Lorentz structure as the SM term, they only affect the dilepton invariant mass spectra, while the lepton angular distributions are not modified. The difference in $\chi^2$ between the measured and predicted cross sections in the $m_{12}$ vs $m_{34}$ parameter plane is therefore used to constrain the possible contributions from contact interactions. Assuming the SM values for all but the tested parameters, limits are set on the contact-interaction coupling strength as shown in Figure 11. Two parameter planes are considered: $\varepsilon_L$ vs $\varepsilon_R$, as well as $\varepsilon_L$ vs $\kappa$, where $\kappa$ is the coupling of the Higgs boson to the Z bosons and $\varepsilon_R = 0.48 \cdot \varepsilon_L$ [72]. Since the addition of the contact terms changes the Higgs-boson production rate, in principle limits could be set based on the inclusive Higgs-boson cross sections alone. In this case, the obtained allowed area in Figure 11(a) would be circular, but the addition of the invariant mass spectra improves the limit, especially for negative $\varepsilon_L$ and positive $\varepsilon_R$. The addition of the shape
information also improves the limit in the $\epsilon_L$ vs $\kappa$ parameter plane. It can be seen that the expected and observed limits are a slightly shifted with respect to each other, but no significant deviation is observed.

11 Conclusion

Measurements of the inclusive and differential fiducial cross sections of Higgs-boson production in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel have been presented. They are based on data extracted from $\sqrt{s} = 13$ TeV proton-proton collisions recorded by the ATLAS detector at the LHC in 2015 and 2016. The inclusive fiducial cross section in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel is measured to be $3.62^{+0.53}_{-0.50}$ (stat) $^{+0.25}_{-0.20}$ (sys) fb, in agreement with the Standard Model prediction of $2.91\pm 0.13$ fb. The inclusive fiducial cross section is also extrapolated to the total phase space which includes all Standard Model Higgs-boson decays. Several differential fiducial cross sections are measured for observables sensitive to the Higgs-boson production and decay, including kinematic distributions of the jets produced together with the Higgs boson. Good agreement is found between the data and the predictions of the Standard Model. The extracted cross-section distributions are used to constrain anomalous Higgs-boson interactions with Standard Model particles using the pseudo-observable framework.

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