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Determination of the Relative Sign of the Higgs Boson Couplings to *W* and *Z* Bosons Using *WH* Production via Vector-Boson Fusion with the ATLAS Detector

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The associated production of Higgs and W bosons via vector-boson fusion is highly sensitive to the relative sign of the Higgs boson couplings to W and Z bosons. In this Letter, two searches for this process are presented, using 140 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. The first search targets scenarios with opposite-sign couplings of the W and Z bosons to the Higgs boson, while the second targets standard model-like scenarios with same-sign couplings. Both analyses consider Higgs boson decays into a pair of b quarks and W boson decays with an electron or muon. The data exclude the opposite-sign coupling hypothesis with a significance beyond 5σ, and the observed (expected) upper limit set on the cross section for vector-boson fusion WH production is 9.0 (8.7) times the standard model value at 95% confidence level.

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The study of the Higgs boson's couplings to W and Z bosons offers a crucial means of testing electroweak symmetry breaking in the standard model (SM). These couplings can be parametrized in terms of the coupling modifiers κ_W and κ_Z, where values of 1 correspond to the SM expectation, or in terms of their ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$ [1]. Any deviation of λ_{WZ} from 1 would indicate a violation of the SM's custodial symmetry and be a clear sign of physics beyond the standard model (BSM).

By combining measurements of many Higgs boson production and decay modes, the ATLAS [2] and CMS [3] collaborations have measured $|\lambda_{WZ}|$ to be consistent with 1 with a precision of about 6%. However, this relies primarily on decays into WW^* or ZZ^*, vector-boson fusion (VBF) production, and WH and ZH associated production, all of which scale with the squares of κ_W and κ_Z. Therefore, the relative sign of these parameters is nearly unconstrained by current measurements, and they are both assumed to be positive in the coupling combinations. Negative values of λ_{WZ} are predicted by various models in which the observed Higgs boson is part of an isospin multiplet larger than a doublet [4], as in the Georgi-Machacek model [5], making an experimental determination of its sign a key priority. In contrast to those processes, the VBF WH production mechanism [6] includes diagrams where the Higgs boson couples to either a W or Z boson, as shown in Fig. 1. These diagrams interfere destructively in the SM, preserving unitarization of longitudinal gauge-boson scattering, but the interference becomes constructive for negative values of λ_{WZ}. This leads to an enhancement in the cross section, particularly for events with large Higgs or W boson momentum. Therefore, a measurement of this process can be used to constrain the available (κ_Z, κ_W) parameter space with either the same or opposite sign. Furthermore, the enhancement is due to tree-level interference, and therefore does not rely on assumptions regarding BSM loop contributions. Other proposals to measure the sign of λ_{WZ} include exploiting one-loop interference effects in $H \to 4\ell$ decays [7], or using W^+W^-H production [8].

This Letter presents two searches for VBF WH production at the LHC, each using 140.1 ± 1.2 fb^{-1} [9] of $\sqrt{s} = 13$ TeV pp collision data collected by the ATLAS detector during 2015–2018. The first search ("negative λ_{WZ}") targets BSM scenarios with a negative coupling ratio, while the second ("positive λ_{WZ}") targets SM-like production. Both analyses consider Higgs boson decays into $b\bar{b}$

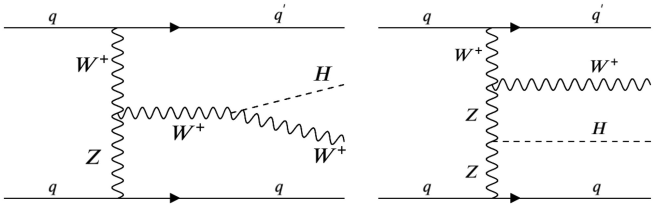

FIG. 1. Examples of leading-order Feynman diagrams for VBF WH production, where the Higgs boson interacts with either a W or Z boson. These diagrams interfere destructively if the Higgs boson couplings to W and Z have the same sign, and constructively if they have opposite sign.

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and W boson decays with an electron or muon (directly or via a τ lepton). This leads to a final state with two b jets, two additional jets from the protons, a charged lepton, and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the neutrino(s).

The ATLAS experiment [10] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle [11]. It consists of an inner detector (ID) for tracking surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 100 kHz on average depending on the data-taking conditions. An extensive software suite [12] 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.

The VBF WH process was simulated at leading-order accuracy in α_{s} with MADGRAPH5_AMC@NLO [13] for the matrix element calculation, interfaced to PYTHIA8 [14] for parton showering, hadronization, and multiple parton interactions. The NNPDF3.0NLO parton distribution function set [15] was used. Predictions were obtained for various values of κ_W and κ_Z using the procedure outlined in Ref. [6]. Because the Lagrangian is insensitive to an overall sign change, only positive values of κ_W were simulated. The largest backgrounds come from $t\bar{t}$, $W+$jets, and Wt single-top production, with smaller contributions from t- and s-channel single-top, $Z+$jets, VV, VH, $t\bar{t}H$, and $t\bar{t}V$ production ($V=W$ or Z). Backgrounds from $t\bar{t}$ and single top quark production were simulated with POWHEG [16,17] interfaced to PYTHIA8. Overlap between Wt and $t\bar{t}$ production was handled using the diagram removal scheme [18]. The $W+$jets and $Z+$jets processes were simulated with SHERPA2.2.1 [19] for the matrix element and parton showering. Different parton multiplicities were merged using the CKKW-L [20] technique. Electroweak production of WZ plus two jets was simulated at leading order with MADGRAPH5_AMC@NLO interfaced to PYTHIA8. Other VV processes were simulated with SHERPA, version 2.2.1 for quark-initiated processes and 2.2.2 for gluon-initiated processes. Other Higgs boson processes were generated with POWHEG, with the MiNLO procedure [21] applied for quark-induced VH, and with PYTHIA8 used for parton showering. The $t\bar{t}V$ process was simulated at NLO with MADGRAPH5_AMC@NLO interfaced to PYTHIA8. The background arising from misidentified or nonprompt leptons is evaluated using events with inverted lepton isolation requirements. This background is seen to populate kinematic regions with low momentum objects and is found to be negligible after applying the final selection criteria that define the signal and control regions.

Events in the electron channel were selected online using a single-electron trigger [22]. In the muon channel, events where the vector sum of the offline $E_{\mathrm{T}}^{\mathrm{miss}}$ and the muon p_{T} is greater than 150 GeV were selected with an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger [23], while below this threshold a single-muon trigger [24] was used. (The trigger-level $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation does not include muons, making this vector sum a close approximation of the trigger-level $E_{\mathrm{T}}^{\mathrm{miss}}$.) Because of the changing beam conditions, the kinematic and isolation requirements on the trigger objects varied during the data-taking period. Electrons are reconstructed offline by matching clusters of energy deposits in the electromagnetic calorimeter to tracks in the ID, which are fitted allowing for energy loss due to bremsstrahlung [25]. Events in the electron channel must have one electron candidate with $p_{\mathrm{T}} > 27$ GeV and $|\eta| < 2.47$ passing the “Tight” likelihood identification criteria and the “HighPtCaloOnly” isolation criteria of Ref. [25]. The electron must furthermore be matched to the primary vertex (the primary vertex is taken as the vertex with the highest sum of squared transverse momenta of associated tracks) by requiring $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \sin(\theta)| < 0.5$ mm, where d_0 is the track’s transverse impact parameter, σ_{d_0} is its uncertainty, and z_0 is the longitudinal impact parameter. Muons are reconstructed offline by matching tracks in the ID and muon spectrometer, accounting for energy loss in the calorimeters [26]. Events in the muon channel must have one muon satisfying $p_{\mathrm{T}} > 25$ GeV (27 GeV) if an $E_{\mathrm{T}}^{\mathrm{miss}}$ (a single-muon) trigger was used, $|\eta| < 2.5$, “Medium” quality, and “HighPtTrackOnly” isolation, as defined in Ref. [26]. Similarly to electrons, the track must satisfy $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \sin(\theta)| < 0.5$ mm. In both channels, events are rejected if a second lepton is present. For this veto, the p_{T} requirement is lowered to 7 GeV, “Loose” identification and isolation requirements are applied [25,26], and the muon pseudorapidity range is widened to $|\eta| < 2.7$.

Jets are reconstructed from particle-flow objects [27], combined using the anti-k_t [28] algorithm with a radius parameter of 0.4. Jets in the central region ($|\eta| < 2.5$) must have $p_{\mathrm{T}} > 20$ GeV, while the p_{T} requirement is raised to 30 GeV for forward jets ($2.5 < |\eta| < 4.5$). To reduce the effect of multiple collisions per bunch crossing, jets in the central (forward) region with $p_{\mathrm{T}} < 60$ GeV (120 GeV) must have a jet vertex tagger [29] score > 0.5 (forward jet vertex tagger [30] score < 0.5). Jets in the central region may be “b tagged”, i.e., identified as containing a b-hadron decay, by combining information from sources such as secondary-vertex reconstruction, track impact parameter measurements, and decay-chain fitting. The deep-learning algorithm DL1r [31,32] is used, with a working point that has 70% efficiency for b jets from top quark decays. The rates at which charm and light-flavor jets are incorrectly tagged as b jets are around 10% and 0.3%, respectively [33,34]. In addition to the standard jet calibration [27],

TABLE I. Definition of the signal regions used in the analyses. The SRs for the positive-λ_{WZ} analysis are orthogonal: events in $\mathrm{SR}^{+}_{\mathrm{tight}}$ are excluded from $\mathrm{SR}^{+}_{\mathrm{loose}}$. The definition of the W boson system is given in the text.

Variable	Description	SR^{-}	$\mathrm{SR}^{+}_{\mathrm{loose}}$	$\mathrm{SR}^{+}_{\mathrm{tight}}$
$m_{b\bar{b}}$	Invariant mass of the two b jets ($b\bar{b}$ system).	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV
$\Delta R_{b\bar{b}}$	ΔR between the two b jets.	< 1.2	< 1.6	< 1.2
$p_{\mathrm{T}}^{b\bar{b}}$	p_{T} of the $b\bar{b}$ system.	> 250 GeV	> 100 GeV	> 180 GeV
m_{jj}	Invariant mass of the VBF jets.	$\cdots$	> 600 GeV	> 1000 GeV
Δy_{jj}	Rapidity separation of the VBF jets.	> 4.4	> 3.0	> 3.0
$m_{\mathrm{top}}^{\mathrm{lep}}$	Invariant mass of the W and either b jet that is closest to 172.7 GeV (m_{top}).	> 260 GeV	> 260 GeV	> 260 GeV
$\xi_{Wb\bar{b}}$	$(\lvert y_{Wb\bar{b}} - y_{jj}\rvert / \Delta y_{jj})$, where $y_{Wb\bar{b}}$ (y_{jj}) is the rapidity of the $Wb\bar{b}$ (VBF-jet) system.	< 0.3	< 0.3	< 0.3
$\Delta\phi(Wb\bar{b}, jj)$	Azimuthal separation between the $Wb\bar{b}$ system and the VBF-jet system.	$\cdots$	$\cdots$	> 2.7
$N_{\mathrm{jets}}^{\mathrm{veto}}$	Number of nontagged, non-VBF jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$.	$\cdots$	≤ 1	$= 0$

two corrections are applied to b jets to improve their energy resolution [35]. First, if any "Medium" [26] muons with $p_{\mathrm{T}} > 5$ GeV and $|\eta| < 2.5$ are found within a cone of jet-p_{T}-dependent size around the jet axis, the four-momentum of the closest muon is added to that of the jet. After this, a residual correction is applied to equalize the response to jets with leptonic or hadronic decays of heavy-flavor hadrons. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the negative vector sum of the transverse momenta of all jets and leptons in the event, plus a track-based soft term accounting for other charged particles associated to the primary vertex [36].

Events must have exactly one charged lepton, exactly two b-tagged jets, and at least two nontagged jets. The two highest-p_{T} nontagged jets are chosen as the VBF jets, and these are required to have a rapidity separation of $\Delta y_{jj} > 3$. After these requirements, approximately 430 000 background events, primarily $t\bar{t}$, are expected from simulation, compared to 860 signal events if $\kappa_W = 1$ and $\kappa_Z = -1$, or 50 if both parameter values are 1. Selection criteria are applied to several kinematic variables to increase the signal-to-background ratio. These include the VBF jets' invariant mass m_{jj} and rapidity separation Δy_{jj}, as well as the b jets' invariant mass $m_{b\bar{b}}$, transverse momentum $p_{\mathrm{T}}^{b\bar{b}}$, and angular separation $\Delta R_{b\bar{b}}$. The W boson is reconstructed by summing the four-momenta of the lepton and neutrino, where the neutrino is assumed to have p_{T} equal to the observed $E_{\mathrm{T}}^{\mathrm{miss}}$ and η equal to that of the charged lepton. This is used to calculate the mass $m_{\mathrm{top}}^{\mathrm{lep}}$ of leptonically decaying top quarks, the centrality $\xi_{Wb\bar{b}}$, and $\Delta\phi(Wb\bar{b}, jj)$, according to the definitions in Table I. Finally, $N_{\mathrm{jets}}^{\mathrm{veto}}$ is defined as the number of jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, which are not VBF or b-tagged jets. In the negative-λ_{WZ} analysis, a single signal region named SR^{-} is used, while the positive-λ_{WZ} analysis uses two orthogonal regions, $\mathrm{SR}^{+}_{\mathrm{loose}}$ and $\mathrm{SR}^{+}_{\mathrm{tight}}$, to enhance the sensitivity to the smaller SM signal. The selection criteria that define these regions are given in Table I; they were chosen to maximize the statistical significance, while keeping enough simulated events for robust estimation of the backgrounds and systematic uncertainties. Compared to the negative-λ_{WZ} signal, the SM signal has lower Higgs boson p_{T}, but similar VBF jet p_{T} and additional jet activity. This motivates the higher $p_{\mathrm{T}}^{b\bar{b}}$ threshold in SR^{-}, and the requirements on m_{jj} and $N_{\mathrm{jets}}^{\mathrm{veto}}$ in $\mathrm{SR}^{+}_{\mathrm{loose}}$ and $\mathrm{SR}^{+}_{\mathrm{tight}}$. Distributions of the key kinematic observables used to define the signal regions are presented as Supplemental Material [37].

In order to improve the background estimation, control regions (CRs) are defined for $t\bar{t}$, $W+\mathrm{jets}$, and Wt, separately for the two analyses. The CRs are dominated by the targeted background and depleted of signal, while maintaining key kinematic features of the signal regions (SRs). The definitions of the CRs are given in the Appendix. For each analysis, the signal region(s) and the CRs are used together in a binned profile likelihood fit [38,39]. The number of events in each region is taken as the observable. The normalization of each of the main backgrounds is determined with an unconstrained parameter in the fit, $k_{t\bar{t}}$, k_W, or k_{Wt}, while systematic uncertainties are treated as nuisance parameters with Gaussian or Poisson constraints.

Systematic uncertainties considered for the electrons and muons include those in the trigger, reconstruction, identification, and isolation efficiencies, and the energy or momentum scale and resolution [25,26]. For jets, uncertainties are considered for the energy scale and resolution [40], the vertex tagging efficiency [29,30], and the b-tagging efficiency for b jets [32], c jets [33], and light jets [34]. Uncertainties in the momenta of all objects are propagated to the $E_{\mathrm{T}}^{\mathrm{miss}}$; additional uncertainties in the $E_{\mathrm{T}}^{\mathrm{miss}}$ are considered for the soft term [36] and for the trigger efficiency. Systematic uncertainties in the modeling of the main backgrounds are assessed by replacing the nominal Monte Carlo (MC) predictions described previously with ones from MADGRAPH5_AMC@NLO interfaced to PYTHIA8, and, for $t\bar{t}$ and Wt, by using HERWIG7 as an alternative parton shower algorithm. The treatment of overlap between $t\bar{t}$ and Wt is varied by using the alternative diagram subtraction scheme [41]. These uncertainties are symmetrized. Additionally, the renormalization and factorization scales are varied by a factor of 2, and, for $t\bar{t}$ and Wt, other parameters sensitive to initial-state radiation are also varied [42]. Because the normalization of these backgrounds is unconstrained in the likelihood fit, the systematic uncertainties affect only the relative contribution in each region. Uncertainties in the cross section and acceptance of the smaller backgrounds are also considered, but their impact on the analysis is small. For the VBF WH signal, the renormalization and factorization scales, the parton distribution function, and α_s are varied [43]. In addition, an uncertainty in the modeling of additional jets in the positive-λ_{WZ} analysis is assessed by using an alternative MC sample with up to one additional parton in the matrix element, merged using the CKKW-L technique. The total uncertainties of the signal yields in the SRs range from 11% to 27%.

Table II presents the normalization factors and background yields in each SR obtained from the fit, as well as the predicted signal and observed data yields. No significant pulls or constraints on any nuisance parameters are observed. Because the CRs are not fully pure in the targeted background, the normalization factors for these backgrounds are anticorrelated by up to 71% (for instance, a higher value of $k_{t\bar{t}}$ would imply more $t\bar{t}$ in the $W+\text{jets}$ CR, and therefore a lower k_W; see the Supplemental Material [37] for more information). This results in the total predicted yield having an uncertainty smaller than the uncertainty in some individual components. The postfit values of $k_{t\bar{t}}$ and k_W are close to unity, indicating good modeling by the simulation. The values of k_{Wt} are significantly below 1 because the MC prediction exceeds the data in the Wt CRs. The phase space selected in this analysis is highly sensitive to the treatment of $t\bar{t}$–Wt overlap; when using the alternative diagram substraction scheme, a deficit of MC events is seen in the Wt CRs, and values of k_{Wt} close to 3 are obtained. The difference between the baseline MC prediction and data is therefore smaller than the difference between the two MC predictions used to estimate the systematic uncertainty. Moreover, because the Wt normalization is determined from the fit to data, the uncertainty in the measured signal strength from this source is less than 10% of the total uncertainty.

TABLE II. Normalization factors, expected background and signal yields, and observed data yields in each signal region. The background yields are given after the fit to data, while the signal yields show both the prefit expectation and the fitted values. The VBF WH signal corresponds to the prediction with $\kappa_W = 1$, $\kappa_Z = -1$ for SR$^-$, and $\kappa_W = 1$, $\kappa_Z = 1$ for SR$^+_\text{loose}$ and SR$^+_\text{tight}$. The uncertainty in the total background is smaller than the quadrature sum of individual uncertainty components because of correlations.

	Negative λ_{WZ}	Positive λ_{WZ}
$k_{t\bar{t}}$	$0.88^{+0.30}_{-0.35}$	$0.96^{+0.21}_{-0.23}$
k_W	$1.12^{+0.34}_{-0.25}$	$1.25^{+0.33}_{-0.24}$
k_{Wt}	$0.32^{+0.39}_{-0.13}$	$0.31^{+0.37}_{-0.14}$
$\mu = \sigma/\sigma_\text{pred}$	$-0.027^{+0.054}_{-0.057}$	$0.9^{+4.0}_{-4.3}$

	SR$^-$	SR$^+_\text{loose}$	SR$^+_\text{tight}$
$t\bar{t}$	42 ± 19	172 ± 35	15.0 ± 5.8
$W+\text{jets}$	26 ± 13	84 ± 32	14.1 ± 7.6
Wt	4.6 ± 7.0	8 ± 13	0.8 ± 1.5
Other background	5.4 ± 1.6	16.2 ± 4.2	3.0 ± 1.5
Total background	77.7 ± 8.6	279 ± 15	32.9 ± 5.8
VBF WH, prefit	285 ± 45	4.15 ± 0.56	2.30 ± 0.62
VBF WH, postfit	-8 ± 17	4 ± 17	2.2 ± 9.8
Data	70	274	37

In the negative-λ_{WZ} analysis, 70 data events are observed in SR$^-$, compared to an expectation of 80.6 ± 8.6 assuming the SM (including 2.93 ± 0.35 signal events), or 361 ± 46 in the $\kappa_W = 1$, $\kappa_Z = -1$ scenario. (This is less than the sum of signal and background in Table II, due to the effect that signal contamination in the CRs would have on the background normalization factors.) Figure 2 shows confidence regions in the (κ_Z, κ_W) plane derived from the fit. These are compared with the confidence regions obtained from a combination of the ATLAS Higgs boson measurements collected in Ref. [2]. This combination assumes that all coupling modifiers other than κ_W and κ_Z are positive. The resulting fit excludes negative values of κ_W, primarily because of interference with the top quark in the loop decay $H \to \gamma\gamma$. However, a region of parameter space with negative values of κ_Z lies within one of the 2σ boundaries from the previous measurements. This region is excluded by the present analysis with significance much greater than 5σ. Thus the sign of λ_{WZ} is determined to be positive.

In the positive-λ_{WZ} analysis, 274 (37) events are observed in SR$^+_\text{loose}$ (SR$^+_\text{tight}$), compared to an expected background of 279 ± 15 (32.9 ± 5.8), and a SM signal of 4.15 ± 0.56 (2.30 ± 0.62). The fitted value of the signal strength $\mu = \sigma/\sigma_\text{pred}$ is $0.9^{+2.3}_{-2.6}(\text{stat})^{+3.3}_{-3.4}(\text{syst}) = 0.9^{+4.0}_{-4.3}$, indicating compatibility of the data with both the SM and background-only hypotheses. The largest systematic uncertainties come from the $W+\text{jets}$ and $t\bar{t}$ modeling, and the jet energy resolution. An upper limit of 9.0 is set on the signal strength at 95% confidence level (CL), compared to an expected limit of 8.7. The 95% CL limit on the cross section for SM-like

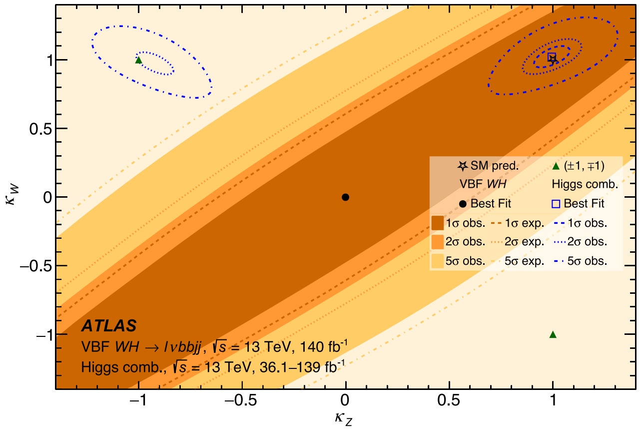

FIG. 2. Fit results in the (κ_Z, κ_W) plane, using the negative-λ_{WZ} analysis. The results are overlaid with the confidence regions (shown in blue) from a separate fit using a combination of the Higgs boson measurements collected in Ref. [2]. This fit assumes that all Higgs boson couplings besides the ones represented are positive, and that only SM particles contribute to loop processes. Confidence regions are constructed from the log-likelihood ratio $\Lambda_{\mathrm{LR}} = -2\ln(L/L_{\max})$, where $L_{\max}$ is the likelihood for the best-fit point, which is shown as a black dot for the VBF WH analysis or a blue dot for the Higgs combination. The 1σ, 2σ, and 5σ regions are defined by Λ_{LR} values smaller than 2.30, 6.18, and 28.7, respectively. The SM value is marked with a star, while green triangles mark the points with $\kappa_Z = \pm 1$, $\kappa_W = \mp 1$.

VBF WH production times the branching ratio $H \to b\bar{b}$ is 308 fb.

In conclusion, the VBF WH process has been studied by the ATLAS experiment, using 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV. Events with two b jets, a charged lepton, and two additional jets with a large rapidity gap are considered. No excess of events is observed above the SM expectation. The 95% CL upper limit set on the cross section for SM-like VBF WH production is 9.0 times the SM prediction, compared to an expected limit of 8.7. The W and Z boson couplings to the Higgs boson are determined to have the same sign, with previously unexcluded opposite-sign hypotheses now excluded with significance beyond 5σ.

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End Matter

Appendix—In order to improve the background estimation, control regions (CRs) are defined for $t\bar{t}$, $W +$ jets, and Wt, separately for the two analyses. The CRs are designed to be dominated by the targeted background and depleted of signal, while maintaining important kinematic features of the signal regions. Table III presents the definitions of the CRs for each of the two analyses. The $t\bar{t}$ CRs use the high $m_{b\bar{b}}$ sideband, and consider values of Δy_{jj} or m_{jj} that are lower than in the SRs. The $t\bar{t}$ events with high $m_{\mathrm{top}}^{\mathrm{lep}}$ often have a

TABLE III. Definitions of the control regions for $t\bar{t}$, $W +$ jets, and Wt. The W boson's transverse momentum p_{T}^{W} is the vector sum of the lepton p_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$; the W boson's transverse mass is calculated as $m_{\mathrm{T}}^{W} = \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\ell}(1 - \cos\phi)}$, where ϕ is the azimuthal angle between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$; p_{T}^{j1} is the p_{T} of the leading VBF jet. Other variables are defined in Table I.

Variable	$t\bar{t}$ CR$^-$	$t\bar{t}$ CR$^+$	$W +$ jets CR$^-$	$W +$ jets CR$^+$	Wt CR$^-$	Wt CR$^+$
$m_{b\bar{b}}$	> 145 GeV	> 145 GeV	< 70 GeV	< 70 GeV	> 145 GeV	> 145 GeV
$\Delta R_{b\bar{b}}$	< 1.2	< 1.2	$< 2.23 - 0.007 p_{\mathrm{T}}^{b\bar{b}}/\mathrm{GeV}$	$< 2.23 - 0.007 p_{\mathrm{T}}^{b\bar{b}}/\mathrm{GeV}$	> 1.5	> 1.6
$p_{\mathrm{T}}^{b\bar{b}}$	> 200 GeV	$\cdots$	$\in (150, 250)$ GeV	> 80 GeV	> 250 GeV	> 180 GeV
$m_{\mathrm{top}}^{\mathrm{lep}}$	> 260 GeV	> 220 GeV	> 275 GeV	> 260 GeV	> 320 GeV	> 320 GeV
Δy_{jj}	$\in (3, 4.4)$	> 3	> 3	> 3	> 3	> 3
m_{jj}	$\cdots$	$\in (400, 1000)$ GeV	$\cdots$	> 500 GeV	$\cdots$	> 500 GeV
$N_{\mathrm{jets}}^{\mathrm{veto}}$	$\cdots$	< 2	$\cdots$	< 1	$\cdots$	< 2
p_{T}^{W}	$\cdots$	< 350 GeV	$\cdots$	$\cdots$	> 250 GeV	> 250 GeV
m_{T}^{W}	$\cdots$	$\cdots$	$\cdots$	< 200 GeV	$\cdots$	$\cdots$
p_{T}^{j1}	$\cdots$	$\cdots$	> 70 GeV	> 70 GeV	< 350 GeV	< 350 GeV

misidentified charm jet in place of the b jet from leptonic top quark decay; to preserve this feature, the $t\bar{t}$ CRs maintain a minimum threshold for this variable. The $W+\text{jets}$ CRs use a two-dimensional cut on $\Delta R_{b\bar{b}}$ and $p_{\mathrm{T}}^{b\bar{b}}$ to find events where the b jets are too close together to be consistent with the Higgs boson mass. The Wt CRs use high values of $\Delta R_{b\bar{b}}$ to remove signal, and high values of $m_{\mathrm{top}}^{\mathrm{lep}}$ and W boson p_{T} to reduce the contamination from $t\bar{t}$ events.

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