Measurement of VH, H→bb⁻ production as a function of the vector-boson transverse momentum in 13 TeV pp collisions with the ATLAS detector

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Measurement of VH, H → b¯b production as a function of the vector-boson transverse momentum in 13 TeV pp collisions with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: Cross-sections of associated production of a Higgs boson decaying into bottom-quark pairs and an electroweak gauge boson, W or Z, decaying into leptons are measured as a function of the gauge boson transverse momentum. The measurements are performed in kinematic fiducial volumes defined in the ‘simplified template cross-section’ framework. The results are obtained using 79.8 fb\(^{-1}\) of proton-proton collisions recorded by the ATLAS detector at the Large Hadron Collider at a centre-of-mass energy of 13 TeV. All measurements are found to be in agreement with the Standard Model predictions, and limits are set on the parameters of an effective Lagrangian sensitive to modifications of the Higgs boson couplings to the electroweak gauge bosons.

Keywords: Hadron-Hadron scattering (experiments), Higgs physics

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1 Introduction

A particle consistent with the Standard Model (SM) predictions for the Higgs boson [1–4] was observed in 2012 by the ATLAS and CMS collaborations [5, 6] at the LHC. Further analysis of ATLAS and CMS data collected in proton-proton (pp) collisions at centre-of-mass energies of 7 TeV, 8 TeV and 13 TeV in two LHC data-taking periods (Runs 1 and 2) has led to precise measurements of the mass of this particle (around 125 GeV) [7–9], tests of its spin and parity (\(J^P = 0^+\)) against alternative hypotheses [10, 11], as well as to measurements of its production and decay rates [12–14].

Recently, experiments at the LHC observed Higgs boson production in association with weak gauge bosons \(V = W, Z\) (VH production) [15] and Higgs boson decays into pairs of bottom quarks (\(H \rightarrow bb\)) [15, 16]. With these results, the four most important Higgs boson production modes predicted by the SM, gluon-gluon fusion (ggF), vector-boson fusion (VBF), and associated production of a Higgs boson with either a weak gauge boson (VH) or a top-quark pair (t\(t\)H) are established. Similarly, several of the main modes of Higgs boson decays into fermionic (\(b\bar{b}, \tau\tau\)) and bosonic (WW, ZZ, \(\gamma\gamma\)) final states are observed. All results, typically expressed in the form of ‘signal strengths’, defined as the ratio of the observed to the expected product of the production cross-section times branching ratio into a certain final state, are consistent with SM predictions within uncertainties.

To probe the kinematic properties of Higgs boson production in more detail, to reduce the impact of theoretical uncertainties on the measurements and to make the measurements easier to compare with future updated calculations, the framework of simplified template cross-sections (STXS) has been introduced [17, 18]. In this framework, the cross-sections
for the various Higgs boson production modes are measured in exclusive regions carefully defined by fiducial selections based on the kinematic properties of Higgs boson production. The extrapolation from the phase space selected by the analysis criteria to that for which the cross-section measurements are presented is thus reduced.

The STXS measurements are designed to proceed in stages of increasing granularity with more recorded data. In ‘stage 0’, cross-sections are measured separately for the four main production modes in a fiducial Higgs boson rapidity region $|y_H| < 2.5$, mainly driven by the ATLAS and CMS detector acceptances for most of the reconstructed objects (leptons, photons and $b$-jets). In ‘stage 1’ these regions are split into 31 subregions according to kinematic properties such as the number of particle-level jets with transverse momentum $p_T > 30$ GeV (excluding any jets from Higgs boson decays), the transverse momentum of the Higgs boson, or the transverse momentum of the weak gauge boson $V$ for $VH$, $V \to$ leptons production. In simulation, particle-level jets are built by clustering all generated stable particles ($c\tau > 10$ mm), excluding the decay products of the Higgs boson as well as the neutrinos and charged leptons from the decays of the weak gauge boson, using the anti-$k_t$ clustering algorithm [19] with a radius parameter $R = 0.4$.

Stage-0 STXS were measured recently with 36.1 fb$^{-1}$ of 13 TeV ATLAS data using $H \to \gamma\gamma$ [20] and $H \to ZZ^* \to 4\ell$ decays [21], with results in agreement with SM predictions. In addition, refs. [20] and [21] contain some ‘reduced’ stage-1 STXS measurements of ggF and VBF regions, after merging together regions where the data lack sufficient sensitivity to Higgs boson production. Given the low $VH$ production cross-sections, the only Higgs decay mode that can currently be measured is $H \to bb$, with its large branching ratio of 58%. This paper presents a measurement of ‘reduced’ stage-1 $VH$ STXS (defined in section 3) using $H \to bb$ decays with 79.8 fb$^{-1}$ of 13 TeV $pp$ collisions collected by ATLAS between 2015 and 2017. The results are used to investigate the strength and tensor structure of the interactions of the Higgs boson with vector bosons using an effective Lagrangian approach [22].

2 Data and simulation samples

The data were collected with the ATLAS detector [23, 24] between 2015 and 2017, triggered by isolated charged leptons or large transverse momentum imbalance, $E_T^{\text{miss}}$. Only events with good data quality were kept.

The Monte Carlo simulation samples used for the measurements presented here are identical to those used for the measurement of the inclusive $VH$, $H \to bb$ signal strength [15]. Several samples of simulated events were produced for the signal ($q\bar{q} \to WH$, $q\bar{q} \to ZH$ and $gg \to ZH$) and main background ($t\bar{t}$, single-top, $V+$jets and diboson) processes. They were used to optimise the analysis criteria and to determine the expected

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1ATLAS 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. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. When dealing with massive particles, the rapidity $y = 1/2 \ln[(E + p_z)/(E - p_z)]$ is used, where $E$ is the energy and $p_z$ is the $z$-component of the momentum.
signal and background distributions of the discriminating variables used in the final fit to the data. The multijet background is largely suppressed by the selection criteria and is estimated using data-driven techniques.

The signal templates in each STXS region were obtained from simulated $q\bar{q} \rightarrow WH$ and $qq \rightarrow ZH$ events with zero or one additional jet, calculated at next-to-leading order (NLO), generated with the POWHEG-BOX v2 + GoSAM + MiNLO generators [25–28]. The contribution from loop-induced $gg \rightarrow ZH$ production was simulated at leading order (LO) using the POWHEG-BOX v2 generator [25]. Additional scale factors were applied to the $q\bar{q} \rightarrow VH$ processes as a function of the generated vector-boson transverse momentum ($p_T^V$) to account for electroweak (EW) corrections at NLO. These factors were determined from the ratio between the $VH$ differential cross-sections computed with and without these corrections by the HAWK program [29, 30]. The mass of the Higgs boson was fixed at 125 GeV.

In the measurement of the $pp \rightarrow ZH$ cross-sections, the relative contributions of the $q\bar{q} \rightarrow ZH$ and $gg \rightarrow ZH$ processes are determined by the most accurate theoretical cross-section predictions currently available: next-to-next-to-leading order (NNLO) in QCD and NLO in EW [31–37] for $q\bar{q} \rightarrow ZH$, and next-to-leading order and next-to-leading logarithm (NLO+NLL) in QCD [38–42] for $gg \rightarrow ZH$.

3 Event selection and categorisation

The object reconstruction, event selection and classification into categories used for the measurements, are identical to those described in ref. [15]. The selection and the event categories are briefly summarised below.

Events are retained if they are consistent with one of the typical signatures of $VH$, $H \rightarrow b\bar{b}$ production and decay, with $Z \rightarrow \nu\bar{\nu}$, $W \rightarrow \ell\nu$ or $Z \rightarrow \ell\ell$ ($\ell = e, \mu$). Vector-boson decays into $\tau$-leptons are not targeted explicitly. However, they satisfy the selection criteria with reduced efficiency in the case of leptonic $\tau$-lepton decays.

In particular, events are kept if they contain at most two isolated electrons or muons, and two good-quality high-$p_T$ ($> 45, 20$ GeV) jets with $|\eta| < 2.5$ satisfying $b$-jet identification (‘$b$-tagging’) requirements (which have an average efficiency of 70% for jets containing $b$-hadrons that are produced in inclusive $t\bar{t}$ events [43]). The two $b$-jet candidates are used to reconstruct the Higgs boson candidate; their invariant mass is denoted by $m_{bb}$. Additional jets are required to have $p_T > 20$ GeV for $|\eta| < 2.5$ or $p_T > 30$ GeV for $2.5 < |\eta| < 4.5$, and not be identified as $b$-jets.

Events with either zero, one or two isolated electrons or muons are classified as ‘0-lepton’, ‘1-lepton’ or ‘2-lepton’ events, respectively. The 0-lepton events and the 1-lepton events are required to have transverse momentum imbalance, as expected from the neutrinos from $Z \rightarrow \nu\bar{\nu}$ or $W \rightarrow \ell\nu$ decays; in the 2-lepton events, the leptons must have the same flavour (and opposite charge for events with muons) and an invariant mass close to the $Z$ boson mass.

Additional requirements are applied to suppress background from QCD production of multijet events in the 0-lepton and 1-lepton channels. To suppress the large $t\bar{t}$ background,
Table 1. Summary of the reconstructed-event categories. Categories with relatively large fractions of the total expected signal yields are referred to as ‘signal regions’ (SR), while those with negligible expected signal yield, mainly designed to constrain some background processes, are called ‘control regions’ (CR). The quantity $m_{\text{top}}$ is the reconstructed mass of a semileptonically decaying top-quark candidate in the 1-lepton channel. The calculation of $m_{\text{top}}$ uses the four-momenta of one of the two $b$-jet candidates, the lepton, and the hypothetical neutrino produced in the event. The neutrino four-momentum is derived using the $W$ boson mass constraint [15] and $m_{\text{top}}$ is then reconstructed from the combination of the $b$-jet candidate and the value of the neutrino longitudinal momentum that yields the smallest top-quark candidate mass. The $m_{\text{top}} \leq 225$ GeV requirement in the 1-lepton signal region is needed to maintain orthogonality with the $W$+HF control region.

Events with four or more jets are discarded in the 0-lepton and 1-lepton channels. Finally, a requirement on the reconstructed transverse momentum $p_T^{V_r}$ of the vector boson $V$ is applied. It is computed, depending on the number, $N_{\text{lep}}$, of selected electrons and muons, as either the missing transverse momentum $E_{\text{T}}^{\text{miss}}$ ($N_{\text{lep}} = 0$), the magnitude of the vector sum of the missing transverse momentum and the lepton $p_T$ ($N_{\text{lep}} = 1$), or the dilepton $p_T$ ($N_{\text{lep}} = 2$). The minimum value of $p_T^{V_r}$ is 150 GeV in the 0- and 1-lepton channels, and 75 GeV in the 2-lepton channel.

Events satisfying the previous criteria are classified into eight categories (also called signal regions in the following), shown in table 1, with different signal-to-background ratios. These categories are defined by the number of jets, $N_{\text{jet}}$ (including the two $b$-jet candidates), $N_{\text{lep}}$, and $p_T^{V_r}$. Additional categories (also called control regions in the following) containing events satisfying alternative selections are introduced to constrain some background processes such as $W$ boson production in association with jets containing heavy-flavour hadrons ($W$+HF), or top-quark pair production. The signal contribution in such categories is expected to be negligible.

4 Cross-section measurements

The reduced $VH$, $V \to$ leptons stage-1 STXS regions used in this paper are summarised in table 2, which also indicates which reconstructed-event categories are most sensitive in
The stage-1 regions are modified (i) by splitting the two $ZH$, $p_T^Z < 150$ GeV regions (from $q\bar{q}$ and $gg$) into four regions, based on whether $p_T^Z < 75$ GeV or $75 < p_T^Z < 150$ GeV; (ii) by adding a $p_T^Z < 250$ GeV requirement to the $gg \rightarrow ZH$, $p_T^Z > 150$ GeV regions (with zero or at least one extra particle-level jet); and (iii) by adding a separate $gg \rightarrow ZH$, $p_T^Z > 250$ GeV region. The three regions $WH$, $p_T^W < 150$ GeV, $q\bar{q} \rightarrow ZH$, $p_T^Z < 75$ GeV and $gg \rightarrow ZH$, $p_T^Z < 75$ GeV, in which the current analysis is not sensitive and whose corresponding cross-sections are fixed to the SM prediction in the fit, are not shown.

Table 2. The 3-POI and 5-POI ‘reduced stage-1’ sets of merged regions used for the measurements, the corresponding kinematic regions of the stage-1 $VH$ simplified template cross-sections, and the reconstructed-event categories that are most sensitive in each merged region. The stage-1 regions are modified (i) by splitting the two $ZH$, $p_T^Z < 150$ GeV regions (from $q\bar{q}$ and $gg$) into four regions, based on whether $p_T^Z < 75$ GeV or $75 < p_T^Z < 150$ GeV; (ii) by adding a $p_T^Z < 250$ GeV requirement to the $gg \rightarrow ZH$, $p_T^Z > 150$ GeV regions (with zero or at least one extra particle-level jet); and (iii) by adding a separate $gg \rightarrow ZH$, $p_T^Z > 250$ GeV region. The three regions $WH$, $p_T^W < 150$ GeV, $q\bar{q} \rightarrow ZH$, $p_T^Z < 75$ GeV and $gg \rightarrow ZH$, $p_T^Z < 75$ GeV, in which the current analysis is not sensitive and whose corresponding cross-sections are fixed to the SM prediction in the fit, are not shown.

Each region. All leptonic decays of the weak gauge bosons (including $Z \rightarrow \tau\tau$ and $W \rightarrow \tau\nu$) are considered for the STXS definition.

Compared to the original stage-1 proposal presented in ref. [17], the following changes have been made for the reduced $VH$, $V \rightarrow$ leptons stage-1 STXS regions of table 2:

- the $p_T^Z < 150$ GeV stage-1 regions are split into two subregions, $p_T^Z < 75$ GeV and $75 < p_T^Z < 150$ GeV, to avoid theory uncertainties from extrapolations to a phase space not accessible to this measurement;
- an additional $gg \rightarrow ZH$, $p_T^Z > 250$ GeV region has been introduced, similarly to what is already done for $q\bar{q} \rightarrow ZH$.

These two changes lead to a total of 14 modified stage-1 regions, which are then combined together in reduced stage-1 regions, chosen to keep the total uncertainty in the measurements near or below 100%, in the following way:

- the $q\bar{q} \rightarrow ZH$ and $gg \rightarrow ZH$ regions are merged. There are currently not enough data events to distinguish $q\bar{q} \rightarrow ZH$ from gluon-induced $ZH$ production despite their different kinematic properties;
- the $150 < p_T^V < 250$ GeV regions with zero or at least one particle-level jet are merged.
Two sets of reduced stage-1 regions are considered. In one, called the ‘5-POI (parameters of interest)’ scheme, five cross-sections, three for $ZH$ production ($75 < p_T^Z < 150$ GeV, $150 < p_T^Z < 250$ GeV and $p_T^Z > 250$ GeV) and two for $WH$ production ($150 < p_T^W < 250$ GeV and $p_T^W > 250$ GeV), are measured. In the other one, called the ‘3-POI’ scheme, three cross-sections, two for $ZH$ ($75 < p_T^Z < 150$ GeV and $p_T^Z > 150$ GeV) and one for $WH$ ($p_T^W > 150$ GeV), are measured. The 5-POI scheme leads to measurements that have total uncertainties larger than those in the 3-POI scheme, but are more sensitive to enhancements at high $p_T^V$ from potential anomalous interactions between the Higgs boson and the EW gauge bosons.

The reconstructed-event categories do not distinguish between events with generated $p_T^V$ below or above 250 GeV. Discrimination between the two $p_T^V$ regions 150–250 GeV and > 250 GeV is provided by the different shapes of the boosted-decision-tree discriminant (BDT$_{VH}$) used in the final fit to the data, as illustrated in figure 1 in the case of the 1-lepton, 2-jet category. This arises from the fact that the reconstructed $p_T^{V,b}$ is largely correlated with the BDT$_{VH}$ output, for which it constitutes one of the most discriminating input variables together with $m_{bb}$ and the angular separation of the two $b$-jets.
The product of the signal cross-section times the $H \to b\bar{b}$ branching ratio and the total leptonic decay branching ratio for $W$ or $Z$ bosons is determined in each of the reduced stage-1 regions by a binned maximum-likelihood fit to the data. The cross-sections are not constrained to be positive in the fit. Signal and background templates of the discriminating variables, determined from the simulation or data control regions, are used to extract the signal and background yields. A simultaneous fit is performed to all the signal and control regions. Systematic uncertainties are included in the likelihood function as nuisance parameters.

The likelihood function is very similar to that described in ref. [15]. In particular, the same observables are used, namely $\text{BDT}_{VH}$ in the signal regions and either the invariant mass $m_{bb}$ of the two $b$-jets or the event yield in the control regions. The treatment of the background and of its uncertainties is also unchanged. The only differences relative to the likelihood function in ref. [15] concern the treatment of the signal:

- Instead of a single signal shape (for $\text{BDT}_{VH}$ or $m_{bb}$) or yield per category, multiple shapes or yields are introduced, one for each reduced stage-1 STXS region under study.
- Instead of a single parameter of interest, the inclusive signal strength, the fit has multiple parameters of interest, i.e. the cross-sections of the reduced stage-1 regions, multiplied by the $H \to b\bar{b}$ and $V \to$ leptons branching ratios.
- Overall theoretical cross-section and branching ratio uncertainties, which affect the signal strength measurements but not the STXS measurements, are not included in the likelihood function.

The expected signal shapes of the discriminating variable distributions and the acceptance times efficiency (referred to as ‘acceptance’ in the following) in each reduced stage-1 region are determined from simulated samples of SM $VH$, $V \to$ leptons, $H \to b\bar{b}$ events. The acceptance of each reconstructed-event category for signal events from the different regions of the 5-POI reduced stage-1 scheme is shown in figure 2a. The fraction of signal events in each reconstructed-event category originating from the different regions in the same scheme is shown in figure 2b.

As shown in figure 2a, the current analysis is not sensitive to $WH$ events with $p_T^W < 150$ GeV and to $ZH$ events with $p_T^Z < 75$ GeV, since their acceptance in each category is at the level of 0.1% or smaller. Therefore, in the fits the signal cross-section in these regions is constrained to the SM prediction, within the theoretical uncertainties. Since these regions contribute only marginally to the selected event sample, the impact on the final results is negligible. A cross-check in which the relative signal cross-section uncertainty for the $p_T^W < 150$ GeV and $p_T^Z < 75$ GeV regions is conservatively set to 70% of the prediction (i.e. about seven times the nominal uncertainty) leads to variations of the measured STXS below 1%.

The sources of systematic uncertainty are identical to those described in ref. [15], except for those associated with the Higgs boson signal simulation, which are re-evaluated [44]. In this re-evaluation the uncertainties are separated into two groups:
Figure 2. In the 5-POI reduced stage-1 scheme, (a) the acceptance (including the efficiency of the experimental selection) for \(VH, V \rightarrow \text{leptons}, H \rightarrow b\bar{b}\) events of each reconstructed-event category (y-axis) for each STXS signal region (x-axis), in percent; (b) the fraction of signal (in percent) from each STXS signal region (x-axis) in every reconstructed-event category (y-axis). Entries with acceptance times efficiency below 0.01% or signal fractions below 0.1% are not shown.

- uncertainties affecting signal modelling — i.e. acceptance and shape of kinematic distributions — in each of the three or five reduced stage-1 regions (hereafter referred to as theoretical modelling uncertainties), and

- uncertainties in the prediction of the production cross-section for each of these regions (hereafter referred to as theoretical cross-section uncertainties).

While theoretical modelling uncertainties enter the measurement of the STXS, theoretical cross-section uncertainties do not affect the results, but only the predictions with which they are compared. The consequent reduction of the impact of the theoretical uncertainties on the results with respect to the signal strength measurements is one of the main advantages of measuring STXS.

The two groups of systematic uncertainties are estimated for high-granularity STXS regions, and then merged into the reduced scheme under consideration. This approach
makes it easy to compute the systematic uncertainties for merging schemes different from those presented here. The uncertainties are evaluated by dividing the phase space into five $p_T^V$ regions (with the following lower edges: 0 GeV, 75 GeV, 150 GeV, 250 GeV and 400 GeV), and each $p_T^V$ region into three bins depending on the number of particle-level jets (zero, one, or at least two), independently for the $q\bar{q} \to VH$ and $gg \to ZH$ processes. When two STXS regions are merged, their relative theoretical cross-section uncertainties lead to a modelling uncertainty. These uncertainties are evaluated as the remnant of the theoretical cross-section uncertainties for the high-granularity regions after the subtraction of the theoretical cross-section uncertainty for the merged region.

The high-granularity regions are used to calculate theoretical cross-section uncertainties for the missing higher-order terms in the QCD perturbative expansion and for the uncertainties induced by the choices of the parton distribution function (PDF) and $\alpha_S$. Fourteen independent sources of uncertainties due to the missing higher-order terms lead to total uncertainties of 3%–4% for $q\bar{q} \to VH$ and 40%–50% for $gg \to ZH$ with $p_T^V > 75$ GeV [44]. Thirty-one independent sources of PDF and $\alpha_S$ uncertainties, each of them usually smaller than 1%, lead to a total quadrature sum between 2% and 3% depending on the STXS region. The theoretical modelling uncertainties change the shapes of the reconstructed $p_T^{Vr}$ and $m_{bb}$ distributions in the same way as described in ref. [15]. Four independent sources for the QCD expansion and two independent sources for the PDF and $\alpha_S$ choices are considered.

Systematic uncertainties in the signal acceptance and shape of the $p_T^{Vr}$ and $m_{bb}$ distributions due to the parton shower (PS) and underlying event (UE) models are estimated from the variations of acceptance and shapes of simulated events after changing the PYTHIA 8 PS parameters or after replacing PYTHIA 8 with HERWIG 7 for the PS and UE models [15]. The signal acceptance uncertainties due to the PS and UE models (five independent sources) are typically of the order of 1% (5%–15%) with a maximum of 10% (30%) for the $q\bar{q} \to VH$ ($gg \to ZH$) production mode. Two independent nuisance parameters account for the systematic uncertainties induced by the PS and UE models in the $p_T^{Vr}$ and $m_{bb}$ distributions. In addition, a systematic uncertainty due to the EW corrections is parameterised as a change in shape of the $p_T^V$ distributions for the $q\bar{q} \to VH$ processes [15].

5 Results

The measured reduced stage-1 $VH$ cross-sections times the $H \to b\bar{b}$ and $V \to$ leptons branching ratios, $\sigma \times B$, in the 5-POI and 3-POI schemes, together with the SM predictions, are summarised in table 3. The results of the 5-POI scheme are also illustrated in figure 3. The SM predictions are shown together with the theoretical cross-section uncertainty for the merged regions computed as described in the previous section. The measurements are in agreement with the SM predictions.

The cross-sections measured in the $p_T^V > 150$ GeV intervals are not equal to the sum of those measured for $150 < p_T^V < 250$ GeV and $p_T^V > 250$ GeV. This is because the signal template for $p_T^V > 150$ GeV in the 3-POI fit is computed from the sum of the templates of the two regions assuming that the ratio of yields in those regions is that predicted
Table 3. Best-fit values and uncertainties for the VH, V → leptons reduced stage-1 simplified template cross-sections times the H → bb branching ratio, in the 5-POI (top five rows) and 3-POI (bottom three rows) schemes. The SM predictions for each region, computed using the inclusive cross-section calculations and the simulated event samples described in section 2, are also shown. The contributions to the total uncertainty in the measurements from statistical (Stat. unc.) or systematic uncertainties (Syst. unc.) in the signal modelling (Th. sig.), background modelling (Th. bkg.), and in experimental performance (Exp.) are given separately. The total systematic uncertainty, equal to the difference in quadrature between the total uncertainty and the statistical uncertainty, differs from the sum in quadrature of the Th. Sig., Th. Bkg., and Exp. systematic uncertainties due to correlations. All leptonic decays of the V bosons (including those to τ-leptons, \( \ell = e, \mu, \tau \)) are considered.

by the SM, while in the 5-POI fit the normalisations of the two templates are floated independently.

The cross-sections are measured with relative uncertainties varying between 50% and 125% in the 5-POI case, and between 29% and 56% for the 3-POI. The largest uncertainties are statistical, except for the WH cross-sections with \( p_T^W > 150 \text{ GeV} \) in the 3-POI case and with \( 150 < p_T^W < 250 \text{ GeV} \) in the 5-POI case. In the 5-POI case, an anti-correlation of the order of 40%–60% is observed between the cross-sections in the ranges \( p_T^V > 250 \text{ GeV} \) and \( 150 < p_T^V < 250 \text{ GeV} \), which are measured with the same reconstructed-event categories.

The dominant systematic uncertainties are due to the limited number of simulated background events and the theoretical modelling of the background processes. The uncertainties due to the theoretical modelling of the VH signal are small, with relative values ranging between 6% and 12%. The uncertainties in the predictions are 2–3 times larger for ZH than for WH in the same \( p_T^V \) interval due to the limited precision of the theoretical calculations of the \( gg \rightarrow ZH \) process.
6 Constraints on anomalous Higgs boson interactions

The strength and tensor structure of the Higgs boson interactions are investigated using an effective Lagrangian approach [22]. Extra terms of the form $c_i^{(D)} O_i^{(D)} / \Lambda^{D-4}$, where $\Lambda$ is the energy scale of the new interactions, $O_i^{(D)}$ are dimension-$D$ operators, and $c_i^{(D)}$ are numerical coefficients, are added to the SM Lagrangian to obtain an effective Lagrangian inspired by that in ref. [45]. Only dimension $D = 6$ operators are considered in this study, since dimension $D = 5$ operators violate lepton or baryon number, while dimension $D > 6$ operators are further suppressed by powers of $\Lambda$.

The results presented in this paper focus on the coefficients of the operators in the ‘Strongly Interacting Light Higgs’ formulation [46]. This formalism is defined as the effective theory of a strongly interacting sector in which a light composite Higgs boson arises as a pseudo Goldstone boson, and is responsible for EW symmetry breaking. Among such operators, four directly affect the $VH$ cross-sections because they introduce new Higgs boson interactions with $W$ bosons ($O_{HW}$, $O_W$) and $Z$ bosons (all four operators):

- $O_{HW} = i (D^a H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$,
- $O_{HB} = i (D^a H)^\dagger (D^\nu H) B_{\mu\nu}^a$,
- $O_W = \frac{i}{2} \left( H^\dagger \sigma^a D^\nu H \right) D^\nu W_{\mu\nu}^a$,
- $O_B = \frac{i}{2} \left( H^\dagger D^\nu H \right) \partial^\nu B_{\mu\nu}$.

The corresponding $CP$-odd operators $\hat{O}_{HW}$, $\hat{O}_{HB}$, $\hat{O}_W$, and $\hat{O}_B$, are not considered.
Modifications of the $gg \to ZH$ production cross-section are only introduced by either higher-dimension ($D \geq 8$) operators or corrections that are formally at NNLO in QCD, and are not included in this study, in which the expected $gg \to ZH$ contribution is kept fixed to the SM prediction.

The operator $O_d = y_d |H|^2 \bar{Q}_L H d_R$ (plus Hermitian conjugate) with Yukawa coupling strength $y_d$, which modifies the coupling between the Higgs boson and down-type quarks, induces variations of the partial width $\Gamma_{bb}^H$ and of the total Higgs boson width $\Gamma_H$, and therefore of the $H \to bb$ branching ratio. This operator affects the measured cross-sections in the same way in each region.

Constraints are set on the coefficients of the five $O_W, O_B, O_{HW}, O_{HB}$ and $O_d$ operators in the ‘Higgs Effective Lagrangian’ (HEL) implementation [47], using the known relations between such coefficients and the stage-1 STXS based on leading-order predictions [48]. Such relations include interference terms between the SM and non-SM amplitudes that are linear in the coefficients and of order $1/\Lambda^2$, and the SM-independent contributions that are quadratic in the coefficients and of order $1/\Lambda^4$. In the HEL implementation, the coefficients $c_i$ of interest are recast into the following dimensionless coefficients:

$$\bar{c}_{HW} = \frac{m_W^2 c_{HW}}{g \Lambda^2}, \quad \bar{c}_{HB} = \frac{m_W^2 c_{HB}}{g' \Lambda^2}, \quad \bar{c}_W = \frac{m_W^2 c_W}{g \Lambda^2}, \quad \bar{c}_B = \frac{m_W^2 c_B}{g' \Lambda^2}, \quad \bar{c}_d = \frac{v^2 c_d}{\Lambda^2},$$

where $g$ and $g'$ are the SU(2) and U(1) SM gauge couplings, and $v$ is the vacuum expectation value of the Higgs boson field. These dimensionless coefficients are equal to zero in the SM.

The sum $\bar{c}_W + \bar{c}_B$ is strongly constrained by precision EW data [49] and is thus assumed here to be zero, and constraints are set on $\bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_W - \bar{c}_B$ and $\bar{c}_d$. The relations between the HEL coefficients and the reduced STXS measured in this paper are obtained by averaging the relations for the regions that are merged with weights proportional to their respective cross-sections.

Simultaneous maximum-likelihood fits to the five STXS measured in the 5-POI scheme are performed to determine $\bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_W - \bar{c}_B$ and $\bar{c}_d$. Due to the large sensitivity to the Higgs boson anomalous couplings to vector bosons provided by the $p_T^V > 250$ GeV cross-sections, the 5-POI results place tighter constraints on these coefficients (e.g. approximately a factor two for $\bar{c}_{HW}$) than do the 3-POI results. For this reason, constraints obtained with the 3-POI results are not shown here.

In each fit, all coefficients but one are assumed to vanish, and 68% and 95% confidence level (CL) one-dimensional intervals are inferred for the remaining coefficient. The negative-log-likelihood one-dimensional projections are shown in figure 4, and the 68% and 95% CL intervals for $\bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_W - \bar{c}_B$ and $\bar{c}_d$ are summarised in table 4. The parameters $\bar{c}_{HW}$ and $\bar{c}_W - \bar{c}_B$ are constrained at 95% CL to be no more than a few percent, while the constraint on $\bar{c}_{HB}$ is about five times worse, and the constraint on $\bar{c}_d$ is of order unity. For comparison, table 4 also shows the 68% and 95% CL intervals for the dimensionless coefficients when the SM-independent contributions, which are of the same order ($1/\Lambda^4$) as the dimension-8 operators that are neglected, are not considered. The constraints are typically 50% stronger than when the SM-independent contributions are not neglected.
7 Conclusion

Using 79.8 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton-proton collisions collected by the ATLAS detector at the LHC, the cross-sections for the associated production of a Higgs boson decaying into bottom-quark pairs and an electroweak gauge boson $W$ or $Z$ decaying into leptons are measured as functions of the vector-boson transverse momentum $p_{T}^{V}$. The cross-sections are measured for Higgs bosons in a fiducial volume with rapidity $|y_{H}| < 2.5$, in the ‘simplified template cross-section’ framework.

The measurements are performed for two different choices of the number of $p_{T}^{V}$ intervals. The results have relative uncertainties varying between 50% and 125% in one case, and between 29% and 56% in the other. The measurements are in agreement with the Standard Model predictions, even in high $p_{T}^{V}$ ($> 250$ GeV) regions that are most sensitive to enhancements from potential anomalous interactions between the Higgs boson and the electroweak gauge bosons.

Figure 4. The observed (solid) and expected (dotted) profiled negative-log-likelihood functions for the one-dimensional fits to constrain the coefficients (a) $c_{HW}$, (b) $c_{HB}$, (c) $c_{W} - c_{B}$ and (d) $c_{d}$ of an effective Lagrangian (described in the text), when the other coefficients are assumed to vanish.
The expected and observed 68% CL (four top rows) and 95% CL (four bottom rows) intervals for the effective Lagrangian coefficients $\hat{c}_{HW}$, $\hat{c}_{HB}$, $\hat{c}_{W} - \hat{c}_{B}$ and $\hat{c}_{d}$ when the other coefficients are assumed to vanish. Each row is composed of two sub-rows: the first one uses the interference between SM and non-SM amplitudes and the SM-independent contributions, while the second sub-row uses only the interference between SM and non-SM amplitudes.

One-dimensional limits on four linear combinations of the coefficients of effective Lagrangian operators affecting the Higgs boson couplings to the electroweak gauge bosons and to down-type quarks have also been set. For two of these parameters the constraint has a precision of a few percent.

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80 (a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora(B), Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio De Janeiro(C), Universidade Federal de São João del Rei (UFSJ), São João del Rei(D), Instituto de Física, Universidade de São Paulo, São Paulo; Brazil
81 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
82 Graduate School of Science, Kobe University, Kobe; Japan
83 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow(B), Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
84 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
85 Faculty of Science, Kyoto University, Kyoto; Japan
86 Kyoto University of Education, Kyoto; Japan
87 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
88 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
89 Physics Department, Lancaster University, Lancaster; United Kingdom
90 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
91 Department of Experimental Particle Physics, Józef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
92 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
93 Department of Physics, Royal Holloway University of London, Egham; United Kingdom
94 Department of Physics and Astronomy, University College London, London; United Kingdom
95 Louisiana Tech University, Ruston LA; United States of America
96 Fysiska institutionen, Lunds universitet, Lund; Sweden
97 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France
98 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
99 Institut für Physik, Universität Mainz, Mainz; Germany
100 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
101 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
102 Department of Physics, University of Massachusetts, Amherst MA; United States of America
103 Department of Physics, McGill University, Montreal QC; Canada
104 School of Physics, University of Melbourne, Victoria; Australia
105 Department of Physics, University of Michigan, Ann Arbor MI; United States of America
106 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
107 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus
108 Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus
109 Group of Particle Physics, University of Montreal, Montreal QC; Canada
110 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia
111 Institute for Theoretical and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow; Russia
112 National Research Nuclear University MEPhI, Moscow; Russia
113 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia
114 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
115 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
116 Nagasaki Institute of Applied Science, Nagasaki; Japan
117 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
118 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
119 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands

Department of Physics, Northern Illinois University, Dekalb IL; United States of America

(a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk(b); Novosibirsk State University Novosibirsk; Russia

Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia

Department of Physics, New York University, New York NY; United States of America

Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan

Ohio State University, Columbus OH; United States of America

Faculty of Science, Okayama University, Okayama; Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America

Department of Physics, Oklahoma State University, Stillwater OK; United States of America

Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic

Center for High Energy Physics, University of Oregon, Eugene OR; United States of America

LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France

Graduate School of Science, Osaka University, Osaka; Japan

Department of Physics, University of Oslo, Oslo; Norway

Department of Physics, Oxford University, Oxford; United Kingdom

LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France

Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America

Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg; Russia

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America

Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic

Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic

Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America

(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago(b); Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile

Department of Physics, University of Washington, Seattle WA; United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom

Department of Physics, Shinshu University, Nagano; Japan

Department Physik, Universität Siegen, Siegen; Germany

Department of Physics, Simon Fraser University, Burnaby BC; Canada

SLAC National Accelerator Laboratory, Stanford CA; United States of America

Physics Department, Royal Institute of Technology, Stockholm; Sweden

Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America

Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom

School of Physics, University of Sydney, Sydney; Australia
Institute of Physics, Academia Sinica, Taipei; Taiwan

(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; Georgia
Department of Physics, Tbilisi State University, Tbilisi; Georgia
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan
Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
Tomsk State University, Tomsk; Russia
Department of Physics, University of Toronto, Toronto ON; Canada

(b) TRIUMF, Vancouver BC, Department of Physics and Astronomy, York University, Toronto ON; Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
Department of Physics, University of Illinois, Urbana IL; United States of America
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain
Department of Physics, University of British Columbia, Vancouver BC; Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
Department of Physics, University of Warwick, Coventry; United Kingdom
Waseda University, Tokyo; Japan
Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel
Department of Physics, University of Wisconsin, Madison WI; United States of America
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
Department of Physics, Yale University, New Haven CT; United States of America
Yerevan Physics Institute, Yerevan; Armenia

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa
Also at CERN, Geneva; Switzerland
Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
Also at Departamento de Física de la Universitat Autonoma de Barcelona, Barcelona; Spain
Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates
Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece
Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America