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Observation of $H \to bb$ in ATLAS

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Summary. — The measurements of the Higgs boson decays to fermions allow to test the Yukawa couplings and to understand the mass generation of fermions. In the Standard Model, the $H \to b\bar{b}$ decay is the dominating decay with a branching ratio of 58%, although its observation is experimentally challenging at LHC because of the large multijet background. The search for the $H \to b\bar{b}$ decay is therefore performed exploiting the associated production of a Higgs boson with a W or a Z boson ($V = W/Z$), whose leptonic decays make the signature of these processes easier to identify. This paper describes the search for the $VH(\to b\bar{b})$ process using pp collisions data taken by ATLAS at LHC at 13 TeV and presents the first observation of the Higgs coupling to b-quarks. Differential cross section of the $VH(\to b\bar{b})$ production at 13 TeV are also presented.

1. – Introduction

Since the Higgs boson discovery by the ATLAS and the CMS Collaborations at LHC [1, 2], several measurements of production and decay modes predicted by the Standard Model have been performed. With a branching ratio of ∼58%, the dominant decay channel of the Higgs boson is in b-quark pairs ($H \to b\bar{b}$). A direct measurement of this process would directly test the Yukawa coupling to quarks and constrain the total Higgs width. The $H \to b\bar{b}$ search in the dominant gluon-gluon production mode is challenging at LHC, due to the overwhelming background from multijets. Therefore the $H \to b\bar{b}$ coupling is studied in the associated production with a W or Z boson (VH, $V = W, Z$), which represents the most sensitive production mode. The leptonic decays of the vector bosons provide clearer signatures and simpler trigger topologies.

The searches performed by D0 and CDF experiments at Tevatron showed an excess of events with a significance of 2.8 σ [3]. In 2017, ATLAS and CMS Collaborations reported an evidence of $H \to b\bar{b}$ decay, with observed (expected) significance of 3.6 (4.0)

(*) E-mail: `Camilla.Vittori@bo.infn.it` and 3.8 (3.8) σ, respectively, by combining measurements based on 2015 and 2016 Run 2 datasets with results from Run 1 [4, 5].

In this paper, the measurements of the Higgs boson coupling to b-quark pairs in the VH production mode are presented, using data collected by ATLAS during 2015–2017 and corresponding to a luminosity of $41.3\,\mathrm{fb}^{-1}$.

The analysis explores the $ZH \rightarrow \nu\nu b\bar{b}$, $WH \rightarrow l\nu b\bar{b}$ and $ZH \rightarrow l\bar{l}b\bar{b}$ signatures, which correspond to the 0-, 1- and 2-lepton channels, respectively, according to the number of charged leptons (electrons or muons) in the final state. These channels are dominated by V+jets, $t\bar{t}$, single top and diboson background processes. In order to obtain a clear separation of signal events from background, a multivariate analysis is used. The multivariate discriminants are built from variables describing the kinematics in all signal regions and are then combined using a binned maximum likelihood fit, which extract the signal yield and the normalisation of the main irreducible background. The measurements are combined with results from Run 1, with other searched for $b\bar{b}$ decays and with other searches in the VH production mode.

2. – Analysis strategy

The topologies of $VH(H \rightarrow b\bar{b})$ events are characterised in the final state by the presence of 0, 1 or 2 charged lepton and exactly 2 b-jets, which form the Higgs boson decay. The selections of the three different lepton channels are detailed in [6]. Jets are selected in central rapidity region with $p_T > 20\,\mathrm{GeV}$ and the identification of b-jets is performed using a multivariate algorithm (MV2).

Events passing the signal selections are further split according to the jet multiplicity in 2-jet or 3-jets categories, where exactly 2 jets must fulfil the b-tagging requirement. In the 0- and 1-lepton channels, only one additional jet is allowed, to reduce the $t\bar{t}$ background contamination; in the 2-lepton channel more additional jets are accepted in the 3-jet category. Since the signal sensitivity increases as a function of the transverse momentum of the vector boson (p_T^V), the analysis focuses on the high-p_T region defined by $p_T^V > 150\,\mathrm{GeV}$. In the 2-lepton channel the middle-p_T region $75\,\mathrm{GeV} < p_T^V \leq 150\,\mathrm{GeV}$ is also considered.

The main background contributions belong to the production of W and Z bosons in association with light-flavour (V+light) and heavy-flavour (V+HF) jets, top quark (single top and $t\bar{t}$) diboson and multijet events. These processes are estimated through Monte Carlo generators and normalised to the highest-order available cross section calculation. The only exception is given by the multijet, where a data-driven method in dedicated control regions is adopted. While negligible in the 0- and 2-lepton channels, the multijet contribution is ∼2% in the 1-lepton channel.

In order to reduce the contribution of the main irreducible background, given by *W+HF jets*, *Z+HF jets* and $t\bar{t}$ processes, additional requirements on the kinematics of the events are added to the nominal selections for each lepton channel and specific control regions are built [6].

In order to separate signal from background processes, multivariate discriminants (Boosted Decision Tree, BDT) are trained in the eight signal categories. The most discriminating variables are the p_T^V, the di-jets invariant mass (m_{bb}) and the angular separation of the 2 b-jets (ΔR_{bb}). The complete list of the observables entering in the BDT definition can be found in [6]. As shown in fig. 1, a clear separation of signal from background is achieved in the BDT distribution, where the first populate the BDT range close to unity.

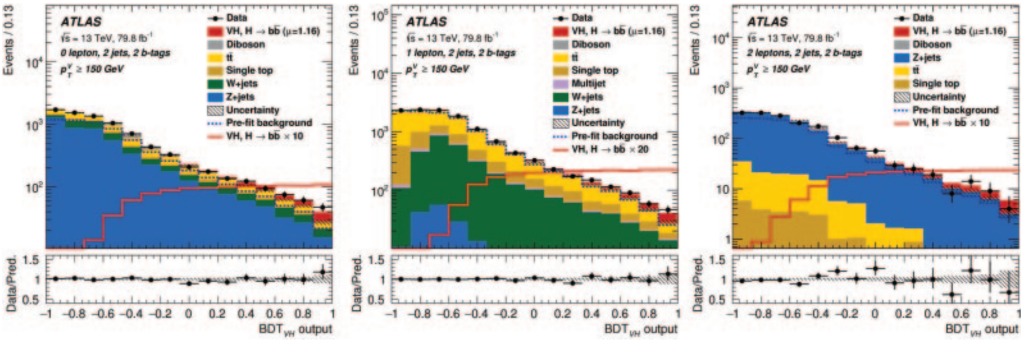

Fig. 1. – Comparison between data and Monte Carlo samples for the BDT distribution in 0- (left), 1- (middle) and 2-lepton channels in signal region for the 2-jet category. The signal and the main irreducible background normalisations have been extracted from the global likelihood fit [6].

The parameter of interest is the signal strength (μ), which represents the ratio of the measured $VH(\rightarrow b\bar{b})$ cross section with respect to the predicted Standard Model one. A maximum likelihood fit of the BDT distribution is used to extract the signal strength and the normalisation of the largest background.

Systematic uncertainties are treated as nuisance parameters in the likelihood. The sources can be divided into four groups: experimental, modelling of the signal, modelling of the background processes and the multijet estimation. The contribution of the uncertainties to the measurement of the signal strength are summarised in table I. The dominant experimental systematic is due to the b-tagging and jet energy corrections.

Table I. – *Breakdown of the contributions to the uncertainty on the ATLAS measurement of the signal strength* (μ) [6].

Source of uncertainty	σ_μ
Total	0.259
Statistical	0.161
Systematic	0.203

Experimental uncertainties			Theoretical and modelling uncertainties	
Jets		0.035	Signal	0.094
E_T^{miss}		0.014	Floating normalisations	0.035
Leptons		0.009	*Z+jets*	0.055
b-tagging	b-jets	0.061	*W+jets*	0.060
	c-jets	0.042	$t\bar{t}$	0.050
	light-jets	0.009	Single-top quark	0.028
	extrapolation	0.008	Diboson	0.054
Pile-up		0.007	Multijet	0.005
Luminosity		0.023	MC statistical	0.070

Systematic on the $VH(\to b\bar{b})$ signal modelling include the cross section normalisation, energy scale and PDF variations, models for parton shower and underlying events. Modelling uncertainties on the background are derived from simulated samples and cover normalisation, acceptance differences and shape effects. The normalisation and relative uncertainties are taken from the most accurate calculations, apart from the main background, which are floating parameters in the global likelihood fit. An additional uncertainty on the multijet estimation in the 1-lepton channel is considered.

3. – Results

In the global likelihood fit, the measured signal strength results in an excess of signal events corresponding to a deviation from the background only hypothesis of 4.9 σ, to be compared with an expectation of 4.3 σ. Figure 2(left) shows the distribution of events in all channels and signal regions combined into bins of $\log_{10}(S/B)$, where S and B are the fitted signal and background yields, respectively. A significant deviation from the Standard Model background only hypothesis is clearly visible.

As a cross-check of the full procedure, the invariant mass of the two b-jets is used as a discriminating variable and a fit on data is performed to extract signal and background yields. Figure 2(right) shows the dijet-mass distribution, where the contributions from all channels, p_T^V regions and jet categories are summed and weighted by their respective $S/(S+B)$, S being the fitted signal and B the total fitted background.

The measured signal strength for the $VH(H \to b\bar{b})$ process is $1.16^{+0.27}_{-0.25}$, with an observed significance of 4.9σ to be compared with an expectation of 4.3σ. This result is first combined with the same type of measurements performed in Run 1, then it is further combined with the result of the searches for a Standard Model $H \to b\bar{b}$ in different production modes, including: VH, gluon-gluon fusion (ggF), vector boson fusion (VBF) and associated production with top quarks (ttH). The combination results in a measured

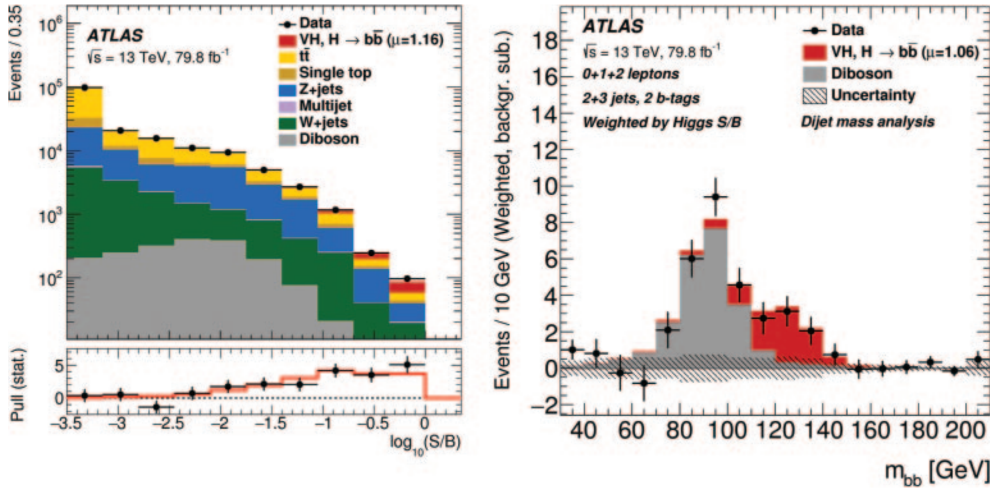

Fig. 2. – The bins of the final BDT discrimant distribution in all regions and lepton-channels are combined into bins of $\log_{10}(S/B)$ (left). Dijet-mass distribution in data after the subtraction of all background, except for the diboson processes (right) [6].

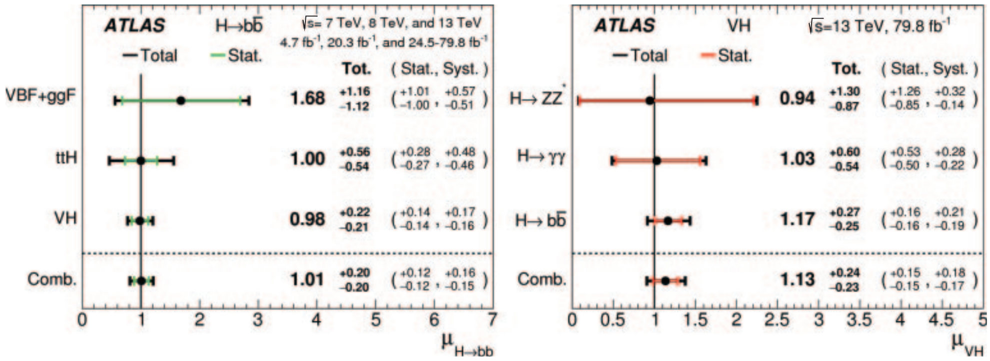

Fig. 3. – Measured post-fit signal strengths for a Higgs boson of mass $m_H = 125\,\mathrm{GeV}$ decaying in two bottom quarks (left) and produced in association with a vector boson (right) [6].

signal strength:

$$\mu_{H\to b\bar{b}} = 1.01 \pm 0.12(\mathrm{stat.})^{+0.16}_{-0.15}(\mathrm{syst.}) \quad (\mathrm{ATLAS}).$$

With an excess of signal events corresponding to an observed significance of 5.5, with respect to the predicted one of 5.4, this measurement represents the first observation of the $H \to b\bar{b}$ decay by the ATLAS Collaboration. The contributions from the various production modes to the final result is presented in fig. 3(left), where the VH production results as the most precise measurement.

The $VH(H \to b\bar{b})$ measurement with Run 2 dataset are combined with the results of the other Run 2 searches for the Higgs boson produced in the VH mode, but decaying into either photons ($H \to \gamma\gamma$) or four leptons via ZZ^* decays ($H \to ZZ^*$). The observed significance for the VH production is 5.3σ, to be compared with an expectation of 4.8σ. The measured signal strength for the combination of all the considered production modes is:

$$\mu_{VH} = 1.13 \pm 0.15(\mathrm{stat.})^{+0.18}_{-0.17}(\mathrm{syst.}),$$

which provides a direct observation of the Higgs boson production in association with vector bosons. The contributions from the different decay channels to the final result are shown in fig. 3(right).

4. – $VH(H \to b\bar{b})$ production as a function p_T^V

Since the VH, $H \to b\bar{b}$ analysis probes the VH production with the greatest sensitivity (see fig. 3(right)), the study has been expanded in a cross section measurement as a function of the vector boson transverse momentum in kinematic fiducial volumes defined within the Simplified Template Cross Section (STXS) framework [7]. The differential analysis uses the event selection and BDT trainings of the inclusive analysis [6]. The cross sections are measured in five regions, according to the truth STXS p_T^V:

- WH production: $150\,\mathrm{GeV} < p_T^W < 250\,\mathrm{GeV}$ and $p_T^W > 250\,\mathrm{GeV}$.
- ZH production: $75\,\mathrm{GeV} < p_T^Z < 150\,\mathrm{GeV}$, $150\,\mathrm{GeV} < p_T^Z < 250\,\mathrm{GeV}$, $p_T^Z > 250\,\mathrm{GeV}$.

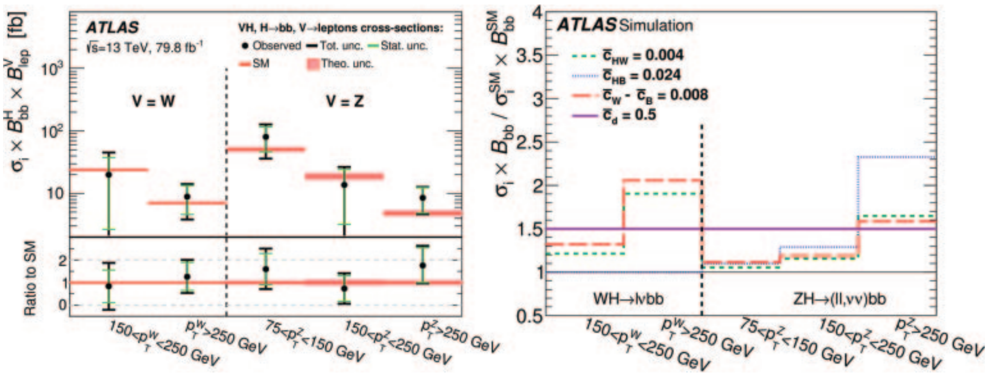

Fig. 4. – Measured cross sections times $H \to b\bar{b}$ and $V \to$ leptons branching ratios for the five fiducial regions (left) and impact on the cross sections for Wilson coefficients that are expected to be excluded at 95% confidence level (right) [7].

In these regions the BDT distributions of the truth STXS templates differ from each other for a given region in reconstructed p_T^V, providing discriminating power to the fit [7]. Figure 4(left) presents the five measured cross sections times branching ratio ($H \to b\bar{b}$ and $W/Z \to l\nu/ll$), which show a very good consistency with the Standard Model predictions.

The Standard Model Lagrangian can be expanded through an Effective Field Theory parametrisation to include Beyond Standard Model represented by higher-order terms [8]. Assuming no contributions from dimension-5 and -7 operators, which, respectively, violate the lepton and baryon numbers and are suppressed from the energy scale of the interactions, the Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM} \simeq \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \bar{c}_i \mathcal{O}_i + \cdots, \tag{1}$$

where Λ is the energy scale of the interaction and $\bar{c}_i$ are the dimensionless coupling constants, so-called Wilson coefficients, to the new operators $\mathcal{O}_i$ calculated with the SILH basis [8]. The differential cross sections are sensitive to Wilson coefficients and, thus, to modifications of the Higgs boson coupling to the W/Z bosons and down-type quarks (see fig. 4(right)). Limits at 95% confidence level can be placed on these parameters: the constrain on $\bar{c}_{HW}$ and $\bar{c}_W - \bar{c}_B$ has a precision of a few percent.

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