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Letter

Search for pair production of boosted Higgs bosons via vector-boson fusion in the $b\bar{b}b\bar{b}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

A search for Higgs boson pair production via vector-boson fusion is performed in the Lorentz-boosted regime, where a Higgs boson candidate is reconstructed as a single large-radius jet, using 140 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Only Higgs boson decays into bottom quark pairs are considered. The search is particularly sensitive to the quartic coupling between two vector bosons and two Higgs bosons relative to its Standard Model prediction, κ_{2V}. This study constrains κ_{2V} to $0.55 < \kappa_{2V} < 1.49$ at the 95% confidence level. The value $\kappa_{2V} = 0$ is excluded with a significance of 3.8 standard deviations with other Higgs boson couplings fixed to their Standard Model values. A search for new heavy spin-0 resonances that would mediate Higgs boson pair production via vector-boson fusion is carried out in the mass range of 1–5 TeV for the first time under several model and decay-width assumptions. No significant deviation from the Standard Model hypothesis is observed and exclusion limits at the 95% confidence level are derived.

1. Introduction

The discovery of a 125 GeV Higgs boson (H) [1,2] by the ATLAS [3] and CMS [4] Collaborations at the Large Hadron Collider (LHC) [5] has led to an extensive research programme aimed at measuring its properties, including spin and parity [6–12], natural width [7,13–15], and couplings with other elementary particles [16–18]. All measurements to date are consistent with the predictions from the Standard Model (SM) [19–24]. However, certain properties, such as quartic couplings (g_{HHVV}) with vector bosons ($V = W, Z$) and the trilinear self-coupling of the Higgs boson (λ_{HHH}), remain unmeasured. In the SM, the former are related to the HVV couplings through the relation $g^{\mathrm{SM}}_{HHVV} = g^{\mathrm{SM}}_{HVV}/v$, and the latter is predicted to be $\lambda^{\mathrm{SM}}_{HHH} = m_H^2/2v^2$, where m_H is the Higgs boson mass and v is the vacuum expectation value of the Higgs field. Measuring if these relations are consistent with observed data will fundamentally deepen our understanding of the Higgs mechanism.

At the LHC, the coupling modifiers $\kappa_{2V} = g_{HHVV}/g^{\mathrm{SM}}_{HHVV}$ and $\kappa_\lambda = \lambda_{HHH}/\lambda^{\mathrm{SM}}_{HHH}$ are studied via the production of Higgs boson pairs (HH production). In the SM, the main nonresonant HH production modes are via the gluon–gluon fusion process (ggF), with a cross-section of $\sigma^{\mathrm{SM}}_{\mathrm{ggF}} = 31.1^{+2.1}_{-7.2}$ fb at next-to-next-to-leading order in QCD and including an approximation of finite top-quark-mass effects [25–35], and via the vector-boson fusion process (VBF), with a cross-section of $\sigma^{\mathrm{SM}}_{\mathrm{VBF}} = 1.73 \pm 0.04$ fb at next-to-next-to-next-to-leading order in QCD [36–38]. The VBF production cross-section depends critically on the value of κ_{2V} due to destructive interference between Figs. 1(d) and 1(e). For example, a value of $\kappa_{2V} = 0$ leads to a cross-section that is over 15 times the SM prediction. The Higgs bosons produced in non-SM κ_{2V} scenarios are expected to be more energetic and more central in the detector on average relative to the SM $\kappa_{2V} = 1$ scenario [39], resulting in higher acceptances and selection efficiencies in this study. The leading-order Feynman diagrams of the ggF and VBF HH processes are shown in Figs. 1(a) to 1(e). In the SM, the processes depicted in Figs. 1(a) and 1(b) interfere destructively. Other coupling modifiers involved in these processes are of less interest in this analysis. The ggF HH production mode is sensitive to κ_λ while the VBF HH production mode is sensitive to both κ_λ and κ_{2V}. Heavy resonances (X) beyond the SM may contribute to resonant HH production [40,41], as exemplified via the VBF process in Fig. 1(f). The boosted VBF process provides a distinct signature for investigating these resonances, allowing exploration of uncharted phase space. These HH processes were studied with various decay final states by ATLAS and CMS, including $b\bar{b}b\bar{b}$ [42–47], $b\bar{b}\gamma\gamma$ [48–50], $b\bar{b}\tau^+\tau^-$ [51–54], $b\bar{b}WW^*$ [55], $\gamma\gamma WW^*$ [56], WW^*WW^* [57], $b\bar{b}\ell\ell\ell\ell$ [58], $b\bar{b}\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ [59], and their statistical combinations [18,60,61]. No significant excess over the SM background has been observed to date. The most stringent observed (expected) 95%

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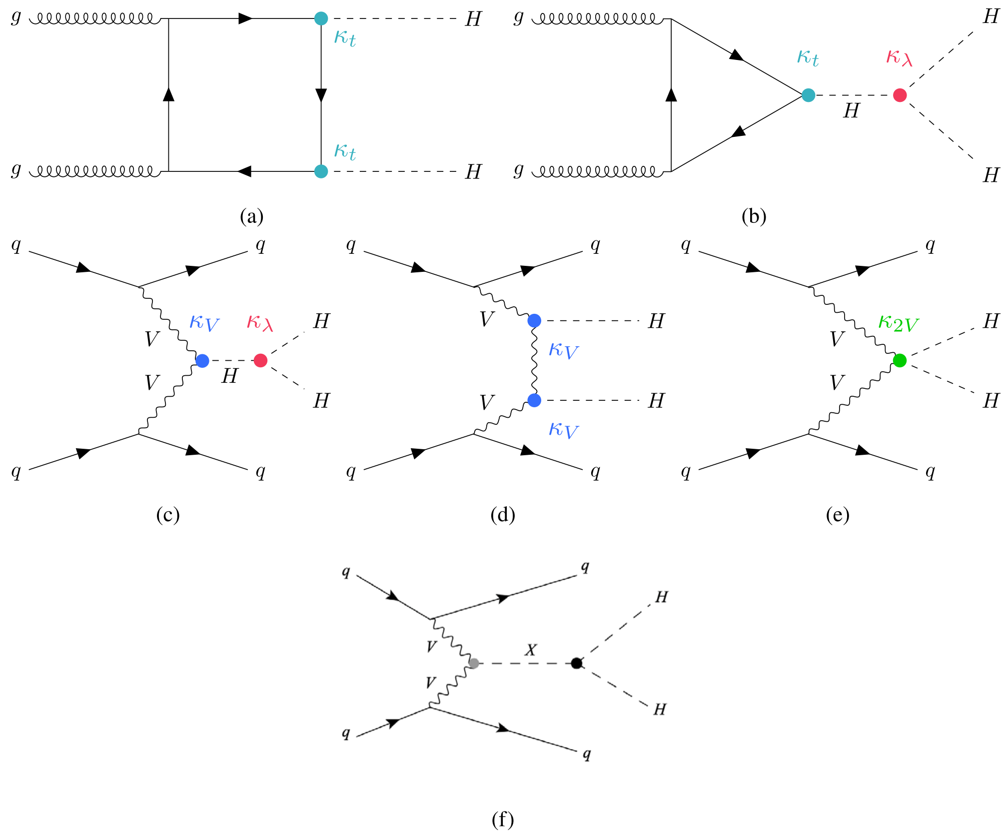


Fig. 1. Examples of leading-order Feynman diagrams for Higgs boson pair production. For nonresonant ggF production, diagram (a) involves solely the top-quark Yukawa coupling, while diagram (b) involves the Higgs boson self-coupling. For nonresonant VBF production, diagram (c) involves the self-coupling, diagram (d) involves solely the coupling to vector bosons, and diagram (e) involves the coupling between two Higgs bosons and two vector bosons. Diagram (f) illustrates the resonant production mode.

confidence level (CL) interval for the κ_{2V} coupling modifier was found to be $0.62 < \kappa_{2V} < 1.41$ ($0.66 < \kappa_{2V} < 1.37$) by searching for nonresonant pair production of highly energetic Higgs bosons decaying into bottom quarks by the CMS Collaboration [47]. In Ref. [43], resonant VBF HH production in the mass range of 260–1000 GeV and non-resonant VBF HH production in the non-boosted regime are searched for and no deviations from the background-only hypothesis are observed.

This paper reports a search for nonresonant and resonant VBF $HH \rightarrow b\bar{b}b\bar{b}$ production using the full Run 2 ATLAS proton–proton (pp) collision data sample with an integrated luminosity of 140 fb^{-1}. The search focuses on a Lorentz-boosted topology, where two high-energy Higgs bosons each form a large-radius jet, referred to as a large-R jet. This topology is particularly sensitive to non-SM values of κ_{2V}, and as such one of the goals of this analysis is to constrain κ_{2V}. Assuming the SM branching ratio of 58.2% for $H \rightarrow b\bar{b}$ [30,62], approximately one third of HH events lead to a $b\bar{b}b\bar{b}$ final state, making it the most abundant HH final state. A machine learning-based double b-tagging technique [63,64] uses the information from the large-R jets and their constituents to identify $H \rightarrow b\bar{b}$ decays. The VBF signature is characterised by the presence of VBF jets that are defined as two small-R jets with large invariant mass and rapidity separation. This signature provides an effective handle for background suppression. To maximise the sensitivity to the κ_{2V} parameter, the nonresonant analysis is combined with the resolved analysis [45] where the four b-quarks are reconstructed as small-R jets. The Higgs bosons considered in the resolved analysis have lower transverse momentum (p_{T}) compared to those in this boosted search. To avoid double counting events in the boosted nonresonant analysis presented in this paper, events that satisfy the resolved and boosted analysis selection are removed from the boosted analysis. For the first time, a search for a new heavy spin-0 resonance that would mediate VBF Higgs boson pair production is carried out in the mass range of 1–5 TeV.

The paper is structured as follows. Section 2 briefly introduces the ATLAS detector. Section 3 details the data and simulation samples used. Section 4 describes the analysis selection. Section 5 explains the background estimate derived from data, and Section 6 covers the multivariate discriminants used. Systematic uncertainties considered are detailed in Section 7. Results are provided in Section 8, and conclusions are given in Section 9.

2. The ATLAS experiment

The ATLAS experiment [3] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) en-

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z c}{E-p_z c}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

ergy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [65] detector, which is located close to the beampipe. A two-level trigger system is used to select events [66]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [67] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Data and simulation

The analysis is performed using Run 2 ATLAS *pp* collision data collected between 2015 and 2018. The average number of interactions per proton bunch crossing (pile-up) is between 13 and 38 interactions, depending on the year [68]. After applying ATLAS data quality requirements [69], the data corresponds to an integrated luminosity of 140 fb^{-1}.

Monte Carlo (MC) simulation is used for the modelling of *HH* processes, top-quark pair production ($t\bar{t}$) and multijet background processes. The $t\bar{t}$ and multijet samples are used solely for event selection optimisation and are identical to those used in Ref. [45]. The final background estimate is obtained through data-driven techniques and described in Section 5. For all *HH* samples, the Higgs boson mass is fixed to 125 GeV. All samples are processed using the ATLAS simulation framework [70] where the detector response is simulated with GEANT4 [71]. The VBF *HH* samples are simulated using MADGRAPH 2.7.3 [72] at leading-order (LO) in quantum chromodynamics (QCD) with the NNPDF3.0NLO parton distribution function (PDF) set [73]. Samples with coupling modifier values $(\kappa_\lambda, \kappa_{2V}, \kappa_V) = (1,1,1)$, $(1,1.5,1)$, $(2,1,1)$, $(10,1,1)$, $(1,1,0.5)$, $(-5,1,0.5)$, $(0,1,1)$, $(1,0,1)$, and $(1,3,1)$ are explicitly generated and a linear combination [45] of the first six of the listed samples is used to determine the expected yields and distributions for any value of $(\kappa_\lambda, \kappa_{2V}, \kappa_V)$. The method is validated using the remaining simulated samples and good agreement is observed. The SM ggF *HH* samples are simulated using the POWHEG BOX v2 generator [74–76] at next-to-leading-order (NLO) in QCD, including finite top-quark-mass effects, using the PDF4LHC15 [77] PDF set. A reweighting technique based on the particle-level invariant mass m_{HH} of the Higgs boson pair is applied to the $\kappa_\lambda = 1$ sample to determine the ggF *HH* yield and kinematic distributions for any value of κ_λ [78]. The ggF *HH* samples are considered as background processes when constraining κ_{2V} and as signal processes when deriving the results related to κ_λ.

The hypothetical heavy spin-0 resonance X that would mediate VBF HH, $pp \to X + jj \to HH + jj$, is simulated using the MADGRAPH5_AMC@NLO 2.6.1 [72] generator at LO in QCD with the NNPDF2.3LO [79] PDF set. The branching ratio of $X \to HH$ is set to 100%. Two resonance-width hypotheses are considered, where the resonance width is denoted by Γ_X: a generic narrow-width signal (Γ_X smaller than the detector resolution of 5–6% of the resonance mass) and a broad-width signal ($\Gamma_X = 20\%$ of the resonance mass) based on the Composite Higgs model [80]. These samples cover a range of resonance masses, denoted by m_X, from 1 TeV to 5 TeV, with increased spacing between the higher mass points and a different number of points between the narrow- and broad-width assumptions. For all resonant and non-resonant *HH* samples, parton showers and hadronisation are simulated using PYTHIA 8.244 [81] with the A14 set of tuned parameters [82] and the NNPDF2.3LO PDF set. EVTGEN 1.7.0 [83] is used to model the properties of heavy-flavour decays. The effects of pile-up are modelled by superimposing each simulated hard-scattering event with inelastic *pp* events simulated using PYTHIA 8.186 [84] with the NNPDF2.3LO PDF set and the A3 set of tuned parameters [85], and is weighted to match the observed pile-up in data.

4. Event selection

Events must satisfy trigger decisions that require minimum transverse energies of the triggered large-R jet. The threshold varies between 360–420 GeV, depending on the year of data taking [66,86,87]. Events are required to contain two Higgs boson candidates and two VBF jets. A Higgs boson candidate is reconstructed as a large-R jet, denoted by J, using the anti-k_t algorithm [88,89] with the radius parameter $R = 1.0$. The large-R jets are reconstructed from topological energy depositions [90] in the calorimeter and are trimmed [91,92] to improve the jet mass resolution and to mitigate the effects of pile-up and soft radiation. A method similar to the one used in Ref. [45] is used to correct the four-momentum of large-R jets by accounting for energy lost to soft out-of-cone radiation and to muons and neutrinos in semileptonic b-hadron decays. This correction improves the jet mass resolution. The mass of a large-R jet (m_J) is calculated using a combination of calorimeter and tracking information [93] to improve the resolution over the whole range of jet p_{T}. The large-R jets must satisfy 250 GeV $< p_{\mathrm{T}} <$ 3000 GeV, $|\eta| < 2.0$ and 50 GeV $< m_J <$ 600 GeV, corresponding to the region where the jet calibration is valid. The two leading p_{T} large-R jets are considered as the Higgs boson candidates, and the leading jet p_{T} criterion is raised to $p_{\mathrm{T}} > 450$ GeV to ensure that the online trigger is fully efficient. The leading (H_1) and sub-leading (H_2) Higgs boson candidates are ordered by their p_{T}. A double b-tagging algorithm based on a deep neural network [63,64] is applied to the large-R jets to identify $H \to b\bar{b}$ decays. The algorithm is trained on large-R jets with masses above 50 GeV and calibrated using a $Z \to b\bar{b}$ control sample in four p_{T}^J regions. When neglecting systematic uncertainties, compared to using variable-radius track-jet b-tagging [94,95], the algorithm provides a sensitivity improvement of up to 50% in expected discovery significance for the $H \to b\bar{b}$ analysis [96]. Events with two Higgs boson candidates satisfying the 60% efficiency working point are referred to as 2PASS events. This working point reduces multijet (top-quark) events by a factor of 92 (31). Events with only one Higgs boson candidate satisfying the 60% efficiency working point are referred to as 1PASS and are used for background estimation. The small-R jets, denoted by j, are reconstructed from particle-flow objects [97] using the anti-k_t algorithm with $R = 0.4$. The jet energy (E) is corrected by applying *in situ* corrections that reduce the contribution from pile-up jets [98]. The small-R jets must have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.5$, and those with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ must satisfy a requirement based on the output of the multivariate jet vertex tagger algorithm [99] to reduce the effect from pile-up. To remove overlap with the Higgs boson candidates, the distance between a small-R jet and the selected Higgs boson candidates must satisfy $\Delta R(J, j) > 1.4$. The two leading p_{T} small-R jets are assigned as VBF jets and required to satisfy the criteria $|\Delta\eta(j,j)| > 3$ and $m_{jj} > 1$ TeV.

After the preselections described above, 1PASS and 2PASS events are separately classified into signal regions (SRs), validation regions (VRs), and control regions (CRs) according to the following criteria defined in the m_{H_1}–m_{H_2} plane. The SR, VR, and CR are disjoint by construction such that there is no overlap between them. Events in the SR reside in the region defined by

$$\sqrt{\left(\frac{m_{H_1} - 124\ \mathrm{GeV}}{1500\ \mathrm{GeV}/m_{H_1}}\right)^2 + \left(\frac{m_{H_2} - 117\ \mathrm{GeV}}{1900\ \mathrm{GeV}/m_{H_2}}\right)^2} < 1.6\ \mathrm{GeV}. \quad (1)$$

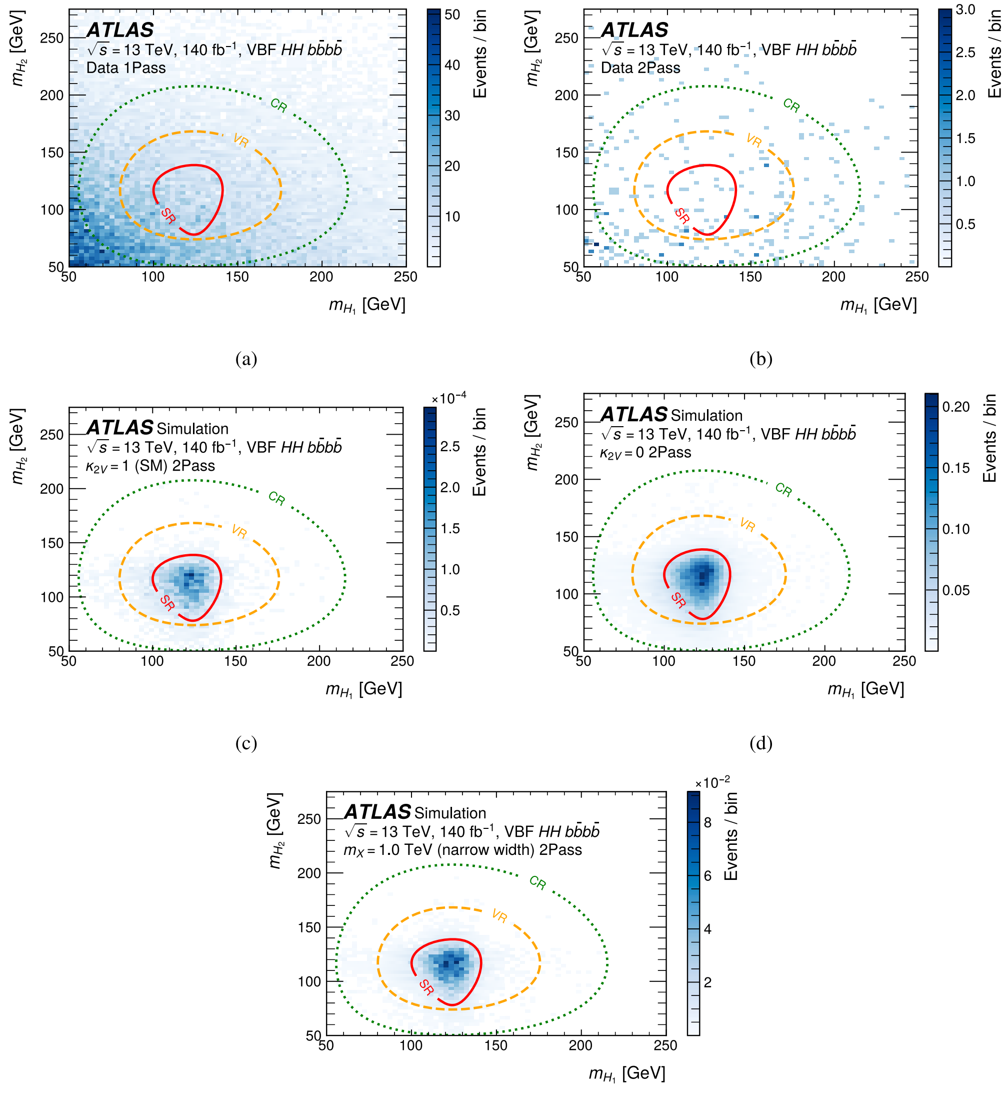


Fig. 2. The mass planes of the reconstructed Higgs boson candidates for the (a) 1Pass and (b) 2Pass selections of the analysis, shown for the data events. The mass planes for the 2Pass selection of the analysis are shown for the (c) VBF SM $\kappa_{2V} = 1$ HH, (d) VBF $\kappa_{2V} = 0$ HH, and (e) $m_X = 1$ TeV spin-0 narrow-width resonance HH samples. The continuous red line describes the Signal Region (SR). The Validation Region (VR) lies between the dashed yellow line and the continuous red line. The Control Region (CR) lies between the dotted green line and the dashed yellow line. The bin sizes are 1.33 GeV by 1.33 GeV.

Events in the VR reside in the region bounded by the SR boundary and

$$\sqrt{\left(\frac{m_{H_1} - 124\text{ GeV}}{0.1\ln(m_{H_1})}\right)^2 + \left(\frac{m_{H_2} - 117\text{ GeV}}{0.1\ln(m_{H_2})}\right)^2} < 100\text{ GeV}, \tag{2}$$

and events in the CR reside in the region bounded by the VR outer boundary and

$$\sqrt{\left(\frac{m_{H_1} - 124\text{ GeV}}{0.1\ln(m_{H_1})}\right)^2 + \left(\frac{m_{H_2} - 117\text{ GeV}}{0.1\ln(m_{H_2})}\right)^2} < 170\text{ GeV}. \tag{3}$$

The variables m_{H_1} and m_{H_2} in these equations are in units of GeV. The values of 124 GeV and 117 GeV in Eqs. (1)–(3) are chosen such that they correspond to the centres of the m_{H_1} and m_{H_2} distributions of the VBF HH events from simulation. These centres deviate from the measured Higgs boson mass of 125 GeV due to detector effects, and energy lost to neutrinos from the b-hadron decays and to out-of-cone radiation. The SR definition is optimised to maximise the overall $S/\sqrt{B}$. The signal S is the yield of $\kappa_{2V} = 0$ VBF HH events in simulation which is chosen to maximise the sensitivity to the κ_{2V} coupling as it is a representative proxy for non-SM κ_{2V} samples. The background B is the expected number of background events estimated by using the $t\bar{t}$ and multijet simulated samples. As multijet background processes preferentially populate the m_{H_1}–m_{H_2} plane in the lower Higgs boson candidate mass region compared to HH processes, Eqs. (2) and (3) help reduce contributions from multijet events. The boundaries of the SR, VR, and CR in the reconstructed m_{H_1}–m_{H_2} plane are shown in Fig. 2 for the 1Pass and 2Pass selections of the analysis. The m_{H_1}–m_{H_2} plane is smoothly falling across the Higgs boson candidate masses. Most HH events are captured by the signal region boundary; the fraction of 2Pass events in the SR is 76% (78%–55%) for nonresonant (resonant 1 TeV–5 TeV) events. The overall signal acceptance times efficiency in the 2Pass SR ranges from 1% for a representative nonresonant non-SM signal sample to 0.02% for the SM nonresonant signal sample due to different kinematics. For the resonant signal samples, the overall acceptance times efficiency ranges from 5% to 10%, depending on the mass and width of the resonance.

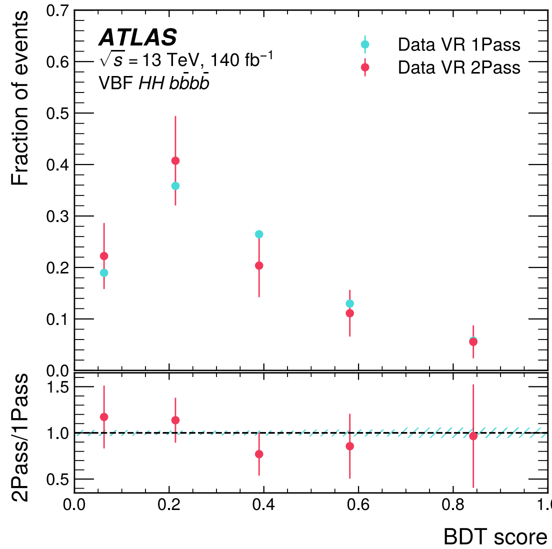


Fig. 3. The BDT score (see Section 6) for data events in the VR for the 2PASS and 1PASS selections. The blue histogram is the distribution in VR 1PASS. The red histogram is the distribution in VR 2PASS. The lower panel shows the ratio of the 2PASS and 1PASS selections. The error bars on the data points represent the statistical uncertainty.

5. Background modelling

Background processes in the SR predominantly originate from non-resonant multijet production of multiple heavy (b/t) quarks and from jets initiated by non-heavy quarks misidentified as originating from heavy quarks. The background contribution coming from single-Higgs boson and diboson events were found to be negligible. The multijet background, which is composed of approximately 10% $t\bar{t}$ events, is estimated by using a data-driven method and 1PASS events. The signal contamination in the 1PASS selection is verified to be at most 1% overall, for any signal considered. In the most signal-like bin of the final discriminant (described in Section 6), it increases to up to 8%, which is below the statistical uncertainty of this bin. As the difference between the shape of the final discriminant in 1PASS and 2PASS events is within statistical uncertainty, as shown in Fig. 3, an inclusive normalisation factor is derived from the CR and applied to the SR. The normalisation factor w is derived by calculating the ratio of the number of events in the CR 2PASS and CR 1PASS: $w = 0.0081 \pm 0.0010$.

The uncertainty is obtained by re-deriving this ratio in the VR and computing the difference between the value of w derived in the CR and the VR, and is used as an overall uncertainty in the multijet yield in the fit described in Section 8. The background estimate in the SR 2PASS is thus obtained by multiplying the relevant distribution in the SR 1PASS by w. Alternative definitions for the CR and VR boundaries, which split the nominal definitions of CR and VR into quadrants, are found to yield values of w that are consistent with the nominal estimate. To cover any potential residual shape differences, a shape uncertainty in the final discriminant is estimated by taking the relative difference between the 1PASS and 2PASS discriminant distributions in the VR and symmetrising around the background estimate.

6. Multivariate discriminants

Boosted decision trees (BDTs) implemented in the XGBoost [100] library are used to separate signal events from background events in the SR. In both the nonresonant and resonant analyses, orthogonality between training, testing, and validation samples is ensured by splitting the available data by event number. Hyperparameters are optimised using the validation samples to enhance the classifier's performance, and

Table 1
Kinematic variables used in the BDT training in both the nonresonant and resonant analyses. Additionally, the truth mass of the resonance is used as an input variable in the resonant analysis.

Physics objects	BDT input variables
Higgs boson candidate (H_i, $i = 1, 2$)	$p_T^{H_i}$, η_{H_i}
Di-Higgs boson system (HH)	p_T^{HH}, η_{HH}, m_{HH}
VBF jets (j_i, $i = 1, 2$)	$p_T^{j_i}$, η_{j_i}, E_{j_i}

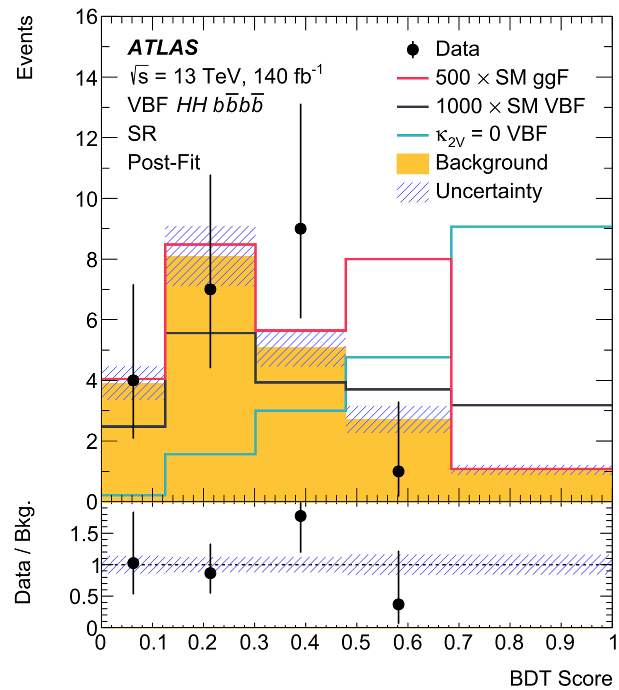
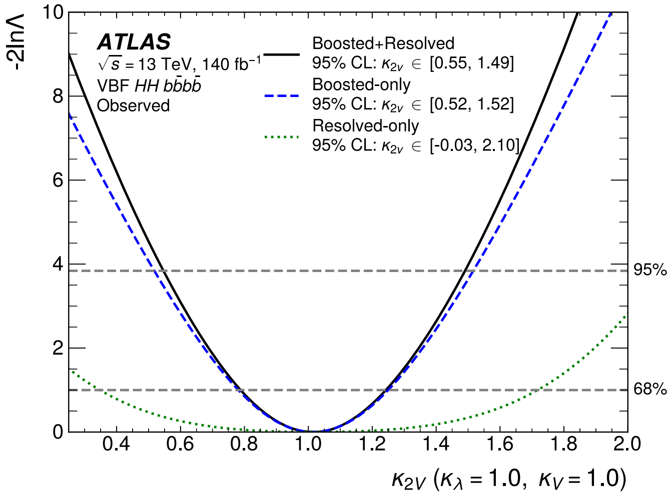


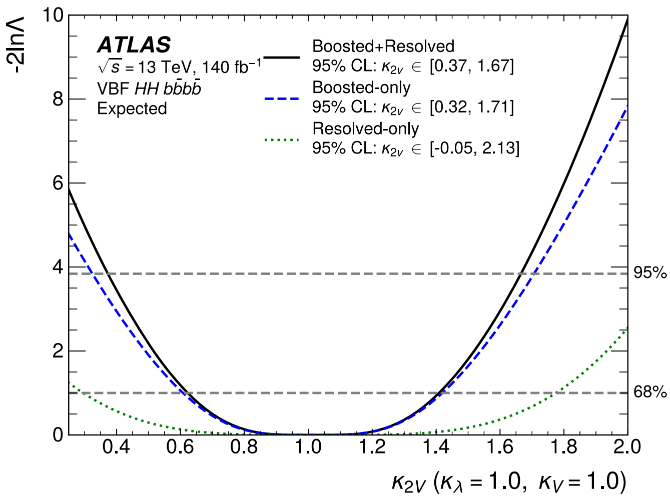
Fig. 4. The distribution of the BDT score used in the nonresonant analysis after a background-only fit to the data in the signal region. The distributions corresponding to the SM ggF HH, SM VBF HH, and $\kappa_{2V} = 0$ VBF HH samples are also shown, in some cases scaled by a factor for visibility. The lower panel shows the ratio of data to the total background prediction, with its uncertainty represented by the shaded band. The error bars on the data points represent the statistical uncertainty.

the kinematic variables used as input are listed in Table 1. In the nonresonant analysis, a BDT is trained to separate $\kappa_{2V} = 0$ signal events from background events consisting of the nonresonant multijet background estimate and SM ggF and VBF HH production events. The $\kappa_{2V} = 0$ signal is chosen as a representative proxy for non-SM values of κ_{2V}, allowing to maximise the sensitivity to the κ_{2V} coupling.

The resonant analysis uses a mass-parameterised BDT (pBDT) to accommodate multiple resonant signals with different mass hypotheses, inspired by parameterised neural networks [101]. In addition to the variables listed in Table 1, the pBDT includes the truth mass of the heavy resonances as an additional input parameter. Signals are composed of thirteen narrow-width MC samples with distinct hypotheses for the truth mass of the heavy resonance. The broad-width samples are not used during training. The background is taken from the data-driven estimate described in Section 5. A random value from the available signal true resonance masses m_X is assigned to each background event in the training. To ensure an adequate number of training events, the requirements on the VBF jets are removed and the double b-tagging working point requirements are relaxed to the 70% efficiency working point during training for the resonant analysis. The nominal selection is reinstated after training.

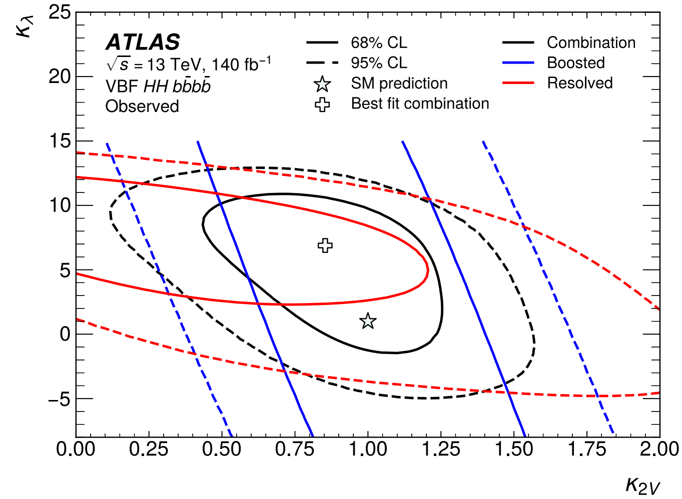


(a)

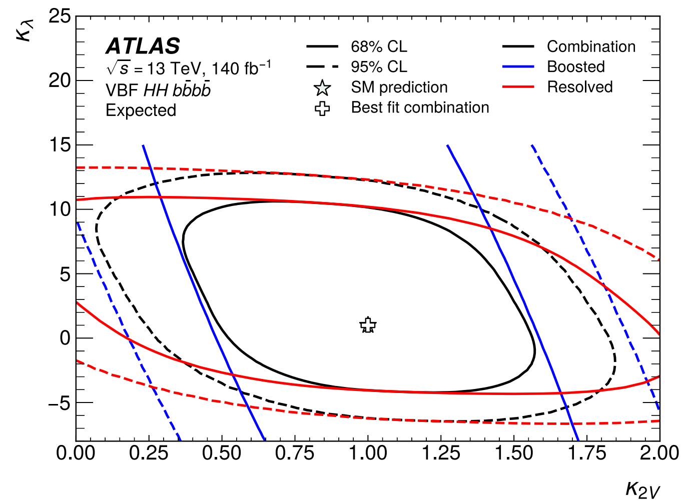


(b)

Fig. 5. Observed (a) and expected (b) values of $-2\ln\Lambda$ as a function of κ_{2V} for the resolved (dotted green) and boosted (dashed blue) analyses, and their combination (solid black), with all other coupling modifiers fixed to their SM predictions.



(a)



(b)

Fig. 6. Observed (a) and expected (b) likelihood contours at the 68% (solid line) and 95% (dashed line) CL in the κ_λ–κ_{2V} plane. The red, blue, and black colours represent the resolved-only, boosted-only, and boosted+resolved combination results, respectively. All other coupling modifiers are fixed to their SM predictions. The SM prediction is indicated by the star, while the best-fit value is denoted by the cross. The shift in the observed value from the SM prediction is driven by the resolved analysis. The observed constraint on κ_λ values from the combination is less stringent than the constraint from the resolved-only fit due to the different best-fit values of the κ_{2V} modifier. The result for κ_λ values above 15 is not plotted for clarity.

7. Systematic uncertainties

Systematic uncertainties in the background and signals are evaluated for a variety of sources. Both a normalisation and shape uncertainty are assigned to the data-driven background estimate, as described in Section 5. Uncertainties resulting from detector effects only affect signal simulation. The impact of the main sources of uncertainty in the signal yield is evaluated for various hypothesised signals. The dominant systematic uncertainty stems from the double b-tagging algorithm (20–30%). It is derived in four p_T^J bins using a $Z \to b\bar{b}$ control sample [64]. As this $Z \to b\bar{b}$ control sample is statistically limited, the systematic uncertainty coming from the double b-tagging algorithm is uncorrelated across the four p_T^J bins. The uncertainty in the integrated luminosity is 0.83% [68]. The uncertainty in the pile-up modelling is $< 0.1\%$. Uncertainties affecting the final state reconstruction and identification include the energy and mass scales of the large-R jets (1–10%), the large-R jet energy resolution and mass resolution ($< 1\%$) [102,103], and the small-R jet energy scale and resolution (1–10%) [98,104]. The efficiency and acceptance of nonresonant and resonant signals are also affected by theoretical modelling uncertainties, such as the parton showering (5–10%) and renormalisation and factorisation scale choices (1–5%). Theoretical uncertainties in the $H \to b\bar{b}$ branching ratio (3.5%) [30] are included. Theoretical uncertainties in the nonresonant ggF and VBF HH cross-sections arising from uncertainties in the PDF and α_s, and the choice of renormalisation scheme and the scale of the top-quark mass, are taken from Refs. [30,31,35]. No theoretical uncertainties in the resonant HH cross-sections are considered. The analysis is ultimately limited by statistical uncertainties.

8. Results

A binned maximum-likelihood fit to the BDT distributions in the 2Pass SR is carried out with the systematic uncertainties parameterised as nuisance parameters. The BDT output binning transformation is the same as the one detailed in Ref. [105]. The observed BDT distribution of data, and the background-only fit to the distribution, is presented in

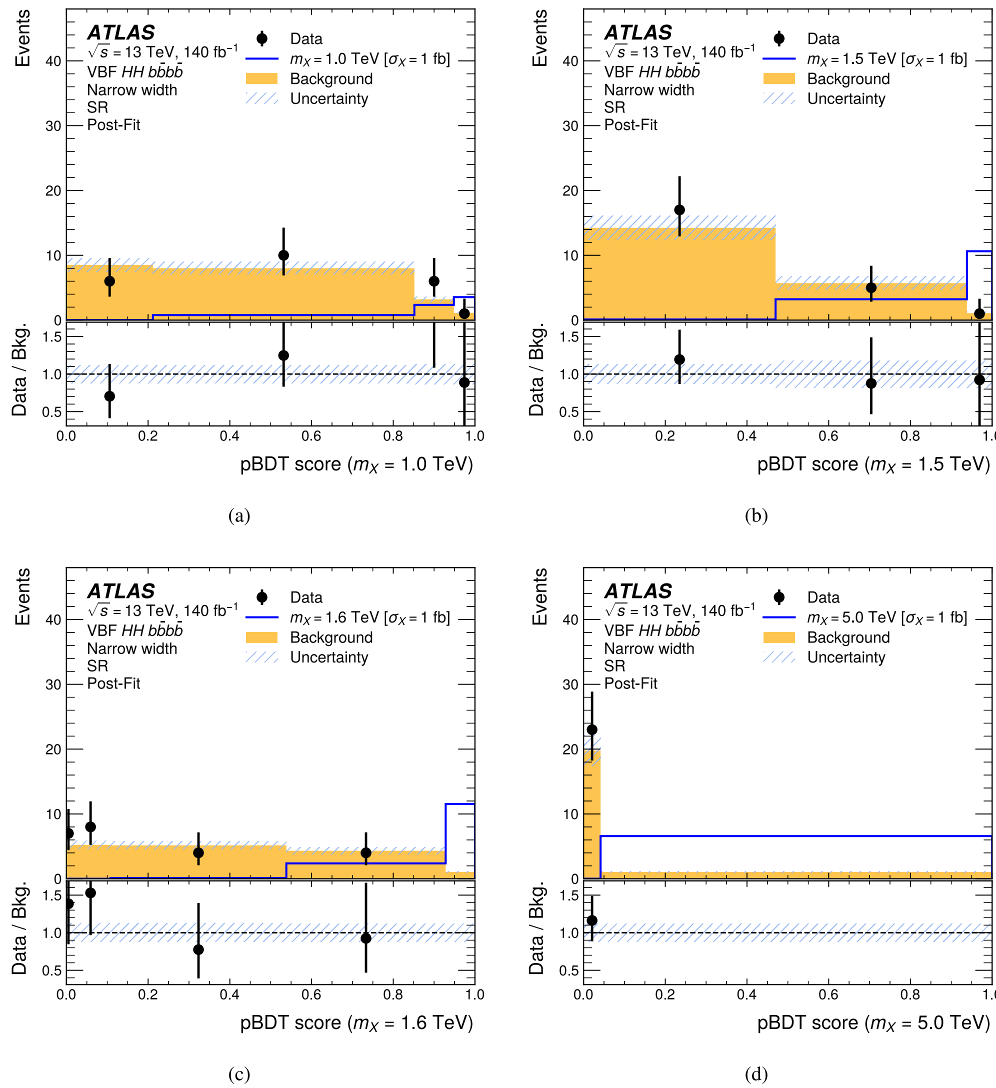
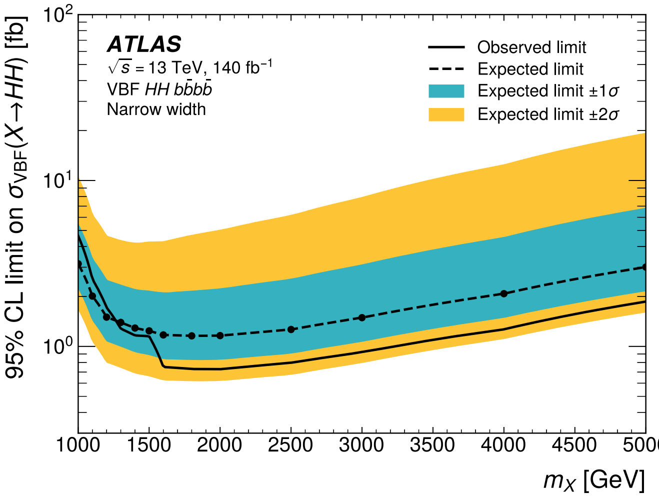


Fig. 7. The distributions of the mass-parameterised BDT score after a background-only fit to the data in the signal region. The truth mass used as input to the mass-parameterised BDT corresponds to (a) $m_X = 1.0$ TeV, (b) $m_X = 1.5$ TeV, (c) $m_X = 1.6$ TeV, and (d) $m_X = 5.0$ TeV. The narrow-width signal of the corresponding mass hypothesis, normalised to a cross-section of 1 fb, is shown. No events are observed in the rightmost bin for $m_X \geq 1.6$ TeV. The binning procedure results in a very narrow first bin for (c). The lower panel shows the ratio of data to the total prediction, with its uncertainty represented by the shaded band. The error bars on the data points represent the statistical uncertainty.

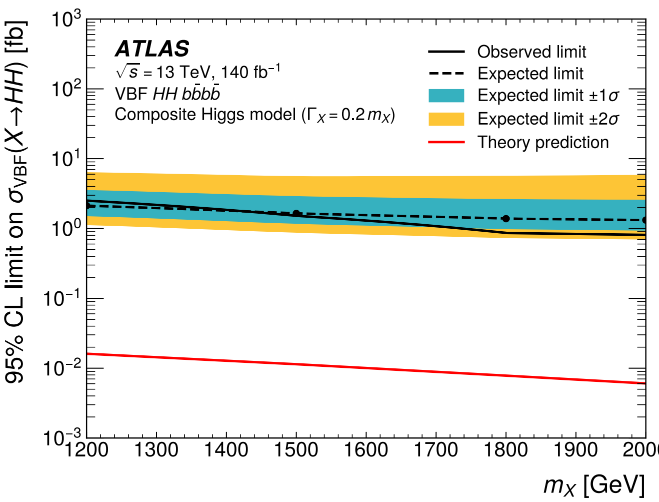
Fig. 4. Good agreement is found between the data and the background-only hypothesis. No data are observed in the most signal-like bin while the expectation from background contributions before the fit is 1.1 ± 0.2 events (1.0 ± 0.2 events after the fit).

In the nonresonant search, a combination with the ggF and VBF categories of the resolved analysis [45] is additionally performed to improve the sensitivity to κ_{2V}. Uncertainties stemming from common sources in both the analyses are correlated. The values of twice the negative-logarithm of the profile likelihood ratio ($-2\ln\Lambda$) as a function of κ_{2V} are shown in Fig. 5 for the resolved and boosted analyses, and their combination. The best-fit κ_{2V} value obtained from the fit to the data is $1.01^{+0.24}_{-0.23}$ for the boosted result and $1.01^{+0.23}_{-0.22}$ for the combined result. The boosted result provides an observed (expected) constraint of $0.52 < \kappa_{2V} < 1.52$ ($0.32 < \kappa_{2V} < 1.71$) at the 95% CL. The observed constraints on κ_{2V} are stronger than expected due to the deficit of data events in the most signal-like bin. The combined observed (expected) constraints obtained are $0.55 < \kappa_{2V} < 1.49$ ($0.37 < \kappa_{2V} < 1.67$) at the 95% CL. The allowed range of κ_{2V} values is reduced by a factor of two compared with previous ATLAS publications [45]. The Higgs boson coupling $\kappa_{2V} = 0$ is excluded with an observed (expected) significance of 3.4 (2.9) standard deviations. When combining the boosted and resolved results, the Higgs boson coupling $\kappa_{2V} = 0$ is excluded with an observed (expected) significance of 3.8 (3.3) standard deviations. These results are obtained assuming κ_λ and all other coupling values are as predicted by the SM. The expected improvement in constraining κ_λ when including the boosted result is found to be marginal compared to the resolved-only result. The exclusion constraints in the two-dimensional κ_λ–κ_{2V} coupling modifier space are presented in Fig. 6. The resolved and boosted analyses are sensitive to complementary coupling parameters; the κ_λ sensitivity is driven by the resolved analysis, while the κ_{2V} sensitivity is dominated by the boosted analysis.

Upper limits at the 95% CL on the cross-section for the narrow- and broad-width resonance assumptions are set in each available signal hypothesis using the asymptotic formula [106] based on the $\mathrm{CL_s}$ method [107]. The observed pBDT distributions of data, together with a signal + background fit, are shown in Fig. 7 for certain narrow-width resonances. The results are shown in Fig. 8 for narrow- and broad-width resonances, which have masses in the range of 1 TeV $\leq m_X \leq$ 5 TeV and 1.2 TeV $\leq m_X \leq$ 2 TeV, respectively. The loss in sensitivity at high mass values is attributed to the smaller efficiency of the double b-tagging al-



(a)



(b)

Fig. 8. Expected (dashed black lines) and observed (solid black lines) 95% CL upper limits on the cross-section of spin-0 heavy resonances with (a) narrow-width and (b) broad-width assumptions. The SM $H \to b\bar{b}$ branching ratio is assumed in both cases. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty ranges for the expected limits are shown as coloured bands. The theoretical prediction for the Composite Higgs model calculated at leading-order [80] under the $\Gamma_X/m_X = 20\%$ assumption is shown as the solid red line.

gorithm in the highly boosted regime. The observed limits at 1.6 TeV (1.8 TeV) and above drop for the narrow-width (broad-width) resonance assumption since no data are observed in the most signal-like bin of these high-mass pBDT distributions, as shown in Fig. 7. In the narrow-width assumption, the observed (expected) 95% CL upper limit range spans from 4.6 fb (3.1 fb) for $m_X = 1$ TeV to 1.9 fb (3.0 fb) for $m_X = 5$ TeV and extends to 0.7 fb (1.2 fb) for $m_X = 1.8$ TeV. In the broad-width assumption, the observed (expected) 95% CL upper limit range decreases from 2.5 fb (2.1 fb) for $m_X = 1.2$ TeV to 0.8 fb (1.3 fb) for $m_X = 2$ TeV.

9. Conclusion

A search for the production of Higgs boson pairs via VBF production in the four b-quark final state is presented. The analysis is based on 140 fb^{-1} of pp collision data recorded with the ATLAS detector at the LHC, and focuses on the Lorentz-boosted regime where each Higgs boson is reconstructed as a large-R jet. This regime yields particular sensitivity to anomalous κ_{2V} values that give rise to energetic Higgs bosons. A machine learning-based double b-tagging technique is employed to enhance the analysis sensitivity, and boosted decision trees are used to discriminate signal from background. The data are found to agree with the background-only hypothesis. The observed (expected) constraints obtained are $0.55 < \kappa_{2V} < 1.49$ ($0.37 < \kappa_{2V} < 1.67$) at the 95% CL. The allowed range of κ_{2V} values is reduced by a factor of two compared with previous ATLAS publications. A value of $\kappa_{2V} = 0$ is excluded with an observed (expected) significance of 3.8 (3.3) standard deviations. A search is also performed for the first time for a new heavy spin-0 resonance that would mediate VBF HH production in a mass range between 1 TeV and 5 TeV. No significant excess of events is observed and exclusion limits at the 95% CL are set on the production cross-section.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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