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Searches for the associated production of a Higgs boson with a single top quark at $\sqrt{s}$ = 13 TeV at CMS

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We present updated results on the search for the production of a Higgs boson in association with a single top quark using the larger LHC Run II dataset. Final states corresponding to two decay modes of the Higgs boson ($b\bar{b}$ and WW/ZZ/$\tau\tau$) have been studied, targeting leptonic decays of the top quark. Limits are placed on the modifiers of the coupling strength of the Higgs to fermions and bosons.

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1. Introduction

Results from Run I indicate that couplings of the Higgs boson to intermediate gauge boson are compatible with the Standard Model (SM)[1]. With available data from Run I, only some of the Higgs to fermion couplings (y_f) have been constrained with large uncertainties, including the coupling to the top quark. According to the SM, $|y_f|$ depends on the fermion mass. Hence coupling strength is largest for top quark, $y_t \sim \mathscr{O}(1)$. At the LHC, y_t can be studied through the pp$\rightarrow$t$\bar{\text{t}}$H production mode, though the measurements are sensitive only to its magnitude. The associated production of single top quarks and a Higgs boson, or tH (including tHq and tHW), is highly sensitive to the relative sign of the Higgs-W and Higgs-top quark couplings due to a strong interference of the leading order diagrams, see Fig. 1. Hence the tH cross section is strongly dependent on the relative sign of y_t and y_W. In the SM, the interference is destructive, leading to very small rates:

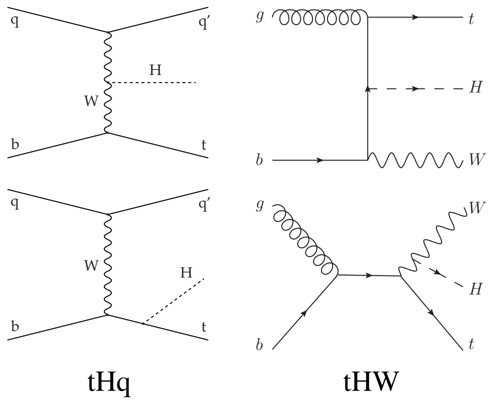

Figure 1: Representative Feynman diagrams for the tH (tHq+tHW) production process[2, 3].

σ(tHq) $\sim$ 71 fb and σ(tHW) $\sim$ 15 fb in pp collisions at $\sqrt{s}$ = 13 TeV. On the other hand, due to effects beyond the SM, anomalous couplings of the Higgs boson can result in large enhancements in the cross section. For example, in the case of a scenario where top-Higgs and W-Higgs couplings have a negative relative sign but are otherwise unchanged (“inverted top coupling", ITC), the cross sections increase more than ten folds. Thus the tH process is extremely interesting to constrain the coupling modifiers w.r.t. the SM fermion and boson couplings, κ_f and κ_V respectively, even with limited amount of integrated luminosity. Search for the tH process in Run II is expected to be more sensitive compared to Run I[2]. The results obtained from the study of two decay modes of the Higgs (b$\bar{\text{b}}$ and WW/ZZ/$\tau\tau$) considering leptonic decay of top quark are presented.

2. Signal modeling for 13 TeV analysis

For the CMS analyses at 13 TeV event weights have been used in order to study the kinematics according to the different choices of the coupling modifiers. The generated signal sample has in total 51 combinations: three κ_V values 0.5, 1, 1.5 and 17 κ_f values in the range (-3, 3). It is to be noted that the event kinematics depend only on the ratio κ_f/κ_V. In the present study 33 unique and independent values of this ratio are considered. It is assumed that all fermion coupling modifiers scale the same way, irrespective of the flavour.

3. Higgs to $b\bar{b}$ analysis

3.1 Event selection

The study is performed using the 2.3 fb^{-1} of collision data collected by CMS in 2015 at $\sqrt{s}$ = 13 TeV[4]. The analysis is optimized for the tHq production mode and the final state requires exactly one isolated lepton, at least three b-tagged jets and at least one non-tagged jet. The kinematic selections include $p_T > 30$ (25) GeV within $|\eta| < 2.1$ (2.4) for electron (muon) while for central jets ($|\eta| < 2.4$) $p_T > 20$ GeV and for forward jets ($|\eta| < 4.7$) $p_T > 40$ GeV is required. Two signal regions are defined depending on the possibility of the presence of a fourth b-jet from initial state gluon splitting: 3-tag (having exactly three b-tagged jets) and 4-tag (having exactly four b-tagged jets). The main background process for this search is the inclusive $t\bar{t}$ production with a cross section of 832 pb.

3.2 Search strategy

A Boosted Decision Tree (BDT) is used to reconstruct the event on the basis of the final state particles chosen. Two *Reconstruction BDT*s are considered to assign the jets in the event to a parent particle (t or H) corresponding to signal (tHq) and background ($t\bar{t}$) hypotheses. For each hypothesis, there are a number of ways the parent particle assignment can be done, so the one with the highest BDT score is chosen. This reconstruction is done for all 51 combinations of (κ_t, κ_V) under both hypotheses. Examples of the BDT response distribution for the signal hypothesis are shown in Fig. 2. Next, the reconstructed objects with BDT determined particle assignment are

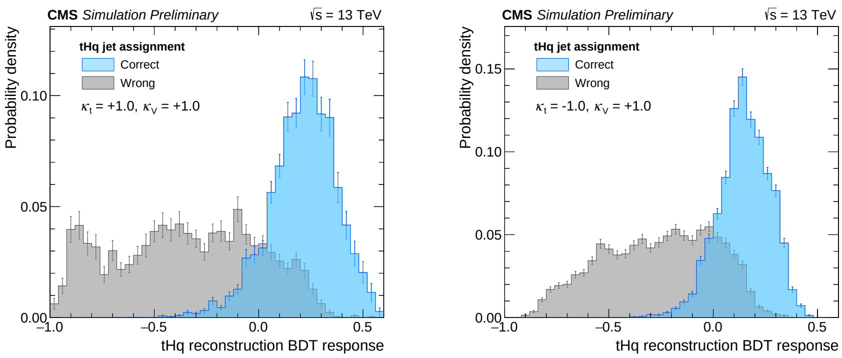

Figure 2: Representative Reconstruction BDT response in the signal hypothesis for SM ($\kappa_t = 1$) and ITC ($\kappa_t = -1$) scenarios[4].

used as input to the *Classification BDT*, which is trained on Monte Carlo (MC) event samples for highest discrimination between the signal and background based on kinematic observables such as aplanarity, Fox-Wolfram moments of the event etc.

3.3 Results

The Classification BDT reponse is binned and its shape is used in a likelihood fit to extract the signal. The fit is performed simultaneously in the two channels, 3-tag and 4-tag. No significant excess is observed above the background-only hypothesis. Assuming the SM ($\kappa_V = \kappa_t = 1$) scenario, upper limits are set on the observed signal strength at 113.7×SM (expected 98.6×SM) at 95% confidence level, as shown in Fig. 3. In the ITC (κ_V = -κ_t = 1) scenario upper limits are set on the observed signal strength at 6.0×SM (expected 6.4×SM) with 95% confidence level.

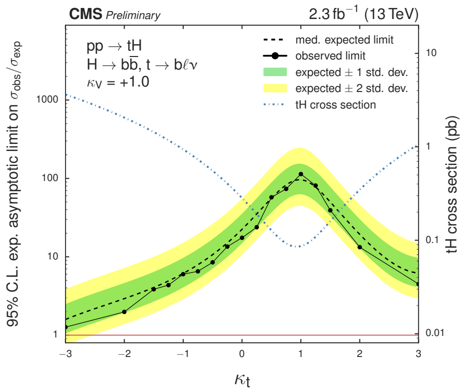

Figure 3: Limits on the tH production cross section for κ_V=1 from $H \to b\bar{b}$ analysis[4].

4. Higgs to multi-lepton analysis

4.1 Event selection

The analysis is done using the full set of data collected by CMS in 2016 corresponding to an integrated luminosity of 35.9 fb^{-1}[5]. The analysis is optimised also in this case as a search for the tHq production. Considering the decay of the Higgs to WW* (dominant), ZZ* and $\tau\tau$, the final state can have at most four leptons. The analysis requires exactly two same sign dilepton ($\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$) or three leptons (3ℓ: $\mu\mu\mu$, $e\mu\mu$, $ee\mu$, eee) in addition to at least one b-tagged jet and at least one non b-tagged jet. The kinematic selection for leptons requires p_T > 25 GeV (leading), 15 GeV (sub-leading) within $|\eta|$ < 2.4 (2.5) for electron (muon) while jets are selected with p_T > 25 GeV for central jets ($|\eta|$ < 2.4) and p_T > 40 GeV for forward jets ($|\eta|$ > 2.4). The dominant background for this channel is also represented by t$\bar{\text{t}}$ when one of the two b-jets from the top decay produces, or is mis-identified as, a lepton. Collectively these are called ‘fakes’ or ‘non-prompt’ leptons, the contributions of which are determined using a data driven method.

4.2 Search Strategy

Optimal discrimination between genuine leptons and fakes is achieved using a multivariate discriminator, developed for the t$\bar{\text{t}}$H multi-lepton analysis, named as *lepton MVA*[6]. This variable is also used for the fake-rate estimation from data and determination of the fake background. The selected events are then given as input to two classification BDTs which are trained to distinguish the signal from the two types of backgrounds: t$\bar{\text{t}}$ (non-prompt leptons) and t$\bar{\text{t}}$V (prompt leptons), where V stands for W and Z. The discriminating variables are pseudorapidity of the non-tagged jet, multiplicity of b-tagged jets etc. The 2 dimensional space formed by the output of the 2 discriminators is divided into rectangular bins in order to maximise the analysis sensitivity. One-dimensional projections of the distributions for the different analyses categories are shown in Fig. 4.

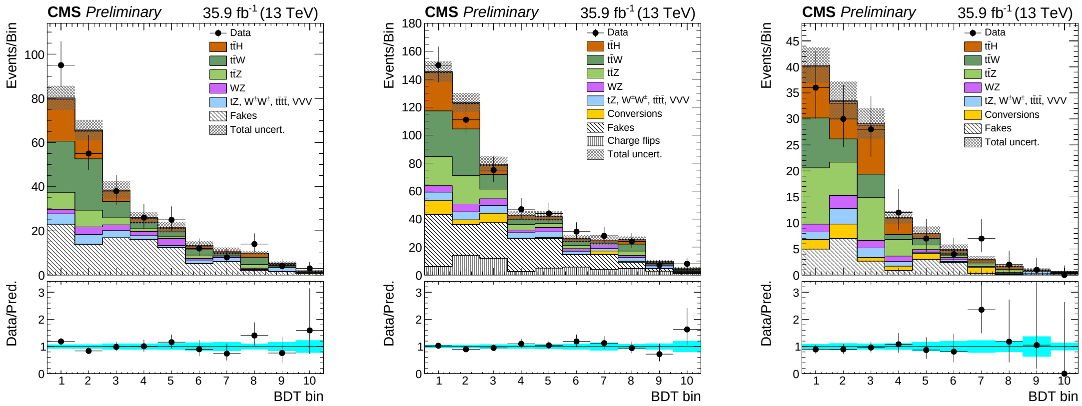

Figure 4: 1D bin-histograms for $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$ and 3ℓ channels respectively[5].

4.3 Results

A maximum likelihood fit is performed on the bin-histograms simultaneously for all channels to obtain the best-fit combined cross section of tH+tt̄H process for a particular κ_t/κ_V ratio. It is to be noted that tt̄H is included in the signal model since its cross section varies as κ_t^2. The best fit signal strength observed in the SM scenario ($\kappa_V/\kappa_t = 1$) is 1.82×SM whereas the signal strength observed in ITC ($\kappa_V/\kappa_t = -1$) case is 0.68×SM. From the signal strengths, the corresponding upper limits on the combined cross secion times branching ratio values are obtained which are shown in Fig. 5. Corresponding to the value $\kappa_t/\kappa_V = 0$, tt̄H contribution vanishes while tHq and tHW rates

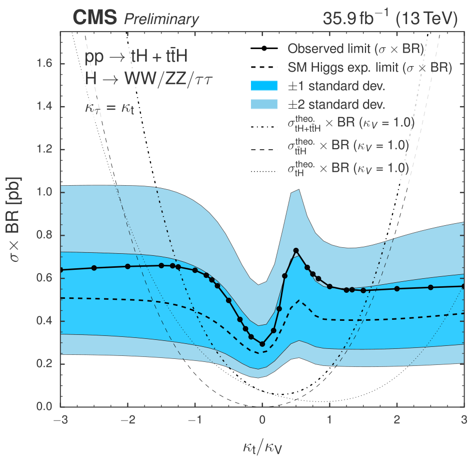

Figure 5: Limits on the tH production cross sections from $H \rightarrow$ multi-lepton analysis[5].

are non-zero. Interestingly, the shape of the observed distribution indicates the minimum value at this choice of couplings. This implies that selected events are more like tt̄H rather than being tH type. This is expected due to the much larger event rate of tt̄H and similarities in the final states. Finally, from the above measurement κ_t can be constrained within the range (-1.25, 1.6) at 95% confidence level for κ_V=1.

5. Conclusions

Collision data from Run II is able to put tighter constraints on the measured values of κ_t compared to Run I. Results from H $\rightarrow \gamma\gamma$ channel are awaited, which was the most sensitive channel for this study at 8 TeV. The measurements from all three Higgs final states will be combined in the near future to give a common range of exclusion for the coupling modifiers.

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