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MEASUREMENT OF THE ASSOCIATED PRODUCTION OF A HIGGS BOSON DECAYING INTO b-QUARKS WITH A VECTOR BOSON AT HIGH TRANSVERSE MOMENTUM WITH THE ATLAS DETECTOR*

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The observation of the decay of the Higgs boson to a $b\bar{b}$ pair in 2018 provided a confirmation of the Yukawa interaction and the first measurement of a Yukawa coupling to down-type quarks. The experimental challenges that the $H \to b\bar{b}$ decay entails at hadron colliders can be addressed by studying the associated Higgs boson production with a vector boson V decaying leptonically. Following the observation, the main focus is now the study of the Higgs boson production cross section as a function of its transverse momentum (p_{T}). These measurements are well motivated by a wide range of Beyond the Standard Model (BSM) theories predicting an enhancement of $VH(H \to b\bar{b})$ events at high transverse momentum with respect to the SM expectations. At such high energy regimes, the Higgs boson is highly Lorentz-boosted and the $H \to b\bar{b}$ decay is reconstructed in the detector as a single object with a two-prong substructure, using novel techniques. The paper will illustrate the measurement of $VH(H \to b\bar{b})$ in the boosted regime performed inclusively, as well as in bins of the vector boson transverse momentum, for $p_{\mathrm{T}}^{V} \in [250, 400)$ GeV and $p_{\mathrm{T}}^{V} \in [400, \infty)$ GeV. Their interpretation using the Effective Field Theory (EFT) framework will also be discussed. The results are based on the full LHC Run 2 dataset collected by the ATLAS experiment, corresponding to an integrated luminosity of 139 fb^{-1}.

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1. Introduction

The observation of the decay of the Higgs boson to a $b\bar{b}$ pair was one of the most sought-after results of the LHC Run 2, since in the SM the Higgs

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boson decays to a $b\bar{b}$ pair with the largest branching ratio (BR $\approx$ 58%) and the $H \to b\bar{b}$ decay represents the only process for which it is possible, given the current experimental sensitivity, to measure the Yukawa coupling to down-type quarks. However, there are several experimental challenges for this measurement at hadron colliders, the biggest of which is the small signal-to-background ratio, the main background being from non-resonant production of quarks and gluons (*QCD processes*).

Given this, despite the relatively low cross section with respect to other production processes ($\sigma_{VH} = 2.25$ pb, $\sigma_H \approx 51$ pb at $\sqrt{s} = 13$ TeV), the associated production of a Higgs boson and a vector boson (VH, $V = W^{\pm}, Z$) is a really important Higgs production mechanism at the LHC. The vector boson leptonic decay modes lead to distinctive signatures that can be efficiently selected, while suppressing most of the background from QCD processes. Three different signatures are targeted by the analysis: $ZH \to \nu\bar{\nu}b\bar{b}$ (0-lepton channel), $WH \to \ell\nu b\bar{b}$ (1-lepton channel) and $ZH \to \ell^-\ell^+b\bar{b}$ (2-lepton channel).

The $H \to b\bar{b}$ and VH processes were observed in 2018 [1] and $VH(H \to b\bar{b})$ was the main contributor, with a measured statistical significance of 4.9σ. The following step is to study the production cross section as a function of the transverse momentum (p_{T}) of the Higgs boson, since several beyond the SM theories predict an enhancement of $VH(H \to b\bar{b})$ events at high p_{T}^H or p_{T}^V [3]. At very high p_{T}^H ($p_{\mathrm{T}}^H > 250$ GeV), the Higgs boson is highly Lorentz-boosted, with the $H \to b\bar{b}$ decay is reconstructed in the detector as a single object (large-radius jet) with a two-prong substructure, as in figure 1. The $VH(H \to b\bar{b})$ boosted analysis aims to study $VH(H \to b\bar{b})$ events in such a high-energy regime [2].

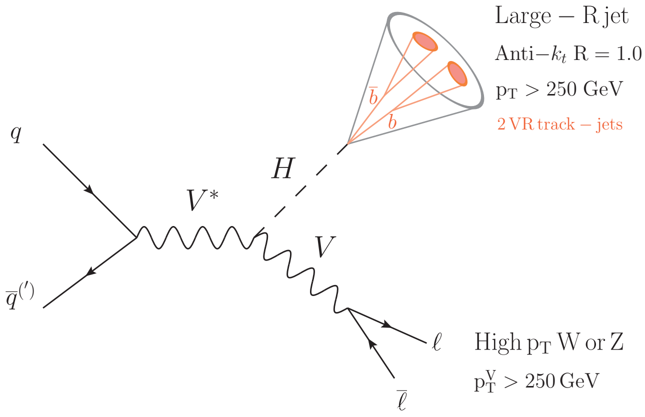

Fig. 1. Sketch of the $VH(H \to b\bar{b})$ process at high Higgs boson transverse momentum.

2. Data and simulation samples

The $VH(H \to b\bar{b})$ boosted analysis is performed with the proton–proton collision data collected by the ATLAS experiment in the full LHC Run 2, from 2015 to 2018, corresponding to an integrated luminosity of 139 fb^{-1} at a center-of-mass energy $\sqrt{s} = 13$ TeV.

The majority of the SM background processes as well as the $VH(H \to b\bar{b})$ signal are simulated with Monte Carlo (MC) simulation packages such as Powheg, PYTHIA 8 and Sherpa. After the generation of the events, all samples are then interfaced with the ATLAS detector simulation based on Geant4.

3. Event selection

The selection criteria of the $VH(H \to b\bar{b})$ boosted analysis aim at reconstructing a boosted Higgs boson candidate, associated to a leptonically-decaying V.

The *Higgs boson candidate* is reconstructed as a large-radius jet with $p_{\mathrm{T}} \geq 250$ GeV, with a substructure of two b-tagged track jets reconstructed inside it. The candidate V boson, instead, is reconstructed based on its leptonic decay and the selection is applied so as to have transverse momentum $p_{\mathrm{T}}^{V} > 250$ GeV. The number of stable[1] charged leptons in the leptonic V decay determines the analysis channel. For example, in the 0-lepton channel, one has $E_{\mathrm{T}}^{\mathrm{miss}} \geq 250$ GeV from the two neutrinos that were not reconstructed in the $ZH \to \nu\bar{\nu}\, b\bar{b}$ decay.

Then, several other selection criteria are applied in order to further suppress background events, making use of the expected kinematics and topology of the events.

4. Event categorisation

After applying the selection criteria, events in all the three lepton channels are then categorised depending on the p_{T} of the vector boson candidate. Events fall into a medium-p_{T}^{V} region if 250 GeV $\leq p_{\mathrm{T}}^{V} <$ 400 GeV and into a high-p_{T}^{V} region for $p_{\mathrm{T}}^{V} \geq 400$ GeV.

In the 0-lepton and 1-lepton channel only, events are further categorised depending on the number of "additional" jets, not matched to the large-radius (Higgs-candidate) jet. Specifically, events that contain an additional b-tagged variable-radius track jet are categorised into a top-quark enriched control region (CR). The other events belong to the signal region (SR).

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[1] Electrons and muons. τ leptons decay within the ATLAS experiment and are, therefore, not considered as stable.

Events in the signal region are further split according to the expected topology of $VH(H \to b\bar{b})$ events at leading order. This categorisation is based on the absence or presence of additional small-radius calorimeter jets. A “high purity” signal region is obtained by vetoing the presence of additional calorimeter jets, otherwise a “low purity” signal region is defined. A summary of the signal and control regions is given in Table I.

TABLE I

Summary of the definition of the analysis regions. Regions with relatively large signal purity are marked with the label SR. Background-enriched regions are marked with the label CR.

Channel	Categories					
	$250 < p_{\mathrm{T}}^{V} < 400$ GeV			$p_{\mathrm{T}}^{V} > 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	SR	SR	CR	SR	SR	CR
1-lepton	SR	SR	CR	SR	SR	CR
2-lepton	SR			SR		

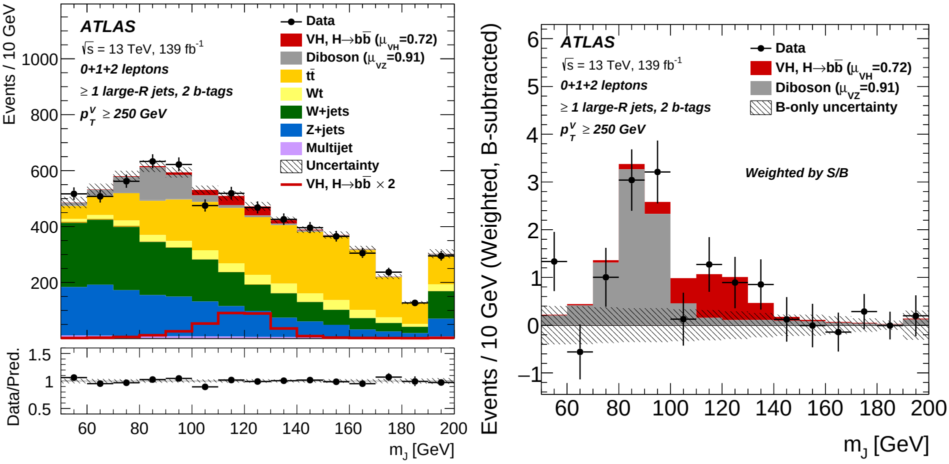
5. Background processes and statistical analysis

The $VH(H \to b\bar{b})$ boosted analysis phase space has an extremely diverse background composition, in terms of processes and m_J spectra. For this reason, the background predictions cannot be fixed using data, but rely crucially on the usage of simulations. In order to be able to do so, “modelling” uncertainties on the accuracy of the simulation prediction are assessed (see figure 2 (a)). The QCD background is largely suppressed by the requirement on the leptonic V decay and is only non-negligible in the 1-lepton channel, where it is evaluated using data-driven methods. In terms of the other background processes, top-quark pair production ($t\bar{t}$) is dominant in the 0-lepton and 1-lepton channels, as well as Z+jets in the 0-lepton and 2-lepton channels, W+jets in the 1-lepton channel (also present in the 0-lepton channel). Other background processes include vector boson pairs production (diboson) and single top (only in the 0-lepton and 1-lepton channel).

The last step of the analysis is to measure the signal yield. In order to do so, a binned profile likelihood fit is performed to the invariant Higgs candidate mass m_J. This fit is done simultaneously to the signal and control regions and all three lepton channels. The fit extracts simultaneously the

$VH(H \to b\bar{b})$ and $VZ(Z \to b\bar{b})$ signal strengths[2], called μ_{VH} and μ_{VZ} respectively. Furthermore, it extracts the normalisation factors for the most important processes $t\bar{t}$, W+jets, Z+jets, thanks to the use of background-enriched control regions.

All systematic uncertainties are inserted in the fit as additional degrees of freedom with Gaussian constraints that the fit is allowed to optimise. Detector systematics on the physics objects and modelling uncertainties are included.



(a) (b)

Fig. 2. Large-radius jet mass distribution combining all three lepton channels and signal regions by (a) stacking them and (b) after background subtraction except for the WZ and ZZ diboson processes.

The measured values for the $VH(H \to b\bar{b})$ and $VZ(Z \to b\bar{b})$ signal strengths are (figure 2 (b)):

$$\mu_{VH} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})\,, \tag{1}$$

$$\mu_{VZ} = 0.92^{+0.29}_{-0.23} = 0.92^{+0.15}_{-0.15}(\text{stat.})^{+0.25}_{-0.17}(\text{syst.}) \tag{2}$$

with an observed (expected) significance for $VH(H \to b\bar{b})$ $\sigma^{bb}_{VH} = 2.1\ (2.7)\sigma$, and an observed (expected) significance for $VZ(Z \to b\bar{b})$ $\sigma^{bb}_{VZ} = 5.3\ (5.7)\ \sigma$, in very good agreement with the SM expectations.

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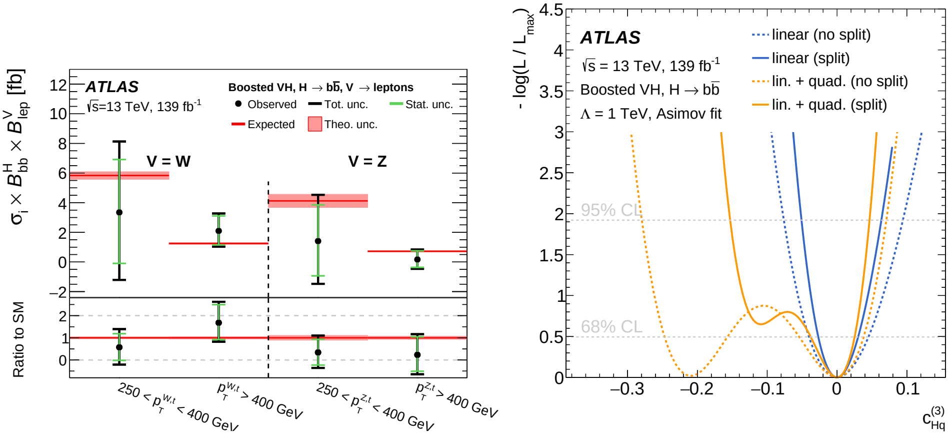
[2] The signal strength parameter for a process is defined as the ratio between the observed cross section of the process and its prediction in the SM.

6. Simplified Template Cross Section measurement and Effective Field Theory interpretation

After the inclusive cross-section measurement, a differential cross-section measurement is provided, in simplified fiducial regions, using the Simplified Template Cross Section (STXS) approach. The STXS measurement is found to be well in agreement with the SM predictions (figure 3 (a)).

Finally, the STXS results are interpreted in an Effective Field Theory (EFT) approach. In this SMEFT approach, the SM Lagrangian is extended with higher-dimensional operators that depend on their Wilson coefficients (c_i). The VH production cross section and the $H \to b\bar{b}$ decay are then parametrised as linear/quadratic functions of the said coefficients and finally the 95% C.L. limits for the coefficients are extracted. In this context, it is interesting to appreciate the effect of the dedicated analysis $p_{\mathrm{T}}^{V} > 400$ GeV bin on the constraints of the EFT operators (figure 3 (b)).



(a) (b)

Fig. 3. Measured VH reduced stage-1.2 simplified template cross-sections times the $H \to b\bar{b}$ and $V \to$ leptons branching fractions (a). Effect of the dedicated bin $p_{\mathrm{T}}^{V} > 400$ GeV on the expected 95% C.L. limits on Wilson Coefficient $c_{Hq}^{(3)}$ in the SMEFT approach (b).

7. Conclusion

The $VH(H \to b\bar{b})$ boosted analysis described in these proceedings is the first analysis probing this process at high p_{T} with the ATLAS experiment, with a dedicated measurement for $p_{\mathrm{T}}^{V} > 400$ GeV. Results, for which an EFT interpretation is provided, are well in agreement with the SM expectations.

REFERENCES

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