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Measurement of $VH, H \rightarrow b\bar{b}$ production as a function of the vector-boson transverse momentum in 13 TeV pp collisions with the ATLAS detector



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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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Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| 2 | Data and simulation samples | 2 |
| 3 | Event selection and categorisation | 3 |
| 4 | Cross-section measurements | 4 |
| 5 | Results | 9 |
| 6 | Constraints on anomalous Higgs boson interactions | 11 |
| 7 | Conclusion | 13 |
| | The ATLAS collaboration | 19 |

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 ($H \rightarrow b\bar{b}$) [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 ($t\bar{t}H$) 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 $|y_H| < 2.5$,¹ 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 , $V \rightarrow$ 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 $H \rightarrow \gamma\gamma$ [20] and $H \rightarrow ZZ^* \rightarrow 4\ell$ 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 boson decay mode that can currently be measured is $H \rightarrow b\bar{b}$, with its large branching ratio of 58%. This paper presents a measurement of ‘reduced’ stage-1 VH STXS (defined in section 3) using $H \rightarrow b\bar{b}$ 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^{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 , $H \rightarrow b\bar{b}$ signal strength [15]. Several samples of simulated events were produced for the signal ($q\bar{q} \rightarrow WH$, $q\bar{q} \rightarrow ZH$ and $gg \rightarrow ZH$) 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

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, 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 $\eta = -\ln \tan(\theta/2)$. 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 $q\bar{q} \rightarrow ZH$ 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 τ -leptons are not targeted explicitly. However, they satisfy the selection criteria with reduced efficiency in the case of leptonic τ -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,

| Channel | Categories | | | | |
|---|--|---------------|-------------------------------|--------|---------------|
| | $75 \text{ GeV} < p_T^{V,r} < 150 \text{ GeV}$ | | $p_T^{V,r} > 150 \text{ GeV}$ | | |
| | 2 jets | ≥ 3 jets | 2 jets | 3 jets | ≥ 3 jets |
| 0-lepton | — | — | SR | SR | — |
| 1-lepton | | | | | |
| $m_{bb} \geq 75 \text{ GeV}$ or $m_{\text{top}} \leq 225 \text{ GeV}$ | — | — | SR | SR | — |
| $m_{bb} < 75 \text{ GeV}$ and $m_{\text{top}} > 225 \text{ GeV}$ | — | — | CR | CR | — |
| 2-lepton | | | | | |
| ee and $\mu\mu$ channels | SR | SR | SR | — | SR |
| $e\mu$ channel | CR | CR | CR | — | CR |

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_{top} is the reconstructed mass of a semileptonically decaying top-quark candidate in the 1-lepton channel. The calculation of m_{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_{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 $m_{\text{top}} \leq 225 \text{ GeV}$ 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_{lep} , of selected electrons and muons, as either the missing transverse momentum E_T^{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_{jet} (including the two b -jet candidates), N_{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 , $V \rightarrow$ 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

| Merged region 3-POI scheme | Merged region 5-POI scheme | Stage 1 (modified) STXS region | Reconstructed-event categories with largest sensitivity | | |
|---|--|---|--|-------------------------------|------------------|
| | | | N_{lep} | $p_{\text{T}}^{V,r}$ interval | N_{jet} |
| $WH, p_{\text{T}}^W > 150 \text{ GeV}$ | $WH, 150 < p_{\text{T}}^W < 250 \text{ GeV}$ | $q\bar{q} \rightarrow WH, 150 < p_{\text{T}}^W < 250 \text{ GeV}, 0\text{-jet}$ $q\bar{q} \rightarrow WH, 150 < p_{\text{T}}^W < 250 \text{ GeV}, \geq 1\text{-jet}$ | 1 | $> 150 \text{ GeV}$ | 2, 3 |
| | $WH, p_{\text{T}}^W > 250 \text{ GeV}$ | $q\bar{q} \rightarrow WH, p_{\text{T}}^W > 250 \text{ GeV}$ | | | |
| $ZH, 75 < p_{\text{T}}^Z < 150 \text{ GeV}$ | $ZH, 75 < p_{\text{T}}^Z < 150 \text{ GeV}$ | $q\bar{q} \rightarrow ZH, 75 < p_{\text{T}}^Z < 150 \text{ GeV}$ $gg \rightarrow ZH, 75 < p_{\text{T}}^Z < 150 \text{ GeV}$ | 2 | 75–150 GeV | 2, ≥ 3 |
| $ZH, p_{\text{T}}^Z > 150 \text{ GeV}$ | $ZH, 150 < p_{\text{T}}^Z < 250 \text{ GeV}$ | $q\bar{q} \rightarrow ZH, 150 < p_{\text{T}}^Z < 250 \text{ GeV}, 0\text{-jet}$ | 0 | $> 150 \text{ GeV}$ | 2, 3 |
| | | $gg \rightarrow ZH, 150 < p_{\text{T}}^Z < 250 \text{ GeV}, 0\text{-jet}$ | | | |
| | | $q\bar{q} \rightarrow ZH, 150 < p_{\text{T}}^Z < 250 \text{ GeV}, \geq 1\text{-jet}$ $gg \rightarrow ZH, 150 < p_{\text{T}}^Z < 250 \text{ GeV}, \geq 1\text{-jet}$ | | | |
| | $ZH, p_{\text{T}}^Z > 250 \text{ GeV}$ | $q\bar{q} \rightarrow ZH, p_{\text{T}}^Z > 250 \text{ GeV}$ $gg \rightarrow ZH, p_{\text{T}}^Z > 250 \text{ GeV}$ | 2 | $> 150 \text{ GeV}$ | 2, ≥ 3 |

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 $ZH, p_{\text{T}}^Z < 150 \text{ GeV}$ regions (from $q\bar{q}$ and gg) into four regions, based on whether $p_{\text{T}}^Z < 75 \text{ GeV}$ or $75 < p_{\text{T}}^Z < 150 \text{ GeV}$; (ii) by adding a $p_{\text{T}}^Z < 250 \text{ GeV}$ requirement to the $gg \rightarrow ZH, p_{\text{T}}^Z > 150 \text{ GeV}$ regions (with zero or at least one extra particle-level jet), and (iii) by adding a separate $gg \rightarrow ZH, p_{\text{T}}^Z > 250 \text{ GeV}$ region. The three regions $WH, p_{\text{T}}^W < 150 \text{ GeV}$, $q\bar{q} \rightarrow ZH, p_{\text{T}}^Z < 75 \text{ GeV}$ and $gg \rightarrow ZH, p_{\text{T}}^Z < 75 \text{ GeV}$, 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 $VH, V \rightarrow \text{leptons}$ stage-1 STXS regions of table 2:

- the $p_{\text{T}}^Z < 150 \text{ GeV}$ stage-1 regions are split into two subregions, $p_{\text{T}}^Z < 75 \text{ GeV}$ and $75 < p_{\text{T}}^Z < 150 \text{ GeV}$, to avoid theory uncertainties from extrapolations to a phase space not accessible to this measurement;
- an additional $gg \rightarrow ZH, p_{\text{T}}^Z > 250 \text{ GeV}$ 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 $150 < p_{\text{T}}^V < 250 \text{ GeV}$ regions with zero or at least one particle-level jet are merged.

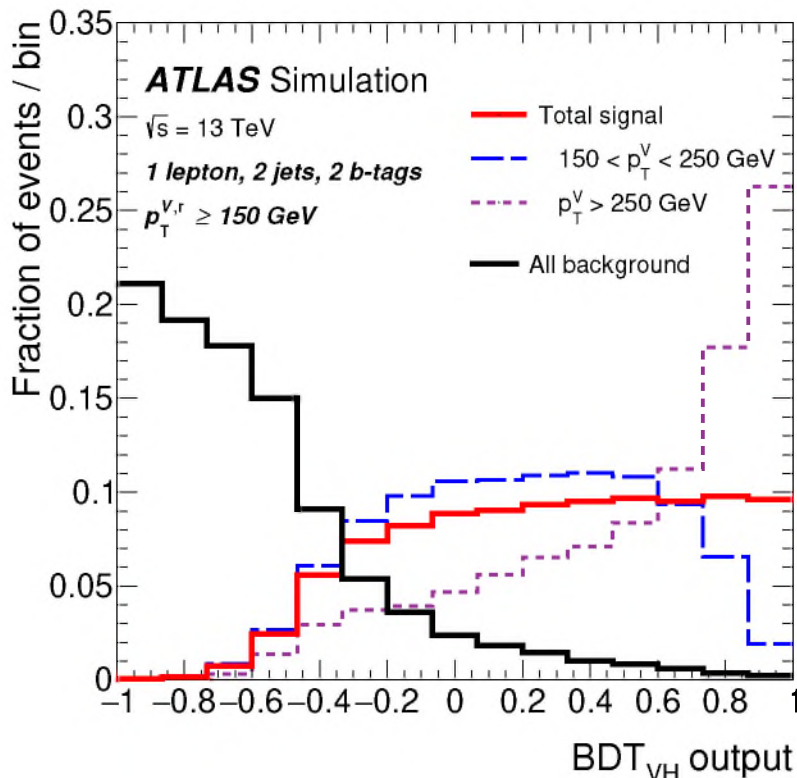


Figure 1. BDT_{VH} distributions for different p_T^V STXS regions in the 1-lepton, 2-jet reconstructed-event category. Only regions contributing at least 10% of the expected signal yield in the reconstructed-event category are displayed. The distributions of the total signal and background are also shown. The BDT_{VH} distributions are scaled to the same (unit) area to highlight the shape differences.

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 $p_T^{V,r}$ 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 $H \rightarrow b\bar{b}$ 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 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 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 $H \rightarrow b\bar{b}$ and $V \rightarrow \text{leptons}$ 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 , $V \rightarrow \text{leptons}$, $H \rightarrow b\bar{b}$ 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 $p_{\text{T}}^W < 150$ GeV and to ZH events with $p_{\text{T}}^Z < 75$ 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 $p_{\text{T}}^W < 150$ GeV and $p_{\text{T}}^Z < 75$ 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:

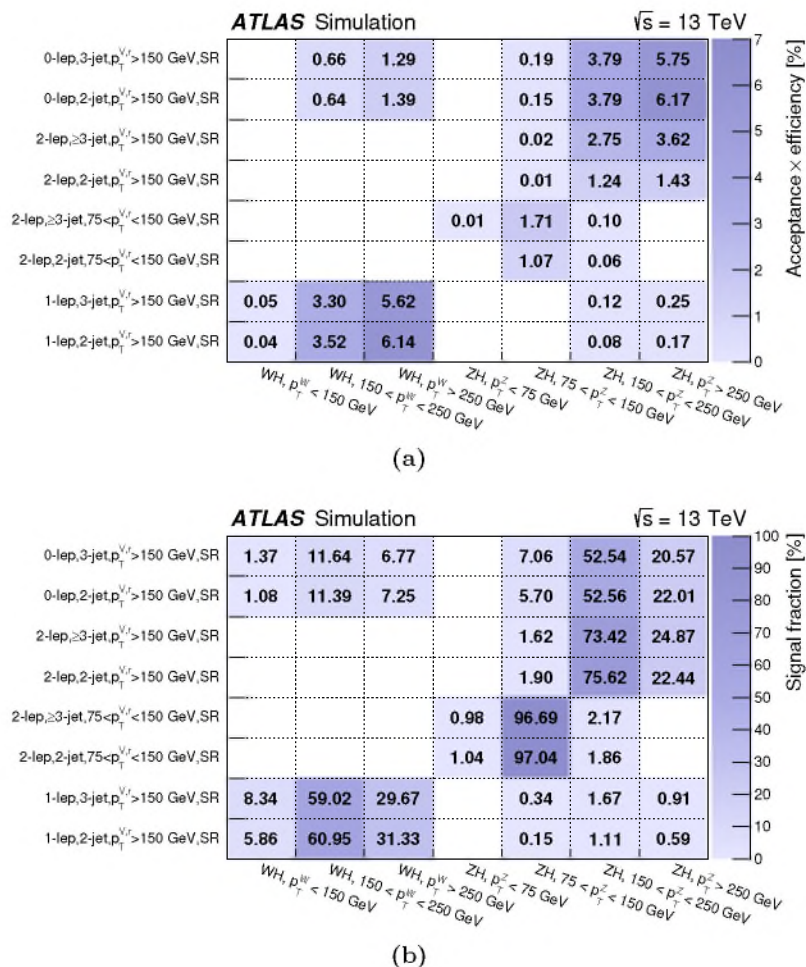


Figure 2. In the 5-POI reduced stage-1 scheme, (a) the acceptance (including the efficiency of the experimental selection) for VH , $V \rightarrow$ leptons, $H \rightarrow b\bar{b}$ events of each reconstructed-event category (y -axis) for each STXS signal region (x -axis), in percent; (b) the fraction 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 $q\bar{q} \rightarrow VH$ and $gg \rightarrow ZH$ 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 α_s . Fourteen independent sources of uncertainties due to the missing higher-order terms lead to total uncertainties of 3%–4% for $q\bar{q} \rightarrow VH$ and 40%–50% for $gg \rightarrow ZH$ with $p_{\text{T}}^V > 75$ GeV [44]. Thirty-one independent sources of PDF and α_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 $p_{\text{T}}^{V,r}$ 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 α_s choices are considered.

Systematic uncertainties in the signal acceptance and shape of the $p_{\text{T}}^{V,r}$ 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 $q\bar{q} \rightarrow VH$ ($gg \rightarrow ZH$) production mode. Two independent nuisance parameters account for the systematic uncertainties induced by the PS and UE models in the $p_{\text{T}}^{V,r}$ 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 $q\bar{q} \rightarrow VH$ processes [15].

5 Results

The measured reduced stage-1 VH cross-sections times the $H \rightarrow b\bar{b}$ and $V \rightarrow$ 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 $p_{\text{T}}^V > 150$ GeV intervals are not equal to the sum of those measured for $150 < p_{\text{T}}^V < 250$ GeV and $p_{\text{T}}^V > 250$ GeV. This is because the signal template for $p_{\text{T}}^V > 150$ 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

| Measurement region ($ y_H < 2.5, H \rightarrow b\bar{b}$) | SM prediction [fb] | Result [fb] | Stat. unc. | | | | Syst. unc. [fb] | | |
|---|-----------------------|----------------|------------|-----------|-----------|-----------|-----------------|----------|------|
| | | | [fb] | | [fb] | | Th. sig. | Th. bkg. | Exp. |
| 5-POI scheme | | | | | | | | | |
| $W \rightarrow \ell\nu; 150 < p_T^V < 250 \text{ GeV}$ | 24.0 \pm 1.1 | 20 \pm 25 | \pm 17 | \pm 2 | \pm 13 | \pm 9 | | | |
| $W \rightarrow \ell\nu; p_T^V > 250 \text{ GeV}$ | 7.1 \pm 0.3 | 8.8 \pm 5.2 | \pm 4.4 | \pm 0.5 | \pm 2.5 | \pm 0.9 | | | |
| $Z \rightarrow \ell\ell, \nu\nu; 75 < p_T^V < 150 \text{ GeV}$ | 50.6 \pm 4.1 | 81 \pm 45 | \pm 35 | \pm 10 | \pm 21 | \pm 19 | | | |
| $Z \rightarrow \ell\ell, \nu\nu; 150 < p_T^V < 250 \text{ GeV}$ | 18.8 \pm 2.4 | 14 \pm 13 | \pm 11 | \pm 1 | \pm 6 | \pm 3 | | | |
| $Z \rightarrow \ell\ell, \nu\nu; p_T^V > 250 \text{ GeV}$ | 4.9 \pm 0.5 | 8.5 \pm 4.0 | \pm 3.7 | \pm 0.8 | \pm 1.2 | \pm 0.6 | | | |
| 3-POI scheme | | | | | | | | | |
| $W \rightarrow \ell\nu; p_T^V > 150 \text{ GeV}$ | 31.1 \pm 1.4 | 35 \pm 14 | \pm 9 | \pm 2 | \pm 9 | \pm 4 | | | |
| $Z \rightarrow \ell\ell, \nu\nu; 75 < p_T^V < 150 \text{ GeV}$ | 50.6 \pm 4.1 | 81 \pm 45 | \pm 35 | \pm 10 | \pm 21 | \pm 19 | | | |
| $Z \rightarrow \ell\ell, \nu\nu; p_T^V > 150 \text{ GeV}$ | 23.7 \pm 3.0 | 28.4 \pm 8.1 | \pm 6.4 | \pm 2.4 | \pm 3.6 | \pm 2.3 | | | |

Table 3. Best-fit values and uncertainties for the $VH, V \rightarrow \text{leptons}$ reduced stage-1 simplified template cross-sections times the $H \rightarrow b\bar{b}$ 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.

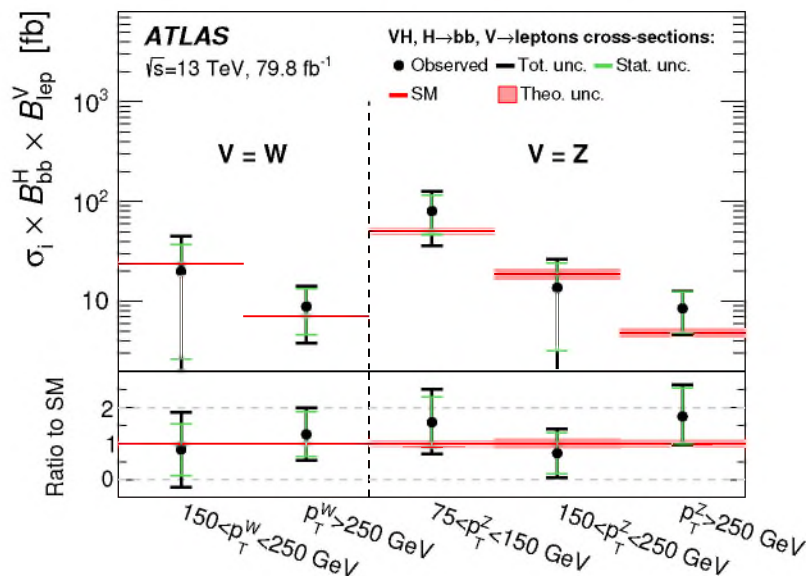


Figure 3. Measured VH , $V \rightarrow$ leptons reduced stage-1 simplified template cross-sections times the $H \rightarrow b\bar{b}$ branching ratio.

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 $c_i^{(D)} \mathcal{O}_i^{(D)} / \Lambda^{D-4}$, where Λ is the energy scale of the new interactions, $\mathcal{O}_i^{(D)}$ 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 Λ .

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 (\mathcal{O}_{HW} , \mathcal{O}_W) and Z bosons (all four operators):

- $\mathcal{O}_{HW} = i (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$,
- $\mathcal{O}_{HB} = i (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$,
- $\mathcal{O}_W = \frac{i}{2} \left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) D^\nu W_{\mu\nu}^a$,
- $\mathcal{O}_B = \frac{i}{2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) \partial^\nu B_{\mu\nu}$.

The corresponding CP -odd operators $\tilde{\mathcal{O}}_{HW}$, $\tilde{\mathcal{O}}_{HB}$, $\tilde{\mathcal{O}}_W$, and $\tilde{\mathcal{O}}_B$, are not considered.

Modifications of the $gg \rightarrow ZH$ 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 $gg \rightarrow ZH$ contribution is kept fixed to the SM prediction.

The operator $\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R$ (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 Γ_H^{bb} and of the total Higgs boson width Γ_H , and therefore of the $H \rightarrow b\bar{b}$ 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 $\mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{HW}, \mathcal{O}_{HB}$ and \mathcal{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:

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

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.

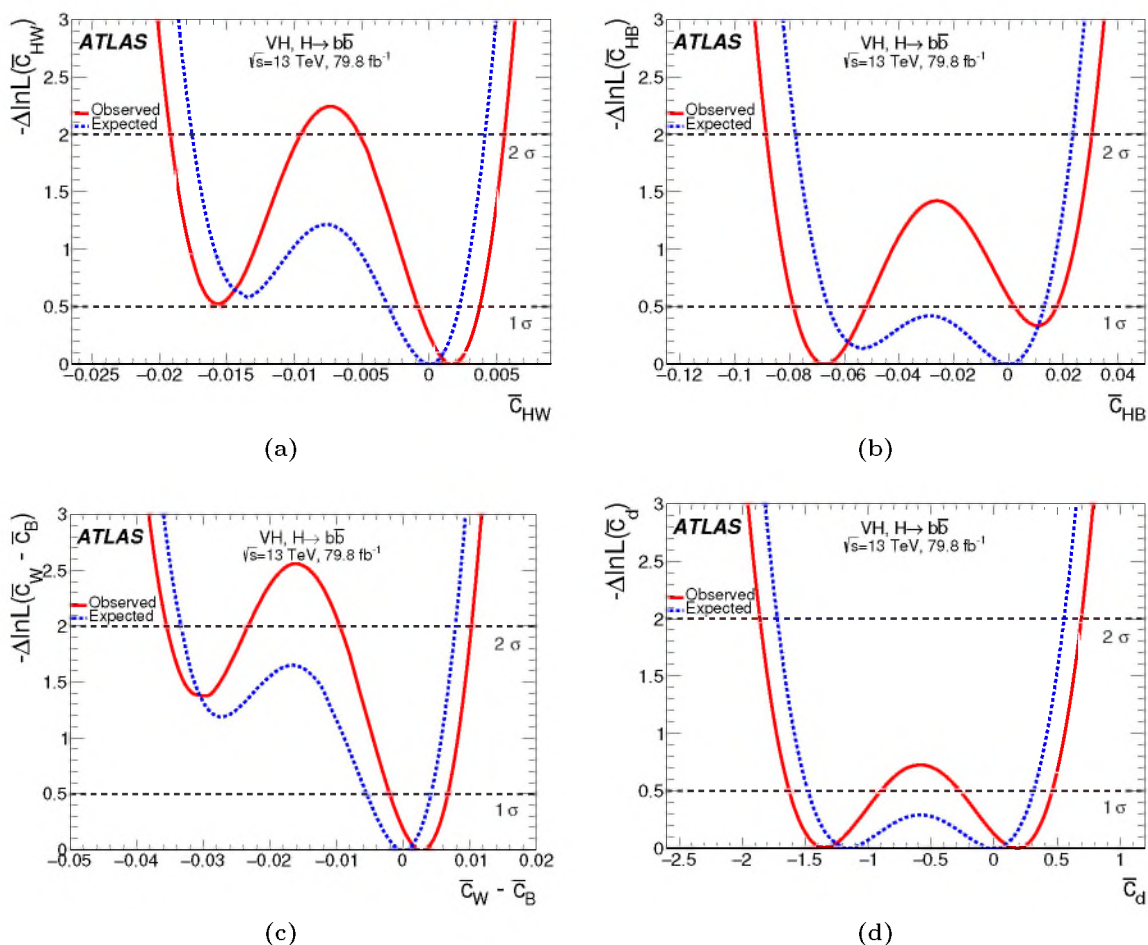


Figure 4. The observed (solid) and expected (dotted) profiled negative-log-likelihood functions for the one-dimensional fits to constrain the coefficients (a) \bar{c}_{HW} , (b) \bar{c}_{HB} , (c) $\bar{c}_W - \bar{c}_B$ and (d) \bar{c}_d of an effective Lagrangian (described in the text), when the other coefficients are assumed to vanish.

7 Conclusion

Using 79.8 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ 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 ($> 250 \text{ GeV}$) regions that are most sensitive to enhancements from potential anomalous interactions between the Higgs boson and the electroweak gauge bosons.

| Coefficient | Expected interval | Observed interval |
|---------------------------------|-------------------|---|
| Results at 68% confidence level | | |
| \bar{c}_{HW} | $[-0.003, 0.002]$ | $[-0.001, 0.004]$ |
| (interference only | $[-0.002, 0.003]$ | $[-0.001, 0.005]$) |
| \bar{c}_{HB} | $[-0.066, 0.013]$ | $[-0.078, -0.055] \cup [0.005, 0.019]$ |
| (interference only | $[-0.016, 0.016]$ | $[-0.005, 0.030]$) |
| $\bar{c}_W - \bar{c}_B$ | $[-0.006, 0.005]$ | $[-0.002, 0.007]$ |
| (interference only | $[-0.005, 0.005]$ | $[-0.002, 0.008]$) |
| \bar{c}_d | $[-1.5, 0.3]$ | $[-1.6, -0.9] \cup [-0.3, 0.4]$ |
| (interference only | $[-0.4, 0.4]$ | $[-0.2, 0.7]$) |
| Results at 95% confidence level | | |
| \bar{c}_{HW} | $[-0.018, 0.004]$ | $[-0.019, -0.010] \cup [-0.005, 0.006]$ |
| (interference only | $[-0.005, 0.005]$ | $[-0.003, 0.008]$) |
| \bar{c}_{HB} | $[-0.078, 0.024]$ | $[-0.090, 0.032]$ |
| (interference only | $[-0.033, 0.033]$ | $[-0.022, 0.049]$) |
| $\bar{c}_W - \bar{c}_B$ | $[-0.034, 0.008]$ | $[-0.036, -0.024] \cup [-0.009, 0.010]$ |
| (interference only | $[-0.009, 0.010]$ | $[-0.006, 0.014]$) |
| \bar{c}_d | $[-1.7, 0.5]$ | $[-1.9, 0.7]$ |
| (interference only | $[-0.8, 0.8]$ | $[-0.6, 1.1]$) |

Table 4. The expected and observed 68% CL (four top rows) and 95% CL (four bottom rows) intervals for the effective Lagrangian coefficients \bar{c}_{HW} , \bar{c}_{HB} , $\bar{c}_W - \bar{c}_B$ and \bar{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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The ATLAS collaboration

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