Search for Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state using $pp$ collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Abstract

Searches for both resonant and non-resonant production of pairs of Higgs bosons ($hh$) are performed in the $b\bar{b}\gamma\gamma$ final state using 3.2 fb$^{-1}$ of proton–proton collision data at 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. An upper limit of 3.9 pb on the cross-section for non-resonant production is extracted at the 95% confidence level, while the expected limit is 5.4 pb. In the search for a narrow $X \rightarrow hh$ resonance, the observed limit ranges between 7.0 pb and 4.0 pb for masses of the resonance between 275 and 400 GeV. The corresponding expected limit varies between 7.5 pb and 4.4 pb for the same mass range.
1 Introduction

In 2012, the ATLAS and CMS experiments at the Large Hadron Collider (LHC) discovered a particle with couplings to elementary fermions and bosons consistent with those of the Standard Model (SM) Higgs boson, $h$ [1, 2]. No significant deviations from the SM expectation have been shown in further studies of the properties of the newly-observed resonance [3–6], and its mass, $m_h$, has been measured to be $125.09 \pm 0.24$ GeV [7]. The discovery of a SM-like Higgs boson opens up many new channels in the search for potential beyond the Standard Model (BSM) physics. A search is presented here for the production of pairs of Higgs bosons in 3.2 fb$^{-1}$ of proton–proton ($pp$) collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector. The Higgs boson pair, which could be produced either through a resonant state $X$ decaying via $X \rightarrow hh$ or through production processes that do not involve a resonance, is then required to decay through the $hh \rightarrow b\bar{b}\gamma\gamma$ channel. A similar analysis carried out by ATLAS using 20 fb$^{-1}$ of 8 TeV data found a modest excess of events, 2.4 standard deviations from the background-only hypothesis [8].

Within the SM, the cross-section for production of Higgs boson pairs is several orders of magnitude below single Higgs production rate. This results from a combination of the reduced phase-space from requiring an additional on-shell Higgs boson, the need to have one additional interaction vertex and the destructive interference [9] between the two leading-order production diagrams, which are shown in Fig. 1 (a) and (b). Accordingly, the SM production of Higgs boson pairs is not expected to be observable using
Figure 1: Leading-order production modes for Higgs boson pairs in the SM through (a) a heavy-quark loop and (b) the Higgs self-coupling. The total SM contribution is the sum of the two modes, which includes significant destructive interference. BSM Higgs boson pair production could proceed through changes in the SM Higgs couplings in (a) and (b), or through (c) an intermediate resonance, $X$.

the datasets so far recorded by the ATLAS experiment. However, a variety of new physics models predict enhancements to this cross-section. Therefore, the observation of Higgs boson pairs would provide supporting evidence for BSM physics.

Models with two Higgs doublets (2HDMs), such as the minimal supersymmetric extension of the SM [10], twin Higgs models [11] and composite Higgs models [12, 13], predict the existence of a heavy Higgs boson that could itself decay to two lighter, SM-like, scalar partners, as shown in Fig. 1 (c). Other BSM processes that could result in resonant decays to two Higgs bosons include gravitons [14], radions [15] and stoponium [16]. Finally, a deviation from the SM value of the self-coupling $\lambda_{hhh}$, could increase the non-resonant production rate by reducing the effect of the destructive interference [17].

The $b\bar{b}\gamma\gamma$ final state is particularly promising for this search, as it benefits from the large branching fraction of the $h \to b\bar{b}$ decay (58% [18]) and the clean diphoton signal, due to high $m_{\gamma\gamma}$ resolution, on top of a smooth continuum diphoton background from multijet and multiphoton SM processes. For resonances with masses above 400 GeV, search channels such as $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^−$ have better sensitivity due to the higher branching fractions of the SM Higgs boson decays to $b\bar{b}$ and $\tau^+\tau^−$ (6.3% [18]) with respect to $\gamma\gamma$ (0.23% [18]) [19, 20]. For this reason, this search focuses on resonances with masses in the range $275 \text{ GeV} < m_X < 400 \text{ GeV}$, as well as on non-resonant production with similar kinematic properties to the SM Higgs-pair (di-Higgs) production but with an enhanced rate with respect to the SM one.

2 Data and simulated samples

2.1 The ATLAS detector

The ATLAS experiment [21] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and nearly $4\pi$ coverage in solid angle. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The inner tracking detector, consisting

\begin{itemize}
  \item $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.
\end{itemize}
of silicon pixel, silicon micro-strip, and transition radiation tracking systems, covers the pseudorapidity range $|\eta| < 2.5$. The innermost pixel layer, the insertable B-layer, was added between the first and second runs of the LHC, around a new, narrower and thinner beam pipe [22]. Lead/liquid-argon (LAr) sampling calorimeters with high granularity provide energy measurements of EM showers. A hadronic (iron/scintillator-tile) calorimeter covers the central pseudorapidity range $(|\eta| < 1.7)$. The end-cap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each and with bending power in the range 2.0–7.5 T m. It includes a system of precision tracking chambers and fast detectors for triggering purposes. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted event rate to at most 75 kHz. This is followed by a software-based trigger level that reduces the accepted event rate to an average of 400 Hz, depending on the data-taking conditions.

2.2 Data selection

The analysis uses the full $pp$ data sample collected at $\sqrt{s} = 13$ TeV by the ATLAS detector in 2015, corresponding to an integrated luminosity of $3.2 \pm 0.2$ fb$^{-1}$. All events considered are required to belong to specific run periods during which the detector and trigger system satisfy a set of data-quality criteria. Events are selected from colliding proton bunches using a trigger which requires the presence of two photons, one with transverse momentum ($p_T$) greater than 35 GeV and the second with $p_T > 25$ GeV. The photon identification criteria used in the trigger are less strict than those subsequently used for this analysis, as detailed in Sec. 3.

2.3 Simulated event samples

The background estimation is carried out using data-driven methods whenever possible – in particular, data are used to estimate the continuum diphoton contribution from SM processes with multiple photons and jets, which forms the dominant background for this search. Monte Carlo event generators are used to validate data-driven estimates, to simulate various signal hypotheses, as well as for event selection optimisation and the subtraction of SM single-Higgs backgrounds.

This analysis uses simulated samples of non-resonant SM di-Higgs production, as well as resonant BSM di-Higgs production for five different mass points (275, 300, 325, 350 and 400 GeV). These are simulated using an effective field theory (EFT) model implemented in MadGraph5_aMC@NLO v2.2.2 [23] at leading-order (LO) and interfaced to the $\text{Pythia}$ 8.186 [24, 25] parton shower model. In each case, the A14 tune [26] is used together with the NNPDF2.3LO parton distribution function (PDF) set [27]. For samples simulating non-resonant di-Higgs production, the cross-sections are normalised to the SM prediction of 37.9 fb, calculated at next-to-next-to-leading order (NNLO) in QCD by the LHC Higgs Cross-Section Working Group [28]. For samples simulating resonant di-Higgs production, the resonance is chosen to have a narrow decay width.

Simulated samples of the dominant continuum backgrounds of processes with multiple jets and photons are used for optimisation of the event and object selections. These are, for the most part, generated with MadGraph5_aMC@NLO v2.2.2, interfaced to the $\text{Pythia}$ 8.186 parton shower model. For the background process of two photons and up to three jets, events are instead produced using the Sherpa
2.1.1 generator, requiring two photons, each with $p_T > 20$ GeV. Matrix elements are calculated at leading-order, in disjoint regions of photon $p_T$, for up to 3 partons in the lowest $p_T$ region, or 4 otherwise, and are merged with the Sherpa parton shower [30] using the ME+PS@LO prescription [31]. The CT10 PDF set [32] is used in conjunction with dedicated parton shower tuning developed by the Sherpa authors.

Events are also generated for the six single-Higgs production modes with the highest cross-sections: gluon-gluon fusion (ggF), vector-boson fusion (VBF), associated production with a $W$ or $Z$ boson ($Wh$ or $Zh$), and associated production with a pair of top or bottom quarks, $t\bar{t}h$ and $b\bar{b}h$. The ggF and VBF samples are simulated using Powheg-Box v2 [33–35] with the CT10 PDF set in the matrix element. The ggF samples are normalised to the calculation at NNLO in QCD [36–41] with next-to-leading order (NLO) electroweak (EW) corrections also included [42, 43]. The VBF samples are normalised to the cross-section calculated at NLO in QCD with NLO EW corrections [44–46] and an approximate NNLO QCD correction applied [47]. The $Wh$ and $Zh$ samples are generated using Pythia 8.186 and normalised to cross-sections calculated at NNLO in QCD [48] with NLO EW corrections [49]. The $t\bar{t}h$ samples are generated using Pythia 8.186 and normalised to a calculation at NLO in QCD [50–53]. The $b\bar{b}h$ samples are simulated using MadGraph5_AMC@NLO v2.2.2 in NLO mode [23]. For each of these six samples, the Pythia 8.186 parton shower is used for the modelling of non-perturbative effects. In the case of the ggF and VBF samples, the AZNLO tune [54] of Pythia is used, together with the CTEQ6L1 PDF set [55]. For the other four samples, the A14 tune of Pythia is used with the NNPDF2.3LO PDF set.

For all of the simulated samples discussed above, the EvtGen v1.2.0 program [56] is used for modelling the properties of the bottom- and charm-hadron decays. Multiple overlaid $pp$ collisions occurring in the same bunch crossing, “pileup”, are simulated with the soft QCD processes of Pythia 8.186 using the A2 tune [57] and the MSTW2008LO PDF set [58]. The number of overlaid collisions simulated in each event is chosen to match the distribution of this quantity observed in 2015 running conditions. Additional event-level reweighting is applied to ensure that this distribution of number of overlaid collisions exactly matches that occurring in the data used in this analysis. The final-state particles are passed through either a GEANT4 [59] simulation of the ATLAS detector [60], or through the ATLAS fast simulation framework, which has been extensively cross-checked against the GEANT4 model. The output from this detector simulation step is then reconstructed using the same software as the data. Only the samples associated with single-Higgs and di-Higgs production use the GEANT4 simulation, all other samples use the fast simulation framework.

3 Object and event selection

The final state in this analysis consists of two isolated photons, accompanied by two jets, both identified as containing a $b$-hadron decay ($b$-jet). The following subsections detail the selection and identification of all detector-level objects used in the analysis, followed by the event selection criteria and the categorisation into signal and background control regions. The selection requirements are kept as close as possible to those used in the 8 TeV data analysis [8], with the exception of those that are affected by the updated performance of the ATLAS detector, such as the subtraction of jets arising from pileup and the identification of $b$-jets.
3.1 Object selection

Energy deposits in the EM calorimeter are grouped together into projective towers, made from the presampler and the three electromagnetic calorimeter layers, of size $0.075 \times 0.125$ in the $\Delta \eta \times \Delta \phi$ plane [61]. Energy clusters are reconstructed from these towers using a sliding window algorithm that looks for local maxima with transverse energies exceeding 2.5 GeV. Tracks reconstructed in the inner detector are extrapolated into the calorimeter. High-quality tracks matched to clusters are classified as electron candidates, while clusters with no matching tracks are classified as unconverted photon candidates. Clusters matched to tracks consistent with the hypothesis of a $\gamma \rightarrow e^+ e^-$ conversion process are classified as converted photon candidates. Photon energies are determined by first rebuilding the calorimeter clusters, using sizes of $\Delta \eta \times \Delta \phi = 0.075 \times 0.175$ in the barrel region and $0.125 \times 0.125$ in the end-cap, before summing the energies of all cells belonging to the associated cluster [62]. Simulation-based corrections are applied to account for energy losses and leakage outside the cluster [63]. After reconstruction, tight photon identification criteria [64], based on the lateral and longitudinal energy profiles of EM showers in the calorimeter, are applied. The reconstruction efficiency for both converted and unconverted photons is 97%. The identification efficiency varies with the transverse energy ($E_T$) between 25 and 200 GeV. It ranges from 90% to 98% for converted photons and from 85% to 95% for unconverted photons. All photon candidates are required to pass a set of calorimeter- and track-based isolation criteria designed to reject backgrounds and to maximise the signal significance of simulated $h \rightarrow \gamma \gamma$ events against the continuum background [65]. Calorimeter-based isolation uses the sum of the energies of all topological clusters of calorimeter cells within $\Delta R = 0.2$ of the photon candidate, excluding clusters associated to the photon candidate. Track-based isolation uses the transverse momenta of tracks, summing them for all tracks with $p_T > 1$ GeV within $\Delta R = 0.2$ of the photon candidate, excluding tracks from photon conversions. Photons passing the isolation criteria are then required to fall within the fiducial region of the EM calorimeter defined by $|\eta| < 2.37$, excluding the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$). Among the photons satisfying the isolation and fiducial cuts, the two with the highest-$E_T$ are required to have $E_T/m_{\gamma\gamma} > 0.35$ (0.25) respectively, where $m_{\gamma\gamma}$ is the invariant mass of the diphoton system [62].

Jets are reconstructed using the anti-$k_t$ algorithm [66] with distance parameter $R = 0.4$, and are required to have $|\eta| < 2.5$ and $p_T > 25$ GeV. The inputs to jet reconstruction are three-dimensional topological clusters of calorimeter cells taken at the EM scale [67–69]. The dependence of jet kinematics on pileup is suppressed by applying an ambient energy correction taken as the event median $E_T$-density, evaluated event-by-event from calorimeter information, multiplied by the jet area [70]. A further correction, dependent on the number of reconstructed primary vertices and to the average number of interactions per bunch crossing, is then applied to remove residual pileup effects. To further suppress jets produced in additional pileup interactions, a jet vertex tagging algorithm (JVT) is used [71]. JVT is a multivariate discriminant calculated from two track-based variables designed to suppress pileup jets while maintaining a high hard-scatter jet efficiency that is stable as a function of the number of primary vertices in the event. A minimum JVT value is required for each jet with $|\eta| < 2.4$ and $p_T < 50$ GeV.

Jets are classified using a multivariate technique designed to discriminate $b$-jets (those containing $b$-hadrons) from $c$-jets (those containing $c$-hadrons) and light jets (all other jets) [72, 73]. The presence or absence of secondary vertices, the impact parameters of the associated tracks and the topologies of weak heavy-quark decays are all taken as inputs to this algorithm. An operating point is chosen such that the $b$-tagging efficiency is 85% with a $c$-jet rejection factor of 2.6 and a light jet rejection factor of 28. This working point was chosen to maximise the significance of the SM non-resonant di-Higgs signal.
production. The highest-\(p_T\) \(b\)-jet must have \(p_T > 55\) GeV, while the next-highest-\(p_T\) \(b\)-jet is required to have \(p_T > 35\) GeV.

Muon candidates are identified by matching a reconstructed ID track with a reconstructed MS track [74, 75]. Medium-quality muons with \(p_T > 4\) GeV and \(|\eta| < 2.5\) are selected. The four-momenta of any muons in a cone of size \(\Delta R = 0.4\) around each reconstructed \(b\)-jet are added to its four-momentum to account for energy losses from semi-leptonic \(b\)-hadron decays; any muons outside this cone are ignored. This small correction improves the energy measurement of \(b\)-jets, as well as the \(b\bar{b}\) invariant mass resolution.

### 3.2 Event selection

All events are required to have a primary vertex consistent with a diphoton production vertex. For this purpose, a neural network trained on a simulated single-Higgs sample at \(\sqrt{s} = 13\) TeV is used. Using an identified diphoton system, directional information from the longitudinal section of the calorimeter and, in the case of converted photons, tracking information, allow the extrapolation of the photon trajectories back to the beam axis. The algorithm uses this information, together with vertex properties such as the sum of the squared transverse momenta or the scalar sum of the transverse momenta of the tracks associated to the vertex, as inputs. The four momenta of the photons and all track-based quantities, such as the photon track isolation and JVT values of the jets, are recalculated with respect to the chosen primary vertex [62].

Events are selected if there are at least two photons and exactly two \(b\)-jets satisfying the criteria outlined in Sec. 3.1. The diphoton invariant mass is initially required to fall within a broad mass window of \(105\) GeV \(< m_{\gamma\gamma} < 160\) GeV. The invariant mass of the \(b\)-jet pair, \(m_{b\bar{b}}\), is chosen to lie between 95 and 135 GeV.

The efficiency of non-resonantly produced di-Higgs events to pass these selection criteria is 10%. The corresponding efficiency for the resonantly produced di-Higgs events increases with the mass of the resonance and ranges from 5% to 8% for \(275 < m_X < 400\) GeV. The efficiency is larger in the non-resonant di-Higgs production since the Higgs decay products tend to have higher \(p_T\) and are more likely to pass the analysis selection than in the case of the resonant production.

The four-momentum of the \(b\bar{b}\) system is scaled by \(m_h / m_{b\bar{b}}\). This improves the \(m_{b\bar{b}\gamma\gamma}\) resolution on average by 60\% across the resonance mass range, as illustrated in Fig. 2 (a), without significantly impacting the shape of the background, as shown in Fig. 2 (b). The impact on the expected yield of the continuum background is small and within the statistical uncertainties, as estimated using the methods described in Sec. 4.2.

Two additional criteria are applied in the search for resonant di-Higgs production. A parametrised double-sided Crystal Ball [76] function is fit to the \(m_{\gamma\gamma}\) distribution in simulated single-Higgs events. The width of this fit, \(\sigma_{m_{\gamma\gamma}}\), is found to be 1.55 GeV. The diphoton mass restriction is tightened to \(2 \sigma_{m_{\gamma\gamma}}\) on each side of the central mass value of \(m_h\). The final signal region is then selected using the smallest window in the \(m_{b\bar{b}\gamma\gamma}\) distribution containing 95\% of the simulated di-Higgs events for each mass hypothesis, \(m_X\). The size of the window increases from 20 to 50 GeV with the mass of the resonance. A linear parametrisation is adopted to calculate the \(m_{b\bar{b}\gamma\gamma}\) mass windows for the resonances which are not simulated. This parametrisation is shown in Fig. 2 (c).
Figure 2: The effect of the \( m_h/m_{bb} \) scaling on the \( m_{bb\gamma\gamma} \) mass resolution is shown (a) for di-Higgs signal samples in the resonant production mode and (b) for data in the 0-tag \( m_{\gamma\gamma} \) sidebands control region, as defined in Sec. 4.1. The mean and standard deviation of the background distribution with the \( m_h \) constraint are 356 ± 7 GeV and 107 ± 5 GeV, respectively. The corresponding properties of the distribution without the \( m_h \) constraint are 341 ± 6 GeV and 103 ± 5 GeV, respectively. The uncertainties are statistical only. In (c) the 95% efficient mass windows (grey shaded area) are presented as a function of the mass of the resonance.

4 Signal and background modelling

Since different event selection criteria are used in the searches for non-resonant and resonant di-Higgs production, slightly different procedures must be used when modelling the signal and background contributions. In each case, the sample of events passing all relevant selection criteria is denoted as 2-tag events, while events with no jets \( b \)-tagged but passing all the other requirements outlined in Sec. 3.1 are called 0-tag events. Events in the 2-tag region are used to test for the presence of signal, while events in the 0-tag region are used to provide a data-driven estimate of the continuum background. For 0-tag events, the two highest \( p_T \) jets are chosen for the analysis. The category with one jet passing and one jet failing the \( b \)-tagging criteria [8] is not used in this analysis.

4.1 Non-resonant di-Higgs production

In the search for non-resonant di-Higgs production, a fit to the \( m_{\gamma\gamma} \) distribution is performed simultaneously in the 0-tag and 2-tag regions. The shapes of the \( m_{\gamma\gamma} \) distributions for simulated di-Higgs and single-Higgs events are parametrised using double-sided Crystal Ball functions. The shape of the continuum diphoton background is extracted from an exponential fit to the sidebands of the \( m_{\gamma\gamma} \) distribution, where the sidebands are defined as the region 105 GeV < \( m_{\gamma\gamma} \) < 160 GeV but excluding the window of \( m_h \pm 2 \sigma_{m_{\gamma\gamma}} \). The same exponential decay constant is used in both the 0-tag and 2-tag regions. The normalisation is defined by the number of observed events in the 0-tag and 2-tag regions, respectively. The choice of the fit function and the uncertainties associated with this choice are described in Sec. 5.
4.2 Resonant di-Higgs production

In the search for the resonant di-Higgs production, a counting approach is adopted in order to estimate the number of signal and background events. The signal region in the 2-tag category is defined by requiring $m_{\gamma\gamma}$ to be inside $m_h \pm 2 \sigma_{m_{\gamma\gamma}}$, and by using additional $m_{bb\gamma\gamma}$ requirements that depend on the resonance mass hypothesis. The total number of continuum background events in the signal region (SR), $N_{SR}^B$, is estimated using:

$$N_{SR}^B = N_{SB} \frac{\varepsilon_{m_{\gamma\gamma}}^B}{1 - \varepsilon_{m_{\gamma\gamma}}^B} \varepsilon_{m_{bb\gamma\gamma}}^B,$$

where $N_{SB}$ is the number of observed events in the $m_{\gamma\gamma}$ sidebands, $\varepsilon_{m_{\gamma\gamma}}^B$ is the efficiency to pass the $m_{\gamma\gamma}$ window cuts and $\varepsilon_{m_{bb\gamma\gamma}}^B$ is the efficiency to pass the $m_{bb\gamma\gamma}$ mass window cuts. The denominator of the $m_{\gamma\gamma}$ extrapolation factor $(1 - \varepsilon_{m_{\gamma\gamma}}^B)$ compensates for the fact that $N_{SB}$ represents the number of events in the $m_{\gamma\gamma}$ sidebands, whereas $\varepsilon_{m_{\gamma\gamma}}^B$ is derived with respect to the full $m_{\gamma\gamma}$ spectrum. A diagram representing this background estimation technique is shown in Fig. 3.

The calculation of $\varepsilon_{m_{\gamma\gamma}}^B$ is performed by fitting an exponential to the $m_{\gamma\gamma}$ distribution in the data in the 0-tag region, and then calculating integrals in the full mass range and in the $m_{\gamma\gamma}$ mass window. It yields $0.126 \pm 0.001$ and the corresponding extrapolation factor $\varepsilon_{m_{\gamma\gamma}}^B / (1 - \varepsilon_{m_{\gamma\gamma}}^B)$ is $0.144 \pm 0.001$. Only the statistical uncertainty is quoted here; this uncertainty is obtained through a Monte Carlo method detailed in Sec. 5. Both values are common for all resonant mass points since this requirement is applied before any requirement on $m_{bb\gamma\gamma}$ is made.

The value of $\varepsilon_{m_{bb\gamma\gamma}}^B$ is obtained from the $m_{jj\gamma\gamma}$ spectrum in data with zero $b$-jets, which is used to model the shape of the continuum background with two $b$-jets. Such a data-driven approach introduces a
systematic uncertainty related to the assumption that $jj\gamma\gamma$ events have similar kinematics to $b\bar{b}\gamma\gamma$ events; this point is discussed in detail in Sec. 5. The $m_{jj\gamma\gamma}$ distribution is obtained after the $m_{\gamma\gamma}$ selection, and is fit with a Landau function [8]. The contribution from simulated single-Higgs production in this kinematic region is 6%, which is subtracted before performing the fit. The values for $\epsilon_{m_{b\bar{b}\gamma\gamma}}^B$ are calculated per resonance mass hypothesis using the integrals of the fit in the full mass range and in the fixed $m_{b\bar{b}\gamma\gamma}$ windows. The values of the efficiency for the continuum background to pass the $m_{b\bar{b}\gamma\gamma}$ window cut range between 0.09 ± 0.03 and 0.16 ± 0.03 (with statistical uncertainties only) for different resonance mass hypotheses.

Similarly, the contribution from the SM single-Higgs and non-resonant di-Higgs processes in the SR, $N_{SR}^{SM}$ is derived using:

$$N_{SR}^{SM} = N_{SR}^{SM} \epsilon_{m_{\gamma\gamma}}^{SM} \epsilon_{m_{b\bar{b}\gamma\gamma}}^{SM},$$

where $N_{SR}^{SM}$ denotes the sum of the number of single-Higgs and di-Higgs events in the inclusive $m_{\gamma\gamma}$ spectrum. The rates are normalised to the SM expectation. For these simulated events, the value of $\epsilon_{m_{\gamma\gamma}}^{SM}$ is by definition 0.95, and $\epsilon_{m_{b\bar{b}\gamma\gamma}}^{SM}$ is taken directly from simulation.

Finally, the number of expected $X \rightarrow hh$ events is derived from simulation, and is corrected for $\epsilon_{m_{\gamma\gamma}}^{X}$ and $\epsilon_{m_{b\bar{b}\gamma\gamma}}^{X}$. The $m_{\gamma\gamma}$ cut efficiency increases linearly with $m_X$ due to better momentum resolution of photons at higher $p_T$. The value of $\epsilon_{m_{b\bar{b}\gamma\gamma}}^{X}$ is by construction 0.95 for the simulated resonantly-produced di-Higgs events. The uncertainties on all efficiencies quoted above are described in Sec. 5.

Table 1 shows the number of expected events from di-Higgs and single-Higgs production, together with the estimated number of continuum background events in the $m_{\gamma\gamma}$ window, in the non-resonant selection. The number of observed events is also presented. The dominant background in the 0-tag region is $jj\gamma\gamma$ while in the 2-tag region $jj\gamma\gamma$, $jb\gamma\gamma$ and $b\bar{b}\gamma\gamma$ are equally important. Backgrounds with jets misidentified as photons are negligible. This background decomposition is estimated using Monte Carlo simulation.

<table>
<thead>
<tr>
<th>Process</th>
<th>0-tag</th>
<th>2-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum background</td>
<td>35.8 ± 2.1</td>
<td>1.63 ± 0.30</td>
</tr>
<tr>
<td>SM single-Higgs</td>
<td>1.8 ± 1.5</td>
<td>0.14 ± 0.05</td>
</tr>
<tr>
<td>SM di-Higgs</td>
<td>&lt;0.001</td>
<td>0.027 ± 0.006</td>
</tr>
<tr>
<td>Observed</td>
<td>27</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Number of expected and observed events in the $m_{\gamma\gamma}$ mass window in the 0-tag and 2-tag regions in the non-resonant selection, in the 3.2 fb$^{-1}$ of data analysed. For the SM di-Higgs sample, a cross-section of 37.9 fb is assumed, as explained in Sec. 2.

5 Systematic uncertainties

Due to the small numbers of events both predicted and observed, statistical uncertainties are dominant, particularly in the search for di-Higgs resonant production. The systematic uncertainties evaluated for the analysis are described below.
5.1 Uncertainties on the modelling of background processes

The uncertainties from the shape of the continuum diphoton background are described below. First, the statistical uncertainty is assessed using a Monte Carlo method, in which toy distributions are generated by Poisson-fluctuating the value of the content of each bin, as obtained using the nominal exponential fit. These toy distributions are then themselves fit using an exponential function. The efficiency, $\varepsilon_{m_{\gamma\gamma}}$, is recalculated for each toy, and the standard deviation among the toys is taken as the statistical uncertainty on the measured efficiency, which is determined to be a relative uncertainty of $< 1\%$. Three photon control regions are then defined: one with the isolation requirement removed, one with the photon identification loosened and one with both of these changes made simultaneously. Although these control regions are not strictly orthogonal to one another, the overlap of events between them is small. In addition to the nominal exponential fit function, fits are also performed in these control regions using zeroth- and first-order polynomials, as well as a modified second-order exponential. Each of these fits is applied to the $m_{\gamma\gamma}$ spectra in the range 105–160 GeV, while excluding the region 120–130 GeV to avoid contamination from SM single-Higgs events. For each control region, the extrapolated yield in the $m_{\gamma\gamma}$ signal region is calculated for each fit and compared to the yield from the nominal fit. The largest variation is 11%, from the comparison of a zeroth-order polynomial with the nominal exponential, which is taken as the uncertainty on the continuum diphoton background modelling. The above study is also repeated after further dividing the dataset into those events with two $b$-tagged jets and those without $b$-tagged jets. No significant difference in the $m_{\gamma\gamma}$ distribution is found between these cases, hence no uncertainty is assigned when the 0-tag exponential fit is used in the 2-tag signal region.

In the search for resonant di-Higgs production, there is an additional uncertainty on $\varepsilon_{m_{b\bar{b}\gamma\gamma}}$, which has three components, detailed below, that are summed in quadrature: the heavy-flavour uncertainty, the uncertainty from the choice of function used to fit the $m_{b\bar{b}\gamma\gamma}$ spectrum, and the statistical uncertainty inherent to the fitting procedure.

The heavy-flavour uncertainty quantifies any potential bias arising from the use of data without $b$-tagged jets to estimate the shape of the $m_{b\bar{b}\gamma\gamma}$ distributions in the 2-tag region. Landau functions are used to fit the observed $m_{b\bar{b}\gamma\gamma}$ spectrum for events falling into $m_{\gamma\gamma}$ sideband regions, as described in Sec. 4. This fit is performed separately for events with no $b$-tagged jets and for those with two $b$-tagged jets. For each resonance mass hypothesis, the efficiencies are calculated and their relative difference between the 0-tag and 2-tag regions provides a measure of the heavy-flavour uncertainty in the fit. These differences range from 6%, for a resonance mass of 275 GeV, to 11% for a resonance mass of 325 GeV. The largest difference of 11% is then taken as an uncertainty for all the mass hypotheses.

The uncertainty due to the choice of fit function is assessed using the background sample with multiple jets and photons generated with Sherpa. A Landau function is used to fit the 0-tag $m_{jj\gamma\gamma}$ spectrum. For each resonance mass hypothesis, the proportion of background events falling into the previously defined signal mass window is calculated both from the fit and from simply counting the number of simulated events falling into the window. The largest difference between these two methods is 20% and is chosen as a conservative uncertainty arising from the choice of a Landau function to model the shape of the continuum $m_{b\bar{b}\gamma\gamma}$ distribution.

The statistical uncertainty is assessed using the same Monte Carlo method as in the $m_{\gamma\gamma}$ case. Landau fits are used to calculate the window efficiency for each toy, with the standard deviation among the toys providing the mass-hypothesis-dependent statistical uncertainty on the estimated efficiency. The size of this uncertainty ranges from 15% to 30%.
The uncertainty on $\sigma^{SM}_{mbb\gamma\gamma}$ also affects the SM single-Higgs and di-Higgs processes which form part of the background to the search for resonant di-Higgs production. The parametrised signal mass window efficiency for these samples is compared to the value obtained from simply counting the number of simulated events inside the window. The largest difference between these two is taken as a systematic uncertainty on the modelling of the $m_{b\bar{b}\gamma\gamma}$ distribution for these processes: this is found to be 25%.

5.2 Theoretical uncertainties on the signal models

Theoretical uncertainties on the production of single Higgs bosons arise primarily from scale and PDF uncertainties, together with an uncertainty on the rate of associated heavy-flavour production. There are further uncertainties on the $h\rightarrow\gamma\gamma$ and $h\rightarrow b\bar{b}$ branching fractions of $\pm 5\%$ and $\pm 3\%$, respectively, and a further systematic uncertainty, arising from the limited statistical precision of each of the simulated samples used. The scale uncertainties, which can be as large as $+14\%/-24\%$, and PDF uncertainties, which reach up to $\pm 9\%$, are calculated by the LHC Higgs Cross-Section Working Group [28]. Studies on associated heavy-flavour production in $t\bar{t}$ indicate that a 100% uncertainty should be applied to the ggF mode [77]. Similarly, a 100% uncertainty is applied for the Wh and VBF processes, based on studies of $W+b$ production [78]. In the Zh channel, the dominant heavy-flavour contribution comes from $Z\rightarrow b\bar{b}$ and therefore does not arise from additional radiation. The same argument holds for the $t\bar{t}h$ case, in which $b$-jets are produced from the top-quark decays. No additional heavy-flavour uncertainty is applied in either of these cases.

In the search for resonant di-Higgs production, the scale and PDF uncertainties on the NNLO cross-section for SM di-Higgs production are also combined with an additional component arising from the simplifications used in the EFT approximations. The overall uncertainty on this cross-section is $+11/-12\%$.

5.3 Experimental uncertainties

The luminosity scale is derived using van der Meer scans performed during August 2015. The overall uncertainty on the integrated luminosity is 5%, which is derived following the methodology detailed in Ref. [79]. Furthermore, all objects have associated uncertainties arising from differences in their calibration between the data and the simulation.

The efficiency of the diphoton trigger is measured using bootstrap methods [80], and is found to be 99.4%, with a systematic uncertainty of 0.4%. The uncertainty on the efficiency of the neural network primary vertex selection is found to be negligible. The photon identification procedure requires correction factors to bring the simulation into agreement with the data. The full difference between applying and not applying these correction factors is taken as an uncertainty pertaining to photon identification efficiency, which is found to be 2.5%. Two uncertainties arising from the photon isolation correction factors are obtained by shifting the calorimeter- or track-based isolation criteria independently. These shifts are compared to the nominal value and the full differences in these two cases are combined in quadrature to obtain the overall isolation uncertainty of 4%. Systematic uncertainties on the diphoton mass resolution arise through the uncertainties on the energy scale and resolution of the photons. The size of the uncertainty on the diphoton mass resolution ranges from 15% to 30%.

Systematic uncertainties on the dijet mass distribution are analogous to those on the diphoton mass distribution. Systematic uncertainties arising from the uncertainties on the jet energy scale (JES) and jet
energy resolution (JER) are propagated to the $m_{bb}$ spectra and the effects from the multiple uncertainty components are combined in quadrature. The JER uncertainty is found to vary significantly, between 1.7% and 9.8%, for the different mass hypotheses considered, and is therefore parametrised in terms of the mass of the resonance [81, 82]. Uncertainties from the muon calibration [83], for the muons-in-jets correction, and on $b$-tagging uncertainties also contribute [73, 84]. Finally, the pileup reweighting procedure, which matches the distribution of the number of primary vertices from simulation and data, has associated systematic uncertainties that vary from 1% to 2.5% depending on the simulated sample in question.

A summary of the systematic uncertainties on the signal and background simulated samples, as well as on the continuum background, is shown in Table 2. For the non-resonant search mode, SM di-Higgs production is considered as the signal process, with single-Higgs boson production forming the background. In the search for the resonantly produced signal, both SM single-Higgs and di-Higgs production are considered as background processes.

### 6 Results

An unbinned likelihood fit is performed simultaneously in the signal and control regions in the search for non-resonant di-Higgs production. Figure 4 shows the $m_{\gamma\gamma}$ distributions in the 0-tag and 2-tag categories. Within a ± 2 $\sigma_{m_{\gamma\gamma}}$ window around $m_h$, 1.8 events are expected from the combination of continuum and single-Higgs backgrounds (see Table 1) while none are observed. The profile likelihood-ratio test statistic [85] is used to test the background-only or signal-plus-background hypotheses. A modified frequentist method known as CL$_S$ [86] is used to compute the 95% confidence level (CL) exclusion limits. The limits are derived by using pseudo-experiments, since the asymptotic approximation is not a good approximation when event yields are low. Assuming SM branching fractions, the expected upper limit on the non-resonant di-Higgs production cross-section is $5.4^{+2.8}_{-1.0}$ pb. As a result of the deficit observed in the signal region, the observed limit is 3.9 pb, as shown in Fig. 5.

Similarly to the search for the non-resonant di-Higgs production, SM branching fractions for the light Higgs bosons are assumed in the search for the resonantly produced di-Higgs states. The expected exclusion limits at 95% CL vary from 7.5 pb at $m_X = 275$ GeV to 4.4 pb at $m_X = 400$ GeV. They improve at higher resonance masses because of the higher acceptance and selection efficiency. The observed limits vary from 7.0 pb to 4.0 pb in the same mass range. Similarly to the search for the non-resonant production, the limits are obtained using pseudo-experiments. Figure 6 (a) shows the 95% CL upper limits on the cross-section times branching fraction for a narrow resonance with mass $m_X$. These limits are also presented as expected and observed limits on the number of events after the event selection. These are shown in Fig. 6 (b).

The present result excludes excesses above 3 events at 95% CL. The modest excess presented in Ref. [8] would translate into about 2 events in the 2015 dataset, under the assumption that it was induced by a gluon-initiated state, adjusting for the change in acceptance and accounting for the parton-luminosity ratio between 13 TeV and 8 TeV, which is approximately 3 [58].
Table 2: Summary of systematic uncertainties, in percent, for 2-tag events in the signal region. Entries marked ‘-’ indicate that the systematic is not applicable in this category. The luminosity uncertainty is fully correlated across all samples. The jet energy scale uncertainty includes components from various sources, including uncertainties on jets arising from $b$-quarks. The $b$-tagging uncertainties include those from the efficiencies to correctly tag jets arising from $b$-quarks as well as mistagging jets from $c$-quarks and light-flavour quarks. There are two extrapolation uncertainties in $b$-tagging: one is from the extrapolation to high-$p_T$ ($p_T > 300$ GeV) jets and one is from extrapolating $c$-jets to $\tau$-jets. In the table these are combined, although they are treated as independent nuisance parameters in the fit. In the search for $X \rightarrow hh$, the jet energy resolution and $m_{bb\gamma\gamma}$ modelling uncertainties are parametrised in terms of the mass of the resonance, hence the full range of values is quoted.
Figure 4: Observed diphoton invariant mass spectrum in the search for the non-resonant di-Higgs production, together with the corresponding signal-plus-background fit in the (a) 0-tag and (b) 2-tag regions. The individual contributions from single-Higgs production, di-Higgs production and continuum background are shown, together with their sum. The expected rates for single-Higgs and di-Higgs are small and therefore their contributions are barely visible. The bottom insert plots show the difference in number of events between the observed data and the signal-plus-background fit.

Figure 5: Scan of the observed (solid line) and expected (dashed line) \( \text{CL}_{S} \) values as a function of the production cross-section \( \sigma_{hh} \) in the search for the non-resonant di-Higgs production. The green (yellow) band represents the 1\( \sigma \) (2\( \sigma \)) intervals on the expected \( \text{CL}_{S} \) value.

7 Conclusions

Searches for both resonant and non-resonant production of pairs of Higgs bosons are performed in the \( b\bar{b}\gamma\gamma \) final state using 3.2 \( fb^{-1} \) of \( pp \) collision data collected at 13 TeV and recorded with the ATLAS detector at the LHC. SM branching fractions for the light Higgs decays are assumed throughout. No
excess was found with respect to the background-only hypothesis. An upper limit of 3.9 pb on the cross-section for non-resonant production is extracted at the 95% confidence level, while the expected limit is 5.4 pb. In the search for a narrow $X \rightarrow hh$ resonance, the observed limit ranges between 7.0 pb and 4.0 pb for resonances with masses in the range 275–400 GeV. The expected limit varies between 7.5 pb and 4.4 pb, again depending on the mass of the resonance under consideration.

References


[19] ATLAS Collaboration, *Searches for Higgs boson pair production in the $hh \rightarrow b\bar{b}\tau\tau, \gamma\gamma WW^*$, $\gamma bb, bbb\bar{b}$ channels with the ATLAS detector*, Phys. Rev. D 92 (2015) 092004, arXiv: 1509.04670 [hep-ex].


