PROCEEDINGS OF SCIENCE

Searches for rare top quark decay and BSM top interactions in CMS

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Top quark is the heaviest elementary particle within the standard model, this unique property may suggest that top quark play an important role in standard model, or have an opportunity to behave anomalously. The branching ratio of top quark decays to bottom quark and W boson is close to unity, thus a study on its rare decay as well as anomalous interactions of top quark can be served as a probe to physics beyond the standard model. Several analysis targeting top quark rare decay and beyond standard model interactions from CMS will be introduced in this report.

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1. Introduction

The discovery of the 125 GeV Higgs boson in the ATLAS [1, 2] and CMS [3–5] experiment has brought us to a new field in which the most importants task in particle physics are measuring properties of Higgs boson within the standard model (SM) as well as searching for physics beyond the SM (BSM). Top quark is the heaviest elementary particle within SM, and such unique property may suggest that top quark plays an important role within SM as well as having higher possibility than other SM particles to have anomalous interactions.

Flavor-changing neutral current (FCNC) interaction is one of the most important portal to BSM. The FCNC process is forbidden at tree level in the SM and is highly suppressed in loop corrections by the Glashow-Iliopoulos-Maiani mechanism, thus a excess in the FCNF study obviously implies the existence of BSM. On the other hand, charged-lepton flavor violation (CLFV) is treated as a golden channel to search for BSM. CLFV is assumed to be strictly forbidden in the weak interactions due to massless neutrino. However, CLFV is allowed in loop level after the discovery of neutrino oscillation, though the tree level CLFV is still forbidden. Several works targeting on the FCNC and CLFV using top quarks events as well as the CP violation measurement using top quark pair events will be introduced in this report.

2. FCNC in tHq with Higgs decays to bottom quarks

As illustrated in section 1, loop level FCNF is highly suppressed, which leads to a branching fraction of $\mathcal{O}(10^{-17})$ for t→Hu and $\mathcal{O}(10^{-15})$ for t→Hc, which is obviously out of experimental reach. However, some BSM models predict highly enhanced t→Hq branching fractions to $\mathcal{O}(10^{-5})$ for t→Hu and $\mathcal{O}(10^{-4})$ for t→Hc. This analysis [6] searches for tHq FCNC using $\mathrm{H}\to\mathrm{b\bar{b}}$ channel. Two signal production modes arising from the anomalous tHq interaction are considered: the associated production of a single top quark with the Higgs boson from an u or c quark (ST production mode) and the t→Hq FCNC decays of a top quark in top quark-antiquark pair (tt) events (TT production mode). The corresponding Lagrangian with a FCNC coupling (κ_{Hqt}) reads:

$$\mathcal{L} = \sum_{\mathrm{q=u,c}} \frac{g}{\sqrt{2}} \bar{\mathrm{t}}\, \kappa_{\mathrm{Hqt}} \left(f^{\mathrm{L}}_{\mathrm{Hq}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{Hq}} P_{\mathrm{R}} \right) \mathrm{qH} + \mathrm{h.c.}, \quad (1)$$

in which the complex chiral parameters $f^{\mathrm{L}}_{\mathrm{Hq}}$ and $f^{\mathrm{R}}_{\mathrm{Hq}}$ have negligible impact on the kinematics, and are fixed to 0 and 1, respectively.

Events are selected in the final state with exactly one lepton (μ or e) and at least three jets, of which at least two must be identified as b-tagged jets. The selected events are divided into five categories based on the jet and b-tagged jet multiplicities in order to optimize the analysis sensitivity. The number of jets can be exactly three or at least four, and the corresponding categories are denoted as j3 or j4, respectively. Similar to the jet multiplicity, the categories in terms of b jets are indicated as b2, b3, or b4 when the considered event has exactly two, three, or four b jets, respectively. Following these conventions, the jet categories are identified as b2j3, b2j4, b3j3, b3j4, and b4j4. Multivariate data analysis (MVA) method is used in both event reconstruction and separation between signal and backgrounds. Firstly deep neural network (DNN) method is applied to reconstruct signal and backgrounds by correct jet assignment between reco-level and generator-level. Then a boosted decision tree (BDT) is used to separate signal and backgrounds in five categories. The final signal extraction show good agreement between data and SM predictions, limits are set on the cross sections as shown in Fig. 1. The observed (expected) upper limit of BR(t→Hu) at 95% confidence level (CL) is 7.9×10^{-4} (1.1×10^{-3}); the observed (expected) upper limit of BR(t→Hc) at 95% CL is 9.4×10^{-4} (8.6×10^{-4}). The limits on the cross section can be interpreted as the limits on the couplings, the two-dimensional limits on κ_{Hct} and κ_{Hut} are also shown in Fig. 1.

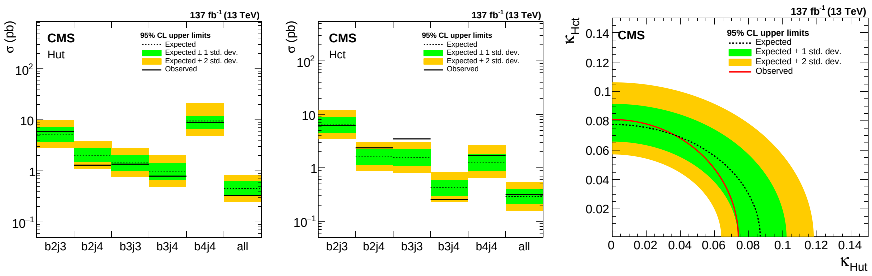

Figure 1: Excluded limits on the product of the cross section and branching fraction at 95% CL for the Hut (left) and Hct (middle) couplings obtained using the BDT distributions. Each jet category and their combination are shown separately. A corresponding two-dimensional limits on κ_{Hct} and κ_{Hut} are shown (right).

3. FCNC in tHq with Higgs decays to photons

The motivation of this analysis [7] is similar with the work in section 2, the difference is this analysis using H→$\gamma\gamma$ channel. The selected events are required to have at least two photons satisfying the identification requirement derived using MVA method. Then two qualified photon candidates are required to have invariant mass in 100–180 GeV to reconstruct the Higgs boson. The selected events are then divided to two categories according to the W boson decay mode from the top quark decay, namely the leptonic and hadronic channel, in which one lepton and zero lepton is required, respectively.

BDT method is used to separate signal and backgrounds for each anomalous coupling, for two different channels as well as on different background types, i.e., the resonant backgrounds (those with Higgs boson) and the non-resonant backgrounds (those without Higgs boson), which lead to eight BDTs totally. The modeling of the input features is validated by comparing their distributions in data and simulation for events passing the preselection and having $m_{\gamma\gamma}$ in the sidebands, defined as the $m_{\gamma\gamma}$ ranges of 100–120 or 130–180 GeV. The resulting BDT scores are also validated in the same way and good agreement between data and predictions is obtained.

The signal extraction is perform by a fit to $m_{\gamma\gamma}$ in seven regions for t→Hu and t→Hc, respectively. The expected $m_{\gamma\gamma}$ distributions of signal and resonant background events are modeled using the sum of a double-sided Crystal Ball function and a Gaussian function. The models are derived from simulation for signal as well as each type of resonant background with the Higgs boson mass fixed to 125.38 GeV. The non-resonant background is modeled directly from data. No significant excess above the background prediction is observed in any of the categories, the observed (expected) 95% CL upper limits on BR(t→Hu) and BR(t→Hc) are 1.9×10^{-4} (3.1×10^{-4}) and

7.3×10^{-4} (5.1×10^{-4}), respectively, as shown in Fig. 2. The corresponding 95% observed (expected) limits on κ_{Hut} and κ_{Hct} are 0.037 (0.047) and 0.071 (0.060), respectively.

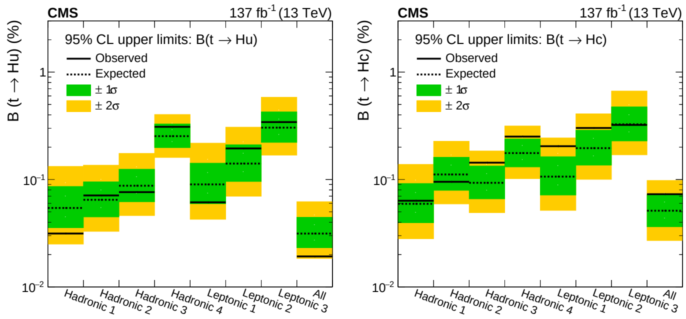

Figure 2: The observed (solid line) and expected (dotted line) 95% CL upper limits on BR(t→Hu) (left) and BR(t→Hc) (right) for each of the hadronic and leptonic categories, defined as described in the text. The last bin gives the overall combined upper limit. The ±1 and ±2 standard deviation variations on the expected limit are given by the green and yellow bands respectively.

4. CLFV in top events

Several measurements of B meson decays that involve leptons have hinted at the presence of possible small violations of lepton universality in recent years. The model accommodating such levels of violation of lepton universality generally also leads to observable effects in lepton flavor violation. In this analysis [8], three Wilson coefficients related to the operators, C_{vector}, C_{scalar}, and C_{tensor} are studied. Those operators can lead to four-fermion interactions involving the top quark, the up or charm quark, and two leptons of different flavor. In addition to top quark decays, CLFV interactions at the LHC contribute to single top quark production in association with a pair of leptons of different flavor. Figure 3 displays representative Feynman diagrams for single top quark production and decay of the top quark in $\mathrm{t\bar{t}}$ production via CLFV interactions.

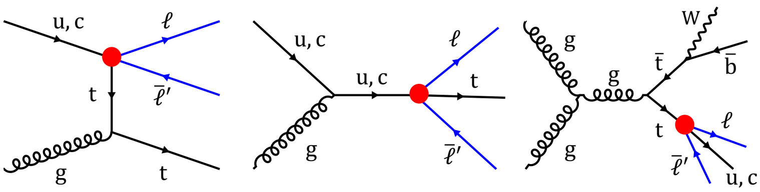

Figure 3: Feynman diagrams for single top quark production (left and middle) and top quark decays in SM $\mathrm{t\bar{t}}$ events (right) via CLFV interactions. The CLFV vertex is marked as a filled circle.

In this analysis, the W bosons in signal events decay hadronically. Thus the selected events are required to have one oppositely charged eμ pair together with multiple jets, of which at least one is tagged as b-jet. BDT method is used to separate signal and backgrounds, mainly the SM $\mathrm{t\bar{t}}$. The BDT training is performed in two categories according to the number of b-jets, with one b-jet or more than one b-jet. The inputs of the training include 5 variables: the p_{T} of the leading lepton, the p_{T} of the leading jet, the distance between the electron and muon, missing p_{T} and number of jets. No obvious deviation between data and SM prediction is observed, 95% CL limits are set on different CLFV operators and are listed in Table 1.

Table 1: Expected and observed 95% CL upper limits on the CLFV Wilson coefficients and top quark CLFV branching fractions.

Vertex	Int.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}]		$\mathcal{B}(10^{-6})$	
	type	Exp	Obs	Exp	Obs
	Vector	0.12	0.12	0.14	0.13
eμtu	Scalar	0.23	0.24	0.06	0.07
	Tensor	0.07	0.06	0.27	0.25
	Vector	0.39	0.37	1.49	1.31
eμtc	Scalar	0.87	0.86	0.91	0.89
	Tensor	0.24	0.21	3.16	2.59

5. CP violation in top-pair events

The CP violation (CPV) predicted in the SM is not enough to explain the matter-dominant universe, a nonzero chromoelectric dipole moment (CEDM) of the top quark can generate sizable CPV in the production of $\mathrm{t\bar{t}}$. This analysis [9] presents the results of new searches for CPV asymmetries in $\mathrm{t\bar{t}}$ events. In a model with contributions from a CEDM, the magnetic and electric couplings between top quarks and gluons (g) are conventionally written as:

$$\mathcal{L} = \frac{g_s}{2}\bar{\mathrm{t}}T^a\sigma^{\mu\nu}(a_\mathrm{t}^\mathrm{g} + i\gamma_5 d_\mathrm{t}^\mathrm{g})\mathrm{t}G^a_{\mu\nu}, \tag{2}$$

where g_s and $G^a_{\mu\nu}$ are the strong coupling constant and the gluon field strength tensor, respectively; t and $\bar{\mathrm{t}}$ are the wavefunctions of the top quark and antiquark; T^a are $SU(3)$ generators; a_t^g refers to the parameter of the chromomagnetic dipole moment; $\sigma^{\mu\nu}$ is defined by the operator $\frac{i}{2}[\gamma^\mu, \gamma^\nu]$; and d_t^g is the CP-odd CEDM. d_t^g can be converted into a dimensionless CEDM parameter d_{tG} as

$$d_\mathrm{t}^\mathrm{g} = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}(d_{\mathrm{tG}}), \tag{3}$$

The one lepton final state of $\mathrm{t\bar{t}}$ is used in the analysis. Four CP-odd observables O_i (i=3,6,12,14) are constructed for the measurement, the presence of CPV can manifest itself through a nonzero value of the asymmetry defined as

$$A_{\mathrm{CP}}(O_i) = \frac{N_{\mathrm{events}}(O_i > 0) - N_{\mathrm{events}}(O_i < 0)}{N_{\mathrm{events}}(O_i > 0) + N_{\mathrm{events}}(O_i < 0)}, i = 3,\ 6,\ 12,\ 14. \tag{4}$$

The measured results on asymmetry of four CP-odd operators are summirized in Table 2, which show good agreement with the SM predictions.

6. Summary

The CMS collaboration has performed several measurements on BSM physics using top quark events, including FCNC using tHq events with Higgs boson decays to bottom quarks or photon,

Table 2: The measured A_{CP} and corresponding d_{tG} values for each of the CP observables using the SM simulation predictions for the dilution factor D in the combined lepton+jets channel. The first uncertainty is statistical and the second is systematic.

CP observable	$A_{CP}(\%)$	d_{tG}
O_3	$-0.10 \pm 0.20 \pm 0.14$	$+0.04 \pm 0.11 \pm 0.07$
O_6	$-0.30 \pm 0.21 \pm 0.16$	$+0.25 \pm 0.20 \pm 0.15$
O_{12}	$+0.12 \pm 0.13 \pm 0.07$	$+0.45 \pm 0.47 \pm 0.27$
O_{14}	$-0.29 \pm 0.16 \pm 0.14$	$-0.81 \pm 0.48 \pm 0.44$

CLFV measurement as well as CP violation measurement using $t\bar{t}$ events. All of these measurements are performed with data collected from 2016 to 2018, which corresponding to a integrated luminosity 137 fb^{-1}. The results of these four measurements are consistent with SM predictions, the observed limits are more stringent than previous results.

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