Searches and measurements of Higgs bosons in association with Heavy Flavours and Higgs boson decays into Heavy Flavours

Lorenzo Bianchini for the ATLAS, CMS and Higgs collaborations.

Abstract

Talk includes LFV decays and FCNC top decays into a Higgs boson and a quark - overlap with Talk on rare H decays to be discussed.

Presented at LHCP2015 The 3rd Conference on Large Hadron Collider Physics
Higgs boson plus heavy flavour: searches and measurements from the LHC Run 1

Lorenzo Bianchini (on behalf of the ATLAS and CMS Collaborations)$^{1,a}$

$^1$ETH Zürich, Institute for Particle Physics, Otto-Stern-Weg 5, 8093 Zürich (Switzerland)

$a$lore.bianchini@gmail.com

Abstract. This talk gives a review of the Run 1 ATLAS and CMS results on searches and measurements of Higgs bosons decaying to, or produced in association with heavy-flavour quarks (charm, bottom, and top quarks). The Standard Model of particle physics predicts that the Higgs boson interacts with the quarks through scalar, flavour-diagonal, Yukawa interactions, whose tree-level coupling strength is also fixed to be proportional to the quark mass. The detection of Higgs bosons decaying to a heavy flavour quark-antiquark pair (bottom and, to a smaller extent, charm quarks), or produced in association with heavy quarks (top and bottom quarks), is therefore the most favourable way to probe the quark Yukawa sector.

INTRODUCTION

The Standard Model (SM) of particle physics becomes a fully predictive theory once the mass of the Higgs boson is specified. In particular, the SM completely determines the Lorentz and the flavour structure of the interactions between the Higgs doublet, $\Phi$, and the quark fields, $\Psi$, in the form of Yukawa interactions $\sim \lambda_{ij} \Psi_i \Psi_j \Phi$. More precisely, the only gauge-invariant, dimension-4 combinations are:

$$
- \sum_{i,j} \left[ \lambda_{ij}^U \bar{Q}_i \sigma_2 u^R_j + \lambda_{ij}^D \bar{Q}_i \Phi d^R_j \right] + h.c.,
$$

(1)

where $\lambda$'s are arbitrary matrices in flavour space. After electroweak symmetry breaking, $\Phi \propto (0, 1/\sqrt{2}(v + H))$, where $v$ is the vacuum expectation value (vev) of the Higgs field, and upon diagonalisation of the quark mass, the Yukawa sector for the quarks becomes

$$
\mathcal{L}_Y \supset \sum_{q=u,d,c,s,b,t} \lambda_q [\bar{q}_L q_R H + \bar{q}_R q_L H], \quad \text{with } \lambda_q = -\frac{\sqrt{2}m_q}{v}.
$$

(2)

To summarise, the SM gives the following predictions on the quark Yukawa quark sector:

1. there is no tree-level CP violation, i.e. there are no tree-level interactions of the form $i\lambda_q q\gamma_5 qH$;
2. there are no tree-level flavour changing neutral currents (FCNC), and the GIM mechanism further suppresses them to be totally negligible;
3. the coupling strength, $\lambda_q$, is proportional to the quark mass, $m_q$.

At the LHC, only production times decay rates of the form $\sigma_{ii\rightarrow H+X} \times B(H \rightarrow f f)$ can be measured for $1 \rightarrow 2$ decays. These rates can be parametrised as $\kappa_i^2 \kappa_f^2 \kappa_H^2$ times the corresponding SM prediction, where $\kappa_i, \kappa_f$ are real-valued modifiers that shift the corresponding coupling strengths with respect to their SM expectation (i.e. $\lambda_q = \kappa_q \lambda_{q}^{\text{SM}}$), while $\kappa_H$ shifts the overall Higgs boson width, and thus depends on all the $\kappa$'s as well as any unknown non-SM width. By measuring the signal rates for a large enough number of channels, it is possible to measure the individual $\kappa$'s or, in a more model-independent approach, their mutual ratios. In general, the production times decay rates are insensitive to the phase of the coupling (i.e. its sign, if the coupling is real). However, in a few cases the phase of the coupling...
matters due to the interference between different amplitudes, and a measurement of the sign (or, more generally, of the relative sign between different couplings) is possible. Finally, searches for events produced by flavour-changing currents, either in production (e.g. $q \to Hq'$) or decay (e.g. $H \to q\bar{q}'$) of the Higgs boson, can provide a direct evidence of discrepancy from the SM.

HEAVY FLAVOUR IN HIGGS DECAY: THE CHARMM AND BOTTOM COUPLINGS

Both the ATLAS [1] and the CMS [2] Collaborations have made extensive searches for Higgs boson decays into a bottom quark-antiquark pair. Due to the large branching ratio and the relatively high experimental separation between jets arising from the hadronisation of bottom and light quarks, where a tag vs untag mistag ratio of about $\sim 0.70 : 0.02$ can be typically achieved, the $H \to b\bar{b}$ signature can be extracted from an otherwise overwhelming multi-jet background with a few tens of fb$^{-1}$ of pp data. Due to the smaller branching ratio and the higher mistag rate, this is much less of the case for $H \to c\bar{c}$, and the whole LHC program will likely be not enough for a direct observation of this exclusive decay.

The charm Yukawa coupling

Given the experimental challenge posed by extracting the $H \to c\bar{c}$ decay at a hadron collider, different approaches have been proposed in the literature to probe the $cH$ coupling strength. In particular, it has been suggested to search for radiative decays of the form $H \to VM$, where $V = W^\pm, Z, \gamma$ and $M$ is a vector meson [3, 4, 5]. The amplitude for the rare decay $H \to J/\Psi\gamma$ depends on the charm Yukawa coupling thanks to the (negative) interference between the direct $H \to c\bar{c} \to J/\Psi\gamma$ amplitude and the indirect amplitude $H \to c\bar{c} \to J/\Psi\gamma$. The resulting branching ratio is however rather small, $\mathcal{B}(H \to J/\Psi\gamma) \approx 3 \cdot 10^{-6}$ [3], making this channel essentially a null test of the SM even with the full HL-LHC program. Searches for this process have been performed by both the ATLAS [6] and CMS [7] Collaborations. As an example, the ATLAS analysis [6] uses events with one high-$p_T$ photon and a muon pair with $m_{\mu\mu}$ within 200 MeV of the $J/\Psi$ mass. A simultaneous unbinned fit to the $m_{\mu\mu}$ and $p_T^{\mu\mu}$ distributions is performed to set limits on the branching ratio. The observed 95% CL upper limits on $\mathcal{B}(H \to J/\Psi\gamma)$ obtained by the ATLAS and CMS experiments are $1.2 \times 10^{-3}$ and $1.5 \times 10^{-3}$, respectively, and are in agreement with the background only expectation.

The bottom quark Yukawa coupling

The measurement of $\sigma_{tH} \times \mathcal{B}(H \to b\bar{b})$ provides the strongest constraint on $\kappa_b$, although model-dependent constraints can be obtained also from channels that do not include this decay mode because $\kappa_{tH}^2$ strongly depends on $\kappa_b$. Three main production channels have been studied, namely associated production (VH), vector boson fusion (VBF), and associated top-Higgs production (tH).

The VH analyses [8, 9] are performed in final states with 0, 1, or 2 leptons, targeting the decay $Z \to \nu\bar{\nu}, W^\pm \to \ell^\pm\nu$, and $Z \to \ell^+\ell^-$, respectively. The CMS analysis [9] further includes a channel where one jet is identified as a hadronically-decaying tau lepton. At least two jets tagged as b jets are required. Events are split into categories of increasingly larger transverse momentum of the reconstructed vector boson. The invariant mass of the di-jet system peaks around the true Higgs mass with an experimental resolutions of about 15% (Fig. 1, left). The dominant non-resonant background are $V$+jets and $t\bar{t}$, and are estimated using Monte Carlo (MC) simulation normalised in data control regions. Multivariate classifiers that use kinematic and b tagging information from the whole event are used to improve the signal/background separation. The observed (expected) signal $p$-values for a Higgs boson mass of 125 GeV are $1.4\sigma$ ($2.6\sigma$) and $2.1\sigma$ ($2.1\sigma$) for the ATLAS and CMS analyses, respectively. At the time of the publication, the CMS analysis [9] did not include the $gg \to ZH$ sub-process as part of the signal. After its inclusion, the expected $p$-value becomes $2.5\sigma$ [10].

A fully-hadronic analysis of four-jet final states with a VBF-like topology has been performed to search for $H \to b\bar{b}$ decays produced through vector boson fusion [10]. Several variables that exploit the properties of the VBF-jet system, the flavour tagging of the jets, and the overall event activity are used to select signal events with increasing purity. Simultaneous fits to the di-jet mass spectra in the various event categories are used to extract the signal yield (Fig. 1, centre). The observed (expected) significance is $2.5\sigma$ ($0.8\sigma$).

Searches for $t\bar{t}$ production in association with a Higgs boson that decays to bottom quarks have been performed in single and di-lepton final states [11, 12, 13]. The ttH signature is characterised by several jets, four of which are
coming from the hadronisation of b quarks. The dominant background is the hadronic production of a top quark-antiquark pair with additional jets. The analysis is performed in mutually exclusive event categories based on the number of jets and b-tagged jets, which allows to account for the possibility that some of the b-jets have not been tagged. Multivariate discriminants based on the event kinematics and the b tagging properties of the jets are used to extract the signal yield. The observed (expected) exclusion limit at the 95% confidence level (CL) are 3.4 (2.2) and 4.1 (3.5) times the SM expectation, for the ATLAS and CMS experiments, respectively.

The combination of the ATLAS VH and ttH measurement yields a combined value of $\mu^{\bar{b}b} = 0.63^{+0.39}_{-0.37}$ [14], while the combination of the CMS VH, ttH, and VBF measurements gives $\mu^{\bar{b}b} = 1.03^{+0.44}_{-0.42}$ corresponding to a $p$-value of 2.6σ under the background-only hypothesis [10]. In terms of the signal strength modifier $\kappa_b$, a model-dependent fit that assumes no beyond the SM (BSM) particles in the loops or in decay yields a best-fit value $\kappa_b = 0.64^{+0.31}_{-0.27}$ [14] and $\kappa_b = 0.64^{+0.28}_{-0.29}$ [15], respectively (Fig. 2).

Although the SM $\bar{b}bH$ production cross section is almost a factor of two larger than $ttH$, it is experimentally much more challenging. In the minimal supersymmetric extension of the SM (MSSM), the heavy CP-even ($H$) and the CP-odd ($A$) Higgs bosons eigenstates (collectively denoted by $\Phi$) are almost degenerate in mass in the so-called decoupling regime, and their production cross section via $\bar{b}b\Phi$ is enhanced for large value of $\tan\beta \equiv v_2/v_1$. The
branching ratio is also increased for large value of $\tan\beta$, thus making the $b\bar{b}\Phi$, $\Phi \rightarrow b\bar{b}$ an appealing channel. However, the huge multi-jet background makes its less sensitive than the competing $\Phi \rightarrow \tau^+\tau^-$ search. On the positive side, radiative corrections involving high mass SUSY states (the so-called threshold parameter $\Delta_b$) can affect the value of $\sigma(b\bar{b}\Phi) \times B(\Phi \rightarrow b\bar{b})$ differently from $\sigma(b\bar{b}\Phi) \times B(\Phi \rightarrow \tau^+\tau^-)$, in such a way that a higher sensitivity to the SUSY radiate corrections, hence on the SUSY parameters, is retained by the former [16].

A search for a narrow high-mass $\Phi \rightarrow b\bar{b}$ resonance in all-hadronic final states has been performed by the CMS Collaboration [17] using events with three jets and exactly two (control region) or exactly three b tagged jets (signal region). The control region is used to derive data-driven templates for the di-jet invariant mass spectrum corresponding to different jet flavour assignments. A fit to the invariant mass distribution is then used to set limits. No evidence of a signal is found, and the results are used to set limits for some MSSM benchmark scenarios [17].

### HEAVY FLAVOUR IN HIGGS PRODUCTION: THE TOP COUPLING

Owing to its large mass, the top quark cannot be produced in the decay of an on-shell Higgs boson. Both the Higgs boson production cross section and the branching ratio for $H \rightarrow \gamma\gamma$ are sensitive to the top Yukawa coupling because these two amplitudes involve loops of top quarks that contain a $t\bar{t}H$ vertex. In order to perform model-independent measurements of the coupling, i.e. without assumptions on the loop structure, one would desire to make a direct measurement of the coupling strength through amplitudes that probe the $t\bar{t}H$ vertex at the tree-level.

**Production of a top quark-antiquark pair in association with a Higgs boson**

Searches for $t\bar{t}H$ production in the $H \rightarrow b\bar{b}$ channel have been already discussed in Section a). These analyses have been complemented with measurements targeting other exclusive decay modes, namely $H \rightarrow \gamma\gamma$, $H \rightarrow W^+W^-$, $H \rightarrow ZZ^*$, and $H \rightarrow \tau^+\tau^-$. The latter is searched in three distinctive signatures, corresponding to exactly two same-sign leptons, exactly three leptons, and exactly four leptons. Table 1 summarises the results for the various channels in terms of exclusion limits and best-fit value of the signal strength modifier $\mu_{H\ell t}$. When combined together, the observed (expected) $p$-values for the background-only hypothesis are $2.5\sigma (1.5\sigma)$ and $3.6\sigma (1.2\sigma)$, as obtained by the ATLAS and CMS Collaborations, respectively.

| $H \rightarrow b\bar{b}$ | 3.4 (2.2), 4.1 (3.5) | 1.5$^{+1.1}_{-1.0}$, 0.7$^{+1.9}_{-1.9}$ | 11, 12 |
| $H \rightarrow \gamma\gamma$ | 6.7 (4.9), 7.4 (4.7) | 1.4$^{+1.4}_{-1.3}$, 2.7$^{+2.6}_{-2.5}$ | 18, 12 |
| $H \rightarrow W^+W^-$ | 4.7 (2.4), 6.6 (2.4) | 2.1$^{+1.4}_{-1.2}$, 3.7$^{+1.8}_{-1.7}$ | 19, 12 |

*The first (second) entry are the results reported by the ATLAS (CMS) Collaboration.*

| $H \rightarrow b\bar{b}$ | 3.4 (2.2), 4.1 (3.5) | 1.5$^{+1.1}_{-1.0}$, 0.7$^{+1.9}_{-1.9}$ | 11, 12 |
| $H \rightarrow \gamma\gamma$ | 6.7 (4.9), 7.4 (4.7) | 1.4$^{+1.4}_{-1.3}$, 2.7$^{+2.6}_{-2.5}$ | 18, 12 |
| $H \rightarrow W^+W^-$ | 4.7 (2.4), 6.6 (2.4) | 2.1$^{+1.4}_{-1.2}$, 3.7$^{+1.8}_{-1.7}$ | 19, 12 |

### Production of a single-top quark in association with a Higgs boson

The single-top quark production in association with a Higgs boson ($tH$) has a rather small cross section ($\approx 18$ fb at $\sqrt{s} = 8$ TeV). The dominant production mechanism through $t$-channel exchange of a $W$ boson ($tHq$) is suppressed by the negative interference between amplitudes containing the $W^\mu H$ and $t\bar{t}H$ vertices. The destructive interference is close to maximal for $k_\nu = k_\tau = 1$, implying that large deviations from the SM expectation can be obtained for non-SM values of $k_i$, in particular for $k_i/k_\nu < 1$.

The ATLAS Collaboration has performed an inclusive search for top quark(s) plus Higgs bosons in the $H \rightarrow \gamma\gamma$ final states. Figure 3 (left) shows the effect of including the $tH$ production in the coupling fit combination. Owing to its non-trivial dependence on $k_\ell$, this channel has the unique feature of lifting the sign degeneracy of the likelihood, if no further assumption is made on $B(H \rightarrow \gamma\gamma)$. The corresponding best-fit value of $k_\ell$ obtained by the CMS Collaboration is reported in Fig. 2 (right).
in Ref. [18], the CMS analyses are specifically optimised to separate the $tHq$ signal from any other Higgs signal, in particular from the larger $tH$ production mechanism. The observed (expected) cross section exclusion limit at the 95% CL is shown in Figure 3 (right), and amounts to 2.8 (2.0) times the SM expectation for a flipped-sign hypothesis ($\kappa_t = -1$). These measurements were not included in the grand combination of Ref. [15].

![Figure 3](image-url)

**FIGURE 3.** Left: the ATLAS likelihood scan as a function of $\kappa_t$ as obtained from an analysis of di-photon events with additional jets [18]. Right: the 95% CL upper limits on $\sigma_{tt}$ as a function of $\mu^\gamma\gamma$, as obtained from a combination of three independent searches for $tHq$ production [20].

### SEARCH FOR FLAVOUR CHANGING DECAYS

As introduced in Sec. a), flavour changing neutral currents are suppressed in the SM. In the Yukawa sector, operators of the form $q \bar{q}' H$, where $q$ and $q'$ are quark with the same isospin number but of different families, are heavily suppressed. The transition $t \rightarrow H c$ is experimentally appealing due to the large $t \bar{t}$ cross section, but in the SM the branching ratio is only of $O(10^{-15})$. However, FCNC naturally appear in almost all extensions of the SM, like two Higgs doublet models (2HDM), or quark singlet models (QS) [21]. As an heuristic example, imagine to introduce a higher dimensional operator in an EFT approach of the form $e_{ij} W_i^\mu W_j^\mu \Phi^3$, with $e_{ij} \propto \Lambda^{-2}$. Expanding $\Phi$ to first order around $v v$, the quark mass matrix becomes proportional to $(v \lambda_{ij} + v^3 e_{ij})$, while the Yukawa matrix is proportional to $(\lambda_{ij} + 3 v^2 e_{ij})$, so unless a special flavour simmetry protects the higher-order operators, the diagonalisation of the mass matrix will not make, in general, the Yukawa matrix diagonal. By introducing an operator of the form $\mathcal{L}_{\text{FCNC}} = -\lambda_{utH} \bar{u} t H - \lambda_{tcH} \bar{t} c H + \text{h.c.}$, the flavour-changing branching ratio can be parametrised as:

$$\mathcal{B}(t \rightarrow (u, c)H) = \frac{\lambda_{utH}^2 + \lambda_{tcH}^2}{g^4|V_{tb}|^2 \chi^2},$$

where $g$ is the weak gauge coupling and $\chi$ is a kinematic function. Both the ATLAS and CMS Collaborations have performed a search for flavour-changing top quark transitions, followed by the decay $H \rightarrow \gamma\gamma$, using zero or one lepton events plus additional jets [22, 23]. Mass constraints on the jet and lepton system are used to suppress non-top backgrounds. The signal is extracted through a maximum likelihood fit to the di-photon mass spectrum, and the corresponding exclusion limits are translated into limits on the FCNC coupling by using Eq. 3. The observed (expected) exclusion limits on $\mathcal{B}(t \rightarrow (u, c)H)$ are 0.79% (0.51%), and 0.47% (0.71%), for the ATLAS and CMS experiments respectively. These results allow to exclude values of $\sqrt{\lambda_{utH}^2 + \lambda_{tcH}^2}$ in excess of about 0.1. The CMS Collaboration has extended this search to multi-lepton final states, with sensitivity comparable to the di-photon channel [24, 25].

### CONCLUSIONS

The Higgs physics program pursued in Run 1 at the LHC is already probing the Yukawa sector of the SM. Searches and measurements of Higgs bosons decaying to heavy quarks, or produced in association with heavy quarks, provide
compatibility tests of the SM. Measurements sensitive to the charm quark Yukawa coupling are presently pursued by hunting the rare decay $H \rightarrow J/\Psi \gamma$. Sensitivity to the bottom quark coupling is provided by searches for the exclusive $H \rightarrow b\bar{b}$ decay, while the top Yukawa coupling can be probed, in the least model-dependent way, by measuring the $t\bar{t}H$ cross section. Dedicated $t\bar{t}H$ measurements are important to rule out anomalous $t\bar{t}H$ couplings. Finally, the flavour structure of the Yukawa sector can be studied by searching for rare FCNC decays of the top quark.

All measurements performed to date show overall consistency with the SM prediction for the quark Yukawa sector. Most important, the larger data set that will be collected during the upcoming Run 2 of the LHC will allow to gather a conclusive evidence of the bottom and top Yukawa coupling.

REFERENCES