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Measurement of the Standard Model Higgs boson produced in association with a vector boson and decaying to a pair of b-quarks in p-p collisions at 13 TeV using the ATLAS detector

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The Higgs boson decays to pairs of b-quarks were measured in associated production with a W or Z boson by the ATLAS collaboration at the Large Hadron Collider (LHC). The decay to b-quarks is of particular importance since it allows a direct measurement of the coupling of the Higgs boson to b-quarks. The highest sensitivity in this channel is obtained when the vector boson produced alongside the Higgs boson decays to leptons. The analysed data were collected in proton-proton collisions at the LHC during Run-2 at a center-of-mass energy of 13 TeV. The final state requires having exactly 2 b-tagged jets and either 0, 1 or 2 charged leptons (electrons or muons) corresponding to the following channels: $Z \to \nu\nu$, $W \to l\nu$ and $Z \to ll$. The analysis benefits from the full Run-2 data and from novel techniques used to improve the analysis sensitivity. The measurements yield the observation of the VH signal as well as the observation of the ZH signal and a strong evidence of the WH signal. The results are validated with the diboson (VZ) analysis by measuring the $VZ, Z \to b\bar{b}$ signal strength, and are cross-checked with an analysis using the di-jet mass rather than the BDT$_{VH}$ output as main discriminant, which also leads to the observation of the VH signal. All the results are in good agreement with the Standard Model expectations.

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1. Motivations for the measurement of $VH, H \to b\bar{b}$

The observation of a particle in 2012 by the ATLAS [1, 2] and CMS [3, 4] experiments consistent with the Standard Model (SM) Higgs boson, opened up a whole new field of research at the Large Hadron Collider. The measurements of this particle allow to refine our understanding of the SM and probe new physics beyond this model. Thus, it is important to measure the Higgs boson in all its production modes and decay channels, to gain as much insight as possible on the Higgs sector of the SM.

The decay of the Higgs boson into pairs of b-quarks is the dominant decay mode, with a predicted branching ratio of 58%. Measuring the Higgs boson in this channel is very important as it allows to constrain the Higgs boson total width when included in Higgs combinations. The existence of this decay is also the only experimental evidence of a coupling of the Higgs boson to down quarks. The production mode that gives the highest sensitivity to this measurement is when the Higgs boson is produced alongside a vector boson (W or Z boson) which will then decay to leptons. When looking at the leptonic decays of the vector boson, this allows to suppress the QCD multi-jet background due to the clean signature of leptons inside the detector. In addition, this production channel allows to measure the Higgs boson coupling to the vector boson at high energies using differential cross-section measurements.

2. Analysis strategy

The events are selected by the analysis after passing a series of selection criteria, intended to reduce the background contamination. The events are then categorised depending on the number of charged leptons in the final state coming from the vector boson decays, corresponding to the 0-, 1-, and 2-lepton channels and targeting the following decays: $Z(\to \nu\bar{\nu})H(\to b\bar{b})$, $W(\to l\nu)H(\to b\bar{b})$ and $Z(\to l\bar{l})H(\to b\bar{b})$ as presented in Figure 1. The lepton can be either an electron or a muon. Since the analysis is looking for $H \to b\bar{b}$ candidates, events with at least 2 b-jets are selected by applying b-tagging requirements.

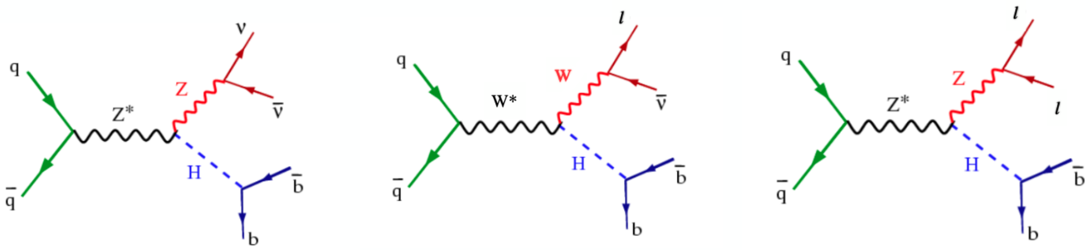

Figure 1: Feynman diagrams representative of the three $VH, H \to b\bar{b}$ channels.

To maximise the sensitivity, the analysis uses a multivariate approach (MVA) based on Boosted Decision Trees (BDTs). The BDTs use simple cuts on kinematic variables to classify an event as being more signal-like or background-like. This approach consists in constructing one discriminant (BDT_{VH}) from the kinematic variables to better distinguish between the VH signal and the sum of the backgrounds. This discriminant is used in the final binned likelihood fit to measure the signal.

State-of-the-art Monte Carlo generators are used to model the dominant background processes: the vector boson produced in association with jets (V+jets) uses Sherpa 2.2.1 [5], top ($t\bar{t}$ and single top) uses PowhegPythia8 [6, 7] and diboson (VZ) uses Sherpa 2.2.1. Data-driven modelling methods have been developed and used to estimate the top background in the 2-lepton channel by extrapolating data events from a top enriched $e\mu$ control region, which allows to reduce the dedicated modelling systematic uncertainties. Similarly, the multi-jet background was modelled using a data-driven template fit method given the difficulty of obtaining enough statistics when using Monte Carlo generators. Modelling uncertainties are assigned to the normalisation and shape prediction of the backgrounds.These uncertainties have a large contribution to the total uncertainty which requires to control them well. This includes a new multi-dimensional reweighting method based on BDTs to get the shape uncertainties of the $t\bar{t}$ and W+jets backgrounds in the 0- and 1-lepton channels. The method consists in training the BDT to distinguish the nominal generator used by the analysis to obtain the background template from an alternative generator with a different tuning. The ratio of the BDT score distribution between the nominal and alternative generator is used to reweight the nominal distribution and make it morph into the alternative generator. The difference between the nominal template and the reweighting is considered as the shape systematic uncertainty.

3. Events Categorisation

Events are classified into categories, defined based on the number of jets in the final state: 2-jet category or a 3-jet category (or $\geq$ 3-jet only in the 2-lepton channel) of which 2 should be b-tagged. Furthermore, three categories have been created depending on the reconstructed transverse momentum of the vector boson (P_{T}^{V}): 75 GeV$< P_{\mathrm{T}}^{V} <$ 150 GeV region (only in the 2-lepton channel), 150 GeV$< P_{\mathrm{T}}^{V} <$ 250 GeV and $P_{\mathrm{T}}^{V} >$ 250 GeV regions. These categories allow to achieve a higher sensitivity at high P_{T}^{V} regime since the signal has a harder spectrum than the backgrounds.

Signal (SR) and control (CR) regions are defined by applying a P_{T}^{V}-dependent selection on the angular separation (ΔR) between the two b-jet candidates, as shown in Figure 2. The control regions are background enriched regions with low signal acceptance.

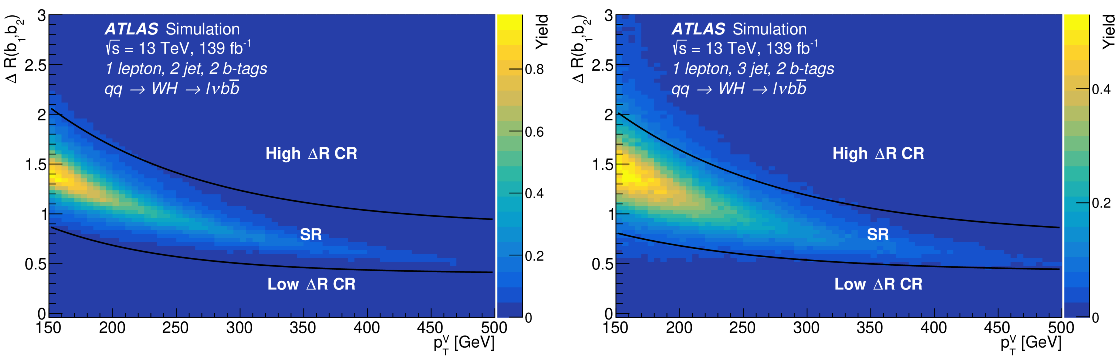

Figure 2: The signal distribution of ΔR_{bb} as a function of the P_{T}^{V} in the 1-lepton channel in the 2-jet (left) and 3-jet (right) categories. The black lines show the cuts used to define the signal (SR) and control (CR) regions [8].

The cuts are common across the three lepton channels, where in the 0- and 1-lepton channels the low ΔR control region contains the majority of W+jets events, whereas the high ΔR control region is pure in top background. However, since Z+jets is the main background in the 2-lepton channel, both the high and low ΔR control regions are enriched in Z+jets events. The analysis counts a total of 14 signal regions, where to each signal region is associated a high and a low control region, making a total of 28 control regions. To measure the signal yield, the BDT$_{VH}$ discriminant is used in the SRs in the binned likelihood fit, and the yield in the control regions. Creating dedicated control regions allows to constrain the normalisation of the dominant background processes and their dedicated systematic uncertainties. In the fit, these constraints are propagated across regions and channels with appropriate uncertainties.

4. Results and Conclusions

The measurement of $VH, H \to b\bar{b}$ was performed using 139 fb^{-1} of data collected by the ATLAS detector in p-p collisions at a center-of-mass energy of 13 TeV [8].

The VH signal is observed with a significance of 6.7σ (6.7σ expected). The ratio of the observed signal yield to the expected yield, known as signal strength, is found to be $\mu_{VH}^{bb}= 1.02^{+0.18}_{-0.17}$. When measuring the WH and ZH signals simultaneously, the measurements yield the observation of ZH and a strong evidence of WH with 5.3σ and 4.0σ (5.1σ and 4.1σ expected) respectively. The measured signal strength were found to be in good agreement with the SM expectations within uncertainties. These measurements were also performed in the context of the simplified template cross-section (STXS) framework [9] in 5 bins defined of the P_{T}^{V} distribution. The results are presented in Figure 3 and are consistent with the SM prediction within uncertainties.

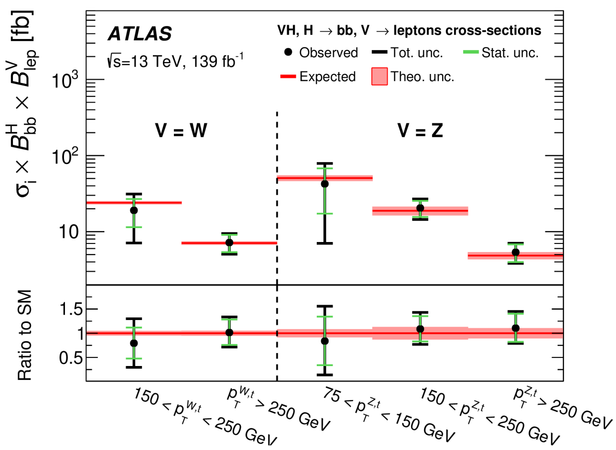

Figure 3: The Measured VH, $V \to$ leptons cross-sections times the $H \to b\bar{b}$ branching fraction in each of the 5 STXS bins [8].

The diboson analysis is a robust validation of the VH results since the VZ process is very similar to VH. This analysis uses a dedicated BDT called BDT$_{VZ}$ as a discriminant, and the results are found to be in good agreement with the SM with $\mu_{VZ}^{bb}= 0.93^{+0.07}_{-0.06}$, therefore validating the VH results.

The results are further cross-checked with an analysis that uses the Higgs boson candidate mass instead of the BDT$_{VH}$ discriminant in the binned likelihood fit. The cross-check analysis also leads to the observation of the VH signal with 5.5σ (4.9σ expected), corresponding to $\mu_{VH}^{bb}= 1.17^{+0.25}_{-0.23}$.

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