PROCEEDINGS OF SCIENCE

PoS(EPS-HEP2023)383

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

Thomas Strebler[a,*] **on behalf of the ATLAS collaboration**

[a] *CPPM,*
Aix-Marseille Université, CNRS/IN2P3, Marseille, France

The study of Higgs boson production in association with one or two top quarks provides a key window into the properties of the two heaviest fundamental particles in the Standard Model, and in particular into their couplings. This contribution presents measurements of tH and ttH production in pp collisions collected at 13 TeV with the ATLAS detector using the full Run 2 dataset of the LHC.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

1. Motivation

In the Standard Model (SM), the coupling of the Higgs boson to the top quark y_t is very large in comparison to the other fermions, which makes it a good opportunity to study in general the Yukawa interactions of the Higgs boson. In principle, this coupling can be studied through the processes involving the $gg \to H$ and $H \to \gamma\gamma$ effective couplings, however only model-dependent constraints can be derived from those, since they involve loop diagrams where beyond-the-Standard Model (BSM) particles could in principle contribute. The associated production of a Higgs boson with a pair of top quarks (ttH) or with a single top quark (tH) offer on the other hand a direct access to the top-Higgs coupling at the tree-level but suffer from relatively low cross-sections, around 507 and 92 fb respectively, which makes them challenging processes to observe at LHC. The tH process involves in particular diagrams with a destructive interference in the SM but in BSM scenarios where the sign of the top-Higgs coupling is inverted, the interference gets constructive and can enhance its cross-section by one order of magnitude, beyond the ttH cross-section.

In general, the CP structure of the top Yukawa coupling can also be probed. The relevant Lagrangian can in particular be parametrised as a function of the top-Higgs coupling modifier κ_t affecting the magnitude of the coupling and a CP-mixing angle α

$$\mathcal{L}_{ttH} = -\kappa_t y_t \phi \bar{\psi}_t \left(\cos\alpha + i\gamma_5 \sin\alpha\right) \psi_t \tag{1}$$

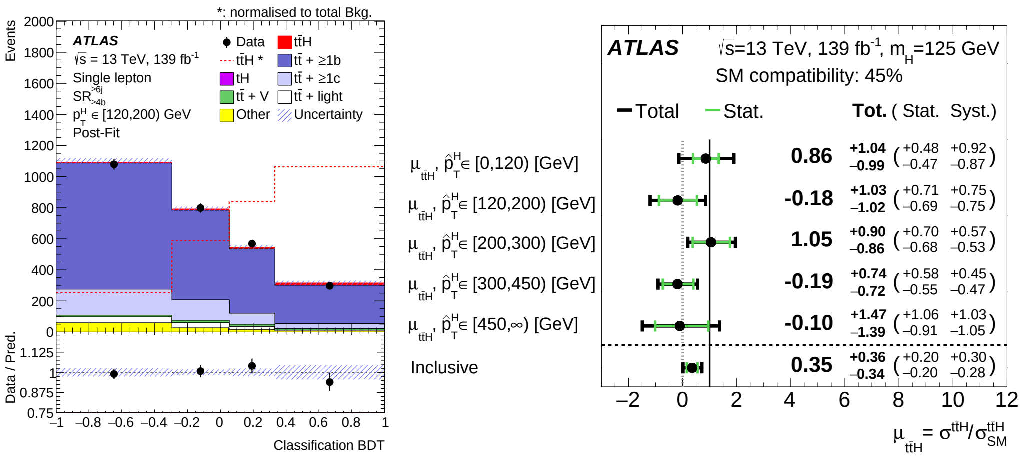
A combined analysis of the ttH and tH processes can then be used to constrain simultaneously κ_t and α.

2. Cross-section and STXS measurements

$ttH, H \to bb$ channel

The $ttH, H \to bb$ channel benefits from the largest branching ratio but its sensitivity is limited by its relatively low purity and the large theoretical uncertainties associated with the irreducible $tt+bb$ background. The large multiplicity of b-jets in this final state is also a challenge to distinguish those stemming from the Higgs and from the top decays and define powerful variables to distinguish the ttH signal from the dominant background. The latest version of this analysis [1], based on the full 139 fb^{-1} Run 2 dataset, focuses on final states with one or two leptons produced from the top decays. A dedicated category focuses on events with a single lepton event and a boosted $H \to bb$ decay, to improve the sensitivity to ttH events where the Higgs boson is produced with a large transverse momentum. The other categories, targeting events where the Higgs boson has a moderate p_T, are subdivided into signal and control regions based on the number of jets and b-tagged jets. Boosted Decision Trees (BDTs) are used both for jet-parton association and for signal extraction, as illustrated in Figure 1a).

The dominant $tt+bb$ background is modeled using a four-flavour scheme next-to-leading-order simulation, including the additional b-jets at the matrix-element level. Several shape uncertainties are implemented for this background and its normalization is left freely floating in the signal extraction fit. Those are the main sources of uncertainties in the measured signal strength, which is found to be in slight deficit with respect to the SM prediction with $0.35^{+0.36}_{-0.34}$, corresponding to an observed (expected) significance of 1.0σ (2.7σ). The signal strength is also measured differentially in bins of the Higgs boson p_{T}, using the Simplified Template Cross-Section (STXS) formalism. This result is presented in Figure 1b). This measurement includes a bin for $p_{\mathrm{T}} > 450$ GeV where a reasonable precision is achieved thanks to the boosted category.



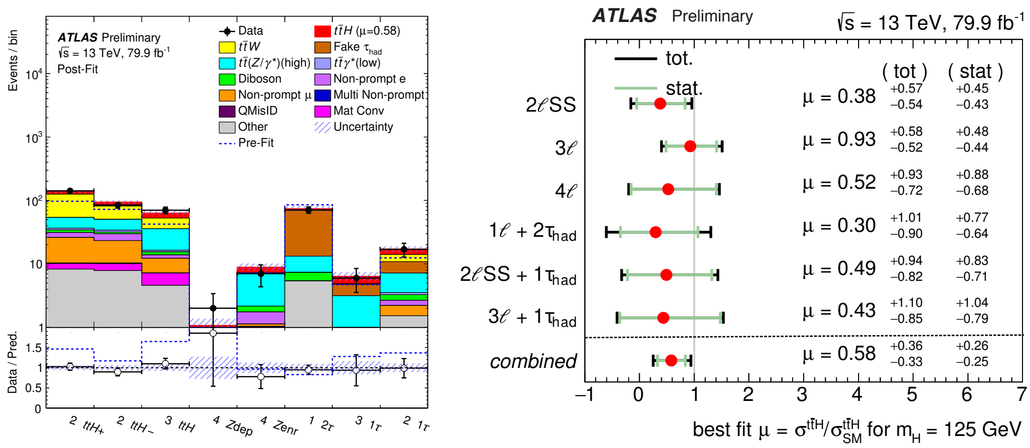
(a) **(b)**

Figure 1: (a) Comparison between data and prediction for the BDT discriminant used the single-lepton $ttH, H \rightarrow bb$ signal region with p_{T}^{H}<120 GeV after the inclusive fit to the data. (b) Signal-strength measurements in the individual STXS p_{T}^{H} bins, as well as the inclusive signal strength [1].

ttH multilepton channel

The last iteration of this analysis [2], based on 79.9 fb^{-1} of Run 2 data, focuses on final states with several leptons and hadronic tau decays (τ_h), which provide good handles to reduce most of the SM backgrounds. The remaining irreducible backgrounds are dominated by ttW and ttZ production, while a sizeable contribution is also expected from reducible backgrounds with non-prompt leptons, jets being mis-identified as τ_h and photon conversions. In order to limit the contamination from those reducible backgrounds, dedicated multi-variate selections have been developed for this analysis to distinguish prompt leptons, produced in W, Z or fully leptonic τ decays, from non-prompt leptons, produced in B hadron decays or due to misreconstructed light hadrons. Signal regions are defined based on the number of leptons and τ_h and are further split depending on the lepton charge and b-jet multiplicity. The contribution from the various backgrounds in the signal regions can be assessed from Figure 2a). Dedicated control regions are used to constrain the normalisation of the backgrounds while simulation is used to estimate the shape of the BDT distributions used for the signal extraction.

This analysis is particularly sensitive to the modeling of the irreducible ttW background, associated with several of the leading systematic uncertainties. The normalisation of the ttW background estimated in this analysis has in particular found to be in excess with respect to its SM expectation, consistently with previous ATLAS and CMS analyses [3, 4]. Recent dedicated ttW measurements carried out in ATLAS [5] should help improving the modeling of this background for future iterations of the ttH multilepton analysis. Combining the different channels, as illustrated in Figure 2b), a signal strength of $0.58^{+0.36}_{-0.33}$ has been measured, associated with a 1.8σ (3.1σ) observed (expected) significance.



(a) **(b)**

Figure 2: (a) Comparison between data and prediction for the event yields in the eight ttH multilepton signal regions after the inclusive fit to the data. (b) Best-fit values of the ttH signal strength and their uncertainties by analysis channel and combined [2].

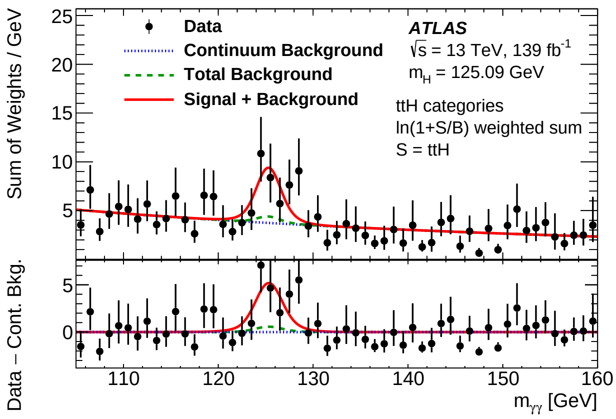
$ttH, H \to \gamma\gamma$ channel

The measurement performed in the $H \to \gamma\gamma$ channel has been performed as part of the inclusive $H \to \gamma\gamma$ STXS measurement [6] based on the full 139 fb^{-1} Run 2 dataset. A multi-classifier BDT is used in that context to assign events to ttH and tH categories. tH categories have in particular been split between subcategories optimised for the SM hypothesis with $\kappa_t = 1$ and the BSM hypothesis with $\kappa_t = -1$, presenting different kinematic properties. Within those STXS categories, a BDT is used to separate the ttH and tH signal from the background and to define subcategories with increasing purity. In those final subcategories, the diphoton invariant mass is ultimately used for the signal extraction, as illustrated in Figure 3a).

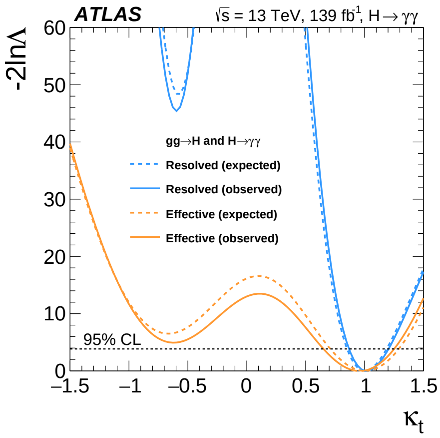
This analysis has provided a measurement of the inclusive ttH signal strength, $0.89^{+0.32}_{-0.30}$, together with differential measurements of the ttH production as a function of the Higgs boson p_T, using the STXS formalism, with uncertainties which are still dominating by their statistical component. Thanks to the dedicated tH categories, BSM scenarios with $\kappa_t < 0$ can also be excluded with a 2.2σ significance, assuming the $gg \to H$ and $H \to \gamma\gamma$ loop diagrams are not resolved but modeled with some independent effective couplings, as presented in Figure 3b).

Combination

A combination of all the ATLAS physics analyses based on Run 2 data focused on Higgs boson production, including the ttH analyses described previously, has been carried out in 2022 [7]. The observation of the combined ttH and tH production has thus been confirmed with a 6.4σ significance. Under the hypothesis of independent effective $gg \to H$ and $H \to \gamma\gamma$ couplings and



(a)



(b)

Figure 3: (a) Combined diphoton invariant mass distributions for categories targeting the ttH production processes. (b) Negative log-likelihood scans as a function of $kapp_t$ in a model where other coupling modifiers are fixed to their SM values. The $H \to \gamma\gamma$ and $gg \to H$ loops are either parameterized as a function of κ_t (blue) or fixed to their SM expectation (orange) [6].

for the scenario in which invisible or undetected non-SM Higgs boson decays are absent, the top coupling modifier has been measured as $\kappa_t = 0.94 \pm 0.11$, with its sensitivity directly driven by the ttH categories. The complementarity between the different ttH channels has also been exploited to carry STXS measurements as a function of the Higgs boson p_{T}. Thanks to the tH categories in the $H \to \gamma\gamma$ analysis a 95% confidence level upper limit on the tH cross-section has also been set at 15 times the Standard Model, which should be improved in the future thanks to dedicated tH analyses covering all Higgs boson decay channels.

3. Top Yukawa CP properties

In addition to the analyses described previously, dedicated analyses aiming at constraining the CP structure of the top-Higgs coupling have also been performed in the $H \to \gamma\gamma$ [8] and $H \to bb$ [9] channels. They follow similar analysis strategies as the previous ones for what regards background estimation and exploit the same BDTs as those to separate the ttH signal from the SM backgrounds. Dedicated discriminants have also been explored for those analyses to distinguish ttH and tH events produced under the CP-odd scenario with $\alpha = 90°$ from those produced under the SM CP-even scenario with $\alpha = 0°$. Another BDT has thus been developed in the $H \to \gamma\gamma$ analysis, based on a combination of angular and kinematic input variables and illustrated in Figure 4, while angular variables based on the estimated top quark four-momenta have been used directly in the $H \to bb$ analysis. Those variables have been combined with the BDTs used for background rejection to define two-dimensional selections and build categories used for the measurement of CP properties. Those analyses have thus been able to exclude in particular the pure CP-odd hypothesis $\alpha = 90°$ with a significance of 1.2σ for $H \to bb$ and 3.9σ for $H \to \gamma\gamma$.

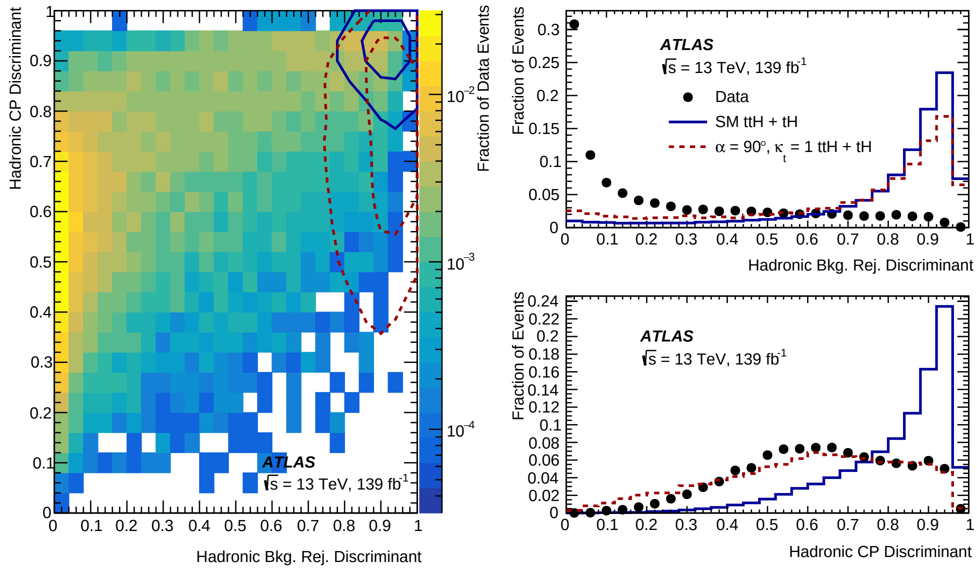


Figure 4: Left: two-dimensional BDT distribution in the selected data events ($m(\gamma\gamma)$ in [105, 160] GeV) from the $ttH, H \to \gamma\gamma$ hadronic region showing the Background Rejection BDT and CP BDT. The inner (outer) contours capture 25% (50%) of the ttH and tH signal events for CP-even (blue) and CP-odd (red) hypotheses. Right: projections onto the background rejection and CP BDT axes [8].

4. Conclusion

The large Run 2 dataset available for physics analyses has allowed to firmly confirm the observation of the ttH production at LHC. This has opened the way for more detailed studies beyond inclusive cross-section measurements, such as differential STXS measurements, studies of the CP properties of the top Yukawa coupling or the search for the rare tH process. For some of the channels considered, the background modeling is now becoming a limiting factor for the sensitivity but dedicated measurements of the $tt + bb$ and ttW backgrounds should improve this for future analyses. Considering in addition that the $H \to \gamma\gamma$ channel is still statistically limited and that new analysis strategies can be explored to improve the sensitivity to the tH production in particular, there will be in principle a large room for improvement with the Run 3 dataset currently being collected.

References

[1] ATLAS Collaboration, *Measurement of Higgs boson decay into b-quarks in associated production with a top-quark pair in pp collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, JHEP 06 (2022) 97

[2] ATLAS Collaboration, *Analysis of* $t\bar{t}H$ *and* $t\bar{t}W$ *production in multilepton final states with the ATLAS detector*, ATLAS-CONF-2019-045

[3] ATLAS Collaboration, *Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector*, Phys. Rev. D 97 (2018) 072003

[4] CMS Collaboration, *Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s}$= 13 TeV*, Eur. Phys. J. C 81 (2021) 378

[5] ATLAS Collaboration, *Measurement of the total and differential cross-sections of $t\bar{t}W$ production in pp collisions at 13 TeV with the ATLAS detector*, ATLAS-CONF-2023-019

[6] ATLAS Collaboration, *Measurement of the properties of Higgs boson production at $\sqrt{s}$=13 TeV in the $H \to \gamma\gamma$ channel using 139* fb^{-1} *of pp collision data with the ATLAS experiment*, JHEP 07 (2023) 088

[7] ATLAS Collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, Nature 607, pages 52-59 (2022)

[8] ATLAS Collaboration, *CP Properties of Higgs Boson Interactions with Top Quarks in the $t\bar{t}H$ and tH Processes Using $H \to \gamma\gamma$ with the ATLAS Detector*, Phys. Rev. Lett. 125 (2020) 061802

[9] ATLAS Collaboration, *Probing the CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ and tH events with $H \to b\bar{b}$ decays using the ATLAS detector at the LHC*, Phys. Lett. B 849 (2024) 138469