Search for Higgs boson pair production in the two bottom quarks plus two photons final state in $pp$ collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

G. Aad et al. (ATLAS Collaboration)

(Received 23 December 2021; accepted 1 August 2022; published 6 September 2022)

Searches are performed for nonresonant and resonant di-Higgs boson production in the $b\bar{b}\gamma\gamma$ final state. The dataset used corresponds to an integrated luminosity of 139 $fb^{-1}$ of proton–proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. No excess above the expected background is found and upper limits on the di-Higgs boson production cross sections are set. A 95% confidence-level upper limit of 4.2 times the cross section predicted by the Standard Model is obtained excluding $pp \rightarrow HH$ nonresonant production, where the expected limit is 5.7 times the Standard Model predicted value. The expected constraints are obtained for a background hypothesis excluding $pp \rightarrow HH$ production. The observed (expected) constraints on the Higgs boson trilinear coupling modifier $\kappa_3$ are determined to be $[−1.5, 6.7]$ ($[−2.4, 7.7]$) at 95% confidence level, where the expected constraints on $\kappa_3$ are obtained excluding $pp \rightarrow HH$ production from the background hypothesis. For resonant production of a new hypothetical scalar particle $X$ ($X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$), limits on the cross section for $pp \rightarrow X \rightarrow HH$ are presented in the narrow-width approximation as a function of $m_X$ in the range $251$ GeV $\leq m_X \leq 1000$ GeV. The observed (expected) limits on the cross section for $pp \rightarrow X \rightarrow HH$ range from 640 fb to 44 fb (391 fb to 46 fb) over the considered mass range.

DOI: 10.1103/PhysRevD.106.052001

I. INTRODUCTION

Since the discovery of the Higgs boson in 2012 [1,2], one of the priorities of the ATLAS and CMS Collaborations has been to better understand the properties of the Brout–Englert–Higgs mechanism [3–8]. The Higgs boson self-coupling provides information about the structure of the Higgs potential. It is possible to directly probe the self-coupling of the Higgs boson by studying Higgs boson pair ($HH$) production. Furthermore, any deviation of the Higgs boson pair production rate from the Standard Model (SM) prediction would point to new physics beyond the Standard Model (BSM) and may be within the sensitivity reach of the proton–proton ($pp$) collision data collected at $\sqrt{s} = 13$ TeV during Run 2 of the Large Hadron Collider (LHC) [9].

At leading order (LO), the production of Higgs boson pairs via gluon–gluon fusion (ggF) proceeds through the two diagrams shown in Fig. 1. These diagrams interfere destructively, leading to a small-production cross section [10–12]. For 13 TeV $pp$ collisions and a Higgs boson mass $m_H = 125.09$ GeV [13], the ggF cross section, calculated at next-to-next-to-leading-order (NNLO) accuracy in the finite top-quark mass approximation (FTapprox), is $\sigma_{HH}$(ggF) $= 31.02^{+2.2\%}_{−1.9\%}(\text{Scale})^{+0.9\%}_{−1.8\%}(m_{\text{top}}) \pm 3.0\%(\alpha_s + \text{PDF})$ fb [14–17], where “Scale” represents the uncertainty due to the finite order of the quantum chromodynamics (QCD) calculation, “$m_{\text{top}}$” the uncertainty related to the top-quark mass scheme [17,18] which is added linearly to the Scale uncertainty, and “$\alpha_s + \text{PDF}$” the effect of uncertainties in the strong coupling constant and parton distribution functions.

The di-Higgs vector-boson fusion (VBF) production cross section, calculated at next-to-next-to-next-to-leading order (N3LO) for $m_H = 125.09$ GeV, is $\sigma_{HH}$(VBF) $= 1.72^{+0.33\%}_{−0.40\%}(\text{Scale}) \pm 2.1\%(\alpha_s + \text{PDF})$ fb [14], which is one order of magnitude lower than the cross section of the ggF process. The VBF production mode provides the analysis with additional sensitivity to the Higgs trilinear coupling, as shown in Fig. 2. Both the ggF and VBF production modes of Higgs boson pairs are considered as signal modes in this paper. The other production modes have lower cross sections [19] and are neglected.

Nonresonant enhancements to the Higgs boson pair cross section can originate either from loop corrections involving new particles, such as light, colored scalars [20], or from non-SM couplings between the Higgs boson and other SM particles. The nonresonant production cross section can also be altered by the trilinear self-coupling, $\lambda_{HHH}$, being different from the SM prediction, as discussed...
Such an effect can be captured by a scale factor $\kappa_{H}$ defined as $\kappa_{H} = \lambda_{H_{SM}}/\lambda_{H_{HH}}$, where $\lambda_{H_{SM}}$ is the SM value of the parameter.

In addition to the nonresonant enhancements, searching for resonant production of Higgs boson pairs is well motivated. Figure 3 shows a ggF production diagram possible in BSM theories predicting the existence of heavy scalar particles that can decay into a pair of Higgs bosons. Such theories include models with two Higgs doublets [23], such as the minimal supersymmetric extension of the SM [24], twin Higgs models [25], and composite Higgs models [26], adding a second complex scalar doublet to the Higgs sector. Alternatively, the Randall-Sundrum model of warped extra dimensions [27] predicts spin-0 radions that could couple to a Higgs boson pair.

This paper presents a search for di-Higgs production in the $b\bar{b}\gamma\gamma$ final state, including dedicated assessments of nonresonant and resonant contributions. The analysis considers the full Run 2 dataset of 139 fb$^{-1}$ at 13 TeV. For both the nonresonant and resonant $HH$ searches, the analysis employs a multivariate method designed to reject background processes, and the statistical results are obtained from a fit of the diphoton invariant mass, $m_{\gamma\gamma}$. For the nonresonant search, data are divided into different categories based on the four-body invariant mass to target different $\kappa_{H}$ ranges. The resonant search focuses on probing the existence of a narrow-width scalar particle $X$ in the mass range $251 < m_{X} < 1000$ GeV decaying into a pair of Higgs bosons. The selection criteria depend on the mass of the probed scalar particle. The main background processes are diphoton-plus-jets production and processes where a Higgs boson is produced and decays into a pair of photons. In the context of the resonant search, nonresonant $HH$ production is considered as a background.

Previous results from the ATLAS Collaboration were obtained in this channel with an integrated luminosity of 36 fb$^{-1}$ of data at 13 TeV collected during Run 2, and they were found to be consistent with SM expectations within uncertainties [28]. The search for nonresonant enhancements of Higgs boson pair production set an observed (expected) 95% confidence level (C.L.) upper limit on the $HH$ cross section of 0.73 (0.93) pb, corresponding to 22
The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and end cap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadron end cap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 Tm and 6.0 Tm across most of the detector. A set of precision chambers covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel and thin-gap chambers in the end cap regions.

Interesting events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [35]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger reduces in order to record events at rate of about 1 kHz. An extensive software suite [36] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

III. DATA AND SIMULATION SAMPLES

This analysis uses $pp$ collision data collected by the ATLAS experiment from 2015 to 2018 with proton beams colliding at a center-of-mass energy of $\sqrt{s} = 13$ TeV. After data quality requirements [37] the full dataset represents an integrated luminosity of $139.0 \pm 2.4$ fb$^{-1}$ [38,39]. The mean number of inelastic $pp$ interactions per bunch crossing is 34.2 [40].

Monte Carlo (MC) simulations are available for the signal as well as most background processes as detailed in the rest of this section. The reducible backgrounds from final states with jets wrongly identified as photons (γ-jet and dijet backgrounds) are, however, estimated using a data-driven technique detailed in Sec. IV C.

Events from ggF nonresonant $HH$ production were generated at next-to-leading-order accuracy in QCD with finite top-quark mass in both the real and virtual corrections (NLO FT) [11], using the POWHEG BOX v2 [41] generator in the finite top-quark mass approximation [42,43] with the
PDF4LHC 15 parton distribution function (PDF) set [44]. The PYTHIA 8.244 generator was used for parton showering, hadronization and underlying-event simulation. HERWIG 7.1.6 was used as an alternative generator to calculate the theory uncertainty from the parton shower. Samples were generated for coupling modifier values $\kappa_1 = 1$ and 10.

For ggF nonresonant $HH$ production, a reweighting method based on the di-Higgs invariant mass $m_{HH}$ is used to provide predictions on the cross section at different $\kappa_1$ values, starting from the existing $\kappa_1 = 1$ sample. The reweighting method derives the scale factors as a function of $\kappa_1$ in bins of $m_{HH}$ by performing a linear combination of samples generated at different $\kappa_1$ values [45]. Histograms of the truth $m_{HH}$ distribution are produced for each $\kappa_1$ sample and the distributions of the other relevant kinematic variables are obtained applying an event-per-event weight on the ratio between the binned $m_{HH}$ distribution for the targeted $\kappa_1$ by the binned $m_{HH}$ distribution for the SM ($\kappa_1 = 1$) sample.

This method was validated by comparing the event yields and the distributions of the relevant Higgs boson kinematic variables, including the $m_{\gamma \gamma}$ variable, of the sample generated with $\kappa_1 = 10$ to the sample generated with $\kappa_1 = 1$ and reweighted to $\kappa_1 = 10$. Good agreement is obtained in all categories. A systematic uncertainty in the range of 3%–4% is associated with the reweighting process, based on the maximum differences of signal yields observed in this validation. For each $\kappa_1$ value, the inclusive cross section is normalized according to Ref. [46]. A fit with a second order polynomial to the MC prediction is performed in each analysis category, in order to parametrize the event yields as a function of $\kappa_1$.

For VBF nonresonant $HH$ production, MadGraph5\_aMC@NLO 2.6.0 [47] was used to generate events at LO [47,48]. The NNPDF3.0LO PDF set [49] was used in the matrix element, interfaced to PYTHIA 8.244. The cross section of the VBF $HH$ process is evaluated at N3LO in QCD [50–52], as outlined in Sec. I. Since samples were generated at LO for four values of the coupling modifier, $\kappa_1 = 0, 1, 2$ and 10, the N3LO-to-LO cross section ratio at the SM value is calculated and this factor is applied to the VBF $HH$ cross section. These samples are used to derive a parametrization of the signal yields in the signal region as a function of $\kappa_1$ by fitting a second-order polynomial to the MC predictions in each analysis category, as described in Sec. IV B 2.

The production of a heavy spin-0 resonance $X$ via ggF and its decay into a pair of Higgs bosons, $pp \rightarrow X \rightarrow HH$, was simulated using MadGraph5\_aMC@NLO 2.6.1 [47] at LO accuracy with the NNPDF2.3LO PDF set. The event generator was interfaced with HERWIG7.1.3 [53,54] to model the parton shower, hadronization, and underlying event. No specific theoretical model for the phenomenology of the new particle is assumed in the process generation. The mass of $X$ was varied between 251 GeV and 1000 GeV in the simulation, while its width was set to 10 MeV. In total 25 $m_X$ mass hypotheses have been generated, corresponding to $m_X = 251, 260, 270, 280, 290, 300, 312.5, 325, 337.5, 350, 375, 400, 425, 450, 475, 500, 550, 600, 650, 700, 750, 800, 850, 900, 1000$ GeV. The interference with nonresonant Higgs boson pair production was neglected.

Production of single Higgs bosons via ggF, VBF, $WH, ZH$ ($qq \rightarrow ZH$ and $gg \rightarrow ZH$), $ttH, tH$ ($t\bar{H}$ and $tH$), and $bbH$ was modeled using the same set of MC samples as described in Ref. [55]. For single Higgs boson production, as well as both nonresonant and resonant di-Higgs production, a Higgs boson mass of 125.09 GeV was assumed [13]. The analysis assumes a branching ratio of 0.227% for the Higgs boson decay into two photons and a branching ratio of 58.2% for the Higgs boson decay into two $b$-quarks [56,57]. The inclusive cross sections of these processes are normalized to the most precise available theoretical values [56].

The $\gamma\gamma +$ jets process was simulated with the SHERPA 2.2.4 [58] generator. QCD NLO-accurate matrix elements for up to one parton, and LO-accurate matrix elements for up to three partons, were calculated with the Comix [59] and OPENLOOPS [60–62] libraries. These were calculated in the five-flavor scheme including $b$-quarks in the massless approximation and merged with the SHERPA parton shower [63] using the MEPS@NLO prescription [64,65] with a dynamic merging cut [66] of 10 GeV. Within the parton shower, $b$-quarks were then treated as being massive. Finally, events from $t\bar{t}\gamma\gamma$ processes were produced with MadGraph5\_aMC@NLO in the four-flavor scheme [47]. The simulation samples used in the analysis are listed in Table I.

Different pileup conditions from additional interactions the same and neighboring bunch crossings were simulated by overlaying the hard-scattering event with inelastic $pp$ events generated by PYTHIA8.186 using the NNPDF2.3LO PDF set and the A3 tune [85]. Differences between the simulated and observed distributions of the number of interactions per bunch crossing are corrected for by applying pileup scale factors to simulated events. A full simulation of the ATLAS detector [86] based on GEANT4 [87] was used to reproduce the detector response to single-Higgs-boson processes. The continuum background and signal samples were processed by AtlFastII [88], a fast simulation of the ATLAS detector response which was shown to be able to accurately simulate diphoton events.

IV. OBJECT AND EVENT SELECTIONS

A. Object selection

Photons are reconstructed from topologically connected clusters [89] of energy deposits in the electromagnetic calorimeter in the region $|\eta| < 2.37$. The transition region between the barrel and end cap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, is excluded. Photon candidates matched to conversion vertices or tracks that are consistent with originating from photon conversions are classified as
converted photons. Those without a matched conversion vertex or track are classified as unconverted photons.

The calibration of the photon energy is based on a multivariate regression algorithm trained with MC samples, where the input variables are corrected with data-driven techniques. The calibrated energy is finally corrected by a data-driven method.

Events are required to have at least one reconstructed collision vertex, defined as a vertex associated with at least two tracks with transverse momentum ($p_T > 0.5$ GeV). The primary vertex is selected from the reconstructed collision vertices using a neural-network algorithm [90] based on the extrapolated photon trajectories and the tracks associated with each candidate vertex.

Photon identification is based on the lateral shower profile of the energy deposits in the first and second electromagnetic calorimeter layers and on the energy leakage fraction in the hadronic calorimeter. It reduces the misidentification of hadronic jets containing large neutral components, primarily $\pi^0$ particles, which decay into a pair of highly collimated photons. “Tight” identification criteria, which are tuned for converted and unconverted photons separately, are applied [90].

To further improve the rejection of misidentified photons, two isolation variables are defined to quantify the activity around a photon. Calorimeter-based isolation $E_T^{iso}$ is defined as the sum of the transverse energy of topological clusters within a cone of size $\Delta R = 0.2$ around the photon, correcting for the energy of the photon candidate itself as well as for an average expected pileup contribution. Track-based isolation $p_T^{iso}$ is defined as the scalar sum of the transverse momenta of all tracks within the cone of $\Delta R = 0.2$ around the photon. Isolated photons must have $E_T^{iso} < 0.065 \cdot E_T$ and $p_T^{iso} < 0.05 \cdot E_T$ (the “loose” working point [90]), where $E_T$ is the transverse energy of the photon. For isolated photons with transverse momenta between 30 GeV and 250 GeV, the identification efficiency for unconverted and converted photons ranges from 84% to 98% [90].

The analysis is performed using the default Tune H7.1.

Electrons are reconstructed from energy deposits measured in the electromagnetic calorimeter which are matched to ID tracks [90]. They are required to satisfy $|\eta| < 2.47$, excluding the calorimeter transition region $1.37 < |\eta| < 1.52$, and have a transverse momentum $p_T > 10$ GeV. Electrons are required to satisfy a “medium” identification criterion based on the use of shower shape, track-cluster matching and TRT parameters in a likelihood-based algorithm [90]. Muons are reconstructed from high-quality tracks found in the MS [92]. A matching of these tracks to ID tracks is required in the region $|\eta| < 2.5$. Muons are required to have $|\eta| < 2.7$ and $p_T > 10$ GeV, and to satisfy a “medium” identification criterion [93]. Both the electrons and muons are matched to the primary vertex via requirements on the tracks’ longitudinal and transverse impact parameters, $|z_0|$ and $|d_0|$, respectively. These requirements are $|z_0| \sin \theta < 0.5$ mm (where $\theta$ is the polar angle of the track) for electrons and muons and $|d_0|/\sigma_{d_0} < 5(3)$ for electrons (muons).

Reconstructed jets are based on particle-flow objects built from noise-suppressed positive-energy topological clusters in the calorimeter and reconstructed tracks [94]. The anti-$k_T$ algorithm [95,96] with a radius parameter of $R = 0.4$ is used. They are required to have rapidity $|y| < 4.4$ and

---

**TABLE I.** Summary of nominal Higgs boson pair signal samples and single-Higgs-boson background samples, split by production mode, and continuum background samples. The generator used in the simulation, the PDF set, and set of tuned parameters (tune) are also provided.

| Process | Generator | PDF set | Showering | Tune |
|---------|-----------|---------|------------|------|
| Nonresonant $ggF$ $HH$ | POWHEG BOXv2+FT [41,42,43] | PDFLHC [44] | PYTHIA8.2 [67] | A14 [68] |
| Nonresonant $VBF$ $HH$ | MadGraph5_aMC@NLO [47] | NNPDF3.0NLO [69] | PYTHIA8.2 | A14 |
| Resonant $ggF$ $HH$ | MadGraph5_aMC@NLO | NNPDF2.3LO | HERWIG7.13 [53,54] | H7.1—Default [70] |
| $ggH$ | NNLOPS [71–73] [74,75] | PDFLHC | PYTHIA8.2 | AZNLO [76] |
| $VBF$ $H$ | POWHEG BOXv2 [41,72–77] | PDFLHC | PYTHIA8.2 | AZNLO |
| $WH$ | POWHEG BOXv2 | PDFLHC | PYTHIA8.2 | AZNLO |
| $gg \to ZH$ | POWHEG BOXv2 | PDFLHC | PYTHIA8.2 | AZNLO |
| $gg \to ZH$ | POWHEG BOXv2 | PDFLHC | PYTHIA8.2 | AZNLO |
| $t\bar{t}H$ | POWHEG BOXv2 [78–80,83,84] | NNPDF3.0NLO | PYTHIA8.2 | A14 |
| $bbH$ | POWHEG BOXv2 | NNPDF3.0NLO | PYTHIA8.2 | A14 |
| $t\bar{t}H$ | MadGraph5_aMC@NLO | NNPDF3.0NLO | PYTHIA8.2 | A14 |
| $t\bar{t}q$ | MadGraph5_aMC@NLO | NNPDF3.0NLO | PYTHIA8.2 | A14 |
| $t\bar{t}Y$ | SHERPA 2.2.4 [58] | NNPDF3.0NLO | SHERPA 2.2.4 | SHERPA 2.2.4 |...|
| $t\bar{t}g$ | MadGraph5_aMC@NLO | NNPDF2.3LO | PYTHIA8.2 | A14 |...|
$p_T > 25$ GeV. To further suppress jets produced in concurrent $pp$ interactions, each jet within the tracking acceptance of $|\eta| < 2.4$, and with $p_T < 60$ GeV, is required to satisfy the “tight” jet-vertex tagger [97] criteria used to identify the jet as originating from the selected primary vertex of the event.

The flavor of jets is determined using a deep-learning neural network, DL1r. The DL1r $b$-tagging is based on distinctive features of $b$-hadron decays in terms of the impact parameters of the tracks and the displaced vertices reconstructed in the inner detector [98]. The inputs of the DL1r network also include discriminating variables constructed by a recurrent neural network (RNNIP) [99], which exploits the spatial and kinematic correlations between tracks originating from the same $b$-hadron. For high-$p_T$ jets, this approach is found to give better performance [100] than a previously used multivariate technique [101]. Operating points are defined by a single selection value on the discriminant output distribution and are chosen to provide a specific $b$-jet efficiency for an inclusive $t\bar{t}$ MC sample. The $b$-tagging requirements result in an efficiency of 77% for jets containing $b$-hadrons ($b$-tagged jets), and the misidentification rate is 1/130 ($1/4.9$) for light-flavor (charm) jets [98]. Scale factors are applied to the simulated events to correct for differences in $b$-tagging efficiency between data and simulation. These scale factors are measured as a function of jet $p_T$ using a likelihood-based method in a sample highly enriched in $t\bar{t}$ events [98]. Only jets with $|\eta| < 2.5$ are considered for flavor-tagging.

The energy of $b$-tagged jets is corrected for the possible contribution of muons from semileptonic $b$-hadron decays. In addition, the undetected energy of the neutrinos and out-of-cone effects are corrected for with scale factors derived as a function of the $b$-jet $p_T$ from a $t\bar{t}$ MC sample. The two corrections together improve the resolution of the invariant mass of the two jets with the highest $b$-tagging score ($m_{bb}$) by about 20%. The procedure closely follows the one used in Ref. [102].

An overlap removal procedure is applied to avoid multiple usage of the same detector signals in the same event. Photons are prioritized in this analysis, requiring the removal of electrons, muons, and jets within $\Delta R = 0.4$ of a selected photon. Next, jets within $\Delta R = 0.2$ of electrons are removed. In the last step, electrons and muons within $\Delta R = 0.4$ of any jet are removed.

The missing transverse momentum $E_T^{\text{miss}}$ in an event is calculated as the magnitude of the negative vectorial sum of the transverse momenta of all selected and calibrated physics objects that can be matched to the primary vertex. A component called the “soft term” is calculated from the residual tracks that originate from the primary vertex but are not associated with any other object and is added to the $E_T^{\text{miss}}$ calculation [103].

### B. Event selection

Both the nonresonant and resonant $HH$ searches employ multivariate analysis techniques to select events. Events are selected if they satisfy a common set of preselection requirements; they are then required to fulfill different requirements for the nonresonant search and the resonant search. Both analyses employ a fit of the diphoton invariant mass distribution to extract the $HH$ signal contribution.

#### 1. Common preselection

For both the nonresonant and resonant analyses, events are selected using diphoton triggers requiring two reconstructed photon candidates with minimum transverse energies of 35 GeV for the leading photon and 25 GeV for the subleading photon, where leading (subleading) refers to the photon candidate with the highest (second-highest) transverse energy [104]. The triggers used in 2015 and 2016 required both photons to satisfy a Loose photon identification criterion, while the Medium criterion [90] was adopted in 2017–2018 to cope with the increased $pp$ interaction rate. Once the full diphoton event selection described in this section is applied, the average trigger efficiency for $H \rightarrow \gamma \gamma$ events is found to be greater than 99% for the 2015–2016 data-taking period, and greater than 98% for the 2017–2018 data-taking period.

On top of the trigger requirements, events are selected if:

(i) At least two photons satisfy the object selection criteria detailed in Sec. IVA.

(ii) The diphoton invariant mass, built with the two leading photons, satisfies $105$ GeV $< m_{\gamma\gamma} < 160$ GeV.

(iii) The leading (subleading) photon $p_T$ is larger than 35% (25%) of the mass of the diphoton system.

(iv) Exactly two $b$-tagged jets are present. In order to remain statistically independent of the ATLAS search for $HH \rightarrow b\bar{b}b\bar{b}$ [105], any event with more than two $b$-jets passing the 77% efficient working point is rejected.

(v) No electrons or muons are present.

(vi) Fewer than six central ($|\eta| < 2.5$) jets are present. This helps to reject $t\bar{t}H$ events where the top quarks decay hadronically.

The acceptance times efficiency of the common preselection for the SM ggF $HH$ simulation sample is 14% and it is 8.5% (14%) for a resonant scalar particle with $m_X = 300$ GeV ($m_X = 500$ GeV). Multivariate techniques are then used to target the nonresonant ggF production mode or the resonant production mode of Higgs boson pairs. For both the nonresonant and resonant analyses, the resulting categories, each based on a boosted decision tree (BDT), must have at least nine continuum background events in the data sideband region. This guarantees that the final selection on the data sideband retains enough events to perform a
FIG. 4. Reconstructed four-body mass for \(m_X = 300\) GeV and \(m_X = 500\) GeV resonant signal benchmarks, for the SM \(HH\) production processes and for the \(\gamma\gamma + \) jets background. Dashed lines represent the distribution of \(m_{b\gamma\gamma}\) while solid lines represent the distribution of \(m_{b\gamma\gamma}^\star\), defined in Sec. IV B 1. Distributions are normalized to unit area.

The invariant mass of the diphoton plus b-tagged jets system, \(m_{b\gamma\gamma}^\star\), is defined as \(m_{b\gamma\gamma}^\star = m_{b\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\) GeV (where 250 GeV is about twice the Higgs boson mass value and \(m_{bb}\) is the invariant mass of the two jets with the highest b-tagging score). It is used to implement selection criteria for both the nonresonant and resonant analyses. Figure 4 shows that, compared with \(m_{b\gamma\gamma}\), the \(m_{b\gamma\gamma}^\star\) variable improves the four-object mass resolution, particularly for resonant signal particles decaying into a pair of Higgs bosons, due to detector resolution effects canceling out.

2. Nonresonant selection

Following the preselection, events are divided into two regions using the value of the \(m_{b\gamma\gamma}^\star\) variable. A high-mass region, with \(m_{b\gamma\gamma}^\star > 350\) GeV, targets the SM signal \((\kappa_j = 1)\), while a low-mass region, with \(m_{b\gamma\gamma}^\star < 350\) GeV, is used to retain sensitivity for BSM signals \((\kappa_j = 10)\). The dependence of \(m_{b\gamma\gamma}^\star\) on \(\kappa_j\) can be seen in Fig. 5.

In each mass region, a dedicated BDT is trained using XGBoost [106] to discriminate between a benchmark \(HH\) signal and a combination of \(\gamma\gamma\), \(t\bar{t}H\), \(ggH\), and \(ZH\) simulated backgrounds. In the high-mass region, the SM \(HH\) sample is used as signal, while in the low-mass region, the \(\kappa_j = 10\) sample is used as signal.

The BDT input variables are summarized in Table II. Identical variable sets are used for high-mass and low-mass categories. The BDT combines several input variables that exploit the different kinematic properties of signal and background events, as well as the b-tagging information. Observables based on the kinematic properties of the reconstructed photons, such as the leading and subleading photon’s angular information, and the transverse momentum of the diphoton system divided by its invariant mass, are combined with jet-based information. The “single topness” variable \(\chi_{Wt}\) is also used. It is defined as

\[
\chi_{Wt} = \min \left( \frac{(m_{j_1j_2} - m_w)}{m_w} \right)^2 + \left( \frac{(m_{j_1j_2} - m_t)}{m_t} \right)^2,
\]

where the minimum is taken over all combinations of three jets in the event (with no requirements on b-tagging status), \(m_w = 80\) GeV, and \(m_t = 173\) GeV. Among the input variables in Table II, \(m_{bb}\) and \(H_T\) show the highest discriminating power against the \(\gamma\gamma + \) jets continuum background. Particular care was taken to ensure that the BDT event selection does not lead to biases in the \(m_{\gamma\gamma}\) background distribution. Variables which have a strong

![ATLAS Simulation](image1.png)

![ATLAS Simulation](image2.png)

(a) ggF \(HH\) production mode

(b) VBF \(HH\) production mode

FIG. 5. The \(m_{b\gamma\gamma}^\star\) distributions after the common preselection for (a) nonresonant ggF \(HH\) and (b) VBF \(HH\) signals with several \(\kappa_j\) values. The value of \(m_{b\gamma\gamma}^\star = 350\) GeV is chosen as the boundary between categories targeting the SM and BSM \(\kappa_j\) signals.
correlation with the diphoton invariant mass are avoided in
the training in order to prevent the BDT event selection
from biasing the $m_{\gamma\gamma}$ background distribution. To this end,
the transverse momentum values of the photons are divided
by $m_{\gamma\gamma}$ before being used as BDT input variables. A check
for potential biases in the $m_{\gamma\gamma}$ background distribution is
described in Sec.VB. The BDT score distributions in the
low-mass and high-mass regions are shown in Fig.6 for
events passing the common preselection. In each mass
region, two categories based on the BDT score are defined.
The boundaries of the categories are chosen by maximizing
the combined number-counting significance [107] using
signal and background yields in the mass window
$120 \text{ GeV} < m_{\gamma\gamma} < 130 \text{ GeV}$ in the chosen categories.
The four resulting BDT categories are defined in Table III.

### 3. Resonant selection

The resonant search uses a multivariate analysis based on
a BDT technique. A potential limitation of a BDT-based
selection is the low number of background events for higher
resonance masses. To overcome this limitation, BDTs are
trained jointly for all resonance masses hypotheses and
background. The signal events corresponding to the differ-
et mass hypotheses are combined. The signal events are
rewighted event-by-event to match the $m_{b\bar{b}\gamma\gamma}$ distribution
of the background events, such that the training is inde-
pendent of the resonant signal mass hypothesis, but it still
retains information of the correlation with the rest of the
event variables. The procedure allows to reduce the
fluctuations of the BDT performance between nearby mass
points. It was checked that the procedure provides similar
or better performance than employing separated BDT
trainings for each individual signal mass hypothesis.

Using the TMVA toolkit [108], two BDTs are trained to
better separate the signal from backgrounds of different
nature; the $\gamma\gamma$ and $t\bar{t}\gamma\gamma$ backgrounds (BDT$_{\gamma\gamma}$) and the single-
Higgs-boson background (BDT$_{\text{Singlet}}$), where the $ZH$ and
$t\bar{t}H$ processes produce the dominant resonant backgrounds.

### Table II. Variables used in the BDT for the nonresonant analysis. All vectors in the event are rotated so that the leading photon $\phi$ is equal to zero, while their relative azimuthal angular differences are kept unchanged.

| Variable | Definition |
|----------|------------|
| $p_T/m_{\gamma\gamma}$ | Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$ |
| $\eta$ and $\phi$ | Pseudorapidity and azimuthal angle of the leading and subleading photon |
| Jet-related kinematic variables | |
| $b$-tag status | Tightest fixed $b$-tag working point (60%, 70%, or 77%) that the jet passes |
| $p_T$, $\eta$ and $\phi$ | Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest $b$-tagging score |
| $p_T^{bb}$, $\eta_{bb}$ and $\phi_{bb}$ | Transverse momentum, pseudorapidity and azimuthal angle of the $b$-tagged jets system |
| $m_{bb}$ | Invariant mass of the two jets with the highest $b$-tagging score |
| $H_T$ | Scalar sum of the $p_T$ of the jets in the event |
| Single topness | For the definition, see Eq. (1) |
| Missing transverse momentum variables | |
| $E_T^{\text{miss}}$ and $\phi^{\text{miss}}$ | Missing transverse momentum and its azimuthal angle |

![FIG. 6. The BDT distribution of the di-Higgs ggF signal for two different values of $k_j$ and the main backgrounds in the (a) low-mass region and (b) high-mass region. Distributions are normalized to unit area. The dashed lines denote the category boundaries. Events with a BDT score below 0.881 in the low-mass region or below 0.857 in the high-mass region are discarded.](052001-8)
The nonresonant $HH$ process is not included in the training of the BDTS. A complete list of the variables used for the BDT training is given in Table IV. The $E_T^{\text{miss}}$ information is used in the training because it is useful in rejecting the single-Higgs-boson background ($tH$ in particular) and the top-antitop background.

The combined BDT score of an event is obtained by combining the two BDT scores in quadrature, as shown in Eq. (2).

$$
\text{BDT}_\text{tot} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \times \sqrt{C_1^2 \left( \frac{\text{BDT}_\text{high} + 1}{2} \right)^2 + C_2^2 \left( \frac{\text{BDT}_\text{low} + 1}{2} \right)^2}.
$$

The two coefficients $C_1$ and $C_2$ ($C_2 = 1 - C_1$) and BDT$_{\text{tot}}$ take values in the range [0, 1]. Only events passing a minimum requirement on the value of BDT$_{\text{tot}}$ are considered in the analysis. To reduce the effect of limited statistics of the Monte Carlo samples in the determination the minimum value required for BDT$_{\text{tot}}$ and of the $C_1$ and $C_2$ coefficients, a two-stage procedure is used. The values of the $C_1$ and $C_2$ as well as the BDT cut value are scanned twice in order to maximize the significance. This two-stage optimization procedure first finds the maximum significance that can be achieved for each resonance mass point independently, leading to different coefficient values and BDT$_{\text{tot}}$ requirement values for the various mass points. A second scan is done to select all coefficients providing a significance within 5% of the maximum value, for each of the resonance mass values. From those possible combinations a common $C_1$ coefficient is sought (resulting in $C_1 = 0.65$) across all the resonances so that the selection will have common coefficients for all resonance mass points, but different BDT$_{\text{tot}}$ values. For each of the resonance mass hypotheses, a requirement is set on the $m_{\text{D}H}$ value to select events within $\pm 2\sigma$ of the expected mean value for signal events (where $\sigma$ is the standard deviation parameter of the Crystal Ball function that best fits the $m_{\text{D}H}$ distribution). In the case of the 900 GeV and 1000 GeV mass hypotheses, the requirement is relaxed to $\pm 4\sigma$ to increase the number of events used for the signal extraction. The BDT$_{\text{tot}}$ distributions are shown in Fig. 7 for two signal hypotheses ($m_X = 300$ GeV and 500 GeV).

### Table III

| Category            | Selection criteria                                                                 |
|---------------------|------------------------------------------------------------------------------------|
| High mass BDT tight | $m_{b\bar{b}\gamma\gamma}^* \geq 350$ GeV, BDT score $\in [0.967, 1]$             |
| High mass BDT loose | $m_{b\bar{b}\gamma\gamma}^* \geq 350$ GeV, BDT score $\in [0.857, 0.967]$         |
| Low mass BDT tight  | $m_{b\bar{b}\gamma\gamma}^* < 350$ GeV, BDT score $\in [0.966, 1]$                |
| Low mass BDT loose  | $m_{b\bar{b}\gamma\gamma}^* < 350$ GeV, BDT score $\in [0.881, 0.966]$            |

The nonresonant $HH$ process is not included in the training of the BDTS. A complete list of the variables used for the BDT training is given in Table IV. The $E_T^{\text{miss}}$ information is used in the training because it is useful in rejecting the single-Higgs-boson background ($tH$ in particular) and the $t\bar{t}$ background.

The combined BDT score of an event is obtained by combining the two BDT scores in quadrature, as shown in Eq. (2).

$$
\text{BDT}_\text{tot} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \times \sqrt{C_1^2 \left( \frac{\text{BDT}_\text{high} + 1}{2} \right)^2 + C_2^2 \left( \frac{\text{BDT}_\text{low} + 1}{2} \right)^2}.
$$

The two coefficients $C_1$ and $C_2$ ($C_2 = 1 - C_1$) and BDT$_{\text{tot}}$ take values in the range [0, 1]. Only events passing a minimum requirement on the value of BDT$_{\text{tot}}$ are considered in the analysis. To reduce the effect of limited statistics of the Monte Carlo samples in the determination the minimum value required for BDT$_{\text{tot}}$ and of the $C_1$ and $C_2$ coefficients, a two-stage procedure is used. The values of the $C_1$ and $C_2$ as well as the BDT cut value are scanned twice in order to maximize the significance. This two-stage optimization procedure first finds the maximum significance that can be achieved for each resonance mass point independently, leading to different coefficient values and BDT$_{\text{tot}}$ requirement values for the various mass points. A second scan is done to select all coefficients providing a significance within 5% of the maximum value, for each of the resonance mass values. From those possible combinations a common $C_1$ coefficient is sought (resulting in $C_1 = 0.65$) across all the resonances so that the selection will have common coefficients for all resonance mass points, but different BDT$_{\text{tot}}$ values. For each of the resonance mass hypotheses, a requirement is set on the $m_{\text{D}H}$ value to select events within $\pm 2\sigma$ of the expected mean value for signal events (where $\sigma$ is the standard deviation parameter of the Crystal Ball function that best fits the $m_{\text{D}H}$ distribution). In the case of the 900 GeV and 1000 GeV mass hypotheses, the requirement is relaxed to $\pm 4\sigma$ to increase the number of events used for the signal extraction. The BDT$_{\text{tot}}$ distributions are shown in Fig. 7 for two signal hypotheses ($m_X = 300$ GeV and 500 GeV).

### Table IV

| Variable                      | Definition                                                                 |
|-------------------------------|---------------------------------------------------------------------------|
| Photon-related kinematic variables | $p_T^\gamma$, $y^\gamma$                                                          |
|                               | Transverse momentum and rapidity of the diphoton system                      |
| $\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$ | Azimuthal angle and $\Delta R$ between the two photons                     |
| Jet-related kinematic variables | $m_{bb}$, $p_T^{bb}$ and $y_{bb}$                                              |
|                               | Invariant mass, transverse momentum and rapidity of the $b$-tagged jets system |
| $\Delta\phi_{bb}$ and $\Delta R_{bb}$ | Azimuthal angle and $\Delta R$ between the two $b$-tagged jets              |
| $N_{\text{jets}}$ and $N_{b\text{-jets}}$ | Number of jets and number of $b$-tagged jets                                |
| $H_T$                         | Scalar sum of the $p_T$ of the jets in the event                             |
| Dijet-related kinematic variables | $m_{\text{D}H}$                                                             |
|                               | Invariant mass of the diphoton plus $b$-tagged jets system                    |
| $\Delta y_{\gamma\gamma,bb}$, $\Delta\phi_{\gamma\gamma,bb}$ and $\Delta R_{\gamma\gamma,bb}$ | Distance in rapidity, azimuthal angle and $\Delta R$ between the diphoton and the $b$-tagged jets system |
| Missing transverse momentum variables | $E_T^{\text{miss}}$                                                            |
|                               | Missing transverse momentum                                                 |
The analysis selection described in Sec. IV B requires two “tight” photons and this region is mainly composed of \( \gamma \gamma \), \( \gamma \)-jet, and dijet events, where either one or two jets are misidentified as photons. The fractional contribution of each component can be estimated using a data-driven approach [109] based on the photon identification and isolation distributions from genuine and misidentified photons. After the common preselection, \((85 \pm 3)\%\) of sideband events are genuine diphoton events, with the remaining \((15 \pm 4)\%\) consisting of \( \gamma \)-jet events and a negligible number of dijet events. The uncertainties in the above fractions include both the statistical and systematic uncertainties, where the systematic uncertainty is estimated by using different photon identification criteria. In the BDT-based categories, the proportion of genuine diphoton events increases but the method suffers from a low event count for both the nonresonant and resonant cases.

Figure 8 shows the level of agreement between data and the background prediction for the \( m_\gamma \) and \( m_{bb\gamma\gamma} \) distributions, after the common preselection. The continuum background is scaled by the \( \gamma \gamma \), \( \gamma \)-jet, and dijet fractions and normalized to the data sideband. The \( \gamma \gamma + \text{jets} \) continuum background is further divided according to the flavors of the two jets (for example \( bb \) or other jets). This decomposition is taken directly from the proportions predicted by the SHERPA event generator, as described in Sec. III, and it is shown for illustration. Figures 9 and 10 show the \( m_\gamma \) distribution after the nonresonant and resonant BDT categorization and for two benchmark mass points \( m_X = 300 \text{ GeV} \) and \( m_X = 500 \text{ GeV} \). The figures illustrate the signal and background composition. The background distributions shown in these figures are not directly used to model the background processes in the analysis workflow explained in Sec. V.

V. SIGNAL AND BACKGROUND PARAMETRIZATION

The signal and backgrounds are extracted by fitting analytic functions to the diphoton invariant mass distribution in the range \( 105 < m_\gamma \gamma < 160 \text{ GeV} \) in both the resonant and nonresonant \( HH \) searches.

A. \( H \rightarrow \gamma \gamma \) parametrization

For the di-Higgs signal and single-Higgs-boson background distributions, the parameterized forms are determined through fits to simulated samples and the expected normalizations are obtained from their theoretical cross sections multiplied by the product of the acceptance times efficiency from the simulation. The diphoton invariant mass distribution shapes are modeled with a double-sided Crystal Ball function [91,110], which is characterized by a Gaussian core and asymmetric power-law tails. This function allows the modeling of event distributions in which non-Gaussian tails can arise from experimental effects, such as photon-energy mismeasurements.

The shape parameters are determined by fitting the diphoton mass distribution in simulation for each category. The width of the fitted function is largely insensitive to the specific signal processes considered in the analysis, with maximum variations of approximately 10\%. For the nonresonant search, the parameterized form of \( m_\gamma \) is obtained from the simulation of the ggF and VBF \( HH \) processes with \( k_\gamma = 1 \), described in Sec. III. No significant dependence of the functional form on \( k_\gamma \) was found. For the resonant search, the functional form is obtained from the simulation of the heavy-resonance signals.
the resolution parameter of the double-sided Crystal Ball functional form fit to the $m_{\gamma\gamma}$ distribution for simulated Higgs boson pair events in the nonresonant categories and for two different mass hypotheses for a heavy resonant signal. For both searches, the chosen functional forms are found to model both the single Higgs and di-Higgs boson events well. As no statistically significant bias is observed in injection tests between the input and fitted signals, the same parametrized functions are used for both the single Higgs and di-Higgs boson processes.

### B. Background parametrization

The continuum diphoton background is modeled using a functional form chosen by fitting a highly populated MC sample. For high mass BDT tight selection, the data-derived fractions of nonresonant $\gamma\gamma$, $\gamma$–jet or jet–$\gamma$, and dijet background are applied and the total background is normalized to the data sideband. The scalar resonance signal is scaled to a total production cross section $\sigma(pp \rightarrow X \rightarrow HH) = 370 \text{ fb}$ for $m_X = 300 \text{ GeV}$ or $\sigma(pp \rightarrow X \rightarrow HH) = 67 \text{ fb}$ for $m_X = 500 \text{ GeV}$, corresponding to the expected exclusion limits presented in Sec. VII C.

**FIG. 8.** Distributions of (a) $m_{\gamma\gamma}$ and (b) $m_{\gamma\gamma}^{*}$ for events satisfying the common preselection criteria. The data-derived fractions of nonresonant $\gamma\gamma$, $\gamma$–jet or jet–$\gamma$, and dijet background are applied and the total background is normalized to the data sideband. The scalar resonance signal is scaled to a total production cross section $\sigma(pp \rightarrow X \rightarrow HH) = 370 \text{ fb}$ for $m_X = 300 \text{ GeV}$ or $\sigma(pp \rightarrow X \rightarrow HH) = 67 \text{ fb}$ for $m_X = 500 \text{ GeV}$, corresponding to the expected exclusion limits presented in Sec. VII C.

**FIG. 9.** Distributions of $m_{\gamma\gamma}$ in all signal categories for the nonresonant $HH$ search: (a) high mass BDT tight, (b) high mass BDT loose, (c) low mass BDT tight, (d) low mass BDT loose. The data-derived fractions of nonresonant $\gamma\gamma$, $\gamma$–jet or jet–$\gamma$, and dijet background are applied and the total background is normalized to the data sideband.
background template. Given the high $\gamma\gamma$ purity quoted in Sec. IV C, the background template is constructed in each category from the $\gamma\gamma + $ jets simulation which is normalized to the data sideband in the mass windows of 105 GeV–120 GeV and 130 GeV–160 GeV in the $m_{\gamma\gamma}$ spectrum.

The potential bias associated with the choice of a specific analytic function to model the continuum background is estimated for each category as prescribed in Refs. [91, 111]. It is obtained as the signal event yield extracted from a signal-plus-background fit to the background-only diphoton invariant mass distribution in the range 105 GeV < $m_{\gamma\gamma}$ < 160 GeV. This bias is also called the “spurious signal.” The number of fitted signal events is computed for Higgs boson masses in intervals of 1 GeV from 121 GeV to 129 GeV. The bias is taken as the largest number of fitted spurious signal events in this 8 GeV mass window. Of the different analytic functions that are tested, the one with the smallest number of parameters is chosen from the functions with a spurious signal smaller than 20% of the data’s statistical uncertainty plus two times the MC statistical uncertainty.

In each category of the nonresonant search and in all the analysis regions defined in the resonant $HH$ search, an exponential function $\exp(a \cdot m_{\gamma\gamma})$ is found to be the best choice since it has the smallest number of degrees of freedom and yields a consistently small bias. Wald tests [112] on data show that the data do not prefer a higher-degree functional form to the exponential form. The bias is found to be at most 40% (60%) of the expected error on the fitted signal yield originating from the data statistics for the nonresonant (resonant) search. The difference in shape between the simulated events and the exponential form measured in the sidebands is found to have a negligible impact on the spurious signal. To study the impact on the spurious signal from the difference in shape between the MC background template and the data sideband, the MC template is reweighted to data using a linear function of $m_{\gamma\gamma}$ determined from the reweighted MC-data difference. The spurious signal value evaluated from the reweighted MC template is found to be compatible with the nominal one used as the systematic uncertainty.

### VI. SYSTEMATIC UNCERTAINTIES

The sensitivity of the analysis is limited by the statistical precision. The assessment of the systematic uncertainties is described below and their impact on the results is discussed in Sec. VII D. The uncertainty in the integrated luminosity of the full Run 2 dataset is 1.7% [39], obtained using the LUCID-2 detector [38] for the primary luminosity measurements.

The continuum background processes of the analysis are estimated from data and are subject to uncertainties related to the potential bias arising from the chosen background model, as described in Sec. V B. The background functional form bias is assessed as an additional uncertainty in the total number of signal events in each category. For the single

### TABLE V. The resolution parameter of the double-sided Crystal Ball functional form and the corresponding statistical uncertainty are obtained from the fit to the $m_{\gamma\gamma}$ distribution for simulated Higgs boson pair events for the nonresonant categories and for two different mass hypotheses for a heavy-resonance signal.

| Category                          | $\sigma_{\text{DSCB}}$ [GeV] |
|----------------------------------|-----------------------------|
| High mass BDT tight             | $1.33 \pm 0.01$             |
| High mass BDT loose             | $1.47 \pm 0.02$             |
| Low mass BDT tight              | $1.50 \pm 0.06$             |
| Low mass BDT loose              | $1.64 \pm 0.03$             |
| Resonant $m_X = 300$ GeV        | $1.78 \pm 0.02$             |
| Resonant $m_X = 500$ GeV        | $1.46 \pm 0.01$             |
Higgs boson and di-Higgs boson production processes, both of which are estimated using simulation, experimental and theoretical systematic uncertainties are propagated through the full analysis procedure, as described in the following.

The efficiency of the diphoton trigger used to select events is evaluated in simulation and data using a bootstrap method and radiative Z decays [113]. The difference between data and MC is taken as a systematic uncertainty. In the diphoton invariant mass range of 105 < m_{\gamma\gamma} < 160 GeV, the trigger efficiency uncertainty affects the acceptance by 1% in each category. The uncertainty in the vertex selection efficiency is assessed by comparing the efficiency of finding photon-pointing vertices in Z \rightarrow e^+e^- events in data with that in simulation [114]. The resulting uncertainty is found to have a negligible effect on the signal selection efficiency.

The systematic uncertainties from the photon identification and isolation efficiencies are estimated following the prescriptions in Ref. [90]. They are evaluated by varying the correction factors for photon selection efficiencies in simulation by the corresponding uncertainties and affect the diphoton selection efficiency. The experimental uncertainties in the photon-energy scale and resolution are obtained from Ref. [90].

The jet-energy scale and resolution uncertainties [115] affect the m_{bb} distribution, while flavor-tagging uncertainties affect the acceptance of the analysis categories. The experimental uncertainties in jet energy scale and resolution are propagated to the E_T^{\text{miss}} calculation. In addition, the uncertainties in the scale and resolution of the E_T^{\text{miss}} soft term are evaluated by using the method described in Ref. [103]. The flavor-tagging uncertainties for b- and c-jets are estimated in \bar{t}t events [98,116], while the misidentification uncertainty of light-flavor jets is determined using dijet events [117]. Additional uncertainties from the b-jet momentum correction accounting for the presence of muons and neutrinos are found to be negligible.

For single Higgs boson and SM \( HH \) production, the effects of theoretical scale uncertainties due to missing higher-order corrections on the production rates are estimated by varying the factorization and renormalization scales up and down from their nominal values by a factor of two, recalculating the cross section in each case, and taking the largest deviation from the nominal cross section as the uncertainty. The uncertainties in SM \( HH \) ggF production arising from the choice of renormalization scheme and scale of the top-quark mass and their combination with those from factorization and renormalization scale variations are based on Ref. [17]. The uncertainties in the cross sections, including effects of PDF + \alpha_s uncertainties, and the uncertainties in the \( H \rightarrow \gamma\gamma \) and \( H \rightarrow b\bar{b} \) branching fractions, are taken from Refs. [14,56]. The uncertainty in the value of the Higgs boson mass is considered [13]. An additional 100% uncertainty is assigned to the single-Higgs-boson ggF and VBF production modes and to Higgs boson production in association with a W boson. This is motivated by studies of heavy-flavor production in association with top-quark pairs [118,119] and of W boson production in association with b-jets [120]. No additional heavy-flavor uncertainty is assigned to the single-Higgs-boson \( t\bar{t}H \) and \( ZH \) production modes, where the dominant heavy-flavor production is already accounted for in the LO process. For all samples, the uncertainty related to the choice of parton showering model is evaluated by comparing the predictions of the nominal MC samples and alternative samples using a different parton showering model. In addition, for the nonresonant \( HH \) production processes, a systematic uncertainty is assigned to the \( \kappa_j \) reweighting, as discussed in Sec. III.

In the resonant search, the systematic uncertainty sources considered are the same as for the nonresonant case, except that uncertainties due to the finite order of the QCD calculations are not assigned to the resonant signal cross section. In this search the SM \( HH \) production processes are considered as background.

**VII. RESULTS**

The statistical framework used to derive the results for both the nonresonant and resonant searches is described in the following.

**A. Statistical framework**

For both the nonresonant and resonant searches, the results of the analysis are obtained from a maximum-likelihood fit of the \( m_{\gamma\gamma} \) distribution in the range 105 GeV < \( m_{\gamma\gamma} \) < 160 GeV, performed simultaneously over all relevant categories described in Sec. IV B. The likelihood function is defined in Eq. (3),

\[
\mathcal{L} = \prod_c \left( \text{Pois}(n_c|N_c(\theta)) \cdot \prod_{i=1}^{n_c} f_c(m_{\gamma\gamma}^i, \theta) \cdot G(\theta) \right),
\]

where for each event \( i \) in a category \( c \), \( n_c \) is the observed number of events, \( N_c \) is the expected number of events, \( f_c \) is the value of the probability density function, \( \theta \) are nuisance parameters, and \( G(\theta) \) are constraint pdfs for the nuisance parameters.

The expected number of events \( N_c(\theta) \), defined in Eq. (4), is the sum of the expected yields from di-Higgs boson production processes, single Higgs boson production, the nonresonant background, as well as the spurious-signal uncertainty,

\[
N_c(\theta) = \mu \cdot N_{HH,c}^{\text{field}}(\theta_{HH}^{\text{field}}) + N_{\text{res},bkg,c}^{\text{field}}(\theta_{\text{res}}^{\text{field}})
+ N_{SS,c} + N_{\text{nonres},bkg,c},
\]
where \( \mu \) is the signal strength, \( \theta_{SS,c} \) represent the nuisance parameters associated with the background function bias and \( \theta_{yield} \) represent the nuisance parameters affecting the event yield, as detailed in Sec. VI. Correlation of the nuisance parameters across different signal and background components, as well as categories, is taken into account. In the case of the nonresonant search, \( N_{bkg,c}^{res} = N_{H,c} \), while in the case of the resonant analysis \( N_{bkg,c}^{res} = N_{H,c} + N_{SMHH,c} \).

The probability density function \( f_c \) represents the shape information. The sum of the double-sided Crystal Ball functions modeling the \( HH \) production processes, single Higgs boson production, and the spurious signal, and of the analytic function modeling the nonresonant background as described in Sec. VIB, is shown in Eq. (5),

\[
f_c(m_{\gamma\gamma}, \theta) = \mu \cdot N_{HH,c}(\theta_{HH}^{yield}) \cdot f_{HH,c}(m_{\gamma\gamma}, \theta_{HH}^{shape}) \\
+ N_{bkg,c}^{res}(\theta_{bkg,c}^{yield}) \cdot f_{bkg,c}^{res}(m_{\gamma\gamma}, \theta_{bkg,c}^{shape}) \\
+ N_{SS,c} \cdot f_{HH,c}(m_{\gamma\gamma}, \theta_{HH}^{shape}) \\
+ N_{bkg,c}^{nonres} \cdot f_{bkg,c}^{nonres}(m_{\gamma\gamma}, \theta_{bkg,c}^{nonres}) / N_c(\theta_{nonres}),
\]

where \( \theta_{shape} \) represent nuisance parameters related to the shape variations of the functional forms. When a nuisance parameter is related to shape and yield variations at the same time, the two effects are correlated.

The nominal yields of the resonant background processes are initially set to values from simulation. The likelihood function includes all the nuisance parameters that describe the systematic uncertainties. The signal strength is a free parameter in the fit. The measurement of the parameter of interest is carried out using a statistical test based on the profile likelihood ratio [107], as shown in Eq. (6),

\[
\Lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})},
\]

where \( \mu \) and \( \theta \) are respectively the parameter of interest and the nuisance parameters. In the numerator, the nuisance parameters are set to their profiled values \( \hat{\theta}(\mu) \), which maximize the likelihood function for a fixed value of the parameter of interest \( \mu \). In the denominator, the parameter of interest and the nuisance parameters are set to the values \( \hat{\mu} \) and \( \hat{\theta} \), respectively, which jointly maximize the likelihood.

In the absence of signal, exclusion limits are set on Higgs boson pair production in the \( b\bar{b}\gamma\gamma \) final state. The limits for both nonresonant and resonant production are calculated.
TABLE VI. The number of data events observed in the 120 GeV < \( m_{\gamma\gamma} < 130 \) GeV window, the number of \( HH \) signal events expected for \( \kappa_2 = 1 \) and for \( \kappa_2 = 10 \), and events expected for single Higgs boson production (estimated using MC simulation), as well as for continuum background. For the single Higgs boson, “Rest” includes the following production modes: VBF, \( WH, tH_q \), and \( tHW \).

The values are obtained from a fit of the Asimov dataset [107] generated under the SM signal-plus-background hypothesis, \( \kappa_2 = 1 \). The continuum background component of the Asimov dataset is obtained from the fit of the data sideband. The uncertainties in \( HH \) signals and single Higgs boson background include the systematic uncertainties discussed in Sec. VI. The uncertainty in the continuum background is given by the sum in quadrature of the statistical uncertainty from the fit to the data and the spurious-signal uncertainty.

|                           | High mass | High mass | Low mass | Low mass |
|---------------------------|-----------|-----------|----------|----------|
|                           | BDT tight | BDT loose | BDT tight | BDT loose |
| Continuum background      | \( 4.9^{+1.1}_{-1.3} \) | \( 9.5^{+1.5}_{-1.7} \) | \( 3.7^{+0.9}_{-1.1} \) | \( 24.9^{+2.3}_{-2.5} \) |
| Single Higgs boson background | \( 0.67^{+0.29}_{-0.13} \) | \( 1.6^{+0.6}_{-0.2} \) | \( 0.23^{+0.09}_{-0.03} \) | \( 1.40^{+0.33}_{-0.16} \) |
| \( ggF + bbH \)           | \( 0.26^{+0.28}_{-0.16} \) | \( 0.4^{+0.3}_{-0.2} \) | \( 0.07^{+0.08}_{-0.04} \) | \( 0.27^{+0.27}_{-0.16} \) |
| \( tH \)                  | \( 0.19^{+0.03}_{-0.03} \) | \( 0.49^{+0.09}_{-0.07} \) | \( 0.107^{+0.02}_{-0.017} \) | \( 0.75^{+0.13}_{-0.11} \) |
| \( ZH \)                  | \( 0.142^{+0.032}_{-0.025} \) | \( 0.48^{+0.09}_{-0.07} \) | \( 0.040^{+0.014}_{-0.011} \) | \( 0.26^{+0.09}_{-0.06} \) |
| Rest                      | \( 0.074^{+0.014}_{-0.014} \) | \( 0.16^{+0.07}_{-0.03} \) | \( 0.012^{+0.008}_{-0.004} \) | \( 0.111^{+0.011}_{-0.002} \) |
| SM \( HH(\kappa_2=1) \) signal | \( 0.87^{+0.10}_{-0.18} \) | \( 0.37^{+0.07}_{-0.04} \) | \( 0.049^{+0.006}_{-0.010} \) | \( 0.079^{+0.008}_{-0.015} \) |
| \( ggF \)                | \( 0.86^{+0.10}_{-0.18} \) | \( 0.35^{+0.07}_{-0.04} \) | \( 0.046^{+0.006}_{-0.010} \) | \( 0.077^{+0.008}_{-0.015} \) |
| VBF                       | \( (12.6^{+1.3}_{-1.2}) \times 10^{-3} \) | \( (16.1^{+1.4}_{-1.2}) \times 10^{-3} \) | \( (3.2^{+0.3}_{-0.4}) \times 10^{-3} \) | \( (6.9^{+0.5}_{-0.6}) \times 10^{-3} \) |
| Alternative \( HH(\kappa_2=10) \) signal | \( 6.5^{+1.0}_{-0.8} \) | \( 3.6^{+0.6}_{-0.4} \) | \( 4.5^{+0.7}_{-0.6} \) | \( 8.5^{+1.3}_{-1.0} \) |

Data                      | 2         | 17        | 5         | 14        |

The increase of the limit value relative to the asymptotic approximation is found to be less than 8% for both the observed and expected upper limits. A check of the expected upper limits using prefit values for the nuisance parameters associated with the systematic uncertainties is the CLS method [121], with the profile-likelihood-ratio-based test statistic \( \hat{q}_\mu \), defined in Eq. (7) [107],

\[
\hat{q}_\mu = \begin{cases} 
-2 \ln \frac{\Lambda(\mu|\hat{\theta}|)}{\Lambda(0|\hat{\theta}|)} & \hat{\mu} < 0, \\
-2 \ln \frac{\Lambda(\mu|\hat{\theta}|)}{\Lambda(\hat{\mu}|\hat{\theta}|)} & 0 \leq \hat{\mu} \leq \mu, \\
0 & \hat{\mu} > \mu. 
\end{cases}
\]

The asymptotic approximation [107] is used for the test-statistic distribution. The inaccuracy of the asymptotic approximation is checked with pseudoexperiment studies for the key results reported in this paper.

B. Nonresonant search results

Figure 11 shows the background fits to the data. No significant excess over the SM background expectations is found, as summarized in Table VI. The statistical analysis sets a 95% C.L. upper limit on the nonresonant \( HH \) production cross section at 130 fb, while 180 fb is expected. An observed (expected) upper limit at 95% C.L. on the signal strength of 4.2 (5.7) times the SM prediction is obtained. The expected constraints are obtained for a background hypothesis excluding \( pp \to HH \) production. For the upper limits on the cross section, all theoretical uncertainties are included, except those related to the signal cross section itself, while constraints on the signal strength are computed including uncertainties in the predicted signal cross section. A check of the results that quantifies the upper limits by using pseudoexperiments is performed and
performed and an increase of 4% relative to the nominal result is found. The difference is dominated by the contribution from the spurious signal.

Upper limits on the $HH$ production cross section are also computed as a function of $\kappa_\lambda$, as shown in Fig. 12. For this purpose, single-Higgs-boson production cross sections and Higgs boson decay branching ratios are assumed to have SM values, and the coupling strength between the Higgs boson and other particles are also set to their SM values [55]. The theory uncertainties related to the signal cross section are not included.

The expected constraints on $\kappa_\lambda$ at 95% C.L., as obtained with a background hypothesis excluding $pp \to HH$ production, are $[-2.4, 7.7]$, whereas the observed constraints are $[-1.5, 6.7]$ at 95% C.L. The inclusion of the VBF $HH$ production mode tightens the constraints by about 5% relative to an alternative fit considering only the ggF production mode.

An alternative statistical analysis consists in determining the best-fit value of the $\kappa_\lambda$ coupling modifier. The best-fit value of $\kappa_\lambda$ and its uncertainty are obtained by means of a negative log-likelihood scan. The coupling strengths of the Higgs boson to fermions and gauge bosons are set to their SM values. The values of the negative log-likelihood ratio, $-2\ln L$, are computed as a function of $\kappa_\lambda$, as shown in Fig. 12. For this purpose, single-Higgs-boson production cross sections and Higgs boson decay branching ratios are assumed to have SM values, and the coupling strength between the Higgs boson and other particles are also set to their SM values [55]. The theory uncertainties related to the signal cross section are not included.

![Graph](image)

**FIG. 13.** Values of the negative log-profile-likelihood ratio ($-2\ln L$) as a function of $\kappa_\lambda$ evaluated for the combination of all the categories of the nonresonant search. The coupling of the Higgs boson to fermions and gauge bosons is set to SM values in the profile likelihood calculation. The expected result corresponds to a Asimov dataset [107] generated under the SM signal-plus-background hypothesis, $\kappa_\lambda = 1$. All systematic uncertainties, including the theoretical uncertainties in the di-Higgs boson production cross section, are included. The intersections of the solid curves and the horizontal dashed lines indicate the 1σ and 2σ confidence level intervals.

![Graph](image)

**FIG. 14.** Data are compared with the background-only fit for the resonant search for the (a) $m_X = 300$ GeV and (b) $m_X = 500$ GeV mass hypotheses. The continuum background, as well as the background from single Higgs boson production and from SM $HH$ production, is considered. The data points in the Figure are the same as shown in Fig. 10.

**TABLE VII.** The number of events observed in the $120 < m_{jj} < 130$ GeV window in data, the number of events expected for scalar resonance signals of masses $m_X = 300$ GeV and $m_X = 500$ GeV assuming a total production cross section $\sigma(pp \to X \to HH)$ equal to the observed exclusion limits of Fig. 15, and events expected for SM $HH$ and single Higgs boson production (estimated using MC simulation), as well as for continuum background. The values are obtained from a fit of the Asimov dataset [107] generated under the signal-plus-background hypothesis. The continuum background component of the Asimov dataset is obtained from the fit of the data sideband. The uncertainties in the resonant signals and the SM $HH$ and single-Higgs-boson backgrounds include the systematic uncertainties discussed in Sec. VI. The uncertainty in the continuum background is given by the sum in quadrature of the statistical uncertainty from the fit to the data and the spurious-signal uncertainty.

| $m_X$ (GeV) | Continuum background | Single Higgs boson background | SM $HH$ background | $X \to HH$ signal | Data |
|-------------|----------------------|------------------------------|-------------------|------------------|------|
| 300         | $5.5^{+1.3}_{-1.5}$  | $0.34^{+0.14}_{-0.07}$      | $0.021^{+0.005}_{-0.009}$ | $6.1^{+0.9}_{-0.8}$ | 6    |
| 500         | $1.6^{+0.6}_{-0.9}$  | $0.40^{+0.18}_{-0.08}$      | $0.20^{+0.09}_{-0.09}$ | $6.1^{+0.8}_{-0.6}$ | 4    |
-2\ln \Lambda(\mu)$, as a function of $\kappa_3$ are shown in Fig. 13. The Asimov dataset [107] is generated under the SM signal-plus-background hypothesis, $\kappa_3 = 1$. All systematic uncertainties, including those of the theoretical prediction of the $HH$ production cross section, are included. The best-fit value corresponds to $\kappa_3 = 2.8^{+0.2}_{-0.2} \times \frac{1.0}{1.0}$ for the $1\sigma$ ($2\sigma$) confidence interval. The expected value corresponds to $\kappa_3 = 1.0^{+0.5}_{-0.2} \times \frac{1.0}{1.0}$ for the $1\sigma$ ($2\sigma$) confidence interval. The second minimum in the expected likelihood scan curve corresponds to a similar fitted signal yield with respect to the $\kappa_3$ point at the first minimum, which is a consequence of a higher cross section, but lower acceptance and worse signal-to-background separation. The $m_{HH}$ distribution has a different shape at each of the two minima, as shown in Fig. 5.

C. Resonant search results

Figure 14 shows the fit to the data of the resonant search for two benchmark values of the mass $m_X$ of a hypothetical scalar particle. No significant excess over the SM background expectations is found, as shown in Table VII. Figure 15 shows the observed and expected upper limits at 95% C.L. on the production cross section of a narrow-width scalar resonance. The observed (expected) upper limits vary between 640–44 fb (391–46 fb) in the range $251 \text{ GeV} \leq m_X \leq 1000 \text{ GeV}$. A check on the upper limits using pseudoexperiments is performed. For the expected limits, the results based on the pseudo-experiments are found to be up to 10% higher compared with those derived based on the asymptotic approximation. As for the observed limits, the pseudoexperiments yield typically 10% higher results compared with the asymptotic approximation in most of the $m_X$ range explored, and the difference increases to 15% for the $m_X = 700 \text{ GeV}$ signal hypothesis.

D. Impact of systematic uncertainties

The dominant systematic uncertainties are listed in Table VIII for both the nonresonant and resonant searches. The main uncertainties are related to the choice of functional form for the continuum background (spurious signal), to the parton showering model, and to the photon energy resolution.

| Source                                      | Type                  | Nonresonant analysis | Resonant analysis |
|---------------------------------------------|-----------------------|----------------------|-------------------|
| Experimental Photon energy resolution       | Norm. + Shape         | 0.4                  | 0.6               |
| Jet energy scale and resolution             | Normalization         | <0.2                | 0.3               |
| Flavor tagging                              | Normalization         | <0.2                | 0.2               |
| Theoretical Factorization and renormalization scale | Normalization         | 0.3                 | <0.2              |
| Parton showering model                      | Norm. + Shape         | 0.6                 | 2.6               |
| Heavy-flavor content                        | Normalization         | 0.3                 | <0.2              |
| $B(H \rightarrow \gamma \gamma, b\bar{b})$ | Normalization         | 0.2                 | <0.2              |
| Spurious signal                             | Normalization         | 3.0                 | 3.3               |

TABLE VIII. Breakdown of the dominant systematic uncertainties. The impact of the uncertainties corresponds to the relative variation of the expected upper limit on the cross section when reevaluating the profile likelihood ratio after fixing the nuisance parameter in question to its best-fit value, while all remaining nuisance parameters remain free to float. The impact is shown in %. Only systematic uncertainties with an impact of at least 0.2% are shown. Uncertainties of the “Norm + Shape” type affect both the normalization and the parameters of the functional form. The rest of the uncertainties affect only the yields.
VIII. CONCLUSIONS

Searches for nonresonant and resonant Higgs boson pair production are performed in the $b\bar{b}\gamma\gamma$ final state using 139 fb$^{-1}$ of 13 TeV $pp$ collision data collected with the ATLAS detector at the LHC. No significant excess above the Standard Model background expectation is observed. A 95% C.L. upper limit of 130 fb is set on the $pp \rightarrow HH$ nonresonant production cross section, where the expected limit is 180 fb. The observed (expected) limit corresponds to 4.2 (5.7) times the cross section predicted by the Standard Model. Constraints on the Higgs boson self-coupling are also derived and limits of $-1.5 < \kappa_{ij} < 6.7$ are obtained, where $-2.4 < \kappa_3 < 7.7$ is expected. The expected constraints on the $HH$ nonresonant production cross section and on $\kappa_3$ are obtained with a background hypothesis excluding $pp \rightarrow HH$ production. For resonant production of a scalar particle $X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$, upper limits on the production cross section are obtained for the narrow-width hypothesis as a function of $m_X$. The observed (expected) upper limits are in the range 640–44 fb (391–46 fb) for $251 \text{GeV} \leq m_X \leq 1000 \text{GeV}$. Compared to the previous ATLAS result based on 36 fb$^{-1}$ of 13 TeV $pp$ collisions, the present analysis uses a dataset about four times larger, incorporates a categorization based on $m_{b\bar{b}\gamma\gamma}$ and multivariate event selections, and expands the analyzed mass range of the resonance search to lower values. The results improve upon the previous ATLAS limits on the $HH \rightarrow b\bar{b}\gamma\gamma$ production cross section by up to a factor of five, and the allowed $\kappa_3$ range shrinks by about a factor of two. For the resonant search, the expected limit on the cross section improves by a factor of two to three depending on the $m_X$ value. Of those improvements, a factor of two arises from the increase in integrated luminosity, while the additional improvement can be attributed to the use of multivariate techniques, more precise object reconstruction and calibration and, for the nonresonant search, the categorization based on $m_{b\bar{b}\gamma\gamma}$. The present analysis also sets constraints that are tighter than those from a combination of ATLAS searches for $HH$ production in up to 36 fb$^{-1}$ of 13 TeV data.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEIN, Poland; FCT, Portugal; MNE/IFA, Romania; JINR; MES of Russia and NRC KI, Russian Federation; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; D/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; COST, ERC, ERDF, Horizon 2020 and Marie Sklodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/ GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [122].

[1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716, 1 (2012).
[2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716, 30 (2012).
[3] F. Englert and R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons, Phys. Rev. Lett. 13, 321 (1964).
[4] P. W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. 12, 132 (1964).
[5] P. W. Higgs, Broken Symmetries and the Masses of Gauge Bosons, Phys. Rev. Lett. 13, 508 (1964).
[6] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global Conservation Laws and Massless Particles, Phys. Rev. Lett. 13, 585 (1964).

[7] P. W. Higgs, Spontaneous symmetry breakdown without massless bosons, Phys. Rev. 145, 1156 (1966).

[8] T. W. B. Kibble, Symmetry breaking in non-abelian gauge theories, Phys. Rev. 155, 1554 (1967).

[9] P. Huang, A. J. Long, and L.-T. Wang, Probing the electroweak phase transition with Higgs factories and gravitational waves, Phys. Rev. D 94, 075008 (2016).

[10] S. Dawson, S. Dittmaier, and M. Spira, Neutral Higgs-boson pair production at hadron colliders: QCD corrections, Phys. Rev. D 58, 115012 (1998).

[11] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence, Phys. Rev. Lett. 117, 012001 (2016); Erratum, Phys. Rev. Lett. 117, 079901 (2016).

[12] D. de Florian and J. Mazzitelli, Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD, Phys. Rev. Lett. 111, 201801 (2013).

[13] ATLAS and CMS Collaborations, Combined Measurement of the Higgs Boson Mass in pp Collisions at \( \sqrt{s} = 7 \) and 8 TeV with the ATLAS and CMS Experiments, Phys. Rev. Lett. 114, 191803 (2015).

[14] J. Alison, M. Gouzevitch, J. Mazzitelli, and C. Vernieri, Higgs boson potential at colliders: Status and perspectives, Rev. Phys. 5, 100045 (2020).

[15] D. Y. Shao, C. S. Li, H. T. Li, and J. Wang, Threshold resummation effects in Higgs boson pair production at the LHC, J. High Energy Phys. 07 (2013) 169.

[16] D. de Florian and J. Mazzitelli, Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC, J. High Energy Phys. 09 (2015) 053.

[17] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Ronca, and M. Spira, \( gg \to HH \): Combined uncertainties, Phys. Rev. D 103, 056002 (2021).

[18] M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. M. Lindert, and J. Mazzitelli, Higgs boson pair production at NNLO with top quark mass effects, J. High Energy Phys. 05 (2018) 059.

[19] R. Frederix, S. Frixiogeneous, H. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, and M. Zaro, Higgs pair production at the LHC with NLO and parton-shower effects, Phys. Lett. B 732, 142 (2014).

[20] G. D. Kribs and A. Martin, Enhanced di-Higgs production through light colored scalars, Phys. Rev. D 86, 095023 (2012).

[21] L. Di Luzio, R. Gröber, and M. Spannowsky, Maxi-sizing the trilinear Higgs self-coupling: How large could it be?, Eur. Phys. J. C 77, 788 (2017).

[22] G. D. Kribs, A. Maier, H. Rzehak, M. Spannowsky, and P. Waite, Electroweak oblique parameters as a probe of the trilinear Higgs boson self-interaction, Phys. Rev. D 95, 093004 (2017).

[23] T. D. Lee, A theory of spontaneous T violation, Phys. Rev. D 8, 1226 (1973).

[24] S. Dimopoulos and H. Georgi, Softly broken supersymmetry and SU(5), Nucl. Phys. B193, 150 (1981).

[25] Z. Chacko, Y. Nomura, M. Papucci, and G. Perez, Natural little hierarchy from a partially goldstone twin Higgs, J. High Energy Phys. 01 (2006) 126.

[26] J. Mrazek, A. Pomarol, R. Rattazzi, M. Redi, J. Serra, and A. Wulzer, The other natural two Higgs doublet model, Nucl. Phys. B853, 1 (2011).

[27] L. Randall and R. Sundrum, Large Mass Hierarchy from a Small Extra Dimension, Phys. Rev. Lett. 83, 3370 (1999).

[28] ATLAS Collaboration, Search for Higgs boson pair production in the \( \gamma\gamma b \bar{b} \) final state with 13 TeV \( pp \) collision data collected by the ATLAS experiment, J. High Energy Phys. 11 (2018) 040.

[29] ATLAS Collaboration, Combination of searches for Higgs boson pairs in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector, Phys. Lett. B 800, 135103 (2020).

[30] CMS Collaboration, Search for nonresonant Higgs boson pair production in final states with two bottom quarks and two photons in proton–proton collisions at \( \sqrt{s} = 13 \) TeV, J. High Energy Phys. 03 (2021) 257.

[31] CMS Collaboration, Search for Higgs boson pair production in the \( \gamma\gamma b \bar{b} \) final state in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV, Phys. Lett. B 788, 7 (2019).

[32] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. 3, S08003 (2008).

[33] ATLAS Collaboration, ATLAS insertable B-layer: Technical design report, Reports No. ATLAS-TDR-19, No. CERN-LHCC-2010-013, 2010, https://cds.cern.ch/record/1291633; Addendum, Reports No. ATLAS-TDR-19-ADD-1, No. CERN-LHCC-2012-009, 2012, https://cds.cern.ch/record/1451888.

[34] B. Abbott et al., Production and integration of the ATLAS Insertable B-Layer, J. Instrum. 13, T05008 (2018).

[35] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, Eur. Phys. J. C 77, 317 (2017).

[36] ATLAS Collaboration, The ATLAS Collaboration software and firmware, Report No. ATL-REPORT-2018-001, 2018, https://cds.cern.ch/record/2767187.

[37] ATLAS Collaboration, ATLAS data quality operations and performance for 2015–2018 data-taking, J. Instrum. 15, P04003 (2020).

[38] G. Avoni et al., The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, J. Instrum. 13, P07017 (2018).

[39] ATLAS Collaboration, Luminosity determination in pp collisions at \( \sqrt{s} = 13 \) TeV using the ATLAS detector at the LHC, Report No. ATLAS-CONF-2019-021, 2019, https://cds.cern.ch/record/2677054.

[40] ATLAS Collaboration, Emulating the impact of additional proton–proton interactions in the ATLAS simulation by pre-sampling sets of inelastic Monte Carlo events, Comput. Softw. Big Sci. 6, 3 (2022).

[41] P. Nason and C. Olea, NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG, J. High Energy Phys. 02 (2010) 037.

[42] G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni, and E. Vryonidou, NLO predictions for Higgs boson pair production with full top quark mass dependence matched to parton showers, J. High Energy Phys. 08 (2017) 088.

[43] G. Heinrich, S. Jones, M. Kerner, G. Luisoni, and L. Scyboz, Probing the trilinear Higgs boson coupling in di-
Higgs production at NLO QCD including parton shower effects, J. High Energy Phys. 06 (2019) 066.

J. Butterworth et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43, 032001 (2016).

ATLAS Collaboration, Validation of signal Monte Carlo event generation in searches for Higgs boson pairs with the ATLAS detector, Report No. ATL-PHYS-PUB-2019-007, 2019, https://cds.cern.ch/record/2665057.

L.-S. Ling, R.-Y. Zhang, W.-G. Ma, L. Guo, W.-H. Li, and F. A. Dreyer and A. Karlberg, Fully differential vector-boson fusion Higgs production via vector boson fusion at hadron colliders, J. High Energy Phys. 07 (2014) 079.

F. Bishara, R. Contino, and J. Rojo, Higgs pair production in vector-boson fusion at the LHC and beyond, Eur. Phys. J. C 77, 481 (2017).

R. D. Ball et al., Parton distributions with LHC data, Nucl. Phys. B867, 244 (2013).

L.-S. Ling, R.-Y. Zhang, W.-G. Ma, L. Guo, W.-H. Li, and X.-Z. Li et al., NNLO QCD corrections to Higgs pair production via vector boson fusion at hadron colliders, Phys. Rev. D 89, 073001 (2014).

F. A. Dreyer and A. Karlberg, Vector-boson fusion Higgs pair production at N3LO, Phys. Rev. D 98, 114016 (2018).

F. A. Dreyer and A. Karlberg, Fully differential vector-boson fusion Higgs pair production at next-to-next-to-leading order, Phys. Rev. D 99, 074028 (2019).

M. Bähr et al., HERWIG++ physics and manual, Eur. Phys. J. C 58, 639 (2008).

J. Bellm et al., HERWIG 7.0/HERWIG++ 3.0 release note, Eur. Phys. J. C 76, 196 (2016).

ATLAS Collaboration, Combined measurements of Higgs boson production and decay using up to 80 fb$^{-1}$ of proton–proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment, Phys. Rev. D 101, 012002 (2020).

D. de Florian et al., Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, arXiv:1610.07922.

A. Djouadi, J. Kalinowski, and M. Spira, HDECAY: A program for Higgs boson decays in the standard model and its supersymmetric extension, Comput. Phys. Commun. 108, 56 (1998).

E. Bothmann et al., Event generation with SHERPA 2.2, SciPost Phys. 7, 034 (2019).

T. Gleisberg and S. Höche, Comix, a new matrix element generator, J. High Energy Phys. 12 (2008) 039.

F. Bucchioni, J.-N. Lang, J. M. Lindert, P. Maierhöfer, S. Pozzorini, H. Zhang, and M. F. Zoller et al., OPENLOOPS2, Eur. Phys. J. C 79, 866 (2019).

F. Cascioli, P. Maierhöfer, and S. Pozzorini, Scattering Amplitudes with Open Loops, Phys. Rev. Lett. 108, 111601 (2012).

A. Denner, S. Dittmaier, and L. Hofer, Collier: A fortran-based complex one-loop library in extended regularizations, Comput. Phys. Commun. 212, 220 (2017).

S. Schumann and F. Krauss, A parton shower algorithm based on Catani–Seymour dipole factorisation, J. High Energy Phys. 03 (2008) 038.

S. Höche, F. Krauss, M. Schönherr, and F. Siegert, A critical appraisal of NLO + PS matching methods, J. High Energy Phys. 09 (2012) 049.

S. Höche, F. Krauss, M. Schönherr, and F. Siegert, QCD matrix elements + parton showers. The NLO case, J. High Energy Phys. 04 (2013) 027.

F. Siegert, A practical guide to event generation for prompt photon production with SHERPA, J. Phys. G 44, 044007 (2017).

T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Iten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA8.2, Comput. Phys. Commun. 191, 159 (2015).

ATLAS Collaboration, ATLAS PYTHIA8 tunes to 7 TeV data, Report No. ATL-PHYS-PUB-2014-021, 2014, https://cds.cern.ch/record/1966419.

R. D. Ball et al., Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040.

S. Gieseke, C. Rühr, and A. Siodmok, Colour reconnections in HERWIG++, Eur. Phys. J. C 72, 2225 (2012).

K. Hamilton, P. Nason, and G. Zanderighi, MINLO: multiscale improved NLO, J. High Energy Phys. 10 (2012) 155.

J. M. Campbell, R. Keith Ellis, R. Frederix, P. Nason, C. Oleari, and C. Williams, NLO Higgs boson production plus one and two jets using the POWHEG BOX, MadGraph4 and MCFM, J. High Energy Phys. 07 (2012) 092.

K. Hamilton, P. Nason, C. Oleari, and G. Zanderighi, Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching, J. High Energy Phys. 05 (2013) 082.

G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC, Nucl. Phys. B737, 73 (2006).

D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC, J. High Energy Phys. 11 (2011) 064.

ATLAS Collaboration, Measurement of the $Z/\gamma^*\rightarrow b\bar{b}$ boson transverse momentum distribution in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2014) 145.

K. Hamilton, P. Nason, E. Re, and G. Zanderighi, NNLOPS simulation of Higgs boson production, J. High Energy Phys. 10 (2013) 222.

P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040.

S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070.

S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, J. High Energy Phys. 06 (2010) 043.

K. Minasov, V. Sanz, and C. Williams, Higher order QCD predictions for associated Higgs production with
anomalous couplings to gauge bosons, J. High Energy Phys. 08 (2016) 039.

[82] G. Lisi, P. Nason, C. Olea, and F. Tramontano, $HVV^\pm/Hz$ + 1 jet at NLO with the POWHEG box interfaced to GoSam and their merging within MiNLO, J. High Energy Phys. 10 (2013) 083.

[83] H.B. Hartanto, B. Jäger, L. Reina, and D. Wackeroth, Higgs boson production in association with top quarks in the POWHEG box, Phys. Rev. D 91, 094003 (2015).

[84] S. Frixione, G. Ridolfi, and P. Nason, A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction, J. High Energy Phys. 09 (2007) 126.

[85] ATLAS Collaboration, ThePYTHIA8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, Report No. ATL-PHYS-PUB-2016-017, 2016, https://cds.cern.ch/record/2206965.

[86] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C 70, 823 (2010).

[87] S. Agostinelli et al. (GEANT4 Collaboration), GEANT 4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).

[88] ATLAS Collaboration, The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim, Report No. ATL-PHYS-PUB-2010-013, 2010, http://cdsweb.cern.ch/record/1300517.

[89] ATLAS Collaboration, Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach, Report No. ATLAS-PHYS-PUB-2017-022, 2017, https://cds.cern.ch/record/2298955.

[90] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, J. Instrum. 14, P12006 (2019).

[91] ATLAS Collaboration, Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys. Rev. D 90, 112015 (2014).

[92] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 76, 292 (2016).

[93] ATLAS Collaboration, Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 81, 578 (2021).

[94] ATLAS Collaboration, Jet reconstruction and performance using particle flow with the ATLAS Detector, Eur. Phys. J. C 77, 466 (2017).

[95] M. Cacciari, G.P. Salam, and G. Soyez, Fastjet user manual, Eur. Phys. J. C 72, 1896 (2012).

[96] M. Cacciari, G.P. Salam, and G. Soyez, The anti-$k_t$ jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[97] ATLAS Collaboration, Tagging and suppression of pileup jets with the ATLAS detector, Report No. ATLAS-CONF-2014-018, 2014, https://cds.cern.ch/record/1700870.

[98] ATLAS Collaboration, ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$, Eur. Phys. J. C 79, 970 (2019).

[99] ATLAS Collaboration, Identification of jets containing b-hadrons with recurrent neural networks at the ATLAS experiment, Report No. ATL-PHYS-PUB-2017-003, 2017, https://cds.cern.ch/record/2255226.

[100] ATLAS Collaboration, Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017–18 LHC run, Report No. ATL-PHYS-PUB-2017-013, 2017, https://cds.cern.ch/record/2273281.

[101] ATLAS Collaboration, Performance of b-jet identification in the ATLAS experiment, J. Instrum. 11, P04008 (2016).

[102] ATLAS Collaboration, Evidence for the $H \rightarrow bb$ decay with the ATLAS detector, J. High Energy Phys. 12 (2017) 024.

[103] ATLAS Collaboration, Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 78, 903 (2018).

[104] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, Eur. Phys. J. C 80, 47 (2020).

[105] ATLAS Collaboration, Search for pair production of Higgs bosons in the $bbbb$ final state using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2019) 030.

[106] T. Chen and C. Guestrin, XGBoost: A scalable tree boosting system, KDD ’16: Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (2016), pp. 785–794, arXiv: 1603.02754.

[107] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71, 1554 (2011); Erratum, Eur. Phys. J. C 73, 2501 (2013).

[108] A. Hocker et al., TMVA—Toolkit for multivariate data analysis, arXiv:physics/0703039.

[109] ATLAS Collaboration, Measurement of isolated-photon pair production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2013) 086.

[110] M. Oreglia, A study of the reactions $\nu^\prime \rightarrow \gamma\gamma\nu$, https://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-236.pdf.

[111] ATLAS Collaboration, Recommendations for the modeling of smooth backgrounds, Report No. ATLAS-PHYS-PUB-2020-028, 2020, https://cds.cern.ch/record/2743717.

[112] A. Wald, Sequential tests of statistical hypotheses, Ann. Math. Stat. 16, 117 (1945).

[113] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, Eur. Phys. J. C 80, 47 (2020).

[114] ATLAS Collaboration, Search for resonances in diphoton events at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2016) 001.

[115] ATLAS Collaboration, Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C 81, 689 (2020).

[116] ATLAS Collaboration, Measurement of b-tagging efficiency of c+jets in $t\bar{t}$ events using a likelihood approach with the ATLAS detector, Report No. ATLAS-CONF-2018-001, 2018, https://cds.cern.ch/record/2306649.

[117] ATLAS Collaboration, Calibration of light-flavour b-jet mistagging rates using ATLAS proton–proton collision data at $\sqrt{s} = 13$ TeV, Report No. ATLAS-CONF-2018-006, 2018, https://cds.cern.ch/record/2314418.
[118] ATLAS Collaboration, Measurements of inclusive and differential fiducial cross-sections of $t\bar{t}$ production with additional heavy-flavour jets in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 04 (2019) 046.

[119] ATLAS Collaboration, Study of heavy-flavor quarks produced in association with top quark pairs at $\sqrt{s} = 7$ TeV using the ATLAS detector, Phys. Rev. D 89, 072012 (2014).

[120] ATLAS Collaboration, Measurement of the cross-section for W boson production in association with b-jets in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 06 (2013) 084.

[121] A. L. Read, Presentation of search results: The CLS technique, J. Phys. G 28, 2693 (2002).

[122] ATLAS Collaboration, ATLAS computing acknowledgements, Report No. ATL-SOFT-PUB-2021-003, https://cds.cern.ch/record/2776662.
SEARCH FOR HIGGS BOSON PAIR PRODUCTION IN THE TWO … PHYS. REV. D 106, 052001 (2022)
A. M. Zaitsev, T. Zakareishvili, N. Zakharchuk, S. Zambito, D. Zanzi, S. V. Zeißen, C. Zeitnitz, G. Zemaityte, J. C. Zeng, O. Zenin, T. Ženiš, S. Zenz, S. Zerradi, D. Zerwas, M. Zgubič, B. Zhang, D. F. Zhang, G. Zhang, J. Zhang, K. Zhang, L. Zhang, M. Zhang, R. Zhang, X. Zhang, X. Zhao, Y. Zhao, A. Zhemchugov, Z. Zheng, D. Zhong, B. Zhou, D. Zhong, H. Zhou, N. Zhou, Y. Zhou, C. Zhu, X. Zhuang, K. Zhukov, V. Zhulanov, D. Ziembinska, N. I. Zimine, S. Zimmermann, M. Ziolkowski, L. Živković, A. Zoccoli, K. Zoch, T. G. Zorbas, O. Zormpa, W. Zou, and L. Zwalinski (ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Department of Physics, University of Alberta, Edmonton, Alberta, Canada
3aDepartment of Physics, Ankara University, Ankara, Turkey
3bIstanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey
3cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
5High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
6Department of Physics, University of Arizona, Tucson, Arizona, USA
7Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
8Physics Department, National and Kapodistrian University of Athens, Athens, Greece
9Physics Department, National Technical University of Athens, Zografou, Greece
10Department of Physics, University of Texas at Austin, Austin, Texas, USA
11Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
11bIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
11cDepartment of Physics, Bogazici University, Istanbul, Turkey
11dDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
12Institut de Física d’Altes Energies (IAFE), Barcelona Institute of Science and Technology, Barcelona, Spain
13aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
13bPhysics Department, Tsinghua University, Beijing, China
13cDepartment of Physics, Nanjing University, Nanjing, China
13dUniversity of Chinese Academy of Science (UCAS), Beijing, China
14Department of Physics, University of Belgrade, Belgrade, Serbia
15Department for Physics and Technology, University of Bergen, Bergen, Norway
16Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
17Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
18Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20aFacultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia
20bDepartamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
21aDipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy
21bINFN Sezione di Bologna, Italy
22Physikalisches Institut, Universität Bonn, Bonn, Germany
23Department of Physics, Boston University, Boston, Massachusetts, USA
24Department of Physics, Brandeis University, Waltham, Massachusetts, USA
25aTransilvania University of Brasov, Brasov, Romania
25bHoria Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25cDepartment of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
25dNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
25eUniversity Politehnica Bucharest, Bucharest, Romania
26aWest University in Timisoara, Timisoara, Romania
26bFaculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
26cDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
27Physics Department, Brookhaven National Laboratory, Upton, New York, USA
28 Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
29 California State University, California, USA
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31a Department of Physics, University of Cape Town, Cape Town, South Africa
31b iThemba Labs, Western Cape, South Africa
31c Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
31d National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
31e University of South Africa, Department of Physics, Pretoria, South Africa
31f School of Physics, University of the Witwatersrand, Johannesburg, South Africa
31g Department of Physics, Carleton University, Ottawa, Ontario, Canada
31h Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
31i Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
31j Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
31k LPMP, Faculté des Sciences, Université Mohammed V, Rabat, Morocco
31l CERN, Geneva, Switzerland
32 Department of Physics, Carleton University, Ottawa, Ontario, Canada
33a Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
33b Faculté des Sciences, Université Mohammed Premier, Oujda, Morocco
33c Faculté des sciences, Université Mohammed V, Rabat, Morocco
33d LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
33e Nevis Laboratory, Columbia University, Irvington, New York, USA
33f Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
33g Dipartimento di Fisica, Università della Calabria, Rende, Italy
33h INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
33i Physics Department, Southern Methodist University, Dallas, Texas, USA
33j Physics Department, University of Texas at Dallas, Richardson, Texas, USA
33k National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
33l Department of Physics, Stockholm University, Sweden
33m Oskar Klein Centre, Stockholm, Sweden
33n Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
33o Institut für Kern- und Teilchenphysik, Technische Universität Dortmund, Dortmund, Germany
33p Department of Physics, Duke University, Durham, North Carolina, USA
34 SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
34a INFN e Laboratori Nazionali di Frascati, Frascati, Italy
35 Physicalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
35a II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
35b Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
35c Dipartimento di Fisica, Università di Genova, Genova, Italy
35d INFN Sezione di Genova, Italy
35e II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
36 SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
36a LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
36b Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
36c Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
36d Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
36e School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
36f Tsung-Dao Lee Institute, Shanghai, China
36g Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
36h Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
36i Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
36j Department of Physics, University of Hong Kong, Hong Kong, China
37 Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
38 Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
38a IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
