Observation of the Higgs decay to beauty quarks

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Abstract. Higgs bosons decaying to $b$-quark pairs were searched in the production associated with vector bosons using 79.8 fb$^{-1}$ data of $pp$ collisions at the center of mass energy of 13 TeV provided by the Large Hadron Collider and recorded by the ATLAS detector. The observed (expected) significance of the signal is 4.9 (4.3) $\sigma$. This result was combined with the $H \rightarrow b\bar{b}$ results of Run 1 and Run 2 datasets for vector boson fusion production and associated production with top quark pairs. A combination with $H \rightarrow \gamma\gamma$ and 4$\ell$ decay modes in associated production with vector bosons was performed using the Run 2 results. The observed (expected) significance of this production modes is 5.3 (4.8) $\sigma$.

1. Introduction
The Higgs boson predicted in the Standard Model (SM) was discovered by the ATLAS and the CMS experiments using $pp$ collisions at the center of mass energy of 7 and 8 TeV provided by the Large Hadron Collider (LHC) in Run 1 [1, 2]. The discovery was mainly driven by the bosonic decay channels: $\gamma\gamma$, $WW^*$ and $ZZ^*$. Detection of the fermionic decays of Higgs boson is essential to examine the origin of mass of the fermions. The decay of the Higgs bosons to $b$-quark pairs happens through the Yukawa coupling to $b$-quark. The branching ratio of this decay is the largest in the SM expectation, and it is approximately 58%. It is important to observe this decay because it allows us to directly detect and measure the Yukawa coupling to the $b$-quark, and also to better constrain the total width and other couplings of Higgs boson under the assumption of SM like coupling structure. In the LHC, the $b\bar{b}$ final state in the main gluon-gluon fusion production mode is very hard to be discriminated from the multi-jet background. Thus, data collected by the ATLAS detector [3] were analysed for the $H \rightarrow b\bar{b}$ decay in the associated production with $t\bar{t}$ ($ttH$), vector boson fusion ($VBF$) and associated production with vector bosons ($VH$). The $VH$ production provides the highest sensitivity of the three production processes.

2. Search for the $H \rightarrow b\bar{b}$ decay in the associated productions with vector bosons
An analysis of the Higgs boson decays to the $b$-quark pairs in the associated production with vector bosons was performed using the 79.8 fb$^{-1}$ data of $pp$ collision at the center of mass energy of 13 TeV provided by the LHC [4].

To suppress the huge multi-jet background in the $b\bar{b}$ final states, leptonic decays of vector bosons were exploited. Vector bosons were required to be produced with high transverse momenta because the $VH$ signal is produced with harder distribution than backgrounds as.

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Figure 1 (left). Events were separated into three analysis channels based on the number of the charged leptons, 0, 1 or 2 lepton signal from $Z$ or $W$ bosons, and define the signal regions (SRs). The event selections and event categorizations for three channels are briefly summarized in Table 1 and in this paragraph. The complete descriptions can be found in Ref.[4]. For the 0 lepton channel, where the associated $Z$ bosons decay to neutrinos, events were collected by Missing $E_T$ triggers and a cut on the Missing $E_T$ were applied at 150 GeV. The Missing $E_T$ represents the transverse momentum of the vector boson ($p_T^{V}$) in this channel. We also required that there were 2 or 3 jets and 2 of them were $b$-tagged. For the 1 lepton channel, which aimed at $WH$ signal and $W$ bosons decaying into electrons or muons, Missing $E_T$ triggers were employed for muon events and single electron triggers for electron events. $p_T^{V}$, which was computed as the vectorial sum of the Missing $E_T$ and the lepton $p_T$, was required to be greater than 150 GeV. The same number of jets and $b$-tagged jets were required as the 0 lepton channel. For the 2 lepton channel, where the associated $Z$ bosons decay to electrons or muons, single electron and muon triggers were employed. The mass of dilepton was required to be consistent with the mass of $Z$ boson (81-101 GeV). This channel included the categories with medium $p_T^{V}$ categories (75-150 GeV) in addition to high $p_T^{V}$ categories (150-∞ GeV), which were commonly considered in the 0 and 1 lepton channels. We also required 2 or more jets and exactly 2 of them were $b$-tagged. The selected events were then categorized based on the number of jets: 2 and 3 jets signal regions were defined for the 0 and 1 lepton channels, and the 2 and more than 2 jets signal regions were defined for the 2 lepton channel. 2 signal regions for both 0 and 1 lepton channel and 4 signal regions for 2 lepton channel were considered based on these definitions.

Table 1. Overview of the event selection and the categorization for 0, 1 and 2 lepton channels. The complete descriptions of the event and object selections can be found in Ref.[4]

|                | 0 lepton                                                                 | 1 lepton                                                                 | 2 lepton                                                                 |
|----------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Signals        | $Z(\rightarrow \nu \bar{\nu})H(\rightarrow bb)$                         | $W^{\pm}(\rightarrow \ell^{\mp} \nu, \ell^{\mp} \bar{\nu})H(\rightarrow bb)$ | $Z(\rightarrow \ell^{+}\ell^{-})H(\rightarrow bb)$                       |
| Triggers       | Missing $E_T$                                                             | Missing $E_T$ (muons)                                                     | Single lepton                                                             |
| $p_T^{V}$      | $> 150$ GeV                                                               | $75$ GeV $< p_T^{V} < 150$ GeV                                           | $> 150$ GeV                                                              |
| Jets           | Exactly 2 / Exactly 3 jets                                               | Exactly 2 / ≥ 3jets                                                       |                                                                          |
| $b$-tagging    | Exacty 2 $b$-tagged jets                                                 |                                                                          |                                                                          |

This analysis was dependent on $b$-jet tagging and energy measurements of $b$-jets. The $b$-tagging algorithm was based on a multivariate technique that takes secondary vertex information and impact parameters of the tracks. The tagging efficiency for the $b$-jets was 70% while the mis-tagging efficiencies for $c$- and light-jets were 13% and 0.3%, respectively. For the $b$-jet energy measurement, a series of corrections was applied. First, the muon energy was recovered in the semi-leptonic decays of $b$-hadrons. This is shown in the blue histogram in Figure 1 (right) while the default is in the black one. The energies of the $b$-jets were scaled by a factor derived for each decay mode and energy range of $b$-jet to take into account neutrino energies in semi-leptonic decay and out-of-cone effect. This is shown in the violet histogram. For 2 lepton channel, the final correction called “kinematic fit” was applied to constrain the $b$-jet energies by imposing momentum balance with the leptonic system in the transverse plane. This is shown in the red histogram.

There exist many background processes in the signal regions. First, there are diboson backgrounds, where one $Z$ boson decays into $b$-quarks and the other decays to leptons or neutrinos. These backgrounds form a peak around 90 GeV in the dijet mass distribution. As non-resonant backgrounds, there are $t\bar{t}$, single-top and vector boson+jets processes. As shown
such as invariant mass of the two leptons in each signal region and was applied (Figure 2). The training was based on kinematic variables, simultaneously in the signal extraction procedure that will be discussed later on.

µ which were the top-\(e\) and \(W\) control regions, 2 of which were the top-\(\mu\) CR in the 1 lepton channel. It was defined by flipping some kinematic cuts of the 1 lepton SRs, and used for constraining \(W+\)jets background. The other control region was the top-\(\mu\) CR in the 2 lepton channel. It was defined by requiring the \(\mu\) final state to collect leptonically decaying \(t\bar{t}\) and single-top processes. This control region was 99% pure. We had 6 control regions, 2 of which were the \(W+\)heavy flavor CRs in the 1 lepton channel and 4 of which were the top-\(\mu\) CRs in the 2 lepton channel. Events in these control regions were fitted simultaneously in the signal extraction procedure that will be discussed later on.

To separate the signal events from the backgrounds, Boosted Decision Tree (BDT) was trained in each signal region and was applied (Figure 2). The training was based on kinematic variables, such as invariant mass of the two \(b\)-jets. The invariant mass and opening angle of two \(b\)-jets, and transverse momentum of the vector bosons were most important and had the largest separation power.

We extracted the signal strength \(\mu\) that was defined as the ratio of observed signal yield with respect to the expected yield by SM. The strategy was that the profile likelihood fit was simultaneously performed in 8 signal regions and 6 control regions. In the fit, the signal strength \(\mu\) was extracted and background shapes and normalizations were constrained at the same time. The constraints of the backgrounds obtained in the control regions were propagated to the \(W+\)jets and \(t\bar{t}\) backgrounds in the signal regions. The BDT discriminants were fitted in the signal regions. The backgrounds were further constrained in the low score bins of the signal regions, and then the signal was extracted in the high score bins.

![Figure 1](image1.png)

**Figure 1.** The post-fit distributions of \(p_T^V\) in the 2 jet and high \(p_T^V\) signal region for the 2 lepton channel (left)[4]. Simulated distributions for backgrounds and signals are shown in the filled histograms and data are shown in the black points. Hatched bands include both systematic and statistic uncertainties. Comparison of dijet mass distributions with \(b\)-jet energy corrections (right) [5]. The distributions shown were derived from simulated signal events in the 2 jet and high \(p_T^V\) signal regions of the 2 lepton channel. Fitted Bulkin functions were superimposed as lines for each correction method.

in Figure 2, the background components differ among the lepton channels. The setups of event generation in MC simulations for signals and backgrounds are described in Ref.[4].

As the first step of the signal and backgrounds modeling approach in the analysis, theoretical uncertainties were derived by comparing different MC generators and setups, such as a QCD scale and parton showers. We also considered experimental uncertainties, such as \(b\)-jet tagging efficiency, which were derived from calibration.

To estimate the backgrounds, two types of control regions (CRs) were defined. Each of these control regions was dedicated to one background component. One of the control regions was \(W+\)heavy flavor CR in the 1 lepton channel. It was defined by flipping some kinematic cuts of the 1 lepton SRs, and used for constraining \(W+\)jets background. The other control region was the top-\(\mu\) CR in the 2 lepton channel. It was defined by requiring the \(\mu\) final state to collect leptonically decaying \(t\bar{t}\) and single-top processes. This control region was 99% pure. We had 6 control regions, 2 of which were the \(W+\)heavy flavor CRs in the 1 lepton channel and 4 of which were the top-\(\mu\) CRs in the 2 lepton channel. Events in these control regions were fitted simultaneously in the signal extraction procedure that will be discussed later on.

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BDTs. The fitted dijet mass distribution is shown in Figure 6. The observed as $VH$ analysis for the event selection, the background modeling and the analysis strategy were used to validate the trained for diboson analysis is shown in Figure 4. The key of this analysis was that the same $VH$ taking the diboson as a signal and $3). The signal strength was found as $p_T^{VH}$ of Run 2 dataset for the $0$ lepton (left), $1$ lepton (middle) and $2$ lepton (right) channels [4].

As a result of the simultaneous fit to $79.8$ fb$^{-1}$ of $VH$ analysis, the $VH, H \rightarrow b\bar{b}$ signal was observed at $4.9$ $\sigma$ while the expected significance was $4.3$ $\sigma$. The signal strength was found to be $\mu_H^{b\bar{b}} = 1.16^{+0.27}_{-0.25}$, which is consistent with the SM expectation (Figure 3). The $WH$ and $ZH$ signal strength were also separately determined with a small correlation.

As a validation, we performed a diboson analysis, in which dedicated BDTs were formed taking the diboson as a signal and $VH$ as a background. The distribution of the BDT scores trained for diboson analysis is shown in Figure 4. The key of this analysis was that the same event selection, the background modeling and the analysis strategy were used to validate the analysis for the $VH$ signal. As a result of this analysis, the signal strength for the diboson was observed as $\mu_{VH}^{Diboson} = 1.20^{+0.20}_{-0.18}$, as shown in Figure 5, which is consistent to the SM prediction. Thus, we concluded that the background modeling and analysis strategy of the analysis for $VH$ signal was validated by this diboson analysis.

Another cross-check was the analysis called “dijet mass analysis” (DMA), in which dijet mass distributions were fitted instead of the outputs of the BDTs. To improve sensitivity that was lost by not using BDTs, additional kinematic cuts were applied. The signal regions were further split with $p_T^V$ at $200$ GeV to exploit better purity of the high $p_T^V$ phase spaces. Finally, the signal strength was found as $\mu_{VH}^{DMA} = 1.06^{+0.36}_{-0.33}$, and it is consistent with the analysis using BDTs. The fitted dijet mass distribution is shown in Figure 6.

![Figure 2](image-url)  
**Figure 2.** The post-fit distributions of BDT output scores in $2$ jet and high $p_T^V$ signal regions for the $0$ lepton (left), $1$ lepton (middle) and $2$ lepton (right) channels [4].

![Figure 3](image-url)  
**Figure 3.** Signal strength of $VH, H \rightarrow b\bar{b}$ process obtained by the signal extracting fit using $79.8$ fb$^{-1}$ of $VH$ analysis [4]. The signal strengths for $WH$, $ZH$ obtained by independently floating two signal strengths in the simultaneous fit are also presented.
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Data

VZ, Z → b̄b

→

b

b

(µ = 1.20)

WW

→

b

b

(µ = 1.06)

ZZ

Run 2 data [13, 14] while the

and the

H

VH

The results for the

channels using Run 2 data

4. Combined result of

VH

production with

H → γγ

and

H → ZZ* → 4ℓ
decay

channels using Run 2 data

The results for the

VH

production with the

H → b̄b
decay mode was combined with the

H → γγ

and the

H → ZZ* → 4ℓ
decays. The

H → γγ

result came from the analysis using 79.8 fb−1 of

Run 2 data [13, 14] while the

H → ZZ* → 4ℓ
result came from the analysis using 36.1 fb−1 of

Run 2 data [15]. The branching fractions to 2 photons, ZZ*, and b-quarks were assumed as the SM expectation in the simultaneous fit to measure the signal strength of the

VH

production
This production mode was observed (expected) at 5.3 (4.8) $\sigma$ and the observed signal strength was $\mu_{VH} = 1.13^{+0.24}_{-0.23}$ as presented in the Figure 8.

Figure 7. Combination of $H \rightarrow bb$ results of VBF, $ttH$ and $VH$ productions using Run 1 and Run 2 data [4]. The signal strengths for each production were obtained by simultaneous fit with independently floating $\mu$ values.

Figure 8. Combination of $VH$ results of $H \rightarrow 4\ell$, $\gamma\gamma$ and $bb$ decays using Run 2 data [4]. The signal strengths for each decay were obtained by simultaneous fit with independently floating $\mu$ values.

5. Conclusion

The results for the $H \rightarrow bb$ decay in the $VH$ production mode using 79.8 fb$^{-1}$ of $pp$ collision data at the center of mass energy of 13 TeV was presented. The $pp$ collisions were provided by the LHC Run 2 and the data were recorded by the ATLAS detector. The signal strength was $\mu_{VH} = 1.16^{+0.27}_{-0.25}$ with observed (expected) significance of 4.9 (4.3) $\sigma$. The diboson and the dijet mass analysis were performed as validations of the main analysis with BDTs. Combining with the results of VBF and $ttH$ production modes and results from Run 1 data, the $H \rightarrow bb$ decay was observed at 5.4 $\sigma$ to be compared with an expectation of 5.5 $\sigma$. The signal strength was $\mu_{H \rightarrow bb} = 1.01^{+0.20}_{-0.20}$. Combining the results of $VH$ production where Higgs boson decays to 2 photons and 4 leptons, this production mode was also observed at 5.3 $\sigma$ to be compared with an expectation of 4.8 $\sigma$. The signal strength was $\mu_{VH} = 1.13^{+0.24}_{-0.23}$.

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