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Higgs boson measurements in third generation decay channels (excluding ttH) with ATLAS and CMS

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The coupling of the Higgs (H) boson to 3rd generation fermions serves as a powerful tool for precision measurements of the Standard Model, but also as a probe for Beyond the Standard Model physics. The following article will review the latest Higgs to 3rd generation fermion decay measurements from the ATLAS and CMS experiments, excluding direct ttH measurements, using LHC proton-proton collision data at $\sqrt{s}$ = 13 TeV. Particular emphasis is placed on the latest measurements of $H \rightarrow b\bar{b}$ via associated vector boson production (VH) from ATLAS, an inclusive search for $H \rightarrow b\bar{b}$ via gluon fusion (ggF) plus jet production from CMS, and a CP-invariance test using $H \rightarrow \tau\tau$ via vector-boson fusion production (VBF).

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1. Introduction

The discovery of the Higgs boson [1–4] in 2012 by the ATLAS and CMS Collaborations [5, 6] using proton-proton (pp) collision data produced by the Large Hadron Collider [7] (LHC), was a fundamentally important turning point for the Standard Model (SM). The Higgs-to-boson couplings were determined via the well established boson decay modes ($H \rightarrow WW^*/ZZ^*$) using data collected in 2011 and 2012 (Run 1), and have since entered an era of precision measurements [8–11].

The direct coupling of the Higgs boson to the fermionic sector on the other hand was only established via the observation of $H \rightarrow \tau\tau$ following the Run 1 ATLAS and CMS combination [12]. The dominant $H \rightarrow b\bar{b}$ decay mode was not observed until 2018 [13, 14] when the addition of the 2015–2017 Run 2 ATLAS and CMS datasets was made available. Following these milestones, further measurement of Higgs to 3$^{\text{rd}}$ generation fermion couplings offers a wide range of novel opportunities, from limit setting of invisible/undetected decays originating from beyond SM (BSM) physics [9, 15], to probes of CP-violation from $H \rightarrow VV$ anomalous couplings [16, 17].

This article will therefore summarise a total of four Higgs to 3$^{\text{rd}}$ generation fermion analyses recently published by the ATLAS and CMS Collaborations. Two additional analyses pertaining to the measurement of the $H \rightarrow \tau\tau$ decay mode using a total integrated luminosity of 77.4 fb^{-1}, and a BSM probe of constraints on anomalous HVV couplings from production of Higgs bosons decaying to τ lepton pairs using an integrated luminosity of 35.9 fb^{-1}, published via the CMS Collaboration are available in Refs. [17, 18], respectively. These however will not be covered in this article as they have been published and summarised in previous proceedings.

2. Measurements of $H \rightarrow \tau\tau$ via vector-boson fusion

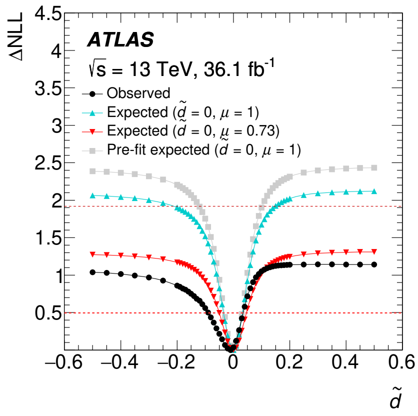
A recent result from ATLAS using $H \rightarrow \tau\tau$ via VBF production as a test of CP-invariance was published [19]. Utilising pp collision data at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV collected by the ATLAS detector with an integrated luminosity of 36.1 fb^{-1}, a model-independent effective Lagrangian density with CP-odd operators of mass dimension six involving the Higgs field and electroweak gauge fields parameterised according to Ref. [20] is tested as a possible extension to the SM. The effective Lagrangian ($\mathcal{L}_{\text{eff}}$) written in the mass basis of the Higgs boson (H), photon (A), and weak gauge bosons ($W^{\pm}/Z^0$) yields a squared VBF matrix element of the form:

$$|\mathcal{M}| = \mathcal{M}_{\text{SM}}^2 + \tilde{d} \cdot 2\mathcal{R}e(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot \mathcal{M}_{\text{CP-odd}}^2 \, , \tag{1}$$

where $\mathcal{M}_{\text{SM}}$ represents the VBF SM matrix element, and $\mathcal{M}_{\text{CP-odd}}$ is the dimension six CP-odd anomalous coupling matrix element. CP-violation in VBF Higgs production is therefore described by a single CP-violating strength parameter $\tilde{d}$ [21]. A genuine CP-odd *Optimal Observable (OO)* [21] that has a (non-)vanishing expectation value under the (CP-violating) SM hypothesis, is utilised as the analysis fit discriminant:

$$\langle OO \rangle = \frac{2\mathcal{R}e(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}. \tag{2}$$

Figure 1a summarises the ΔNLL likelihood scan of the data, and various expectations, as a function of the CP-violating strength parameter $\tilde{d}$, whilst Table 1b summarises the mean values of



(a)

Channel	⟨Optimal Observable⟩
$\tau_{\rm lep}\tau_{\rm lep}$ SF	-0.54 ± 0.72
$\tau_{\rm lep}\tau_{\rm lep}$ DF	0.71 ± 0.81
$\tau_{\rm lep}\tau_{\rm had}$	0.74 ± 0.78
$\tau_{\rm had}\tau_{\rm had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

(b)

Figure 1: The observed ΔNLL curve as a function of the CP-violating strength parameter $\tilde{d}$ (a), and observed mean values of $\langle OO \rangle$ (b). For comparison, expected ΔNLL curves are also shown, generated using pseudo-data sets [19].

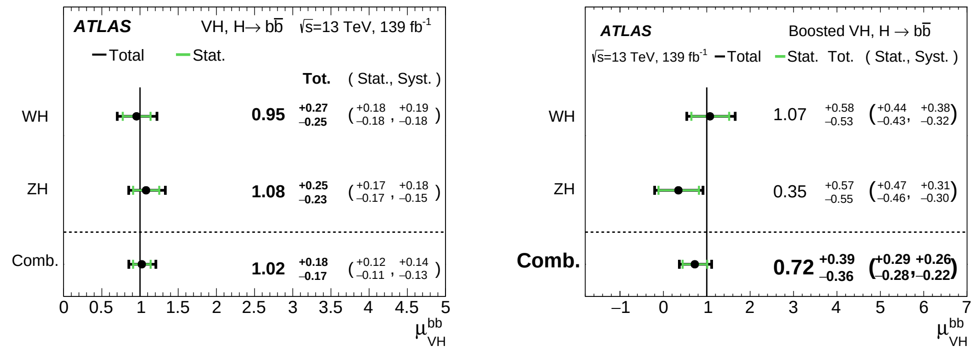
the OO for the four τ decay signatures (di-leptonic, leptonic+hadronic, and di-hadronic). The two demonstrate agreement of the data with no additional anomalous forms of CP-violation, thereby setting limits on anomalous CP-violating HVV couplings of $-0.11 < \tilde{d} < 0.05$ at a 68% confidence level.

3. Measurements of $H \to b\bar{b}$ via associated vector-boson production

Following the discovery of the $H \to b\bar{b}$ decay mode in 2018 [13, 14], two new $H \to b\bar{b}$ measurements of $V(= W^{\pm}/Z^0)H$ production have since been published by the ATLAS Collaboration. The first referred to as *resolved* $VHbb$ [22], reconstructs fully leptonic W/Z-boson decays, whilst the Higgs-boson candidate is reconstructed via requiring exactly two b-tagged anti-$k_{\rm t}$ R=0.4 jets. The second, referred to as *boosted* $VHbb$ [23], adopts the same reconstruction strategy for the leptonically decaying W/Z-boson, but the Higgs-boson is reconstructed using an anti-$k_{\rm t}$ R=1.0 jet (large-R) with two matched b-tagged variable radius anti-$k_{\rm t}$ trackjets to the large-R jet. The former targets a region of phase space where the transverse momentum of the Higgs candidate ($p_{\rm T}^{\rm H}$) exceeds approximately 60 GeV, whilst the latter targets $p_{\rm T}^{\rm H} \gtrapprox 250$ GeV.

Both analyses use the full Run 2 ATLAS pp dataset of 139 fb^{-1}, quoting results on the ratio of the observed vs SM predicted VH production cross-section times $H \to b\bar{b}$ branching ($\mu_{VH}^{b\bar{b}}$), *Simplified Template Cross-Section* (STXS) measurements [24], and Warsaw basis Standard Model low energy Effective Field Theory (EFT) interpretations [25]. For the resolved $VHbb$ analysis $\mu_{VH}^{bb} = 1.02^{+0.12}_{-0.11}$(stat.)$^{+0.14}_{-0.13}$(syst.) is observed, rejecting the background-only hypothesis with a significance of 6.7 standard deviations. Separate results for WH and ZH are also quoted as shown in Figure 2a, with data excesses above the background-only hypothesis of 4.0 and 5.3 standard deviations in significance, respectively.

For the boosted $VHbb$ analysis $\mu_{VH}^{bb} = 0.72^{+0.29}_{-0.28}$(stat.)$^{+0.26}_{-0.22}$(syst.) is observed with a data excess above the background-only hypothesis of 2.1 standard deviations. Figure 2b summarises the μ_{VH}^{bb}



(a) $VHbb$ resolved μ^{bb}_{VH} best-fit values

(b) $VHbb$ boosted μ^{bb}_{VH} best-fit values

Figure 2: Signal strength of VH production cross-section times $H \to b\bar{b}$ branching ratio, μ^{bb}_{VH}, best-fit values, and corresponding errors, for the (a) resolved [22], and (b) boosted [23] analyses.

values for WH, ZH, and the combined VH result.

4. Measurements of $H \to b\bar{b}$ via gluon fusion plus jets

Gluon fusion production of $H \to b\bar{b}$ in association with additional QCD initial state radiation, referred to as ggF+jet, provides an alternative indirect approach to measuring the top Yukawa coupling, in addition to disentangling long-/short-range contributions to ggF production [26].

The recent CMS measurement of ggF+jet production in the $H \to b\bar{b}$ decay mode [27] probes the $p_{\mathrm{T}}^{\mathrm{H}} \gtrapprox 450$ GeV region of phase space through the reconstruction of the Higgs candidate via a single anti-k_{t} R=0.8 jet trimmed/groomed using the Soft-drop algorithm ($z = 0.1, \beta = 0$) [28]. Identification of the $H \to b\bar{b}$ decay is made via a deep-neural network double b-tagger [29] with a 33% efficiency for the $H \to b\bar{b}$ signal and a 1% miss-tag rate for QCD multijet background. The additional QCD radiation is identified via the reconstruction of a single anti-k_{t} R=0.4 radius jet.

An inclusive jet p_{T} signal strength parameter of $\mu_H = 3.7 \pm 1.2(\text{stat.})^{+0.6}_{-0.7}(\text{syst.})^{+0.8}_{-0.5}(\text{theo.})$ is measured, corresponding to a 2.5(1.9)σ excess above the background-only (SM signal) hypothesis. In addition, an unfolded differential measurement of gluon fusion production cross-section times $H \to b\bar{b}$ branching ratio (σ^{bb}_{ggF}) is made using a maximum likelihood unfolding technique like that derived in Section 5 of Ref. [30]. The unfolded differential cross-section is compared to theoretical predictions from Ref. [31] and Powheg+HJ+MiNLO [32], as shown by Figure 3, where inclusively the data exceed the SM prediction with a 1.9σ significance, or a local 2.6σ significant excess for the third p_{T} bin.

5. Conclusion

A review of the most recent results from the ATLAS and CMS Collaborations pertaining to the measurement of $H \to b\bar{b}$ and $H \to \tau\tau$ decay modes has been presented. In the area of Standard Model precision measurements two analyses from the ATLAS Collaboration targeting the associated vector boson production mode (VH) provide updated measurements of the production cross-section, STXS, and tests of EFT extensions in the Warsaw basis with the full Run 2 (2015–2018) dataset.

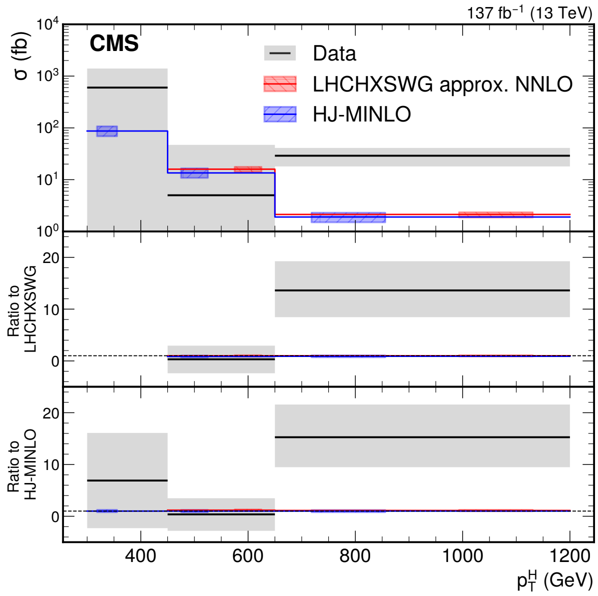


Figure 3: Unfolded differential distribution as a function of the large-R jet p_T for $gg \to H$+jet production, compared to LHC cross-section working NNLO prediction from Ref. [31], and to Powheg+HJ+MiNLO [32] MC generator cross-section prediction [27].

From the CMS Collaboration, a measurement of the fiducial differential gluon fusion cross-section as a function of p_T^H was presented. Addressing the area of BSM physics, a probe of CP-violation from $H \to VV$ anomalous couplings in the Higgs and electroweak sectors using $H \to \tau\tau$ via VBF production from the ATLAS Collaboration was presented.

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