Toward the observation of 2nd and 3rd generation BEH couplings with 13 TeV data

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The data taken at 7 and 8 TeV at the LHC significantly constrain many couplings of the newly discovered Higgs-like boson. Up to now all observations are within uncertainties in agreement with the expectations from a Standard Model Higgs boson. Within the Standard Model (SM) this Higgs boson of 125 GeV is expected to decay predominantly into a pair of bottom and anti-bottom quarks. However, this decay has not been observed yet, neither its expected coupling to 2nd (and 1st) generation fermions. Presented are the latest results of the ATLAS and CMS collaborations using 13 TeV data with regards to Higgs boson couplings to 2nd and 3rd generation fermions.

The couplings to fermions of this newly discovered Higgs-like boson are already strongly constrained by the data taken at the LHC during run 1, where the largest constraints result indirectly from the $H \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ measurements, whose dominant production modes are top loop induced. The most stringent direct constraints result from the ATLAS and CMS searches for $H \rightarrow \tau^+\tau^-$ using run 1 data which in combination surpass the 5 sigma threshold for an observation. Nevertheless, the most abundant decay for the SM Higgs boson, $H \rightarrow b\bar{b}$, has not been confirmed yet, leaving the possibility of an extended Higgs sector with non-SM like couplings to fermions. The run 2 of the LHC opens new opportunities in the search for the Higgs boson couplings to 2nd and 3rd generation fermions. At 13 TeV, the production cross-sections for SM Higgs bosons increase by more than a factor 2 in comparison to run 1. The largest increase is seen for associate production with $t\bar{t}$ which rises by about a factor of 4. The cross-sections of the other production modes increase by a factor 2 to 2.4. The $t\bar{t}$ background sees an increase by more than a factor 3, minimum bias events, W and Z bosons cross-sections only increase by a factor of 1.2 to 1.7. For most Higgs searches this means that $t\bar{t}$ becomes a more important background and the fraction of other backgrounds is slightly reduced. In the following results are presented concerning the couplings of the Higgs boson to fermions which are using the first 13 TeV data.

1 $H \rightarrow b\bar{b}$

In the search for the SM Higgs boson decays to $b\bar{b}$, the dominant production mode, gluon-gluon fusion, suffers from too large backgrounds and poses a significant challenge for triggering and is therefore not pursued. The vector boson fusion process is still difficult to trigger on, but provides sufficient handles to tackle the backgrounds. The most accessible production modes are associated production with vector bosons, which provide high $p_T$ leptons for triggering and background suppression, and at 13 TeV associated production with $t\bar{t}$, which is discussed in $^3$, becomes important due to the large increase in the production cross-section. Finally there is associated production with single top quarks, which however has a very small cross-section.
Figure 1 – (a) The multivariate classifier to select VBF candidate events in events with a single b-jet trigger, and split them into categories of increasing purity ([0.28, 0.87, 0.93, 1.0]). (b) The b-jet pair invariant mass of the purest category. The fitted background model is overlaid.

1.1 $H \rightarrow b\bar{b}$ in vector boson fusion

The vector boson fusion (VBF) production mode is exploited by both ATLAS and CMS. The signature is two more or less central bottom jets from the Higgs boson decay, enclosed by two jets in forward and backward direction. Since there is no colour flow between the forward or backward jets and the jets from the Higgs boson decay, no significant hadronic activity is expected in between. At trigger level the CMS analysis requires 3 jets with decreasing $p_T$ threshold: 92 GeV, 76 GeV, and 64 GeV. To limit the event rate to a reasonable level topological cuts are applied. First an additional 4th jet is required with at least 15 GeV and at least one jet has to be b-tagged. Then, the jet-pair with the largest opening angle, excluding the first and second most bottom like jets, must have an invariant mass $m_{qq} > 200$ GeV. If there is only one b-tagged jet, the requirements are tightened to $m_{qq} > 460$ GeV and $\eta_{qq} > 4.1$. Additionally, the opening angle of the two jets which are considered to originate from the Higgs decay has to fulfill $\Delta \phi_{bb} < 1.6$, where the angle is measured in the plane transverse to the beam direction. In total a trigger efficiency of a $\sim 6\%$ is achieved. In the next step a boosted decision tree is used to select signal like events and split them in categories of increasing purity. The BDT combines multiple variables which are relevant for the VBF topology. In each category the invariant mass of the b-jet pair, $m_{bb}$ is computed and used to extract the signal strength $\mu$ in a simultaneous likelihood fit. The fit uses parametrised shapes for the signal and the backgrounds. The signal and W/Z backgrounds are modelled by a Chrystal-ball function, the top background by a broad Gaussian and the multijet background by a polynomial. The parameters for the signal, W/Z and top background shapes are determined from simulated events. The parameters of the multijet background shape are determined from data. The multijet background shape is identical in all categories except for a multiplicative correction, a linear function of $m_{bb}$.

The resolution of $m_{bb}$ is crucial for the sensitivity. The resolution is impacted by final state gluon radiation and semi-leptonic bottom and charm decays. These effects are mitigated by adding the momenta of adjacent jets with $\Delta R < 0.8$ and $p_T > 15$ GeV and by a multivariate regression to correct the jet $p_T$. The regression exploits jet kinematics, information about the electromagnetic energy fraction, possible pileup contributions, and information about the bottom and charm hadron decays from soft leptons and secondary vertices in the jets. In total the relative resolution improves by about 7%.
The analysis is not yet sensitive but with 2.3 fb$^{-1}$ of 13 TeV data being analysed, already more than half the sensitivity of the run 1 analysis is reached. The run 2 analysis yields a signal strength of $\mu = -3.7^{+2.4}_{-2.5}$. In combination with run 1, a signal strength of $\mu = 1.3^{+1.2}_{-1.1}$ is observed. This translates in an upper limit on $\mu$ of 3.4 at the 95% confidence level (CL).

In ATLAS the VBF topology is exploited in a different way$^5$ which requires an additional photon with $p_T > 25$ GeV. This photon provides additional handles for triggering. It also allows to suppress backgrounds further, because initial and final state photon radiation interfere destructively in the important background processes like $(g/q)b\gamma$, but the interference is constructive in the charged current fusion channel $W^+W^- \rightarrow H$. Otherwise the analysis strategy is similar to the CMS analysis described above. A multivariate classifier is computed to select VBF plus $\gamma$ like events, and to split events into categories of increasing purity, where the variables used in the classifier are only weakly correlated to the di-jet invariant mass. The signal is extracted in a simultaneous likelihood fit of the di-jet mass distribution in all categories. In each of the categories the non-resonant background is modelled with up to 4th order polynomials, the normalisations and the parameters of the non resonant background model are free parameters. With 12.6 fb$^{-1}$ of 13 TeV data the observed signal strength is $\mu = -3.9^{+2.8}_{-2.7}$ which corresponds to an upper limit of 4 at the 95% CL.

1.2 $H \rightarrow b\bar{b}$ in associate production with vector bosons

The most promising channel to observe $H \rightarrow b\bar{b}$ is the associated production with vector bosons WH and ZH. The ATLAS analysis$^6$ considers leptonic vector boson decays, where leptons can be electrons, muons or neutrinos. Events are split according to the number of charged leptons into the 2 lepton channel $ZH \rightarrow b\bar{b}\ell\ell^-$, 1 lepton channel $WH \rightarrow b\bar{b}\ell\nu$ and the zero lepton channel $ZH \rightarrow b\bar{b}\nu\nu$, where central electrons and muons with $p_T > 7$ GeV are counted. Taus are not taken into account. In the 2 and 1 lepton channel at least one of the charged leptons must $p_T > 25$ GeV. The leptons in the final state are used for triggering. In case of the 2 and 1 lepton channel single electron and muon triggers are used at various $p_T$ thresholds. The lowest threshold is 20 GeV for the 3.2 fb$^{-1}$ recorded in 2015 and 24 GeV for the data recorded in 2016. The lowest
threshold triggers are accompanied by an isolation requirement. The triggers are complemented by a missing $E_T$ trigger. At trigger level the missing $E_T$ computation is exclusively based on calorimeter information, and only takes a small fraction of the muon momentum into account. Therefore, the missing $E_T$ provides a close approximation of the vector boson $p_T$ not just in the zero lepton, but also in the 1 lepton, muon channel.

After trigger, events are required to have at least 2 b-tagged jets with $p_T > 45$ GeV and $p_T > 20$ GeV in the central region which comprises pseudo rapidities of $|\eta| < 2.5$. Events are sub categorised according to the jet multiplicities which also includes all jets with $p_T > 20$ GeV and forward jets with $p_T > 30$ GeV and a pseudo rapidity of $2.5 \leq |\eta| < 4.5$. In the zero and 1 lepton channel 2 and 3 jet categories are considered. The 2 lepton channels considers 2 and $\geq 3$ jet categories.

The 1 and zero lepton channels suffer from large multijet backgrounds, which are difficult to model. Thus, their suppression is a primary focus of the event selection. In the 1 lepton channel, the multijet background is largely suppressed by requiring the vector boson $p_T > 150$. In the zero lepton channel this background is further reduced by quantities which correlate missing $E_T$ and other reconstructed objects. In the 2 lepton channel events with a vector boson $p_T \leq 150$ GeV are added as a separate category. the multijet background is here sufficiently suppressed by rejecting all events outside the di-lepton invariant mass window around the nominal Z boson mass ($71 \text{ GeV} < m_{\ell\ell} < 121 \text{ GeV}$), and requiring leptons of the same generation.

In each category a multivariate classifier is computed from mostly kinematic variables which assume a VH event hypothesis. The classifiers are used as the final discriminant in a simultaneous likelihood fit. Free parameters of the fit are the VH signal strength, normalisations of the t\bar{t} background, and Z and W backgrounds which are accompanied by 2 bottom jets. With 13.2 fb$^{-1}$ the analysis reaches nearly the run 1 sensitivity. The observed signal strength amounts to $\mu = 0.21^{+0.51}_{-0.30}$ and the observed upper limit is 1.2 at the 95% CL.

1.3 $H \rightarrow b\bar{b}$ in associate production with single top

Searches for $H \rightarrow b\bar{b}$ in association with a single top is hampered by the small cross-section. In the t-channel and the W associated production channel the cross-section is reduced further by destructive interference between the diagrams in which the Higgs is radiated off the top quark and the W boson. In non-Standard Model scenarios the Yukawa coupling of the top quark could be modified without changing the cross-section of the gluon-gluon fusion Higgs production\textsuperscript{7}. One example would be the inverted top coupling scenario in which the interference would become constructive. CMS conducts such a search\textsuperscript{8} using semi-leptonic top decays into $b\nu$ and $b\mu$. 

![Figure 3](image-url)
The analysis considers final states with 3 or 4 b-jets, one light flavour jet and an electron or muon. The dominant backgrounds are top pair production accompanied by additional jets. The final signal discrimination is performed with a multivariate classifier which combines amongst others variables computed for two event hypotheses: associate Higgs production with a single top, and top pair production. The classifier is trained for each point in the model parameter space independently. An example is given in Figure 4a. An upper limit is computed by fitting simultaneously the classifier in the 3 and 4 b-jet categories. As can be seen in Figure 4b, it is in good agreement with the background only hypothesis. and amounts to 114 times the expected SM cross-section and 6 times the expected cross-section in the inverted top coupling scenario.

2 Φ → τ+τ−

The first analyses searching for heavy bosons decaying into tau pairs which use 13 TeV data target heavy resonances. Such heavy resonances would for example emerge in case of an extended Higgs sector like the one in the Minimal Super Symmetric Model (MSSM) or general 2-Higgs Doublet Models (2HDM). In the MSSM or 2HDMs the coupling to down-type fermions might be enhanced depending on the exact parameters of the model. This motivates searches for scalar bosons in association with bottom quarks: gg → bH, gb → bH. Depending on the model parameters the gluon-gluon fusion gg → H might still be the dominant production process and is also considered. Both ATLAS and CMS performed such an analysis using about 13 fb⁻¹ of 13 TeV data. The ATLAS analysis requires at least one hadronically decaying tau (τ_h). The CMS analysis considers additionally final states with both tau leptons decaying leptonically into one electron and one muon (eμ-channel). The analyses use the transverse mass m_T as final discriminant to avoid the difficulties of the invariant mass reconstruction caused by the neutrinos in the final state. The ATLAS analysis uses missing E_T triggered events with thresholds between 70 and 100 GeV for events with one leptonic tau decay and hadronic tau trigger with threshold increasing from 80 GeV to 125 GeV with increasing instantaneous luminosity. CMS uses electron plus muon, single electron or muon, and di-tau trigger, which lead to final p_T thresholds for leptons and hadronically decaying taus between 10 GeV for the sub-leading electron up to 40 GeV for the case in which both taus decay hadronically.

The ATLAS and CMS event selections follow different strategies with respect to the background rejection. The ATLAS analysis focuses on invariant masses above 200 GeV and strongly
suppresses SM backgrounds in particular by requiring a large opening angle between the two tau candidates. The CMS analysis applies a purer tau identification and extends the sensitivity to lower invariant masses. As a consequence, in the ATLAS analysis the multijet background is more important than \( Z \rightarrow \tau^+\tau^- \) and other electroweak backgrounds. In the CMS analysis multijet background is more efficiently rejected, but there is an important contribution from \( Z \rightarrow \tau^+\tau^- \). In both analysis the t\( t \bar{t} \) background becomes important in the channel focusing on b-associated production.

The observations by ATLAS and CMS are in good agreement with the background only hypothesis for both the b-associated production and gluon-gluon fusion. The ATLAS observed limits on the cross-section times branching ratio range from \( 2.0(2.1) \) pb for \( m_\Phi = 200 \) GeV and \( 0.013(0.014) \) pb for \( m_\Phi = 1.2 \) TeV for gluon-gluon fusion (b-associate production) at the 95\% confidence level, where \( \Phi \) can be either a scalar or pseudoscalar Higgs boson. The corresponding CMS observed limits, displayed in Figure 5, are in the range from 0.93(1.0) pb to 0.019(0.12) pb at the 95\% confidence level.

3 Higgs to fermion decays in extended Higgs sectors

In scenarios with an extended Higgs sector also charged Higgs bosons \( H^\pm \) may appear. For \( m_{H^\pm} > m_t \) the charged Higgs is primarily produced in association with a top quark or a top and a bottom quark. These production modes are targeted by analyses conducted by ATLAS and CMS, each using about 13 fb\(^{-1}\) of 13 TeV data. CMS searches for charged Higgs bosons decaying into \( \tau\nu \), ATLAS for \( H^\pm \rightarrow tb \). The final state is composed of multiple b-jets and light flavour jets. The CMS analysis uses the transverse mass attributed to \( H^\pm \rightarrow \tau\nu \), the ATLAS analysis uses multivariat classifier, which exploit the entire event topology. Within 2 standard deviations both analyses are in good agreement with the background only hypothesis.

A more complicated Higgs sector could also allow for lepton flavour violation which is discussed in more detail in the paper.

4 \( H \rightarrow \mu^+\mu^- \)

The most accessible channel to search for the coupling of Higgs to second generation fermions is \( H \rightarrow \mu^+\mu^- \). Such a search was conducted by ATLAS using 36 fb\(^{-1}\) of 13 TeV. The analysis
targets the gluon-gluon fusion and VBF production modes. The analysis uses single muon triggered events with various $p_T$ thresholds above 26 GeV where the lowest threshold triggers the muon to be isolated. To mitigate the increase of the $t\bar{t}$ background at 13 TeV, events with one or more bottom jets are discarded, where the multivariate b-tagging algorithm has a b-tagging efficiency of 60%. The signal is extracted in a likelihood fit, which fits the di-muon invariant mass simultaneously in several categories. The categories are defined by the di-muon transverse momentum, the centrality of the di-muon system, and by a multivariate classifier to identify VBF events. The variables entering the multivariate classifier are chosen to only have a weak correlation with the di-muon invariant mass. The most significant categories are the high significant VBF region, then the non-central events with medium and high transverse momentum of the di-muon system. In all categories, the non resonant background is modelled by an exponential and the resonant part by a Breit-Wigner folded with a Gaussian centred at zero. The shape parameters of the Breit-Wigner are fixed to the world average measurements of the Z-resonance, and the width of the Gaussian is set to the resolution predicted by the simulation. 

The signal is modelled by a Crystal-Ball function and a Gaussian, where the shape parameters are fixed to the prediction of the simulation. Free parameters of the fit are the exponent of the non-resonant background, the resonant background fraction, the background normalisation and the signal strength $\mu$. The free parameters of the background model are uncorrelated between the categories. The result is statistically limited. The experimental uncertainties amount to 4 to 15%, where the uncertainties are largest in the high significance VBF category. The theoretical uncertainties on the gluon-gluon fusion production cross section are 15 to 25% and about 5% on vector boson fusion in each category. The analysis results in an upper limit on the signal strength $\mu$ at the 95% confidence level of 3. This new result dominates the combination with the analysis of the 7 and 8 TeV data\(^{15}\), which yields an upper limit of 2.8.

5 Summary

The first analyses have been conducted in regards of the coupling of the Higgs boson to 3rd and 2nd generation fermions using 13 TeV data taken by ATLAS and CMS at the LHC during the beginning of run 2. The latest results at the time of writing are summarised in Figure 7. Despite
<table>
<thead>
<tr>
<th>Process</th>
<th>Channel</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>13 TeV</th>
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<td>ATLAS $H \rightarrow \mu^+ \mu^-$</td>
<td>$7 + 8 + 13$ TeV</td>
<td>$-0.13 \pm 1.4$</td>
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<td>$0.78 \pm 0.27$</td>
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<td>ATLAS $H \rightarrow \tau^+ \tau^-$</td>
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<tr>
<td>CMS VBF $H \rightarrow b\bar{b}^* + 8$ TeV</td>
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<td>$1.31 \pm 0.1$</td>
<td>$&lt; 3.4$</td>
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<td>ATLAS VBF $H \rightarrow b\bar{b}$</td>
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Figure 7 – ATLAS and CMS results on SM Higgs boson couplings to 2nd and 3rd generation fermions using 7 TeV, 8 TeV and early 13 TeV data. The numbers in the left column show the observed signal strength $\mu$, and the numbers at the right the corresponding upper limit at the 95% confidence level.

the partially small analysed data fraction, the new analyses already get close or even exceed the sensitivity of run 1 analyses, and very soon, the sensitivity should be good enough to be able to observe the coupling of a SM Higgs boson to $b\bar{b}$. At the LHC up to now searches of the SM Higgs boson to 2nd generation fermions are only attempted in $H \rightarrow \mu^+ \mu^-$. The corresponding ATLAS analysis was updated to 36 fb$^{-1}$ of 13 TeV which allows to improve the limit by more than a factor two to 3 times the SM expectation.

Acknowledgments

This work was conducted with support from the German Federal Ministry for Education and Research (BMBF) under contract 05H15PDCAA.

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2. W.J. Stirling, private communication.