PROCEEDINGS OF SCIENCE

Measurement of the top-Higgs Yukawa coupling in the tHq process with CMS

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The current mandate of the LHC experiments is to precisely determine the properties of the Higgs boson, one of the major interests being the top-Yukawa coupling (y_t) measurement. The Run 2 data have provided evidence of $\mathrm{t\bar{t}H}$ production at the LHC which is sensitive to y_t^2 at the tree level. In contrast, the tHq process provides information on the relative sign of y_t with respect to the Higgs to vector boson coupling (g_{HVV}). According to the Standard Model (SM), the cross section of the tHq process is very low even at 13 TeV centre of mass energy ($\sqrt{s}$). However, in case of anomalous Higgs boson couplings the cross section may be enhanced and be detected with a limited amount of integrated luminosity (L). Results are presented from Run 2 measurements of the tHq process using LHC data collected by the CMS experiment. Future prospects of the search are discussed in the context of High Luminosity LHC (HL-LHC).

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1. Introduction

After the discovery of the Higgs boson in 2012 [1, 2, 3] by the ATLAS [4] and CMS [5] collaborations, the precise measurements of its properties have gained paramount importance. The SM has accurate predictions for the Higgs boson couplings, given its mass which has been measured with better than 2% precision [6] using Run 1 LHC data. In this context, the interpretations are provided in terms of coupling modifiers with respect to SM values: κ_V and κ_t for g_{HVV} and Yukawa couplings y_f respectively. One of the major highlights of Run 2 is the observation of the tt̄H process [18, 19] which probes the top-Yukawa coupling at the tree level. However, the tt̄H production is only sensitive to the magnitude of the coupling as its cross section varies as y_t^2. A complementary measurement is possible using the sub-dominant single top associated production of the Higgs boson (tH) which is sensitive to the relative sign of κ_t with respect to κ_V due to interfering leading order diagrams as shown in Figs. 1 and 2.

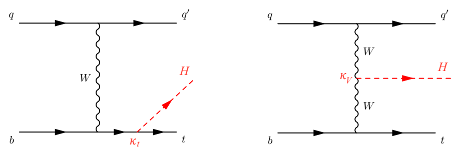

Figure 1: Feynman diagrams contributing to the t-channel tH production.

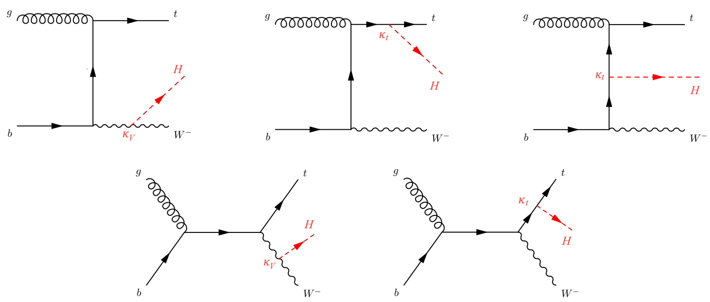

Figure 2: Feynman diagrams contributing to the W-associated tH production.

The dominant t-channel production mode tHq has a cross section of ∼71 fb for pp collisions at $\sqrt{s}$ = 13 TeV. The rate of W-associated production tHW is even smaller, ∼15 fb. Due to effects beyond the SM, anomalous couplings of the Higgs boson can result in large enhancements in the cross sections of both tH production channels. For example, in the inverted top coupling (ITC) scenario i.e., $\kappa_t = -\kappa_V = -1$, the cross section is enhanced by more than ten folds. From LHC Run 1 data a 95% confidence level (CL) upper limit on tHq production in the ITC scenario was extracted for the first time [7] using $L \sim 20$ fb^{-1} at $\sqrt{s} = 8$ TeV yielding an observed upper limit twice that of the expectation. With the increasing amount of data volume available in Run 2, additional coupling scenarios for the Higgs boson has been probed following the Higgs characterization model [8, 9]. The analyses presented here are based on $L \sim 36$ fb^{-1} of data collected by the CMS experiment in 2016 at $\sqrt{s} = 13$ TeV.

2. Multilepton channel

The tHq multilepton final state analysis [11] considers Higgs decays to WW^* and semileptonic decay of the top, resulting in two event categories based on lepton multiplicity: exactly two same sign leptons ($2\ell ss$) or three leptons (3ℓ) in addition to at least one b-tagged jet and at least one non b-tagged jet.

There are two major types of background to the leptonic final state, one originating from prompt leptons (mainly $t\bar{t}W$ and $t\bar{t}Z$ events) and the second consisting of non-prompt leptons or fakes (mainly from $t\bar{t}$+jets) which may be mis-identified jets or real leptons from b/c hadron decays. Selection criteria for well-reconstructed and isolated leptons to efficiently reject non-prompt leptons and estimate their contribution to background follow the $t\bar{t}H$ multilepton analysis [10].

A multivariate technique is used to distinguish the signal against the two major types of background. The two classifier shapes are combined to obtain a one dimensional shape where bin boundaries are defined to contain events having classifier scores within specified ranges.

3. Single lepton + $b\bar{b}$ channel

The $H \to b\bar{b}$ final state of the tHq process is divided in two categories depending on the b-jet multiplicity: 3-tag and 4-tag, where tag denotes the presence of b-tagged jets [12]. The selected events are also required to contain exactly one isolated lepton from semileptonic top decay and at least one un-tagged jet.

This channel is challenged with large $t\bar{t}$ + heavy-flavor background ($t\bar{t}$+HF). A multivariate analysis is carried out to reconstruct kinematic properties of the event using jet-parton assignment, considering either tHq or $t\bar{t}$ hypothesis. These properties are used in a second multivariate analysis to discriminate the signal against the background. In addition, an opposite sign dilepton control region is selected for separating the $t\bar{t}$+HF background from $t\bar{t}$+light-flavor ($t\bar{t}$+LF) backgrounds and constrain them using simultaneous fit to data.

4. Reinterpretation of the $H \to \gamma\gamma$ measurement

The SM production of the tH process with $H \to \gamma\gamma$ is also included in the Higgs boson analysis of the inclusive diphoton final state [13]. The tH events contribute in the "$t\bar{t}H$ hadronic" and "$t\bar{t}H$ leptonic" categories corresponding to fully hadronic or semileptonic decays of the top quarks in $t\bar{t}H$ process.

The tH event yield and kinematic distributions are estimated using scale factors depending on the coupling modifier ratio κ_t/κ_V which modifies the acceptance of signal events and the selection efficiency.

5. Combination of different final states for extracting the tH signal

The above analyses are combined using the statistical framework for Higgs combination [14]. The event selections of the individual channels are mutually exclusive, however, the systematic uncertainties due to common sources such as pileup, b-tag etc. have been considered as completely correlated. A combined maximum likelihood fit is performed on the one dimensional distribution from the multilepton channel, the event classifier discriminator distribution from the $b\bar{b}$ channel and the invariant diphoton mass distribution from the $\gamma\gamma$ final state analysis. The background-only hypothesis considered includes a κ_t dependent $\mathrm{t\bar{t}H}$ contribution to extract the sensitivity to the tH process alone. The observed upper limit on the tH only cross section times branching fraction obtained for the Higgs boson decays to $\mathrm{WW}^*/\mathrm{ZZ}^*/\tau\tau/\mathrm{b\bar{b}}/\gamma\gamma$ in the SM (ITC) scenario is 25 (0.9) times the predicted value [16]. The observed and expected upper limits on the tH only signal strength is shown as a function of κ_t for κ_V=1.0 on the left of Fig. 3.

The 95% CL uncertainties on a parameter of interest can be determined using the profile likelihood ratio test statistic [15], in which experimental and theoretical uncertainties are incorporated via corresponding nuisance parameters. In this analysis, constraints on κ_t are derived from a distribution of the test statistic $-2\Delta\ln\mathscr{L}$ or $-2[\ln\mathscr{L}(\kappa_t)-\ln\mathscr{L}(\hat{\kappa}_t)]$, where the 95% confidence interval covers values lying below 3.84. Here the best-fit value is $\hat{\kappa}_t$ corresponding to the global maximum of the likelihood function. The corresponding κ_t values are constrained inside the ranges (-0.9, -0.5) and (1.0, 2.1) [16] as shown on the right of Fig. 3.

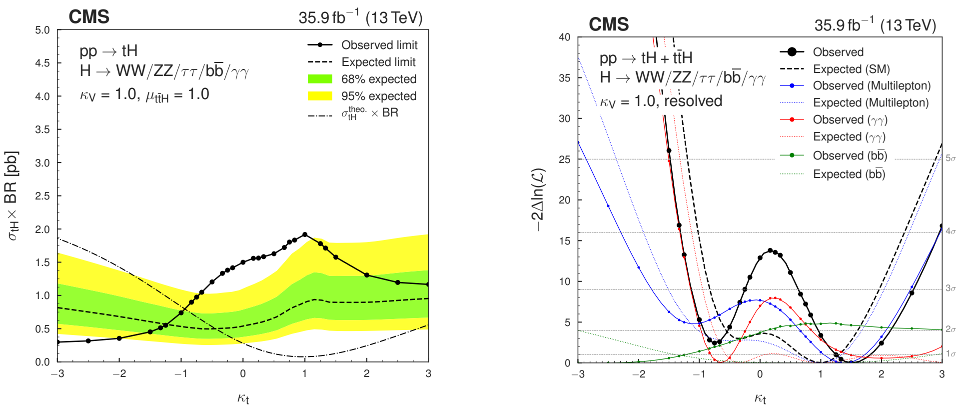

Figure 3: Observed and background-only expected cross section times branching ratio limits on combined tH production where $H \to WW^*/ZZ^*/\tau\tau/b\bar{b}/\gamma\gamma$, as a function of κ_t, for κ_V = 1.0 [16] shown on the left. Scan of $-2\Delta\ln\mathscr{L}$ vs κ_t for the data (black line) and the individual channels (blue, red, and green), compared to the SM expectations (dashed lines) [16] shown on the right.

6. Future prospects of the tH search

From 2026 onwards, the LHC is expected to operate in the high luminosity mode, where the instantaneous luminosity is expected to reach up to 7.5×10^{34} $\mathrm{cm^{-2}s^{-1}}$. A large amount of data (3000 fb^{-1}) will be collected during ten years of run time, paving experimental access to rare processes. However, high luminosity operation will also result in severe detector degradation in performance and high pileup rates, about $140-200$ per event, on average. Detector upgrades are therefore planned to mitigate the anticipated worsening of physics performance of the CMS experiment. The possible improvements in future results have been estimated during 2018 using simple projection scenarios with the help of available statistical methods, in the absence of reliable detector simulations [17].

In the simplest scenario, referred to as S1, it is assumed that all detector effects and systematic uncertainties remain the same as in the 2016 analysis; only the total integrated luminosity has been scaled. Theoretical uncertainties are reduced by a factor of $1/2$ and systematic uncertainties such as lepton identification, b-tagging efficiencies are scaled down as a function of integrated luminosity with a finite lower threshold, labelled as YR 2018 systematics or scenario S2. In both cases the statistical fluctuations of the simulation have been ignored. The analysis at high luminosity will gain from improving the theoretical uncertainties in estimating the background cross sections and also the non-prompt lepton contribution. An improvement by a factor of eight on the expected upper limit on the tH signal strength can be achieved with 3000 fb^{-1} of data, as shown on the left of Fig. 4. Furthermore, it is expected that the future analyses will allow only positive values of κ_t, and with much more restricted range in the presence of a SM like signal. The corresponding negative log-likelihood scan of the test-statistics q for the two scenarios at 3000 fb^{-1} is shown on the right of Fig. 4.

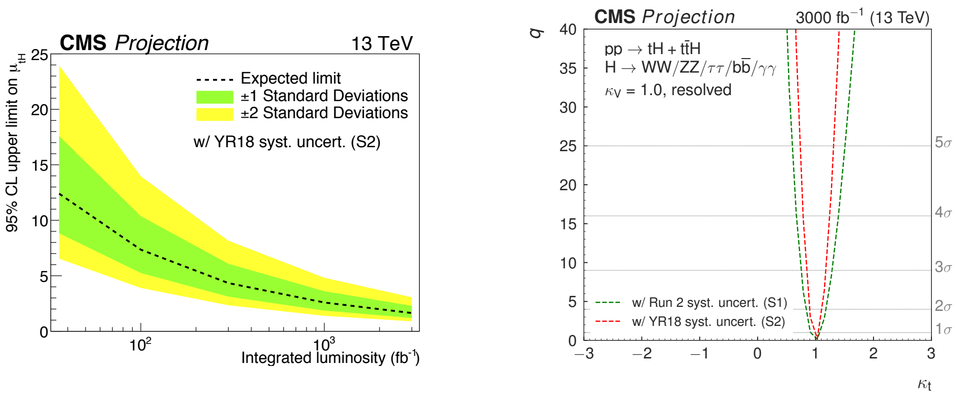

Figure 4: The variation of expected upper limit of the SM like point κ_t=κ_V=1.0 with integrated luminosity for projection scenarios [17] shown on the left. The right figure shows the variation of the test statistics for the two scenarios as a function of κ_t [17].

7. Conclusion

The combined analysis using decay modes $H \to WW^*/ZZ^*/\tau\tau/b\bar{b}/\gamma\gamma$ based on 2016 data improves the earlier 8 TeV results in terms of analysis techniques and sensitivity to the ITC production of the tHq process. Additional scenarios for anomalous Higgs boson couplings are explored to constrain the allowed ranges of κ_t within (-0.9, -0.5) and (1.0, 2.1) at 95% CL using a negative log-likelihood analysis. The sensitivity to the SM production of the tH process is still out of reach with the current dataset. A simple projection to HL-LHC luminosity indicates that the SM production will be accessible in the future.

It is to be noted that a dedicated diphoton channel analysis has yet to be performed which is the most sensitive to negative values of κ_t. In the era of precision physics, tH production plays a key role in the determination of the top-Higgs Yukawa coupling together with the tt̄H process. It remains to be verified how well the projection results compare with the actual LHC data: the future analyses may out-perform the prediction and achieve high precision as early as Run 3.

References

[1] **ATLAS** Collaboration, G. Aad *et al.*, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Phys. Lett.* **B716** (2012) 1–29, `arXiv:1207.7214 [hep-ex]`.

[2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," *Phys. Lett.* **B716** (2012) 30–61, `arXiv:1207.7235 [hep-ex]`.

[3] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson with Mass Near 125 GeV in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV," *JHEP* **06** (2013) 081, `arXiv:1303.4571 [hep-ex]`.

[4] **ATLAS** Collaboration, G. Aad *et al.*, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST* **3** (2008) S08003.

[5] **CMS** Collaboration, S. Chatrchyan *et al.*, "The CMS Experiment at the CERN LHC," *JINST* **3** (2008) S08004.

[6] **ATLAS, CMS** Collaborations, G. Aad *et al.*, "Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments," *Phys. Rev. Lett.* **114** (2015) 191803, `arXiv:1503.07589 [hep-ex]`.

[7] **CMS** Collaboration, V. Khachatryan *et al.*, "Search for the associated production of a Higgs boson with a single top quark in proton-proton collisions at $\sqrt{s} = 8$ TeV," *JHEP* **06** (2016) 177, `arXiv:1509.08159 [hep-ex]`.

[8] P. Artoisenet *et al.*, "A framework for Higgs characterisation," *JHEP* **11** (2013) 043, `arXiv:1306.6464 [hep-ph]`.

[9] F. Demartin, F. Maltoni, K. Mawatari, and M. Zaro, "Higgs production in association with a single top quark at the LHC," *Eur. Phys. J.* **C75** no.~6, (2015) 267, `arXiv:1504.00611 [hep-ph]`.

[10] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Evidence for associated production of a Higgs boson with a top quark pair in final states with electrons, muons, and hadronically decaying τ leptons at $\sqrt{s} = 13$ TeV," *JHEP* **08** (2018) 066, `arXiv:1803.05485 [hep-ex]`.

[11] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for production of a Higgs boson and a single top quark in multilepton final states in proton collisions at $\sqrt{s} = 13$ TeV," Tech. Rep. CMS-PAS-HIG-17-005, CERN, Geneva, 2017.

[12] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for the tH(H$\rightarrow$ b$\bar{\text{b}}$) process in pp collisions at $\sqrt{s} = 13$ TeV and study of Higgs boson couplings," Tech. Rep. CMS-PAS-HIG-17-016, CERN, Geneva, 2018.

[13] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Measurements of Higgs boson properties in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV," *JHEP* **11** (2018) 185, `arXiv:1804.02716 [hep-ex]`.

[14] **ATLAS, CMS, LHC Higgs Combination Group** Collaboration, "Procedure for the LHC Higgs boson search combination in summer 2011", CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-011.

[15] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics," *Eur. Phys. J. C* **71** (2011) 1554, `arXiv:1007.1727 [physics.data-an]`.

[16] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev.* **D99** no.~9, (2019) 092005, `arXiv:1811.09696 [hep-ex]`.

[17] **Physics of the HL-LHC Working Group** Collaboration, M. Cepeda *et al.*, "Higgs Physics at the HL-LHC and HE-LHC," arXiv:1902.00134 [hep-ph].

[18] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of $t\bar{t}$H production," *Phys. Rev. Lett.* **120** no.~23, (2018) 231801, arXiv:1804.02610 [hep-ex].

[19] **ATLAS** Collaboration, M. Aaboud *et al.*, "Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector," *Phys. Lett.* **B784** (2018) 173–191, arXiv:1806.00425 [hep-ex].