PROCEEDINGS OF SCIENCE

tH and ttH production at ATLAS and CMS

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The Higgs coupling to top quarks is an important piece for understanding Higgs physics. The direct way to access its couplings at the LHC is through the associated production of a Higgs boson with a single top quark or with a pair of top quarks. These processes are also good candles to probe the Higgs boson anomalous couplings and CP structure of the Higgs boson. In this contribution, we summarize the ATLAS and CMS analyses that focus on these production modes and consider full LHC Run 2 data.

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1. Introduction

The associated production of a Higgs boson with a pair of top quarks (ttH process) was first observed using data from the 7 TeV and 8 TeV runs and partial luminosity of the 13 TeV data, combining several H final states, by ATLAS [1] and CMS [2]. The second Higgs boson production mode considered in this note, the Higgs boson associated production with a single top quark (tH process) can happen at LHC in two ways: in association with a light quark (tHq) or in association with a W boson (tHW).

In the Standard Model (SM) the production cross section for the ttH process is around 500 fb, while for the tHq (tHW) is 15 fb (70 fb) [3]. That disparity in cross-section requires the tH searches to carefully design analyses regions that target separating this process, specially from the events from the ttH process.

Physics beyond the SM is likely to be discovered through anomalies in the Higgs couplings [4], especially in its coupling to top quarks. In the processes we consider this can manifest both in absolute deviations of the Higgs-top-top coupling (symbolized by the coupling multiplier kt) and as a coupling phase among the scalar and the pseudo-scalar parts of the Higgs field (related to the CP-structure of the coupling). In the SM kt = 1 and the Higgs boson is completely scalar [5].

The kt coupling multiplier squared is a direct multiplier of the rate of the ttH process as well. In the tH processes however, the coupling of the Higgs boson with vector bosons (W and Z bosons) also participates in the production mode. In this case, the coupling multiplier referent of this (kV) is relevant to the process. As usual, in the SM kV = 1. Modifications in kt and or kt modify the tH cross-section as well as the kinematics of this process [3].

2 Analysis considered in this summary.

Below we list of analyses we summarize in these proceedings.

- ttH, where the Higgs boson decays into a pair of bottom quarks (ATLAS) [6].
- ttH +tH, where the Higgs boson decays into leptons (CMS) [7].
- ttH+tH, where the Higgs boson decays into a pair of photons (ATLAS) [8].
- ttH, where the Higgs boson decays into a pair of photons (CMS) [9].

The search that targets higgs decay into bottom quarks [6] produces results in terms of constraints in the signal strength of the ttH process in the SM hypothesis. The CP-phase of the Higgs-top-top coupling is taken into consideration in both analyses that look at the Higgs boson decaying into photons [8,9]. Modifications of the kt are considered in [7, 8] while in [7] modifications of kV are also contemplated. In the next subsections, we highlight some features of each analysis.

1.1 ttH, when the Higgs boson decays into a pair of bottom quarks (ATLAS)

Searches that consider the Higgs boson hadronic decay often have to deal with huge amounts of background. To decrease the quantity of background this search only considers cases where at least one of the top quarks decays leptonically. The events are then categorized into events that contain two leptons (in which most likely both top-quarks decayed leptonically) and events containing one lepton. Further event categorizations are made in terms of the number of jets, b-jets and (for the single lepton case) in terms of boosted Hbb candidates. In some categories a BDT is made to separate the signal and background, while in others a count experiment is done.

The event reconstruction is made in terms of the reconstructed Higgs boson pT, following the simplified template cross-section scheme (STXS) [10]. This improves the sensitivity and re-interpretability of the analysis with respect to BSM physics. Results are produced as upper limits and signal strength constraints on the SM hypothesis and can be seen in Figure 1. Inclusively this analysis observes (expects) the ttH process to be probed with 1.0 (2.7) σ significance. Constraints in the signal strength of the SM hypothesis are also produced in terms of the Higgs boson pT bins. The same final state was analyzed by CMS, with 41.5/fb of Run 2 data [10].

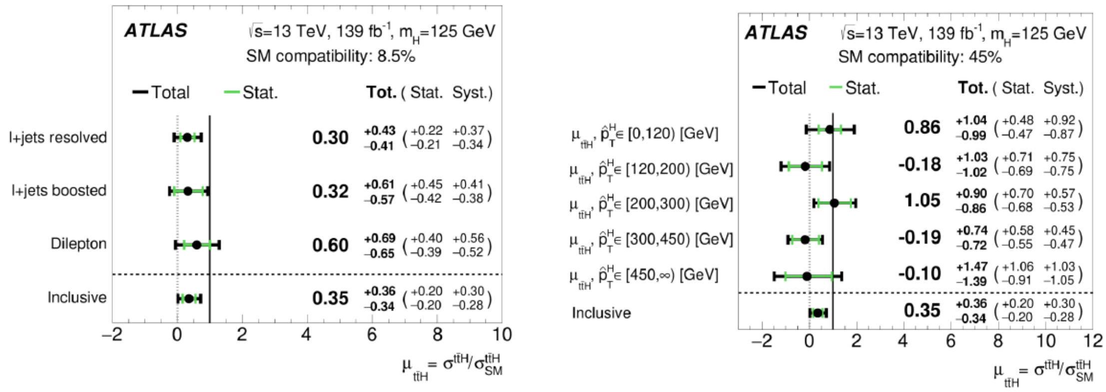

Figure 1: Results of the search [6] in terms of the events categorization (left) and in terms of STXS bins on the Higgs boson pT (right).

1.2 ttH +tH, when the Higgs boson decays into leptons (CMS)

This analysis considers the cases where the Higgs boson decays directly into tau leptons or into light leptons, via the intermediary decay into W and Z bosons. The events are then categorized by the number of tau and light leptons. Ten sub-categories are used, the most sensitive being two same-sign leptons, three leptons, and two same-sign leptons plus one hadronic tau.

Three control regions are added to the fit, to constrain tttW, ttZ, and ZZ backgrounds. The normalization of those is left floating in the fit. An excess of about two sigmas on the ttW normalization was found. A similar result is found on the analysis for the same final state by ATLAS, with 80/fb of Run 2 data [11].

In the three most sensitive categories DNN separates the tH signal from the ttH signals and main backgrounds in that region, otherwise, BDT is made to separate the ttH signal from the main backgrounds. Sub-categorizations in terms of the lepton flavor and number of b-jets are considered when the DNN is used. The output of the MVA is used to fit the signal.

Results are produced both as signal strength constraints on the SM hypothesis and on H coupling modifiers, as can be seen in Figure 2. The observed (expected) significance of the ttH process in this analysis is 4.7 (5.2) σ. From the side of the couplings scans κt is observed to be between the intervals [-0.9,0.7] or [0.7, 1.1] at 95% confidence level.

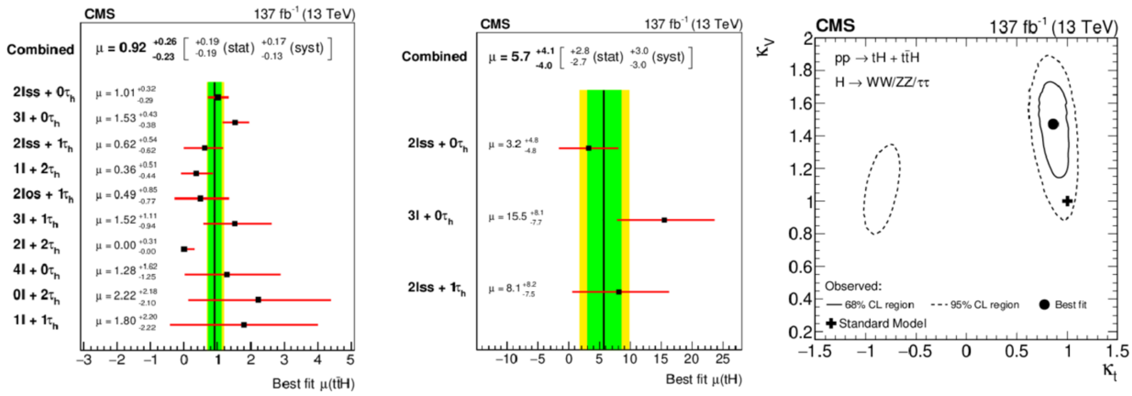

Figure 2: Results of the search [7] in terms of the signal strength of the ttH production (left), in terms of the signal strength of the tH production (center), and in terms of the Higgs boson coupling multipliers relevant to ttH and tH production (right).

1.3 ttH+tH, when the Higgs boson decays into a pair of photons (ATLAS)

Both the tHq and tHW productions are considered along with ttH. Events are categorized into a fully hadronic channel and a semi-leptonic channel. A BDT is used to reconstruct the two top quarks in each region. This information serves as input to two other BDT's. One is to separate the ttH signal from the background and the other separate CP even and CP odd events for both ttH and tH signals. Those are used to define 20 subcategories. The background estimation is data-driven and the signal extraction is made with a fit on the invariant mass of the two leading reconstructed photons on each subcategory.

Results are produced in terms of the product of kt and the sin/cos of the CP angle (α) as defined in [12] and can be seen on the left side of Figure 3. The ttH process as predicted from the SM is observed (expected) with 5.2 (4.4) σ significance, consistent with SM prediction. An upper limit of 12 times the tH signal as in SM is set. The CP angle α > 43° is excluded at 95% CL. Pure pseudo-scalar CP structure of the t-t-H coupling is observed (expected) to be excluded with 3.9 (2.5) σ significance.

1.4 ttH, when the Higgs boson decays into a pair of photons (CMS)

Events are categorized between fully hadronic and when at least one of the top quarks decays leptonically. A BDT is made to separate the ttH signal from the background. This same BDT is used to subcategorize the events, optimizing the expected significance of the SM ttH process or the expected sensitivity of the CP structure of the t-t-H coupling, depending on the interpretation of the results being considered. The background estimation is data-driven and the signal extraction is made with a fit on the invariant mass of the two leading reconstructed photons on each subcategory.

Results are produced in terms of the CP structure of the t-t-H coupling as defined on [13], as can be seen on the right side of Figure 3. The observed (expected) signal significance of the SM ttH process is 6.6 (4.7) σ significance. Pure pseudo scalar CP structure of the t-t-H coupling is excluded with 3.2 (2.6) σ significance.

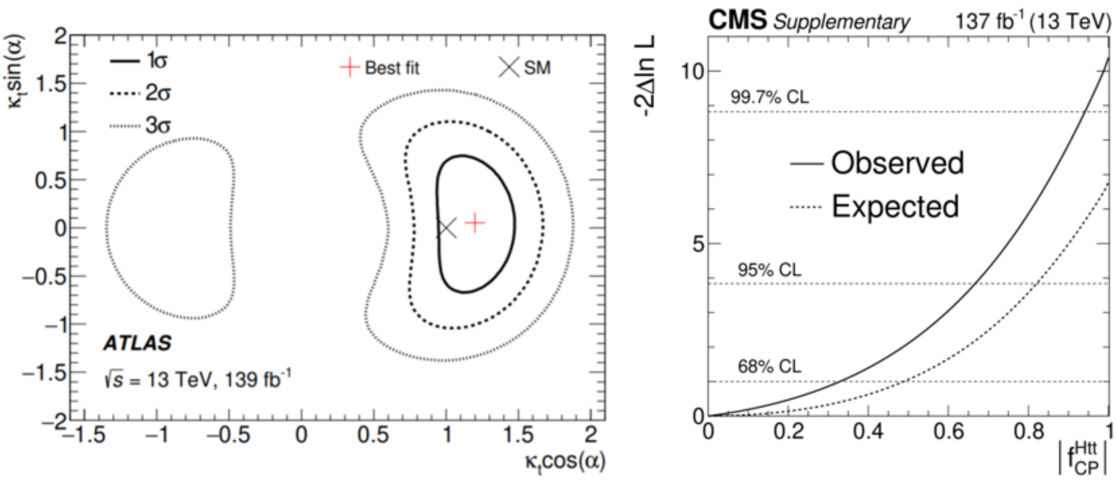

Figure 3: Results of the search [8] in terms of the product of kt and the sin/cos of the CP angle (left) and results of the search [9] in terms of the CP structure the t-t-H coupling (right).

2 Other results that may interest the reader

In this section, we highlight which also considers the full run 2 luminosity and includes results featuring the ttH and tH processes in the results, which were not included here, but may be of interest to the reader.

- ATLAS results, combining Higgs boson several decay modes [14].
- ATLAS result on H →ZZ* → 4l [15].
- Results on H → γγ, which contains STXS measurements produced by ATLAS and CMS by ATLAS [16] and CMS [17].

Conclusion

Several analyses with the full run2 luminosity of the LHC targeting the tH, ttH processes were presented. Different Aspects of the process are explored. The ATLAS analysis considering H →bb constrains the signal strength differentially. The CMS analysis considering H →WW*/ZZ*/ττ→ multi-lepton measures the tH and ttH production modes and explores its effect on constraining the t-t-H and V-V-H couplings simultaneously. Both the ATLAS and CMS analyses considering the H →γγ decay observe the ttH signal and probe the CP structure of the t-t-H coupling. All the results are compatible with the SM.

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