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Measurements of Higgs boson associated production with top quarks at the ATLAS experiment

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The Higgs boson production in association with top quarks provides a unique probe of the top Yukawa coupling. This contribution covers the latest measurements of Higgs boson production in association with top quarks ($t\bar{t}H$ and tH), targeting Higgs boson decays to b-quarks, final states with multiple leptons, hadronic taus or photons. Results of cross-section as well as charge-parity measurements performed using data collected with the ATLAS detector at the LHC are presented.

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1. Introduction

The study of Higgs boson production in association with top quarks provides a direct probe of the top Yukawa coupling. Associated production with a pair of top quarks ($t\bar{t}H$) has been observed in 2018 by the ATLAS [1] and CMS Collaborations [2], using a combination of decay channels. Associated production with a single top quark (tH) has yet to be observed due to its small cross-section. It is particularly sensitive to deviations from the Standard Model (SM) due to the interference with the tWH production process and it provides sensitivity to the sign of the coupling.

Multiple decay modes can be targeted. The $H \rightarrow b\bar{b}$ and $H \rightarrow WW^*, \tau\tau, ZZ^*$ channels (section 2 and 3, respectively) have large branching ratios but suffer from large irreducible backgrounds from $t\bar{t}b\bar{b}$ and $t\bar{t}Z/t\bar{t}W$ production. The $H \rightarrow \tau\tau$ channel exploits fully hadronic τ and top decays (section 4). The $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels have low branching ratios which can be compensated by very clean final state signatures that can be triggered on and precisely reconstructed (section 5 and 6, respectively). Due to the large dataset collected by the ATLAS experiment at the LHC [3], charge-parity (CP) measurements are becoming a possibility and have been performed in the $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$ channels.

2. $H \rightarrow b\bar{b}$

A cross-section measurement of $t\bar{t}H$ production has been performed in the $H \rightarrow b\bar{b}$ decay mode, using the full LHC Run-2 dataset collected by the ATLAS experiment, corresponding to an integrated luminosity of 139 fb^{-1} [4]. Events with exactly one or two leptons are analyzed in exclusive single-lepton or dilepton categories. In each category, analysis regions are defined based on the number of jets and b-jets. In the single-lepton channel, a specific region, referred to as 'boosted', is defined to collect events in which the Higgs boson has a high transverse momentum ($p_{\mathrm{T}} > 300$ GeV). Multivariate algorithms are used to separate signal from backgrounds, and their output distributions are used as discriminant variables in the signal-enriched regions. A combined profile likelihood fit is performed to extract the signal, including all analysis regions.

Taking advantage of the possibility of reconstructing the Higgs boson kinematics in the $H \rightarrow b\bar{b}$ channel, the cross-section is measured as a function of the Higgs boson transverse momentum, in the simplified template cross-section formalism (STXS). The best-fit value of the inclusive signal strength is $0.35^{+0.36}_{-0.34}$. The values of the signal strengths in each Higgs boson p_{T} bin are also compatible with the SM expectations within the uncertainties.

Following closely the strategy of the cross-section measurement analysis, a dedicated CP measurement has also been performed [5]. An admixture of CP-even and CP-odd states is still allowed and would be a clear indication of new physics. This admixture can be parameterized by a CP-mixing angle, α, where $\alpha = 0(90)^{\circ}$ corresponds to pure CP-even (odd). A coupling modifier, κ_t^0, accounts for overall changes in the cross-section. One of the main differences with respect to the cross-section analysis is that tH production is also considered as signal, being particularly sensitive to the sign of the coupling. Additionally, angular variables are used as discriminant variables in newly defined signal-enriched regions (based on the ouput of the machine learning algorithms for signal vs background separation). The observed exclusion contours in the $\kappa_t^0\cos(\alpha)$-$\kappa_t^0\sin(\alpha)$ plane are shown in Figure 1. The best fit value of α is marked with a dark blue star.

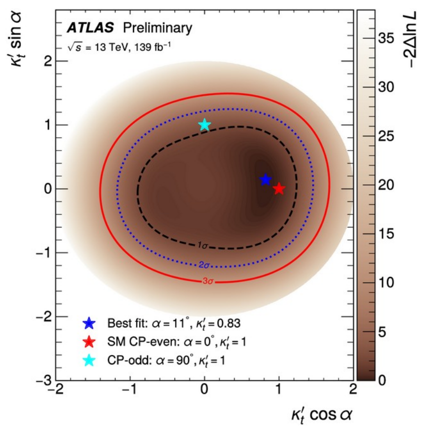

Figure 1: The observed exclusion contours in the $k_t^0\cos(\alpha)$-$k_t^0\sin(\alpha)$ plane in $t\bar{t}H \to b\,\bar{b}$ [5].

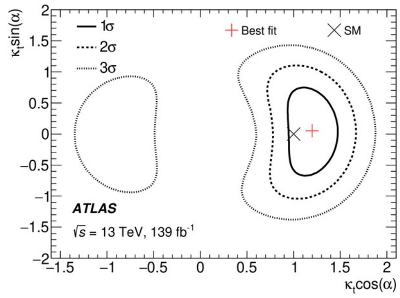

Figure 2: Two-dimensional likelihood contours for $k_t\cos(\alpha)$ and $k_t\sin(\alpha)$ with ggF and $H \to \gamma\gamma$ constrained by the Higgs boson coupling combination [6].

3. $H \to WW^*, \tau\tau, ZZ^*$ (multilepton)

A search for $t\bar{t}H$ production in multilepton final states is presented, using $\sqrt{s} = 13$ TeV proton collisions data collected with the ATLAS experiment between 2015 and 2017, corresponding to a total integrated luminosity of 80 fb^{-1} [7]. Multilepton signatures are primarily sensitive to $H \to WW^*, \tau\tau, ZZ^*$ decays. Six channels are defined based on the number and flavor of loosely identified lepton candidates: two same-charge light leptons ($2\ell SS$); three (3ℓ) and four light leptons (4ℓ); one light lepton and two opposite-charge hadronically decaying τ-lepton candidates ($1\ell 2\tau_{\text{had}}$); two same-charge light leptons and one hadronically decaying τ-lepton candidate ($2\ell SS 1\tau_{\text{had}}$); and three light leptons plus one hadronically decaying τ-lepton candidate ($3\ell 1\tau_{\text{had}}$). The discrimination between $t\bar{t}H$ signal and backgrounds is enhanced by multivariate algorithms in the $2\ell SS$, 3ℓ and $1\ell 2\tau_{\text{had}}$ channels and by additional selection criteria in the 4ℓ channel. No further event selection is applied in the $2\ell SS 1\tau_{\text{had}}$ and $3\ell 1\tau_{\text{had}}$ channels. A simultaneous maximum likelihood fit is performed in all analysis regions in order to extract the signal strength, which is measured to be $0.58^{+0.36}_{-0.33}$. Seven independent normalization factors, associated with the $t\bar{t}W$, internal conversion and non-prompt leptons backgrounds, are also measured. The measured normalization factors for the $t\bar{t}W$ background are in the range $1.3 - 1.7$ above the theoretical predictions.

4. $H \to \tau\tau$ hadronic

An inclusive measurement of $pp \to H \to \tau\tau$ is performed simultaneously in the four dominant Higgs boson production modes, using the full Run-2 dataset collected with the ATLAS detector [8]. In the $t\bar{t}H$ production mode only the fully hadronic decays of the top-quarks and of the τ-leptons are considered ($t\bar{t}(0\ell)H \to \tau_{\text{had}}\tau_{\text{had}}$). Hadronic τ candidates are reconstructed from jets and identified using a recurrent neural network. Events with exactly two reconstructed τ_{had} objects with opposite charge and passing the medium identification working point and angular requirements are selected. The $t\bar{t}H$ topology is targeted by requiring at least five or six jets and at least one or two b-tagged jets. Two BDTs are used to enhance $t\bar{t}H$ separation from $Z \to \tau\tau$ and $t\bar{t}$ events. A simple rectangular cut in the plane defined by the two BDT scores defines two $t\bar{t}H$ signal-enriched regions, in which the di-τ reconstructed mass is used as final discriminant. The $t\bar{t}\,(0\ell)\,H \to \tau_{\text{had}}\tau_{\text{had}}$ signal strength is extracted form the simultaneous maximum likelihood fit in all analysis regions: $1.06^{+1.28}_{-1.08}$.

5. $H \to \gamma\gamma$

An STXS measurement of the Higgs boson production cross-section in the di-photon channel has been performed using the full Run-2 dataset collected by the ATLAS experiment [9]. The four dominant Higgs boson production modes are targeted and the analysis is also optimized for the detection of tH. Events with at least two photons passing the loose identification working point are used as input for a neural network that determines the di-photon primary vertex using information about all the reconstructed vertices in the events and the trajectories of the photons. A multiclass BDT is used to categorize events coming from different STXS regions. Single-top associated production processes ($tHqb$ and tWH) are assigned to dedicated categories that are not further subdivided while for $t\bar{t}H$ multiple categories are defined based on the reconstructed Higgs boson p_{T}. Binary BDTs are further utilized to enhance signal discrimination against the continuum background. The di-photon invariant mass is used as final discriminant in a simultaneous maximum likelihood fit with ten $t\bar{t}H/tH$ dedicated regions. The measured signal strength for Higgs boson associated production with top-quarks is $0.92^{+0.27}_{-0.24}$ and an upper limit of eight times the SM expectation is achieved for single-top associated production.

A dedicated CP measurement has been performed in the same Higgs boson decay channel and using the same dataset [6]. It shares some similarities with the previously described measurement, namely the diphoton primary vertex identification, the signal modeling and the discriminant variable, but it targets specifically the $t\bar{t}H/tH$ production modes, in the semileptonic and fully hadronic $t\bar{t}$ decay channels. Two BDTs are trained to separate $t\bar{t}H$ from backgrounds and CP-even from CP-odd $t\bar{t}H/tH$. Analysis categories are defined based on rectangular cuts in the 2-dimensional BDT space which are combined in a maximum likelihood fit to extract the value of the CP-mixing angle (Figure 2). Values of $|\alpha| > 43^{\circ}$ are excluded at 95% CL and a pure CP-odd coupling is disfavored at 39σ.

6. $H \to ZZ^{*} \to 4l$

An STXS measurement of the Higgs boson production cross-section in the $H \to ZZ^{*} \to 4\ell$ decay channel has been performed using the full Run-2 dataset collected by the ATLAS experiment [10]. At least two same-flavor, opposite-charge lepton pairs are required, resulting in at least one lepton quadruplet per event. All leptons in the quadruplet are required to pass isolation and angular separation requirements. A mass requirement is applied to the leading lepton pair to ensure that it originates from a Z-boson decay. The four leptons are required to originate from a common vertex and be consistent with the Higgs boson mass. Two $t\bar{t}H$-enriched regions are defined: one targeting the fully hadronic decay of the $t\bar{t}$ pair and one lepton enriched, targeting the semileptonic and dileptonic decays. Due to the low number of signal events expected, the leptonic region is taken inclusively and the event yield is used as final discriminant. A neural network is applied in the hadronic region to further separate $t\bar{t}H$ from $t\bar{t}V$ and gluon fusion backgrounds. The measured $t\bar{t}H$ signal strength is $1.7^{+1.7}_{-1.2}$, largely limited by statistical uncertainties and significantly less precise that other production modes, which highlights the challenges and opportunities of studying Higgs boson production in association with top quarks.

7. Conclusions

The exploration of Higgs boson production in association with top quarks by the ATLAS experiment at the LHC is well underway. Final states with leptons, bosons and quarks have been targeted and, owing to the large dataset already collected, CP measurements are becoming a possibility. Statistical independence between different analyses is ensured by orthogonality requirements.

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