PROCEEDINGS OF SCIENCE

Higgs decays to third-generation fermions at ATLAS and CMS

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After the successful data-taking periods between 2015 and 2018, an important goal of both collaborations, ATLAS and CMS, is the analysis of the full available dataset which provides perfect conditions for precision measurements in the Higgs sector. These proceedings discuss the most recent analyses by the ATLAS and CMS collaborations in which the Higgs boson decays into a pair of bottom quarks or τ leptons among them analyses which drive the sensitivity in the respective channels such as the ATLAS VH($\mathrm{b\bar{b}}$) measurement or the H$\rightarrow\tau\bar{\tau}$ CMS results. Moreover, it contains the first differential fiducial Higgs cross section measurement in final states with τ leptons, a result presented by the CMS collaboration at the LHCP2021 conference for the first time.

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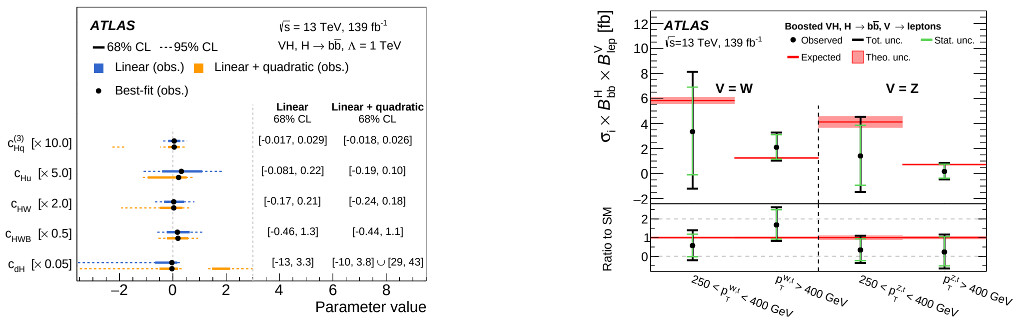
1. Introduction

With the collection of the Run II dataset at a center of mass energy of 13 TeV by the ATLAS [1] and CMS [2] experiments containing approximately 150 fb^{-1} of data [3, 4], Higgs physics [5–7] entered the era of precision measurements.

This review focuses on analyses conducted with the full Run II datasets which target Higgs boson decays to a pair of bottom quarks or τ leptons. It highlights results beyond inclusive cross sections measurements such as measurements of simplified template cross sections (STXS) [8, 9], differential measurements and measurements of effective Higgs couplings [10, 11].

2. H→b$\bar{\text{b}}$

Higgs boson decays into a bottom quark pair are the dominant decay channel of the Higgs boson with a branching ratio of 58% for a Higgs boson mass of 125 GeV. The decay channel H→b$\bar{\text{b}}$ was independently observed in 2018 by the ATLAS and CMS collaborations using Run I and partial Run II datasets [12, 13]. So far, all measurements provided are consistent with predictions from the Standard Model (SM).



(a) **(b)**

Figure 1: Wilson coefficient [10, 11] measurement of the dim-6 operators by the ATLAS VH(b$\bar{\text{b}}$) analysis (a) [14] and STXS measurement by the ATLAS VH(b$\bar{\text{b}}$) analysis targeting the regime with Higgs boson $p_T > 250$ GeV (b) [15].

Higgs production in association with a vector boson Higgs production in association with a W or Z boson decaying into leptons provides the most sensitive production channel for H→b$\bar{\text{b}}$ measurements because the leptonically decaying vector boson gives a handle to significantly reduce backgrounds resulting from multi-jet production. Dominant backgrounds for the measurement are vector boson production in association with jets, top quark production and diboson events.

ATLAS provides two measurements using the full Run II dataset targeting the resolved and boosted regime [14, 15]. The resolved analysis performs a template fit to a boosted decision tree (BDT) output. Besides the total signal strength which is determined to be $\mu_{\mathrm{VH}} = 1.02^{+0.12}_{-0.11}(\mathrm{stat.})^{+0.14}_{-0.13}(\mathrm{syst.})$ with a observed (expected) significance of 6.7 (6.7) standard deviations, STXS measurements and limits on parameters of effective Lagrangian are provided (see Fig. 1a) [14]. The result significantly improves with respect to the analysis which contributed to the H→b$\bar{\text{b}}$ observation. In particular the uncertainty resulting from limited number of simulated events could be reduced, leading to experimental uncertainties dominating the current measurement [14].

The boosted analysis targets events in which the Higgs boson's transverse momentum (p_T) is larger than 250 GeV and it is reconstructed as single large radius jet. The signal is extracted using the large radius jet mass and dominated by statistical uncertainties. Results are provided in terms of the STXS with vector boson $p_T > 250\,\text{GeV}$ as shown in Fig. 1b [15]. The combination of the resolved and the boosted analysis is not carried out due to the significant overlap of events in both analysis selections.

Vector boson fusion induced Higgs production Events in which the Higgs boson is produced via vector boson fusion and further decays into bottom quarks are characterized by the presence of jets with large rapidity gap and reduced hadronic activity between the forward jets as well as the presence of two b jets. ATLAS provides a measurement using the full Run II dataset using an adversarial neural network (ANN) for event categorization which is decorrelated from the invariant mass of the bottom quarks [16]. The ANN allows also additional suppression of events in which the Higgs boson is produced via gluon-gluon fusion. Dominant backgrounds are mostly non-resonant QCD multi-jet events and $Z\to b\bar{b}$ whose contribution is estimated with an embedding technique using $Z\to\mu^+\mu^-$ data. The signal strength is obtained from a simultaneous fit to the invariant mass of the bottom quarks with an observed (expected) significance of 2.6 (2.8) standard deviations. The measurement is dominated by statistical uncertainties and background modelling uncertainties.

Gluon-gluon fusion induced Higgs production Higgs bosons produced via gluon-gluon fusion and decaying to bottom quarks are very challenging to discriminate from the large QCD backgrounds. Thus, ATLAS and CMS consider in this channel only events in which the Higgs boson is produced with high p_T and thus can be reconstructed as single large radius jet.

The CMS measurement [17] uses events in which the Higgs boson is produced with at least $p_T > 450\,\text{GeV}$ and can be reconstructed as a single large radius jet with a distance parameter $\Delta R = 0.8$. The jet is tagged as resulting from a double b decay by the DeepDoubleB tagging algorithm [18, 19]. Signal extraction is based on the soft-drop groomed jet mass [20] and limited by statistical uncertainties and uncertainties related to the QCD background estimation. The observed (expected) significance is 2.5 (0.7) standard deviations which means a 1.9 standard deviation from the SM expectation [17].

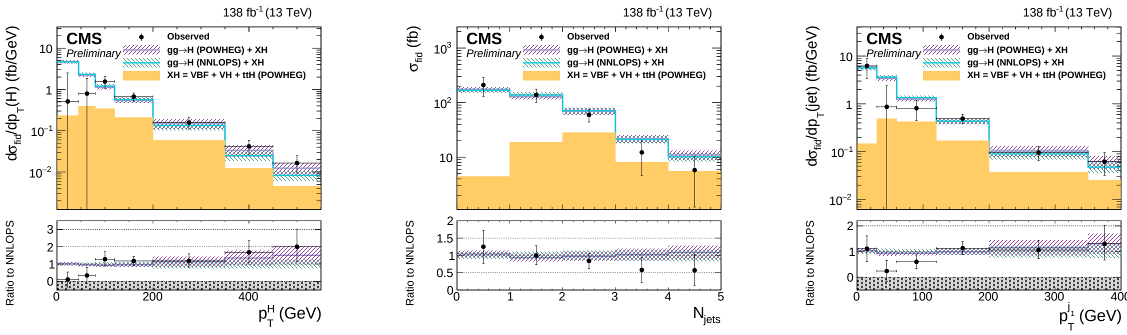
The ATLAS collaboration presents a similar result targeting events in which the Higgs boson is produced at high p_T up to the TeV scale [21]. The Higgs boson is reconstructed as a single large radius jet ($\Delta R = 1.0$) which is further associated with track jets which are used to exploit the substructure and heavy-flavour content of the fat jet. The signal extraction and uncertainties are similar to the CMS measurement. Besides the inclusive signal strength result, ATLAS presents cross section measurements in fiducial and differential regions [21]. No significant deviation from the SM was found.

3. $H\to\tau\bar{\tau}$

Higgs boson decays into τ leptons are the dominant leptonic decay channel of the SM-like Higgs boson. Although the expected branching ratio of only 6% is almost one order of magnitude smaller than the branching ratio of $H\to b\bar{b}$, smaller background contributions allow more precise measurements. The most sensitive Higgs production channel with Higgs bosons decaying into τ leptons is vector boson fusion followed by gluon-gluon fusion.

Inclusive Measurement The measurement by the CMS collaboration of the H→$\tau\bar{\tau}$ process [22] selects events based on the number of electrons, muons and hadronically decaying τ candidates which are required to have opposite charge. Major backgrounds arise from Z→$\tau\bar{\tau}$ [23]. Improvements with respect to previous measurements from CMS [24, 25] mostly result from an improved DNN based τ identification algorithm and a finer event categorization. Signal is extracted using the two-dimensional distribution of the invariant mass of the τ lepton pair and a category specific kinematic variable (τ lepton p_T, invariant mass of the additional jets or the reconstructed Higgs boson p_T). The measurement is dominated by signal prediction uncertainties and uncertainties related to the identification of τ leptons. Results are presented not only as inclusive cross section measurements, but also in terms of different stages of STXS [22].

Differential Measurement The CMS collaboration presents a new analysis for LHCP2021 which is an extension of the H→$\tau\bar{\tau}$ analysis to a differential cross section measurement in terms of Higgs boson p_T, jet multiplicity and leading jet p_T [26]. The result is the first fiducial differential measurement of the Higgs boson cross section in final states with τ leptons and it significantly improves the differential measurements over other final states in phase spaces with large jet multiplicity (at least two additional jets are present) or final states where the Higgs boson is highly boosted (Higgs boson p_T > 120 GeV and p_T < 600 GeV). Similar to the inclusive cross section measurement, the H→$\tau\bar{\tau}$ signal is extracted using two-dimensional distributions where one of the axis is the invariant mass of the τ leptons and the other the differential variable. Regularized unfolding is applied to the differential distributions in order to obtain generator-level signal strengths as shown in Fig. 2 [26].



(a) Higgs boson p_T **(b)** Number of jets **(c)** Leading jet p_T

Figure 2: Results of the first differential fiducial Higgs boson cross section measurements in final state with τ leptons. The plots contain the observed and expected differential fiducial cross sections in terms of the kinematic variable specified in the corresponding subcaption [26].

4. Summary and Outlook

Direct searches which allow to access Higgs boson couplings without loop-effects are essential probes of the SM and are most promising using third generation fermions. Since the discoveries of Higgs boson couplings to bottom quarks and Higgs decays to τ leptons, the experiments have presented updated, improved analyses, e.g. the ATLAS VH($b\bar{b}$) or CMS H→$\tau\bar{\tau}$ analyses. The updates include new interpretations such as STXS measurements, constraints on anomalous couplings as well as limits on Wilson coefficients. There are still outstanding single Higgs boson results using the full Run II datasets such as ATLAS H→$\tau\bar{\tau}$ and CMS VH($b\bar{b}$) measurements which will provide additional sensitivity and thus better understanding of the Higgs sector.

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