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Measurement of the associated production of the Higgs boson with a vector boson in 13 TeV pp collisions with the ATLAS detector

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Summary. — After the Higgs discovery at LHC in 2012, most of ATLAS analyses are focusing the attention on precision measurements of Higgs kinematic properties and on the search of new decay modes sensitive to physics Beyond the Standard Model. One of the most interesting channels is the Higgs boson decay into two b-quarks due to the large branching ratio (58%). The best sensitivity is presently obtained by studying the associated Higgs boson production with a vector boson V ($V = W$ or Z) decaying leptonically. The same dataset has been re-interpreted in the Simplified Template Cross Section framework. This framework facilitates the measurement of the differential $pp \to VH$ cross section used to extract information on the Higgs couplings and to put limits on Beyond the Standard Model effects. In this paper an overview of the most recent results on the observation of VH production and $H \to b\bar{b}$ decay mode will be presented, together with the measurements of the $VH, H \to b\bar{b}$ production as a function of the vector boson transverse momentum.

1. – Introduction

During the Run-1 of the LHC, a Higgs-boson–like particle was discovered by the ATLAS and CMS Collaborations [1, 2]. The discovery was driven by the bosonic decay channels: $H \to \gamma\gamma$, $H \to WW^*$ and $H \to ZZ^*$. Detection of the fermionic decays of the Higgs boson is essential to examine the origin of the mass of the fermions. Among all the processes, the Higgs boson decay to b-quarks is particularly interesting, thanks to its branching ratio of about 58% for a Higgs boson mass at 125 GeV (fig. 1(a)). The main process for Higgs boson production with $m_H = 125$ GeV is the gluon-gluon fusion (fig. 1(b)) but the search in the $H \to b\bar{b}$ channel is affected by large backgrounds arising from multi-jet production. The best sensitivity is presently obtained by studying the Higgs boson produced in association with a V ($V = W$ or Z) vector boson —a production mode with a cross section which is more than one order of magnitude lower than the gluon-gluon fusion process.

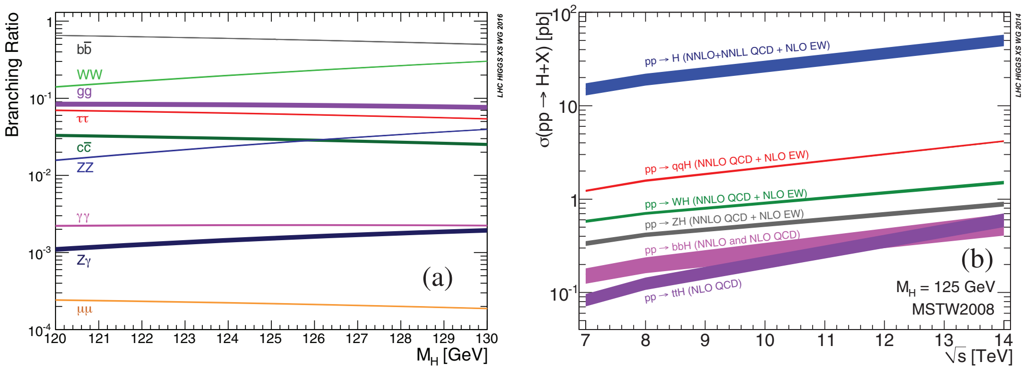

Fig. 1. – (a) Predicted branching ratios of Higgs boson as a function of its mass. (b) Cross section production of Higgs boson with $m_H = 125\,\text{GeV}$ as a function of the center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ [3].

2. – $VH, H \to b\bar{b}$ analysis

The VH production is the most sensitive production mode for the search of the Higgs boson decaying in two bottom quarks. To suppress the huge multi-jet background in the $b\bar{b}$ final states, leptonic decays of the vector boson are selected ($Z \to \nu\nu$, $W \to \nu l$, $Z \to ll$). Events are separated into three analysis channels in the so-called 0-, 1- and 2-lepton channels, based on the number of the charged leptons (electrons or muons) coming from the V boson decay.

In the $VH(H \to b\bar{b})$ analysis described in this document and performed with data collected by the ATLAS detector [4], physics objects are reconstructed as follows. Electrons are reconstructed from topological clusters of energy deposits in the electromagnetic calorimeter and matched to a track in the Inner Detector. All the electrons are required to have a $p_T > 7\,\text{GeV}$ and $|\eta| < 2.47$.

Muons are constructed combining the measurements of the Inner Detector and Muon Spectrometer. All the muons are required to be in the acceptance of the Muon Spectrometer ($|\eta| < 2.7$), to have a $p_T > 7\,\text{GeV}$ and to have small impact parameters.

The jets are reconstructed from noise-suppressed energy clusters in the calorimeters and by applying the anti-k_T algorithm to the ensemble of reconstructed clusters. The radius parameter R used is $R = 0.4$. In the analysis the jets used are required to have a $p_T > 20\,\text{GeV}$ if they are in the central region ($|\eta| < 2.5$) or to have a $p_T > 30\,\text{GeV}$ if they are in the forward region ($2.5 < |\eta| < 4.5$). Jets containing b-hadrons are identified using the multivariate b-tagging algorithm MV2c10 [5] which makes use of observables with discriminating information provided by an impact parameter algorithm, an inclusive secondary vertex finding algorithm and a multi-vertex finding algorithm. The algorithm is tuned to produce an average efficiency of 70% for b-jets in simulated $t\bar{t}$ events.

The missing transverse energy (E_T^{miss}) is used to measure the transverse momentum of the neutrino and it is derived from the momentum imbalanced in the transverse plane to the beam axis using the calorimeter information. The missing transverse momentum can also be constructed using only inner detector tracks (p_T^{miss}). This quantity provides a robust estimate of the missing transverse momentum which is less sensitive to the pile-up. In the analysis E_T^{miss} is required to be $>150\,\text{GeV}$ in the 0-lepton channel and $>30\,\text{GeV}$

in the electron sub-channel. The latter cut is applied to reduce the background from the multi-jet production. In the 0-lepton angular cuts in the separation between E_T^{miss} and p_T^{miss} are used to suppress multi-jet events.

In the 0-lepton and 1-lepton muon sub-channels the online event selection relies on the missing transverse momentum E_T^{miss} whose threshold varies according to the LHC instantaneous luminosity. On the other hand single lepton triggers have been used in the 1-lepton electron sub-channel and 2-lepton channel. The offline event selection is performed using physics objects, *i.e.*, jets, electrons, muons, reconstructed from the detector signals.

To increase the signal-to-background ratio, the three channels are further categorized according to the vector boson transverse momentum p_T^V. In 0- and 1-lepton channels only one p_T^V region is defined, $p_T^V > 150\,\mathrm{GeV}$. Due to a stronger background suppression at low p_T^V, in the 2-lepton channel one additional region has been added for $75\,\mathrm{GeV} < p_T^V < 150\,\mathrm{GeV}$. Selected events are further split into two categories depending on whether additional, untagged jets are present. In the 0- and 1-lepton channels, only one such jet is allowed, while in the 2-lepton channel any number of jets is accepted.

In the 0-lepton channel, a selection on the scalar sum H_T of the transverse momenta of all the jets in the events is placed. In the 2-jets events it is required that $H_T > 120\,\mathrm{GeV}$, instead in 3-jets events $H_T > 150\,\mathrm{GeV}$. This cut is introduced to remove a portion of the phase space in which the trigger efficiency depends on the jet multiplicity. Finally, requirements on the angular distance between reconstructed objects are used to suppress QCD multi-jet background in the 0-lepton channel.

Events in the 1-lepton channel are required to contain exactly one electron or muon. In this channel, control regions (CRs) are built to estimate the backgrounds. The CRs are background-enriched regions used in the fitting stage to extract background information. In the 1-lepton channel, CRs enriched in W+jets events are obtained by applying two additional cuts on the invariant mass of the $b\bar{b}$-system ($m_{bb} < 75\,\mathrm{GeV}$) and on the reconstructed top mass ($m_{top} > 225\,\mathrm{GeV}$). The latter is calculated as the invariant mass of the lepton, the reconstructed neutrino and the b-tagged jet that yields the lowest mass value. This cut is applied in order to reduce the $t\bar{t}$ contamination inside the CR.

Events in the 2-lepton channel are required to have two charged leptons with the same flavor in the final state. To suppress backgrounds with non-resonant lepton pairs there is an additional cut on the invariant mass of the two leptons ($81\,\mathrm{GeV} < m_{ll} < 101\,\mathrm{GeV}$). Moreover, in the 2-lepton channel the CRs are defined to suppress $t\bar{t}$ backgrounds by requiring events with one electron and one muon in the final state.

Table I summarizes the event selection and categorization applied in the analysis.

To maximize the sensitivity to the Higgs boson signal the analysis deploys a multivariate discriminant, built from variables which describe the kinematics of the selected events. Eight to thirteen input variables describing the kinematics of the events are used depending on the channels and m_{bb}, p_T^V and $\Delta R(b_1, b_2)$ (where b_1 and b_2 refer to the two b-tagged jets) are the most discriminating ones. The Boosted Decision Tree (BDT) is the multivariate discriminant used in the analysis. It is trained and evaluated in each lepton channel and in each kinematic region separately. It takes kinematic variables that describe the event as input and it gives as output a variable called BDT that tends to separate signal from background events. The BDT outputs are then combined using a binned maximum likelihood fit to extract the signal strength μ and the background normalizations. Figure 2 shows the BDT output post-fit distributions in the three lepton channels of the data overlaid with the simulation in the signal region. The signal strength

Table I. – *Summary of the event selection and categorization in the 0-, 1- and 2-lepton channels* [6].

Selection	0-lepton	1 lepton channel		2-lepton
		e sub-channel	μ sub-channel	
Trigger	E_T^{miss}	single lepton	E_T^{miss}	Single lepton
Leptons	–	$p_T > 27\,\text{GeV}$	$p_T > 25\,\text{GeV}$	$p_T > 27\,\text{GeV}$
E_T^{miss}	$>150\,\text{GeV}$	$>30\,\text{GeV}$	–	–
m_{ll}	–	–		$81 < m_{ll} < 101\,\text{GeV}$
Jets	exactly 2/3 jets			exactly 2/$\geq$3 jets
Jet p_T	$>20\,\text{GeV}$ for $\lvert\eta\rvert < 2.5$			
b-jets	exactly 2 b-jets			
Lead. b-jet p_t	$>45\,\text{GeV}$			
H_T	$>120\,\text{GeV}$ in 2 jets $>150\,\text{GeV}$ in 3 jets	–		–
$\min[\Delta\phi(E_T^{miss}, \text{jets})]$	$>20°$ in 2 jets $>30°$ in 3 jets	–		–
$\Delta\phi(E_T^{miss}, bb)$	$>120°$	–		–
$\Delta\phi(b_1, b_2)$	$<140°$	–		–
$\Delta\phi(E_T^{miss}, p_T^{miss})$	$< 90°$	–		–
p_T^V regions		$>150\,\text{GeV}$		$75\,\text{GeV} < p_T^V < 150\,\text{GeV}$ $p_T^V > 150\,\text{GeV}$
Signal regions	–	$m_{bb} \geq 75\,\text{GeV}$ or $m_{top} \leq 225$		same-flavour leptons opposite-sign charges (only $\mu\mu$)
Control regions	–	$m_{bb} < 75\,\text{GeV}$ or $m_{top} \leq 225$		different-flavour leptons opposite-sign charges

μ is equal to

$$\mu = \mu_{VH} \cdot \mu_{H\to b\bar{b}} = \frac{(\sigma(VH) \times BR(H \to b\bar{b}))_{measured}}{(\sigma(VH) \times BR(H \to b\bar{b}))_{expected}(SM)}, \tag{1}$$

where σ is the VH cross section and BR is the branching ratio $H \to b\bar{b}$. The signal strength is used to evaluate the agreement/discrepancy of the result with the SM prediction.

Considering all the data collected by the ATLAS Collaboration from 2015 to 2017 at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $79.8\,\text{fb}^{-1}$, an excess of events over the expected background from other Standard Model processes is found with an observed (expected) significance of 4.9 (4.3) standard deviations [6]. The fitted value of the signal strength parameter is $\mu = 1.16^{+0.27}_{-0.25}$.

The $VH(H \to b\bar{b})$ result is further combined with results for the Standard Model Higgs boson decaying into a $b\bar{b}$ pair produced in association with a $t\bar{t}$ pair or in the vector boson fusion production mode. Using the Run 1 and Run 2 dataset, the observed significance is

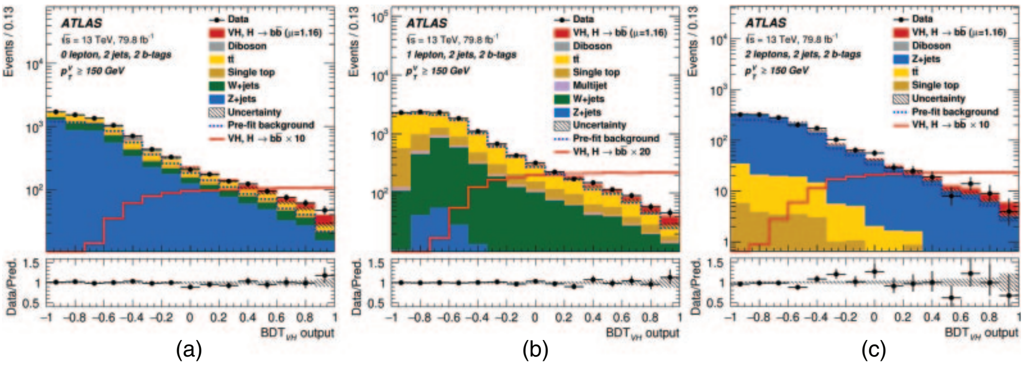

Fig. 2. – The BDT output post-fit distributions in the 0-lepton (a), 1-lepton (b) and 2-lepton (c) channels, in the 2-jet category [6].

of 5.4 standard deviations, to be compared to an expectation of 5.5 standard deviations (fig. 3(a)).

Moreover, the $VH(H \to b\bar{b})$ result is combined with other searches for the Higgs boson produced in the VH production mode, but decaying either in four leptons or into two photons. Using the Run 2 dataset, the observed significance is 5.2 standard deviations, to be compared with an expectation of 4.8 standard deviations (fig. 3(b)). In both combinations, the leading sensitivity is coming from the $VH(H \to b\bar{b})$ analysis.

3. – Simplified Template Cross Sections

After the observation of the VH production and $H \to b\bar{b}$ decay mode, the same dataset is used to measure the differential cross section in the Simplified Template Cross Sections (STXS) framework [7]. The STXS measurements are an evolution of the standard signal strength measurement targeting the reduction of the theory dependence, both in terms of uncertainties and underlying physics model. Event selection, event categorization

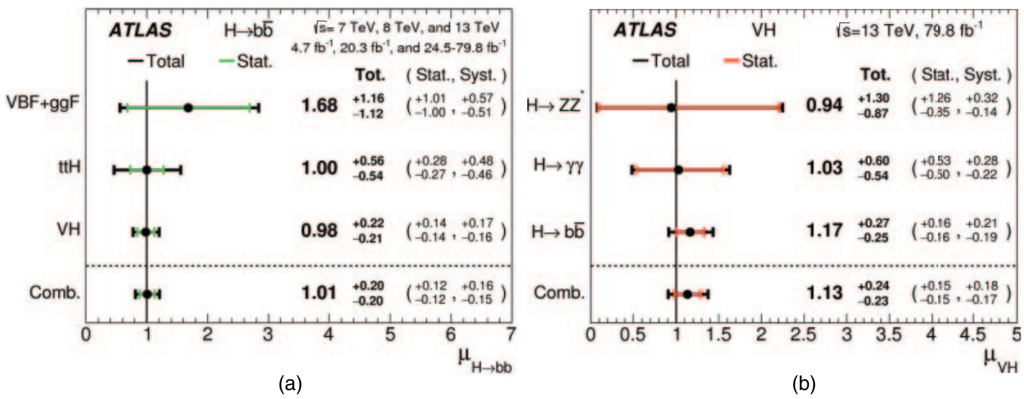

Fig. 3. – Measured post-fit signal strengths for a Higgs boson decaying in two bottom quarks (a) and produced in association with a vector boson (b) [6].

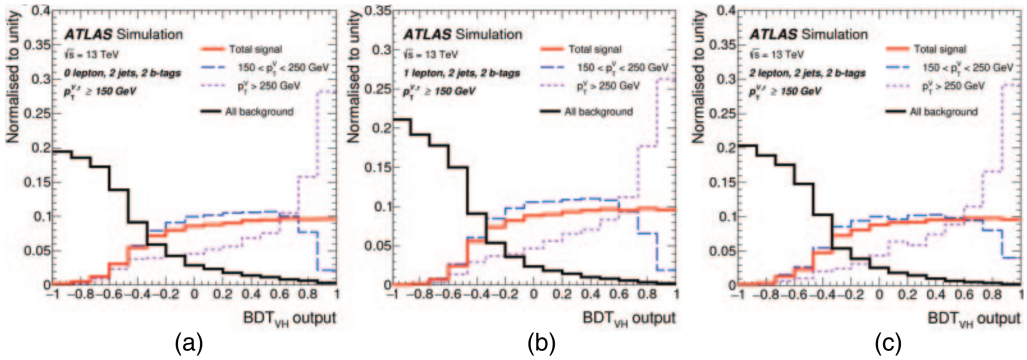

Fig. 4. – BDT distributions for different p_T^V STXS regions in the 0-lepton (a), 1-lepton (b) and 2-lepton (c) channel, in 2-jet reconstructed-event category [8].

and background modelling are left unchanged, but a finer granularity is used in the signal parametrization, allowing for more advanced theoretical interpretations of the measurement. At generator level, the WH and ZH production modes are separated, and the signal is split in different regions depending on the transverse momentum p_T^V of the V boson. Three momentum regions are selected: $75 < p_T^V < 150\,\text{GeV}$, $150 < p_T^V < 250\,\text{GeV}$ and $p_T^V > 250\,\text{GeV}$. The cuts at 75 GeV and 150 GeV are consistent with the selection applied in the analysis at reconstruction level. The other cut at 250 GeV is applied to isolate high-energy events which could be sensitive to Beyond the Standard Model (BSM) effects. For the WH case, the differential cross section in the first bin is fixed to the SM prediction in the fit procedure because of lack of statistics. The splitting in different regions optimizes the discrimination power of the fit procedure, due to the different shape of the BDT output for the STXS template distributions as shown in fig. 4.

The fit procedure adopted in the STXS framework to extract a measurement of the differential cross section is similar to the one used in the $VH(H \to b\bar{b})$ analysis. The main difference is that, instead of a single parameter of interest, the signal strength μ, the fit has multiple parameters of interest which are the different cross sections in each region. The VH cross sections times the $H \to b\bar{b}$ branching ratio, together with the SM prediction, are shown in fig. 5(a). Good agreement between the measurements and the SM prediction is observed [8].

The measurement in STXS model can be used as input for studying BSM effects. The Standard Model Lagrangian can be expanded with an Effective Field Theory parametrization to describe BSM physics by adding a set of dimension-6 operators,

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2, \tag{2}$$

where Λ represents the energy scale of New Physics and c_i are coupling constants, called Wilson coefficients [9]. Among all dimension-6 operators, only five of them affect directly the cross sections times branching ratio measured in this analysis because they introduce new Higgs boson interactions with W bosons and Z bosons. The coefficients of these operators, expressed in the Strongly Interacting Light Higgs (SILH) formulation [10], are c_{HW}, c_{HB}, c_W, c_B and c_d. Using a set of equations relating the STXS measurements with EFT parameters, it is possible to constrain the Wilson coefficient values which reflect

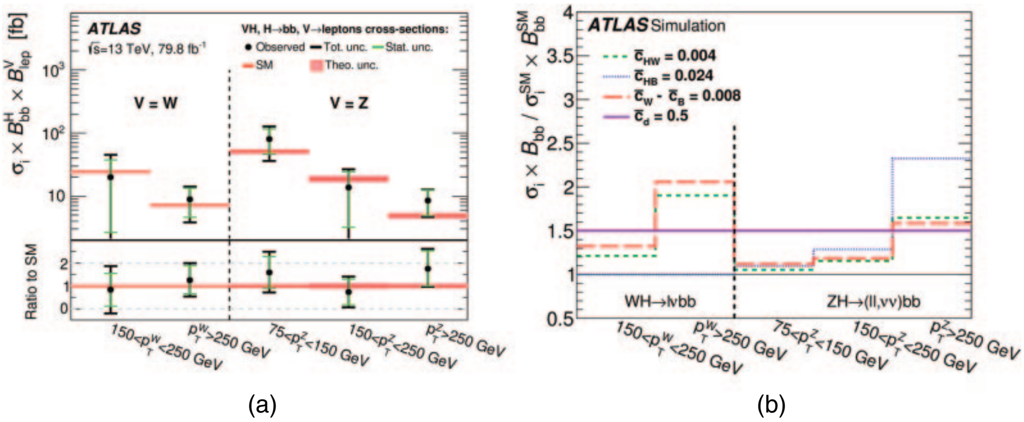

Fig. 5. – (a) Measured VH cross sections times the $H \to b\bar{b}$ branching ratio. (b) Impact on the STXS measurements of the effective Lagrangian operators for the values of the Wilson coefficients that are expected to be excluded at 95% confidence level [8].

TABLE II. – *Observed 95% CL intervals for the effective Lagrangian coefficients* c_{HW}, c_{HB}, c_W, c_B *and* c_d *when the other coefficients are assumed to vanish* [8].

Coefficient	Interval
c_{HW}	$[-0.003, 0.008]$
c_{HB}	$[-0.022, 0.049]$
$c_W - c_B$	$[-0.006, 0.014]$
c_d	$[-0.6, 1.1]$

constraints on masses or couplings of new particles in many BSM theories. A likelihood fit is performed to extract the intervals for the EFT coefficients with 95% confidence level (CL). In the fit all coefficients except one are assumed to vanish. The results are summarized in table II. As expected, due to the agreement obtained by the STXS measurements and SM predictions, the values extracted for the EFT coefficients are compatible with zero.

The expected effects of the EFT parameters on the SM cross sections for the STXS bins are shown in fig. 5(b). The variations, expressed in terms of $\sigma_i \times BR_{bb}/\sigma_i^{SM} \times BR_{bb}^{SM}$, are obtained by assuming for each parameter the value of the upper limit of the corresponding interval expected to be excluded at 95% CL. The plot clearly shows that bigger deviations from SM are more evident at high energy.

4. – Conclusion

The $VH(H \to b\bar{b})$ analysis using data collected by the ATLAS experiment from 2015 to 2017 at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $79.8\,\text{fb}^{-1}$, has been presented. An excess over the expected background is observed with a signal strength of $\mu = 1.16^{+0.27}_{-0.25}$ and an observed (expected) significance of 4.9 (4.3) standard deviations.

The $VH(H \to b\bar{b})$ result is further combined with results for Standard Model Higgs boson decaying into a $b\bar{b}$ pair but produced in association with a $t\bar{t}$ pair and vector boson fusion production mode in order to perform a search of $H \to b\bar{b}$ decay. Using the Run 1 and Run 2 dataset, the observed significance is of 5.4 standard deviations, to be compared with an expectation of 5.5 deviations. This provides the first observation of the $H \to b\bar{b}$ decay modes.

Moreover, combining the $VH(H \to b\bar{b})$ result with other Run 2 searches for the Higgs boson in the VH production mode but decaying to either four leptons or diphotons, the first observation of the Higgs boson production in association with a vector boson has been measured. Using the Run 2 dataset, the observed significance is 5.2 standard deviations, to be compared with an expectation of 4.8 standard deviations.

Using the STXS framework, the Run 2 dataset has been used to perform the first differential $pp \to VH$ cross section measurement. The results are in agreement with the SM predictions. Additionally, limits on the effective Lagragian coefficients used to describe BSM effects have been set.

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