Enhancing $thj$ Production from Top-Higgs FCNC Couplings

Lei Wu

ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia

(Dated: July 24, 2014)

Abstract

In this paper, we study the single top and Higgs associated production $pp \to thj$ in the presence of top-Higgs FCNC couplings at the LHC. Under the current constraints, we find that the full cross section of $pp \to thj$ can be sizably enhanced in comparison with the SM predictions at 8 and 14 TeV LHC. We further explore the observability of top-Higgs FCNC couplings through $pp \to t(\to b\ell^+\nu\ell)h(\to \gamma\gamma)j$ and find that the branching ratios $Br(t \to qh)$, $Br(t \to uh)$ and $Br(t \to ch)$ can be respectively probed to 0.19%, 0.26%, 0.29% at 3σ sensitivity at 14 TeV LHC with $\mathcal{L} = 3000$ fb$^{-1}$.

PACS numbers: 14.65.Ha, 14.80.Ly, 11.30.Hv
I. INTRODUCTION

The discovery of the Higgs boson at the LHC is a great triumph of the Standard Model (SM) and marks a new era in the particle physics [1, 2]. Given the large uncertainties of the current Higgs data, there remains a plenty of room for new physics in Higgs sector [3]. So the precise measurement of the Higgs boson’s properties will be a dominant task at the LHC in the next decades.

Concerning the probe of new physics through the Higgs boson, the Yukawa couplings can play the important role since they are sensitive to new flavor dynamics beyond the SM. In particular, top quark, as the heaviest SM fermion, owns the strongest Yukawa coupling and has the preference to reveal the new interactions at the electroweak scale [4]. One of the interesting things is that the top quark is just heavier than the observed Higgs boson, which makes the top quark flavor changing neutral current (FCNC) processes \( t \to h q \) \((q = u, c)\) be accessible in kinematics. In the SM, these top quark FCNC transitions are extremely suppressed by the G.I.M. mechanism [5]. But they can be greatly enhanced by the extended flavor structures in many new physics models, for example the minimal supersymmetric model (MSSM) with/without R-parity [6, 7], two-Higgs-doublet model (2HDM) type-III [8, 9], and the other miscellaneous models [10–12]. So the study of top-Higgs FCNC interactions is a common interest of the theory and experiment communities [13, 14]. However, up to now, the null results of the searches for \( t \to q h \) at the LHC give the strong limits on the top-Higgs FCNC couplings. Among them, the most stringent constraint \( Br(t \to hc) < 0.56\% \) at 95% C.L. was reported by the CMS collaboration from a combination of the multilepton channel and the diphoton plus lepton channel [15]. Except for the widely studied \( t \to q h \) decays, the importance of the single top+Higgs production \( pp \to th \) in probing the top-Higgs FCNC couplings has been also emphasized in the recent theoretical studies [16–21].

In this paper, we investigate the top-Higgs FCNC interactions through \( pp \to thj \) with the sequent decays \( t \to b\ell^+\nu \) and \( h \to \gamma\gamma \) at the LHC. In the SM, the process \( pp \to thj \) can only be induced by the weak charged current interaction and has a relative small cross section, which is about 18 (88) fb at 8 (14) TeV LHC. However, such a process is found to be very sensitive to modifications of the Higgs couplings [22–28]. Among them, the top-Higgs FCNC couplings can sizably enhance \( thj \) cross section due to the new contributions induced by the strong interaction. Besides, unlike \( t\bar{t} \) production, the process \( pp \to thj \) also includes the
contributions of the non-resonant FCNC productions and is affected by the initial parton distributions, which can be used to disentangle the FCNC couplings of the top quark with light quarks. So it is worthwhile to perform a complete calculation of \( pp \rightarrow thj \) in the presence of the top-Higgs FCNC couplings by including the contributions of \( hj \) resonant production from \( t\bar{t} \) and other non-resonant productions, and explore its sensitivity to probe the top-Higgs FCNC couplings at the LHC.

This paper is arranged as follows. In Sec. II, we set up the notations and briefly describe the top-Higgs FCNC interactions. In Sec. III, we discuss the observability of the top-Higgs FCNC couplings through the process \( pp \rightarrow thj \) at 14 TeV LHC. Finally, a summary is given in Sec. IV.

II. TOP-HIGGS FCNC INTERACTIONS

A general effective Lagrangian describing the top-Higgs FCNC interaction can be written as

\[
-\mathcal{L}_{tqh} = \kappa_{tqh}^L \bar{t}_L q_R h + \kappa_{tqh}^R \bar{t}_R q_L h + h.c.,
\]

(1)

where \( h \) is the SM Higgs boson, and the real parameter \( \kappa_{tqh}^{L,R} \) denote the left-handed and right-handed FCNC couplings of the Higgs boson to the light up-type quarks \( q = u, c \). By neglecting the light quark masses and assuming the dominant top decay width \( t \rightarrow bW \), the Leading Order (LO) branching ratio of \( t \rightarrow qh \) can be approximately given by,

\[
Br(t \rightarrow qh) = \frac{\kappa_{tqh}^L}{2\sqrt{2}m_t^2 G_F} \frac{(1 - x_h^2)^2}{(1 - x_W^2)^2(1 + 2x_W^2)}.
\]

(2)

where \( G_F \) is the Fermi constant, \( x_W = m_W/m_t \) and \( x_h = m_h/m_t \). The NLO QCD correction to \( Br(t \rightarrow qh) \) is estimated as 10% according to the results of high order corrections to \( t \rightarrow bW \) [29] and \( t \rightarrow ch \) [30]. In some specific models, the left-handed coupling \( \kappa_{tqh}^L \) is not expected to be large because its relation with the CKM mixing parameter. Also, \( \sqrt{\kappa_{tqh}^L + \kappa_{tqh}^R} \) can be constrained by the low energy observables, such as \( B^0 - \bar{B^0} \) mixing [9, 31]. However, we do not consider these indirect constraints in our study since they are model-dependent and their relevance strongly depends on the assumptions made for the generation of the quark flavor structures [32]. On the other hand, the CMS collaboration reported a model-independent bound \( \sqrt{\kappa_{tqh}^L + \kappa_{tqh}^R} < 0.14 \) at 95% C.L. from the combined result of multilepton and diphoton in \( t\bar{t} \) production [15], which indicates \( |\kappa_{tqh}^{L,R}| \) should be
less than 0.14. In our work, we assume $\kappa_{tqh}^L = \kappa_{tqh}^R = \kappa_{tqh}$ and require $\kappa_{tqh} \leq 0.1$ to satisfy the direct constraint from the CMS result.

III. NUMERICAL CALCULATIONS AND DISCUSSIONS

We implement the top-Higgs FCNC interactions by using the package FeynRules \[33\] and calculate the LO cross section of $pp \to thj$ with MadGraph5 \[34\]. We use CTEQ6L as the parton distribution function (PDF) \[35\] and set the renormalization scale $\mu_R$ and factorization scale $\mu_F$ to be $\mu_R = \mu_F = (m_t + m_h)/2$. The SM input parameters are taken as follows \[36\]:

\[
\begin{align*}
m_t &= 173.07 \text{ GeV}, \\
m_Z &= 91.1876 \text{ GeV}, \\
\alpha(m_Z) &= 1/127.9, \\
\sin^2 \theta_W &= 0.231, \\
m_h &= 125 \text{ GeV}, \\
\alpha_s(m_Z) &= 0.1185.
\end{align*}
\]

FIG. 1: The dependence of the cross sections $\sigma_{thj}$ at 8 and 14 TeV LHC on the top-Higgs FCNC couplings $\kappa_{tqh}$ for case (I) – (III). The SM NLO QCD predictions of $thj$ production are taken from the Ref. The conjugate processes have been included in the calculations.

In Fig, we show the dependence of the cross sections $\sigma_{thj}$ on the top-Higgs FCNC couplings $\kappa_{tqh}$ at 8 and 14 TeV LHC respectively for three different cases: (I) $\kappa_{tqh} = \kappa_{tuh} = \kappa_{tch}$, (II) $\kappa_{tqh} = \kappa_{tuh}, \kappa_{tch} = 0$ and (III) $\kappa_{tqh} = \kappa_{tch}, \kappa_{tuh} = 0$. From Fig, we can have the following observations:
• Case-(I): When $\kappa_{tqh} = 0.1$, the total cross section of $pp \rightarrow thj$ at 8 and 14 TeV LHC can be respectively enhanced up to nearly 215 and 173 times the SM predictions. For the smaller values of $\kappa_{tqh}$, the cross section will decrease and become comparable with the SM prediction when $\kappa_{tqh} \sim 0.01$. Here it should be mentioned that although the CMS collaboration has performed a search for $thj$ event at $\sqrt{s} = 8$ TeV and given a 95% upper limit on the $thj$ cross section $\sigma_{thj} < 2.24$ pb, this bound is not suitable for our case because a forward jet with $|\eta| > 1.0$ is required in the experimental analysis. We can also see that the full cross section of $pp \rightarrow thj$ is 1.23(1.18) times larger than the one of $pp \rightarrow t\bar{t} \rightarrow thj$ at 8 (14) TeV LHC due to the contributions of the non-resonant productions of $hj$. By assuming the high order correction factor of $pp \rightarrow thj$ same as $pp \rightarrow t\bar{t}$, we can improve the current upper limit of $\kappa_{tqh}$ from 0.1 to 0.08 at 8 TeV LHC [15]. So we can expect that the full result of $pp \rightarrow thj$ production will be better to extract the constraints on top-Higgs FCNC couplings in the future experimental analysis.

• Case-(II) and (III): For the same values of $\kappa_{tuh}$ and $\kappa_{tch}$, the cross section of $pp \rightarrow thj$ in case-(II) is much larger than that in case-(III), since the up-quarks have the larger PDF than the charm-quarks. This feature allows us to separately probe the couplings between $\kappa_{tuh}$ and $\kappa_{tch}$ at the LHC. So, in general, for a given collider energy and luminosity, we can expect the sensitivity to the coupling $\kappa_{tuh}$ will be better than $\kappa_{tch}$.

In the following calculations, we perform the Monte Carlo simulation and explore the sensitivity of 14 TeV LHC to the top-Higgs FCNC couplings through the channel,

$$pp \rightarrow t(\rightarrow b\ell^+\nu_\ell)h(\rightarrow \gamma\gamma)j,$$

which is characterized by two photons appearing as a narrow resonance centered around the Higgs boson mass. So the SM backgrounds to the Eq. (1) include two parts: the resonant and the non-resonant backgrounds. For the former, they mainly come from the processes that have a Higgs boson decaying to diphoton in the final states, such as $Wjj$, $Zhjj$ and $t\bar{t}h$ productions. The additional jets in the $Whjj/Zhjj$ events come from the initial or final state radiations. The cross sections of the resonant backgrounds are normalized to their NLO values; For the latter, the main background processes contain the diphoton events produced in association with top quarks, such as $tj\gamma\gamma$ and $t\bar{t}\gamma\gamma$. The $Wjj\gamma\gamma$ production can also mimic the signal when one light jet is mistagged as a $b$ jet.
We generate signal and backgrounds events with MadGraph5 and perform the parton shower and the fast detector simulations with PYTHIA and Delphes. When generating the parton level events, we assume $\mu_R = \mu_F$ to be the default event-by-event value. We cluster the jets by setting the anti-$k_t$ algorithm with a cone radius $\Delta R = 0.7$. The $b$-jet tagging efficiency ($\epsilon_b$) is formulated as a function of the transverse momentum and rapidity of the jets. The misidentification 10% and 1% for $c$-jets and light jets are also included and the mis-tag of QCD jets is assumed to be the default value as in Delphes. In our simulation, we generate 100k events for the signals and backgrounds respectively.

![Normalized transverse momentum distributions](image)

**FIG. 2:** Normalized transverse momentum distributions of two photons in the signals and backgrounds at 14 TeV LHC.

In Fig 2 we show the transverse momentum distributions of two photons in the signal with $\kappa_{tq_h} = 0.1$ and backgrounds at 14 TeV LHC. Since the two photons in the signal and the resonant backgrounds come from the Higgs boson, they have peaks around $m_h/2$ and possess the harder $p_T$ spectrum than those in the non-resonant backgrounds. According to Fig 2 we can impose the cuts $p_T^{\gamma_1} > 50$ GeV and $p_T^{\gamma_2} > 25$ GeV to suppress the non-resonant backgrounds.

In Fig 3 we present the normalized invariant mass distribution of two photons at 14 TeV LHC. Although the $\gamma\gamma$ decay channel has a small branching ratio, it has the advantage of the good resolution on the $\gamma\gamma$ resonance and is also free from the large QCD backgrounds. From Fig 3 we can see that the spreading of the $\gamma\gamma$ invariant-mass peak at $m_h$ for the signal and the resonant backgrounds is relatively small. We will use a narrow invariant mass window $|M_{\gamma\gamma} - M_h| < 5$ GeV to further reduce the non-resonant backgrounds.
In Fig. 4, we plot the normalized invariant mass distribution of the $b$ jet and lepton at 14 TeV LHC, which is another effective cut to remove the backgrounds. From Fig. 4, we can see that the invariant mass $M_{b_1\ell_1}$ of the signal is always less than the top quark mass since the leading $b$ jet and lepton in our signal come from the same top quark decay. The similar distribution also occurs in the non-resonant background $tj\gamma\gamma$. But other backgrounds can have higher invariant mass $M_{b_1\ell_1}$ than the signal.

According to the above analysis, events are selected to satisfy the following criteria:

- exact one isolated lepton with $p_T(\ell_1) > 20$ GeV and $|\eta_{\ell_1}| < 2$. 

FIG. 3: Normalized invariant mass distribution of two photons at 14 TeV LHC.

FIG. 4: Normalized invariant mass distribution of the $b$ jet and lepton at 14 TeV LHC.
• a hard jet with $p_T(j_1) > 25$ GeV and $|\eta_{j_1}| < 2.5$ and one $b$-jet with $p_T(b_1) > 25$ GeV and $|\eta_{b_1}| < 2.5$;

• two photons with $p_T^{\gamma_1} > 50$ GeV and $p_T^{\gamma_2} > 25$ GeV and their invariant mass $M_{\gamma_1\gamma_2}$ in the range of $M_h \pm 5$ GeV;

• the invariant mass of $b$-jet and lepton $M_{b\ell} < 200$ GeV.

| Cuts | Cross sections (10⁻³ fb⁻¹) |
|------|-----------------------------|
|      | $thj$ | $t\bar{t}$ | $Vhjj$ | $t\bar{t}\gamma\gamma$ | $tjj\gamma\gamma$ |
| Case-I |        |            |       |                |                  |
| (1)   | $\Delta R_{ij} > 0.4$, $i, j = b, j, \gamma$ or $\ell$ | 2.26 | 1.27 | 1.08 | 0.035 | 0.08 | 4.05 | 2.92 | 2.13 |
|       | $p_T^b > 25$ GeV, $|\eta_b| < 2.5$ |            |       |                |                  |
|       | $p_T^j > 20$ GeV, $|\eta_j| < 2.0$ |            |       |                |                  |
|       | $p_T^j > 25$ GeV, $|\eta_j| < 2.5$ |            |       |                |                  |
| Case-II |        |            |       |                |                  |
| (2)   | $p_T^{\gamma_1} > 50$ GeV, $p_T^{\gamma_2} > 25$ GeV | 2.03 | 1.16 | 0.92 | 0.032 | 0.007 | 1.91 | 1.50 | 1.28 |
| Case-III |        |            |       |                |                  |
| (3)   | $M_{b\ell} < 200$ GeV | 1.98 | 1.15 | 0.91 | 0.030 | 0.005 | 1.77 | 1.48 | 0.85 |
| (4)   | $|M_{\gamma_1\gamma_2} - m_h| < 5$ GeV | 1.63 | 0.84 | 0.78 | 0.022 | 0.004 | 0.07 | 0.09 | - |

In Table I, we give the cross sections of the signals in the case (I)–(III) and backgrounds after the cut flow at 14 TeV LHC, where $\kappa_{tqh}$, $\kappa_{tuh}$ and $\kappa_{tch}$ are assumed to be 0.1 respectively.

From Table I we can see that all the non-resonant backgrounds after the cuts of the two photons are reduced by half while the signals and the resonant backgrounds are hurt slightly. Then, the invariant mass of $b$-jet and lepton will greatly remove the backgrounds that do not involve the top quark. Finally, the diphoton invariant mass cut will further suppress the non-resonant backgrounds by half. So at the end of the cut flow, the largest background is $tj\gamma\gamma$, which is followed by $tt\gamma\gamma$.

In Fig.5, we plot the contours of statistic significance $S/\sqrt{B}$ of $pp \to thj$ at 14 TeV LHC for the case (I)–(III) in the plane of $L - \kappa_{tqh}$, where we use the leading order cross section of $pp \to thj$ to estimate the values of the significance due to the lack of high order correction result. From Fig.5, we can see that the flavor changing coupling $\kappa_{tqh}$ can be probed to 0.058 (0.074), 0.067 (0.086) and 0.070 (0.090) at 3σ sensitivity for the case (I), (II) and (III)
FIG. 5: Contour plots in $\mathcal{L} - \kappa_{tqh}$ plane for significance $S/\sqrt{B}$ at 14 TeV LHC. The conjugate processes have been included in the calculations.

respectively, which correspond to the branching ratios $Br(t \rightarrow qh) = 0.19 (0.32)\%$, $Br(t \rightarrow uh) = 0.26 (0.43)\%$ and $Br(t \rightarrow ch) = 0.29 (0.47)\%$ at 14 TeV LHC with $\mathcal{L} = 3000 (1000)$ fb$^{-1}$.

IV. CONCLUSION

In the work, we investigated the process $pp \rightarrow thj$ induced by the top-Higgs FCNC couplings at the LHC. We found that the full cross section of $pp \rightarrow thj$ can be sizably enhanced in comparison with the SM predictions at 8 and 14 TeV LHC under the current constraints. We studied the observability of top-Higgs FCNC couplings through $pp \rightarrow t(\rightarrow b\ell^+\nu_\ell)h(\rightarrow \gamma\gamma)j$ and found that the branching ratios $Br(t \rightarrow qh)$, $Br(t \rightarrow uh)$ and $Br(t \rightarrow ch)$ can be respectively probed to 0.19%, 0.26%, 0.29% at 3$\sigma$ sensitivity at 14 TeV LHC with $\mathcal{L} = 3000$ fb$^{-1}$.

Acknowledgement

This work was supported by the Australian Research Council, the National Natural Science Foundation of China (NNSFC) under grants Nos. 11222548, 11275057 and 11305049, by Specialized Research Fund for the Doctoral Program of Higher Education under Grant
[1] G. Aad et al. (ATLAS Collaboration), Phys. Lett. B 710, 49 (2012).
[2] S. Chatrchyan et al. (CMS Collaboration), Phys. Lett. B 710, 26 (2012).
[3] The recent reviews, see examples: S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully, R. Van Kooten, A. Ajaib and A. Anastassov et al., arXiv:1310.8361 [hep-ex]; C. Englert, A. Freitas, M. Muhlleitner, T. Plehn, M. Rauch, M. Spira and K. Walz, arXiv:1403.7191 [hep-ph];
[4] For top quark reviews, see, e.g., C. S. Li, H. T. Li and D. Y. Shao, arXiv:1401.1101 [hep-ph]; K. Agashe et al. [Top Quark Working Group Collaboration], arXiv:1311.2028 [hep-ph]; C. Zhang and S. Willenbrock, Nuovo Cim. C 033, no. 4, 285 (2010) arXiv:1008.3155 [hep-ph]; W. Bernreuther, J. Phys. G 35, 083001 (2008) arXiv:0805.1333 [hep-ph]; J. A. Aguilar-Saavedra, Nucl. Phys. B 812, 181 (2009) arXiv:0811.3842 [hep-ph]; Nucl. Phys. B 821, 215 (2009) arXiv:0904.2387 [hep-ph]; E. W. N. Glover, et al., Acta Phys. Polon. B 35, 2671 (2004) hep-ph/0410110; D. Chakraborty, J. Konigsberg and D. L. Rainwater, Ann. Rev. Nucl. Part. Sci. 53, 301 (2003) hep-ph/0303092; M. Beneke, et al., hep-ph/0003033.
[5] T. Han, Int. J. Mod. Phys. A 23, 4107 (2008) arXiv:0804.3178 [hep-ph];
[6] J. Cao, C. Han, L. Wu, J. M. Yang and M. Zhang, arXiv:1404.1241 [hep-ph]. T. -J. Gao, T. -F. Feng, F. Sun, H. -B. Zhang and S. -M. Zhao, arXiv:1404.3289 [hep-ph]; S. Bejar, J. Guasch, D. Lopez-Val and J. Sola, Phys. Lett. B 668, 364 (2008) arXiv:0805.0973 [hep-ph]; J. Cao et al., Phys. Rev. D 75, 075021 (2007); M. Frank and I. Turan, Phys. Rev. D 74, 073014 (2006); S. Bejar, J. Guasch and J. Sola, JHEP 0510, 113 (2005) hep-ph/0508043; J. L. Diaz-Cruz, H.-J. He, C.-P. Yuan Phys. Lett. B 179,530 (2002); J. Guasch and J. Sola, Nucl. Phys. B 562, 3 (1999); C. S. Li, R. J. Oakes and J. M. Yang, Phys. Rev. D 49, 293 (1994); J. M. Yang and C. S. Li, Phys. Rev. D 49, 3412 (1994);
[7] Z. -x. Heng, G. -r. Lu, L. Wu and J. M. Yang, Phys. Rev. D 79, 094029 (2009) arXiv:0904.0597 [hep-ph]; J. Cao, Z. Heng, L. Wu and J. M. Yang, Phys. Rev. D 79, 054003 (2009) arXiv:0812.1698 [hep-ph]; J. M. Yang, B.-L. Young and X. Zhang, Phys. Rev. D 58, 055001
(1998); G. Eilam et al., Phys. Lett. B 510, 227 (2001).

[8] T. Han and R. Ruiz, Phys. Rev. D 89, 074045 (2014) [arXiv:1312.3324 [hep-ph]]; K.-F. Chen, W.-S. Hou, C. Kao and M. Kohda, Phys. Lett. B 725, 378 (2013) [arXiv:1304.8037 [hep-ph]]; C. Kao, H.-Y. Cheng, W.-S. Hou and J. Sayre, Phys. Lett. B 716, 225 (2012) [arXiv:1112.1707 [hep-ph]]; A. Arhrib, K. Cheung, C. W. Chiang and T. C. Yuan, Phys. Rev. D 73, 075015 (2006); M. Frank and I. Turan, Phys. Rev. D 72, 035008 (2005); J. A. Aguilar-Saavedra, B. M. Nobre, Phys. Lett. B 553, 251 (2003); E. O. Itlan and I. Turan Phys. Rev. D 67, 015004 (2003); S. Bejar, J. Guasch and J. Sola, Nucl. Phys. B 600, 21 (2001); F. del Aguila, J. A. Aguilar-Saavedra, R. Miquel, Phys. Rev. Lett. 82, 1628 (1999); S. Bar-Shalom et al., Phys. Rev. Lett. 79, 1217 (1997); W. S. Hou, G.-L. Lin and C.-Y. Ma, Phys. Rev. D 56, 7434 (1997); J. L. Diaz-Cruz et al. Phys. Rev. D 41, 891 (1990).

[9] D. Atwood, L. Reina and A. Soni, Phys. Rev. D 55, 3156 (1997) [hep-ph/9609279];

[10] B. Yang, N. Liu and J. Han, [arXiv:1308.4852 [hep-ph]]. L. Wang, L. Wu and J. M. Yang, Phys. Rev. D 85, 075017 (2012) [arXiv:1111.4771 [hep-ph]]; J. Cao, K. Hikasa, L. Wang, L. Wu and J. M. Yang, Phys. Rev. D 85, 014025 (2012) [arXiv:1109.6543 [hep-ph]]; G. Liu and H. -j. Zhang, [arXiv:0708.1553 [hep-ph]].

[11] C. -X. Yue, S. -Y. Cao and Q. -G. Zeng, JHEP 1404, 170 (2014) [arXiv:1401.5159 [hep-ph]]; C. Han, N. Liu, L. Wu and J. M. Yang, Phys. Lett. B 714, 295 (2012) [arXiv:1203.2321 [hep-ph]]; J. Cao, L. Wu and J. M. Yang, Phys. Rev. D 83, 034024 (2011) [arXiv:1011.5564 [hep-ph]]; G. -R. Lu and L. Wu, Chin. Phys. Lett. 27, 031401 (2010). J. Drobnak, S. Fajfer and J. F. Kamenik, JHEP 0903, 077 (2009) [arXiv:0812.0294 [hep-ph]]. J. Cao, Z. Xiong and J. M. Yang, Nucl. Phys. B 651, 87 (2003);

[12] J. Cao, L. Wang, L. Wu and J. M. Yang, Phys. Rev. D 84, 074001 (2011) [arXiv:1101.4456 [hep-ph]]; J. Cao, Z. Heng, L. Wu and J. M. Yang, Phys. Rev. D 81, 014016 (2010) [arXiv:0912.1447 [hep-ph]].

[13] For reviews on top FCNC processes in new physics models, see, e.g., P. M. Ferreira, R. B. Guedes and R. Santos, Phys. Rev. D 77, 114008 (2008) [arXiv:0802.2075 [hep-ph]]; F. Larios, R. Martinez, M. A. Perez, Int. J. Mod. Phys. A 21, 3473 (2006); J. M. Yang, Annals Phys. 316, 529 (2005); J. A. Aguilar-Saavedra, Acta Phys. Polon. B 35, 2695 (2004) [hep-ph/0409342].

[14] E. Yazgan [ATLAS and CDF and CMS and D0 Collaborations], [arXiv:1312.5435 [hep-ex]].
[15] [CMS Collaboration], CMS-PAS-HIG-2014.

[16] A. Greljo, J. F. Kamenik and J. Kopp, JHEP 1407, 046 (2014) [arXiv:1404.1278 [hep-ph]].

[17] S. Khatibi and M. M. Najafabadi, Phys. Rev. D 89, 054011 (2014) [arXiv:1402.3073 [hep-ph]].

[18] A. Greljo, J. F. Kamenik and J. Kopp, JHEP 1407, 046 (2014) [arXiv:1404.1278 [hep-ph]].

[19] Y. Wang, F. P. Huang, C. S. Li, B. H. Li, D. Y. Shao and J. Wang, Phys. Rev. D 86, 094014 (2012) [arXiv:1208.2902 [hep-ph]].

[20] D. Lopez-Val, J. Guasch and J. Sola, JHEP 0712, 054 (2007) [arXiv:0710.0587 [hep-ph]].

[21] J. A. Aguilar-Saavedra and G. C. Branco, Phys. Lett. B 495, 347 (2000) [hep-ph/0004190].

[22] F. Maltoni, K. Paul, T. Stelzer and S. Willenbrock, Phys. Rev. D 64, 094023 (2001) [hep-ph/0106293].

[23] M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, JHEP 1305, 022 (2013) [arXiv:1211.3736 [hep-ph]].

[24] S. Biswas, E. Gabrielli and B. Mele, JHEP 1301, 088 (2013) [arXiv:1211.0499 [hep-ph]].

[25] J. Ellis, D. S. Hwang, K. Sakurai and M. Takeuchi, JHEP 1404, 004 (2014) [arXiv:1312.5736 [hep-ph]].

[26] C. Englert and E. Re, Phys. Rev. D 89, 073020 (2014) [arXiv:1402.0445 [hep-ph]].

[27] J. Chang, K. Cheung, J. S. Lee and C. -T. Lu, JHEP 1405, 062 (2014) [arXiv:1403.2053 [hep-ph]].

[28] A. Kobakhidze, L. Wu and J. Yue, [arXiv:1406.1961 [hep-ph]].

[29] C. S. Li, R. J. Oakes and T. C. Yuan, Phys. Rev. D 43, 3759 (1991).

[30] C. Zhang and F. Maltoni, Phys. Rev. D 88, 054005 (2013) [arXiv:1305.7386 [hep-ph]]; J. Drobnak, S. Fajfer and J. F. Kamenik, Phys. Rev. Lett. 104, 252001 (2010) [arXiv:1004.0620 [hep-ph]]; J. J. Zhang, C. S. Li, J. Gao, H. Zhang, Z. Li, C. -P. Yuan and T. -C. Yuan, Phys. Rev. Lett. 102, 072001 (2009) [arXiv:0810.3889 [hep-ph]].

[31] J. Cao et al., Phys. Rev. D 74, 031701 (2006).

[32] G. C. Branco, W. Grimus and L. Lavoura, Phys. Lett. B 380, 119 (1996); [hep-ph/9601383]; A. S. Joshipura and S. D. Rindani, Phys. Lett. B 260, 149 (1991); T. P. Cheng and M. Sher, Phys. Rev. D 35, 3484 (1987).

[33] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr and B. Fuks, [arXiv:1310.1921 [hep-ph]].

[34] J. Alwall et al., JHEP 1106, 128 (2011).

[35] J. Pumplin et al., JHEP 0602, 032 (2006).
[36] J. Beringer et al., Particle Data Group, Phys. Rev. D 86, 010001 (2012).

[37] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006).

[38] J. de Favereau, et al., arXiv:1307.6346 [hep-ex].

[39] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008).

[40] CMS Collaboration, b-Jet Identification in the CMS Experiment, CMS-PAS-BTV-11-004.