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Search for Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State Using pp Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector

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Searches are performed for resonant and nonresonant Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state using 20 fb⁻¹ of proton-proton collisions at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the CERN Large Hadron Collider. A 95% confidence level upper limit on the cross section times branching ratio of nonresonant production is set at 2.2 pb, while the expected limit is 1.0 pb. The difference derives from a modest excess of events, corresponding to 2.4 standard deviations from the background-only hypothesis. The limit observed in the search for a narrow $X \rightarrow hh$ resonance ranges between 0.7 and 3.5 pb as a function of the resonance mass.

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Within two years of discovering a new boson with a mass near 125 GeV [1,2], the ATLAS and CMS Collaborations have completed a slate of measurements demonstrating that its spin and couplings conform to the predictions of the standard model (SM) Higgs boson within current experimental and theoretical uncertainties [3,4]. Despite the lack of deviations from SM predictions, the Higgs boson h offers a rich potential for new physics searches. This Letter reports on searches for non-SM physics with events consistent with either resonant ($X \rightarrow hh$) or nonresonant pair production of Higgs bosons in the $hh \rightarrow \gamma\gamma b\bar{b}$ channel.

The predicted rate for Higgs boson pair production in the SM is several orders of magnitude smaller than the rate for the single h process [5–8]; hh production is thus not expected to be observable with current LHC data sets. However, a variety of extensions to the SM predict an enhancement of Higgs boson pair production. In two Higgs doublet models (2HDMs) [9–11] the heavier of the neutral scalar Higgs bosons H may decay to a pair of its lighter scalar partners, h . Depending on the parameters of the 2HDM, the $H \rightarrow hh$ production cross section may exceed a picobarn [11]. A deviation of the Higgs boson self-coupling λ_{hhh} from the SM predicted value could also increase the nonresonant production rate. Such deviations could be observed with future data sets [8]. Larger enhancements in the $pp \rightarrow hh$ rate could arise from the top-Higgs quartic $t\bar{t}hh$ coupling predicted in composite models [12,13], or from the addition of light colored scalars to the SM [14]. Resonant production of two Higgs bosons could appear from the production and decay of gravitons, radions, or

stoponium [15–17], as well as from a hidden sector mixing with the observed Higgs boson [18].

The $\gamma\gamma b\bar{b}$ channel is an excellent final state for a search for Higgs boson pair production [19] thanks to the large $h \rightarrow b\bar{b}$ branching ratio, clean diphoton trigger, excellent diphoton invariant mass resolution, and low backgrounds. This channel is particularly important in the search for resonances with mass m_X in the range $260 < m_X < 500$ GeV considered in this Letter, where backgrounds and combinatorics make other channels such as $b\bar{b}b\bar{b}$ or $b\bar{b}\tau^+\tau^-$ challenging.

Processes that do not contain Higgs bosons are estimated from data; all other processes are simulated using Monte Carlo techniques. The standard ATLAS detector simulation [20] based on GEANT4 [21] is used. The simulation parameters are tuned to describe soft components of hadronic final states [22,23]. Simulated minimum bias collisions are overlaid on the hard scatter process, and events are reweighted so that the average number of interactions per bunch crossing (~ 20) matches the observed distribution.

Background events with a single Higgs boson produced in association with a W or Z boson or $t\bar{t}$ (Wh , Zh , $t\bar{t}h$) are simulated with PYTHIA8 [24] using CTEQ6L1 parton distribution functions of the proton (PDFs) [25]. Higgs boson production via gluon or vector-boson fusion (ggF, VBF) is simulated using CT10 PDFs [26] with POWHEG-BOX [27,28] interfaced to PYTHIA8 for showering and hadronization. Cross sections and associated uncertainties are taken from Ref. [29].

Two benchmark signal models are defined: SM Higgs boson pair production for the nonresonance search, and a gluon-initiated, spin-zero resonant state in the narrow-width approximation for the resonance search. The SM hh process is too small to observe with current data sets, but the SM kinematics are used to model generic nonresonant beyond-SM physics. Both models are generated using

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MADGRAPH5 [30,31] and CTEQ6L1 PDFs. A generator filter requires a pair of b quarks and a pair of photons in each event. PYTHIA8 is used to decay the two Higgs bosons, and to shower and hadronize the events. The implementation of SM Higgs boson pair production includes the interference between diagrams with trilinear Higgs boson couplings and box diagrams. For the SM hh process, which is a background to the resonance search, the next-to-leading-order inclusive production cross section of 9.2 fb is taken from Ref. [8]. Resonant samples are generated with a width of 10 MeV (corresponding to a narrow width approximation) at masses $m_X = 260, 300, 350$, and 500 GeV. Production cross sections for benchmark 2HDMs are calculated with SusHi [32], and branching ratios with 2HDMC [33].

The analysis described in this Letter uses the full $\sqrt{s} = 8$ TeV data set of proton-proton collisions recorded by the ATLAS experiment in 2012, corresponding to an integrated luminosity of $20.3 \pm 0.6 \text{ fb}^{-1}$ [34]. Data quality criteria are applied to reject events with diminished detector performance [35,36]. A description of the ATLAS detector can be found elsewhere [37].

The photon and event selection for the present search largely follows those of published ATLAS $h \rightarrow \gamma\gamma$ analyses [3,38]. Events are selected using a loose diphoton trigger that is nearly 100% efficient for events passing the off-line photon selection. Photons are reconstructed starting from clusters of energy deposited in the electromagnetic calorimeter. Events are required to contain two photon candidates whose calorimeter energy clusters match the expectations for photon-induced electromagnetic showers [39,40]. The pseudorapidity [41] η of the two photons must fall within the geometric acceptance of the detector for photons, $|\eta| < 2.37$, excluding the region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.56$). The ratio of the transverse momentum of the leading (subleading) photon to the invariant mass of the pair, $p_T/m_{\gamma\gamma}$, must exceed 0.35(0.25). The invariant mass of the pair is calculated as in Ref. [3]. Photons are required to be isolated: the energy in the calorimeter [3,42] within a cone of size $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around the photon direction must be less than 6 GeV, and the scalar sum of the p_T of the tracks in a cone of $\Delta R = 0.2$ must be less than 2.6 GeV. In addition, the photon pair must satisfy a broad requirement $105 < m_{\gamma\gamma} < 160$ GeV for an event to be considered [3,38].

Jets are reconstructed from clusters of energy in the electromagnetic and hadronic calorimeters using the anti- k_t algorithm [43] with a radius parameter of 0.4, starting from energy deposits grouped into topological clusters [44]. Simulation is used to correct jets for instrumental effects [45] and to account for the average energy in the detector in the event due to additional pp interactions and the underlying event [46]. The calibration is refined using *in situ* measurements. Jets are required to fall within the tracker

acceptance of $|\eta| < 2.5$ and satisfy $p_T > 35$ GeV, with the leading jet in the event required to have $p_T > 55$ GeV. Events with jets arising from noisy regions in the calorimeters, beam backgrounds, or cosmic rays are rejected [45]. Low- p_T jets from additional proton-proton interactions in the same bunch crossing are rejected with a requirement on the scalar sum of the p_T of tracks associated with the jet: for jets with $|\eta| < 2.4$ and $p_T < 50$ GeV, tracks associated with the hard scatter vertex must contribute over 50% of the sum.

Jets from the decay of long-lived heavy-flavor hadrons are selected using a multivariate tagging algorithm (b tagging) [47] with an efficiency of 70% for jets from b -quark fragmentation in $\bar{t}t$ simulation. The four-momenta of muons [48] closer than $\Delta R = 0.4$ to a b -tagged jet and with $p_T > 4$ GeV are included in the jet four-momentum.

Events with at least two photons and two or more jets are selected for further analysis if the invariant mass of the two leading jets is consistent with the decay of a Higgs boson. While the invariant mass resolution for the pairs of b -tagged jets is approximately 13 GeV, the mass window is chosen as $95 < m_{jj} < 135$ GeV to account for the downward shift of the mean from the true value due to effects such as unmeasured neutrinos from semileptonic b decays.

In the nonresonance search, the background and potential signal are fit to the unbinned $m_{\gamma\gamma}$ distribution of all events passing the dijet and diphoton selections described above. This fit has three components: the signal with a pair of Higgs bosons, the background processes with a single Higgs boson resonant at $m_{\gamma\gamma} = m_h$, and the continuum background. The single Higgs boson backgrounds are dominated by the processes with pairs of b quarks, namely $\bar{t}th$ and $(Z \rightarrow b\bar{b})h$, with smaller contributions from ggF , VBF, and Wh . The combined acceptance and selection efficiency for the SM Higgs boson pair production signal is 7.4%. Simulation studies show that the continuum contribution in the signal region is split between events with two photons and events with a single photon in association with a jet faking the second photon. The b -tagged jets include real heavy-flavor jets and mistagged light-flavor jets. The contribution from dileptonic decays of $\bar{t}t$ events where two electrons fake the two photons is roughly 10% of the total background. The contribution from other processes is negligible.

The fit is performed simultaneously in two categories. The first category is the signal region, in which at least two jets are b -tagged. The second is a control region, containing events with fewer than two b tags. The two classes of events are kinematically identical: in the signal region, the mass and p_T requirements defined above must be satisfied by the two leading tagged jets, whereas in the control region, they are met by the two leading jets.

Following earlier ATLAS analyses, the shape of the $m_{\gamma\gamma}$ resonance is described by the sum of a Crystal Ball function and a wide Gaussian component that models the tails of the

distribution [3]. An exponential function describes the continuum backgrounds that fall with $m_{\gamma\gamma}$. The slope of the exponential is shared in the fit between the two categories so that the control region constrains the background shape in the signal region. Figure 1 shows the separate diphoton mass distributions for events with $\geq 2b$ tags and events with $\leq 1b$ tag.

The search for resonant production of pairs of Higgs bosons starts with the same signal selection as above but imposes an additional requirement on $m_{\gamma\gamma b\bar{b}}$. Because of the small number of expected events after this additional requirement, the resonance analysis uses a counting experiment with cuts on $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$, in place of the unbinned fit in $m_{\gamma\gamma}$. The cut on the diphoton mass is set as a window of twice the mass resolution, $\pm 2\sigma_{m_{\gamma\gamma}}$, around the Higgs boson mass $m_h = 125.5$ GeV [3]. For this cut, the $m_{\gamma\gamma}$ resolution is set to the expected value of 1.6 GeV. The acceptance of this requirement on background events without Higgs bosons, $\epsilon_{m_{\gamma\gamma}}$, is measured by fitting an exponential function to the $m_{\gamma\gamma}$ sidebands for events with fewer than two b -tagged jets. For this fit, the $m_{\gamma\gamma}$ region of $m_h \pm 5$ GeV is excluded to eliminate any potential contamination from resonant Higgs boson production. For N observed events with two b tags in the sideband ($|m_{\gamma\gamma} - m_h| > 2\sigma_{m_{\gamma\gamma}}$), the number of expected non-Higgs boson background events $N_{m_{\gamma\gamma}}$ within $2\sigma_{m_{\gamma\gamma}}$ around m_h is given by

$$N_{m_{\gamma\gamma}} = N \frac{\epsilon_{m_{\gamma\gamma}}}{1 - \epsilon_{m_{\gamma\gamma}}}, \quad (1)$$

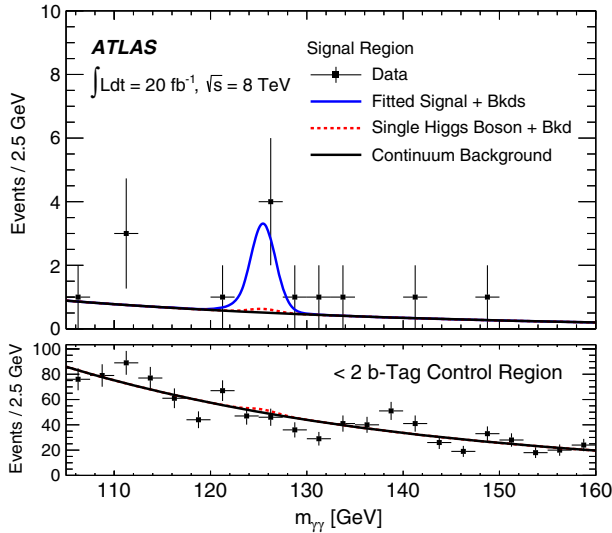


FIG. 1 (color online). Upper plot: diphoton invariant mass spectrum for data and the corresponding fitted signal and background in the signal region for the nonresonance search. Lower plot: the diphoton invariant mass spectrum in the continuum background from events with fewer than two b tags and the corresponding fitted curve, the shape of which is also used in the upper plot.

where the denominator compensates for the fact that $\epsilon_{m_{\gamma\gamma}} = 0.13$ is derived relative to the full $m_{\gamma\gamma}$ spectrum while N contains only those events in the sidebands.

Before reconstructing the four-object mass, $m_{\gamma\gamma b\bar{b}}$, a scaling factor of $m_h/m_{b\bar{b}}$ is applied to the four-momentum of the $b\bar{b}$ system, where m_h is set to the value of 125 GeV used in simulation. This improves the $m_{\gamma\gamma b\bar{b}}$ resolution by 30%–60% depending on the mass hypothesis, without biasing or significantly altering the shape of the background. Requirements are then made on $m_{\gamma\gamma b\bar{b}}$ to select the smallest window containing 95% of the previously selected events, simulated for the narrow resonant signal hypotheses. These requirements vary linearly with the mass m_X of the resonance considered. The width of the signal window varies from 17 GeV at $m_X = 260$ GeV to 60 GeV at $m_X = 500$ GeV. The acceptance for the continuum background to pass this requirement, $\epsilon_{m_{\gamma\gamma b\bar{b}}}$, also varies with m_X . It is measured using events in data with $|m_{\gamma\gamma} - m_h| < 2\sigma_{m_{\gamma\gamma}}$ and fewer than two b tags. Studies in both data sidebands and simulation show that the shapes of $m_{\gamma\gamma b\bar{b}}$ and $m_{\gamma\gamma jj}$ agree within statistical uncertainties. The distribution of $m_{\gamma\gamma jj}$ in data is fitted with a Landau function, which is integrated in the signal window to obtain $\epsilon_{m_{\gamma\gamma b\bar{b}}}$ for each mass hypothesis. The bottom panel of Fig. 2 shows this fit. The value of $\epsilon_{m_{\gamma\gamma b\bar{b}}}$ is small ($< 8\%$) at low and high m_X , and peaks at 18% for $m_X = 300$ GeV. The combined acceptance and selection efficiency for a resonance signal to pass

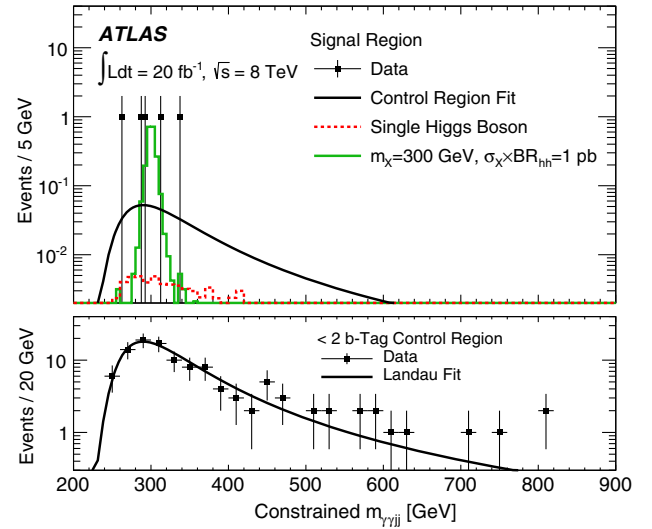


FIG. 2 (color online). Upper plot: the constrained four-object invariant mass $m_{\gamma\gamma jj}$ for data events in the resonance signal region. The expected backgrounds are also shown. A narrow width resonance at 300 GeV is displayed for comparison only. Lower plot: the diphoton invariant mass spectrum in the continuum background from events with fewer than two b tags and the corresponding fitted curve, the shape of which is also used in the upper plot.

all requirements varies from 3.8% at $m_X = 260$ GeV to 8.2% at $m_X = 500$ GeV.

The total background from sources without Higgs boson decays in the resonance analysis N_B is given by

$$N_B = N \frac{\epsilon_{m_{\gamma\gamma}}}{1 - \epsilon_{m_{\gamma\gamma}}} \epsilon_{m_{\gamma\gamma b\bar{b}}}, \quad (2)$$

where N is the number of events in the $m_{\gamma\gamma}$ sidebands, and N_B and $\epsilon_{m_{\gamma\gamma b\bar{b}}}$ are functions of m_X . Uncertainties on this extrapolation are described below.

Because they are not accounted for by the above $m_{\gamma\gamma}$ sideband techniques, contributions from single Higgs bosons produced in association with jets (particularly with $c\bar{c}$ or $b\bar{b}$ pairs) are estimated using simulation. In the resonance analysis, the yield from the nonresonant SM hh processes is similarly included. SM cross sections and branching fractions are assumed in all cases [29].

Most systematic uncertainties are small when compared to statistical uncertainties, in particular for the resonance search.

The evaluation of experimental uncertainties on photon identification (2.4%) and isolation efficiencies (2%) follows the methods used in the inclusive ATLAS $h \rightarrow \gamma\gamma$ analyses [3,38]. The theoretical uncertainties [29] on the single Higgs boson backgrounds are similarly adopted. Because there are no heavy flavor quarks at lowest order associated with ggF or VBF production, additional uncertainties are evaluated for these higher-order processes. These uncertainties are derived from a comparison of simulated predictions to data for similar initial states: gluon-initiated production of $t\bar{t}$ with heavy flavor [49] for ggF, and quark-initiated W boson production with heavy flavor [50] for VBF. Since the ggF and VBF contributions are less than 15% of the expected single Higgs boson yield in the signal region, the net impact of these uncertainties remains small. PDF and scale uncertainties on SM hh production are taken from Ref. [8].

Because of the cuts on the ratio $p_T/m_{\gamma\gamma}$, photon energy scale uncertainties are negligible. The uncertainty of 13% on the diphoton mass resolution $\sigma_{m_{\gamma\gamma}}$ is propagated into the resonance search as a 1.6% uncertainty on the number of events migrating into and out of the signal region. This represents the fraction of events where an upward variation of the photon resolution causes the diphoton mass to leave the $m_h \pm 2\sigma_{m_{\gamma\gamma}}$ window required for the signal region. The uncertainty on m_h impacts the peak position in $m_{\gamma\gamma}$ in the signal plus background fit of the nonresonance analysis, and in the resonance search it is transformed into a 1.7% uncertainty on the number of signal events in the mass window. The uncertainty for the acceptance of the $m_{\gamma\gamma}$ cuts on non-Higgs boson backgrounds is estimated by comparing fits of $m_{\gamma\gamma}$ to data in control regions with reversed photon identification or b -tagging requirements, and using different functional forms. The largest deviation observed from these fits (11%) is used for all searches.

Three components contribute to the uncertainty on $\epsilon_{m_{\gamma\gamma b\bar{b}}}$, and are combined in quadrature. (1) The limited number of events in the control region with fewer than two b tags used for the Landau fit leads to a relative statistical uncertainty of 3%–18% that varies as a function of m_X . (2) The $m_{\gamma\gamma jj}$ shape for untagged jets might not exactly mirror the one for tagged jets. The tagged and untagged samples are compared in simulation and the relative difference in $\epsilon_{m_{\gamma\gamma b\bar{b}}}$ is taken as the uncertainty. This value varies with m_X and is always less than 30%. (3) Finally, an uncertainty of 16%–30%, depending on m_X , is included to cover the choice of the analytic function. This was evaluated via comparisons of Landau shapes to alternate functions in simulation, including Landau shapes where the width varies with $m_{\gamma\gamma b\bar{b}}$, as well as Crystal Ball functions. Potential contamination from SM single Higgs boson processes in the control region is estimated to be less than 4% and is subtracted with negligible impact on the shape.

Uncertainties due to the b -tagging calibration are typically 2%–4% for both the single Higgs boson and signal processes. Uncertainties due to the jet energy scale are 7% (22%) for single Higgs boson backgrounds in the nonresonance (resonance) analysis, and 1.4% (4.4%) for signal processes. Uncertainties due to the jet energy resolution are 4.8% (21%) for single Higgs boson backgrounds, and 6.3% (9.3%) for signal processes. The uncertainty on the integrated luminosity is 2.8%. It is derived, following the same methodology as that detailed in Ref. [34], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

The combined, unbinned signal plus background fit for the nonresonance analysis is shown in Fig. 1. Within a $\pm 2\sigma_{m_{\gamma\gamma}}$ window around the Higgs boson mass, 1.5 events are expected, with 1.3 ± 0.5 from the continuum background and 0.17 ± 0.04 from single Higgs boson production, which is dominated by $t\bar{t}h$ events. About 0.04 events are expected from SM Higgs boson pair production. Five events are observed, corresponding to 2.4σ from the background-only hypothesis, using the test statistic based on the profile likelihood ratio [51] with the hypothesized signal rate set to zero. The 95% confidence level (CL) upper limit on the Higgs boson pair production cross section is calculated using the frequentist CL_s method [52]. Exclusions and significances are evaluated using pseudoexperiments. Assuming SM branching ratios for the light Higgs boson decays, the expected upper limit is $1.0^{+0.5}_{-0.2}$ pb; the observed limit is 2.2 pb.

For the resonance analysis, as before, SM branching fractions for the light Higgs boson are assumed. The expected exclusion improves from 1.7 to 0.7 pb as a function of m_X from 260 to 500 GeV, as shown in Fig. 3. This behavior derives from increased event-level acceptance at larger masses. The observed exclusion ranges from 3.5 to 0.7 pb. The five events selected in the $m_{\gamma\gamma}$ signal

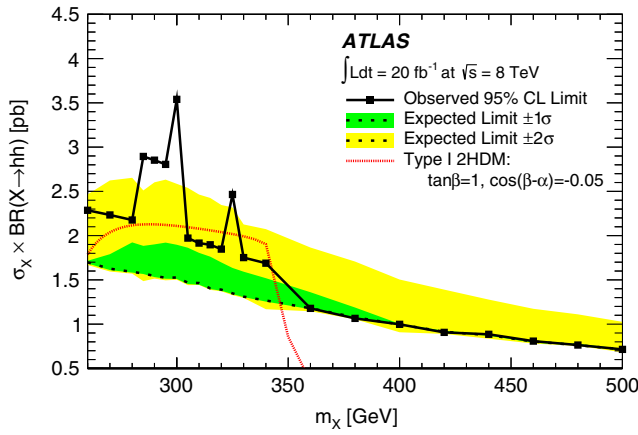


FIG. 3 (color online). A 95% CL upper limit on the cross section times branching ratio of a narrow resonance decaying to pairs of Higgs bosons as a function of m_X (see text for more details).

region are shown in $m_{\gamma\gamma b\bar{b}}$, in Fig. 2. The local probability of compatibility to the background-only hypothesis, p_0 , reaches a minimum of 0.002 at $m_X = 300$ GeV, corresponding to 3.0σ . The number of events lying within the $m_{\gamma\gamma b\bar{b}}$ window of each mass hypothesis is readily apparent in “steps” in the exclusion plot. The step size used for the limit is reduced in the range near the observed events, to show this structure. A look-elsewhere effect [53,54] is evaluated by generating pseudodatasets of the background-only hypothesis, and identifying the mass hypothesis with the lowest p value in each. The global probability of an excess as significant as the observation to occur at any mass in the range studied is found to be 0.019, corresponding to 2.1σ .

The limits derived are juxtaposed in Fig. 3 with the prediction for an illustrative type I 2HDM [32,33,55] not excluded by current data with $\cos(\beta - \alpha) = -0.05$ and $\tan(\beta) = 1$. The heavy Higgs bosons are taken to be degenerate in mass, and the mass of the lightest CP -even Higgs boson is set to 125 GeV. All major production mechanisms of $H \rightarrow hh$ are considered. Cross sections and branching ratios were calculated as described in Ref. [56].

In conclusion, this Letter presents searches for resonant and nonresonant Higgs boson pair production using 20.3 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8$ TeV generated by the Large Hadron Collider and recorded by the ATLAS detector in 2012. A 95% confidence level upper limit is placed on the nonresonant production cross section at 2.2 pb, while the expected limit is $1.0^{+0.5}_{-0.2}$ pb. The difference derives from a small excess of events, corresponding to 2.4σ .

In the search for a narrow resonance decaying to a pair of Higgs bosons, the expected exclusion on the production cross section falls from 1.7 pb for a resonance at 260 GeV to 0.7 pb at 500 GeV. The observed exclusion ranges from

0.7–3.5 pb. It is weaker than expected for resonances below 350 GeV.

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