Probing anomalous top-Higgs couplings at the HL-LHC via $H \rightarrow WW^*$ decay channels

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Outline

1. Motivation
2. Calculation framework
3. Numerical results and discussions
4. Conclusion

1.Motivation

- Processes mediated by Flavor Changing Neutral Currents (FCNCs) are very rare in the SM due to the GIM mechanism:

$$\mathrm{Br}(t \to qX) \sim \mathbf{10^{-17}\text{-}10^{-12}} \text{ (where } q = u/c,\ X = g/\gamma/Z/H) ,$$

which is far beyond the current sensitivity of the experiments.

- In many NP models, some FCNC processes can be greatly enhanced by the new particles in the loop diagrams or extending the flavor structures, for example
  - Minimal Supersymmetric Standard Model (MSSM),
  - R-parity-violating Supersymmetry (RPV-SUSY),
  - 2HDM with flavor-violating Yukawa couplings (2HDM -FV),
  - 2HDM flavor conserving (FC) case (2HDM-FC),
  - Warped extra dimensions (RS) ,
  - Little Higgs with T-parity (LHT) models, etc.

K. Agashe et al., *Top quark working group report*, (2013), arXiv: 1311.2028 [hep-ph].

Table 1: A summary of expectations for t → cH branching fractions in various NP models.

Models	MSSM	RPV-SUSY	2HDM (FV)	2HDM (FC)	RS	CH model	LHT
Br($t \to cH$)	$\leq 10^{-5}$	$\leq 10^{-9}$	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-4}$	$\leq 10^{-4}$	$\leq 10^{-5}$

- J. A. Aguilar-Saavedra, hep-ph/0409342.
- S. Bejar, J. Guasch, and J. Sola, Nucl. Phys. B **600** (2001) 21.
- J. Guasch and J. Sola, Nucl. Phys. B **562** (1999) 3.
- J. M. Yang, B.-L. Young, and X. Zhang, Phys. Rev. D **58** (1998) 055001.
- K. Agashe, G. Perez, and A. Soni, Phys. Rev. D **75** (2007) 015002.
- K. Agashe and R. Contino, Phys. Rev. D 80 (2009) 075016.
- B. Yang, Z. Liu, N. Liu, Chin.Phys. C41 (2017 043103.

These branching ratios significantly improved in the certain parameter spaces of many different NP beyond the SM and are close to the current experimental limits.

Thus any experimental signatures of such FCNC processes will serve as a clear signal for NP Beyond the SM !

- The upcoming project of the High-Luminosity (HL-LHC) is expected to reach 3000 fb^{-1}, which will open new possibility for precise measurement of top-quark properties as well as allow for probe NP by studying rare top decays . Using 13 TeV data, the ATLAS and CMS collaborations have set the observed (expected) upper limits for Br(t → qH) at 95% C.L.

$$Br(t \to uH) \leq 2.4(1.7) \times 10^{-3}$$
$$Br(t \to cH) \leq 2.2(1.6) \times 10^{-3}$$
ATLAS

$$Br(t \to uH) \leq 4.7(4.3) \times 10^{-3}$$
$$Br(t \to cH) \leq 4.7(4.4) \times 10^{-3}$$
CMS

ATLAS Collaboration, **JHEP 1710 (2017) 129.** CMS Collaboration, **JHEP 1806 (1018) 102.**

- The discovery of the SM-like Higgs boson at the LHC made possible the search for FCNC top quark couplings associated with a Higgs boson. We study the prospects of probing the top-Higgs FCNC tqH coupling by considering the processes tH associated production and top pair production through leptonic top quark decays and H → WW^*:

$$pp \to t(\to W^+ b \to \ell^+ \nu_\ell b) H(\to WW^*)$$
$$pp \to t(\to W^+ b \to \ell^+ \nu_\ell b)\bar{t}(\to Hq \to WW^* q)$$

Same-sign 2-lepton(SS2L)

Tri-lepton (3L)

The semileptonic and fully leptonic decay channels from H → WW*

2.Calculation framework

The general Lagrangian for FCNC top interactions with the Higgs boson can be written as

$$\mathcal{L} = \kappa_{tuH}\bar{t}Hu + \kappa_{tcH}\bar{t}Hc + h.c.,$$

After neglecting all the light quark masses, the branching ratio of $t \rightarrow qH$ can be approximately given by

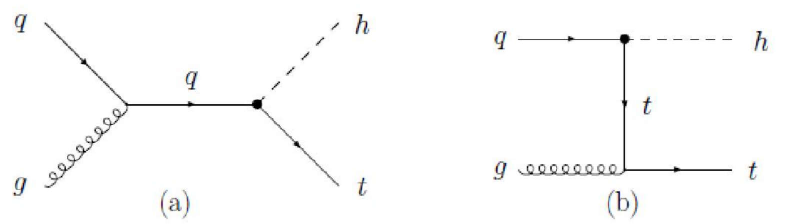
$$Br(t \rightarrow qH) = \frac{\kappa_{tqH}^2}{\sqrt{2}m_t^2 G_F}\frac{(1-x_h^2)^2}{(1-x_W^2)^2(1+2x_W^2)}\lambda_{QCD} \approx 0.58\kappa_{tqH}^2$$

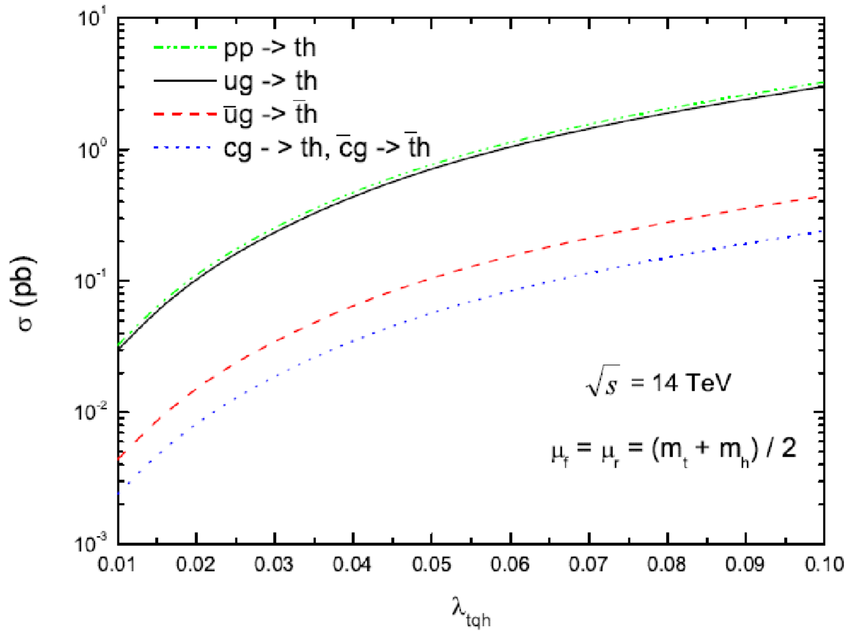
Here the factor λ_{QCD} is the NLO QCD correction to Br(t → qH) and equals about 1.1.

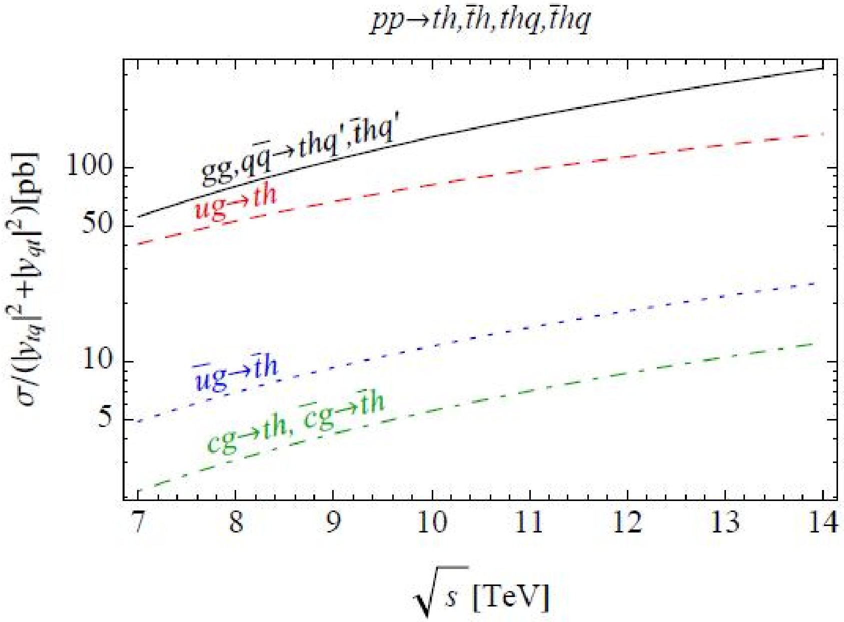
J. J. Zhang, C. S. Li, J. Gao, H. Zhang, Z. Li, C. -P. Yuan and T. -C. Yuan, **Phys. Rev.Lett. 102** (2009) 072001.

3. Numerical results and discussions

Production Cross Section







Admir Greljo et al., JHEP 1407(2014) 046

3.1 SS2L channel

$$pp \to t(\to W^+b \to \ell^+\nu_\ell b)H(\to WW^* \to \ell^+ \nu jj),$$
$$pp \to t(\to W^+b \to \ell^+\nu_\ell b)\bar{t}(\to Hq \to WW^* q \to \ell^+ \nu jjq),$$

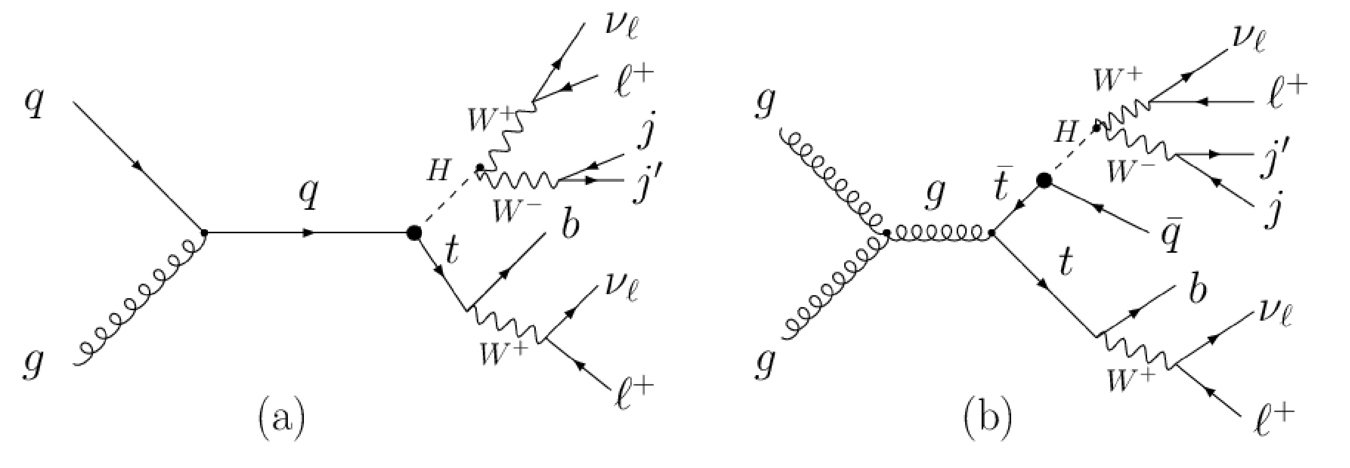


Fig 1:The representative Feynman diagrams

- Signal: two same-sign leptons + at least 3 jets (one b jet) + missing transverse energy.
- Backgrounds:

$t\bar{t}, t\bar{t}V\,(V = W, Z), WWjj, WZjj$ $t\bar{t}h, 4t, VVV, tHj......$

The B meson decays

Negligible after applying the selection cuts

MadGraph5-aMC@NLO + Pythia 6.4 + Delphes 3

MadAnalysis 5 for analysis

All of these signal and backgrounds events are generated at LO. The high order corrections for the dominant backgrounds are considered by including a K-factor, which is 1.04 for *WWjj*,1.24 for *ttW* and 1.39 for *ttZ*, respectively.

The dominant top-pair background is normalized to the NNLO QCD cross section of 953.6 pb. The K-factor for the tH prodution cross section is taken as 1.5 at the 14 TeV LHC.

T. Melia, K. Melnikov, R.Rontsch, G. Zanderighi, JHEP 1012 (2010) 053;

J.M. Campbell, R.K.Ellis, JHEP 1207 (2012) 052;

A. Kardos, Z. Trocsanyi, C. Papadopoulos, Phys. Rev. D 85 (2012) 054015;

Y. Wang, F. P. Huang, C. S. Li, B. H. Li, D. Y. Shao, J. Wang, Phys. Rev. D 86 (2012) 094014.

Basic cuts: $p_T(\ell) > 10GeV, p_T(j,b) > 15GeV, \left|\eta_{\ell,j,b}\right| < 2.5$

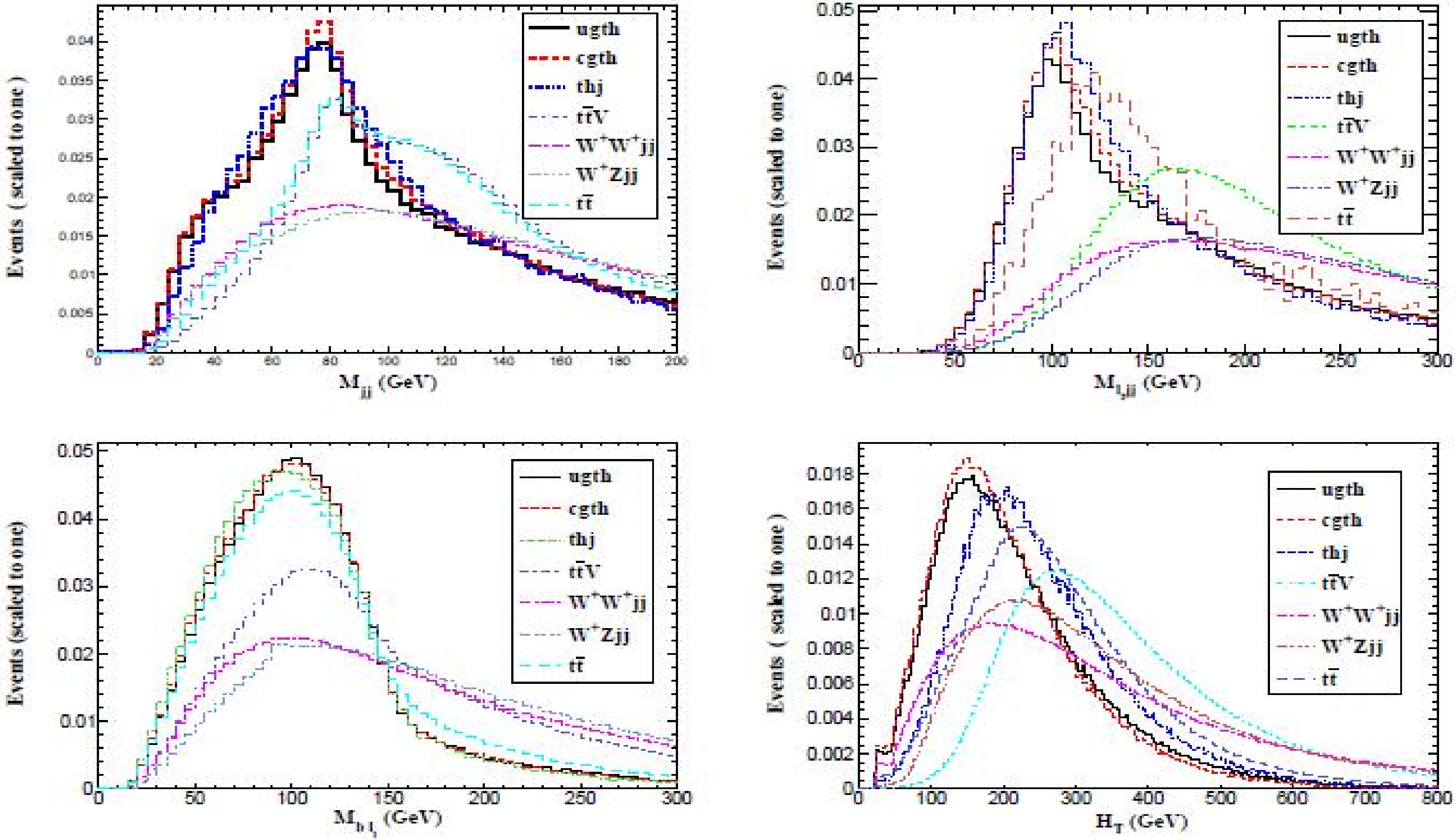


FIG. 2: Normalized distributions for the signals and the backgrounds.

Based on these distributions, we impose a further set of cuts:

- Cut 1: $N(\ell)=2, p_T(\ell_1)>20GeV, p_T(\ell_2)>10GeV, N(b)=1,$
  $\boxed{M_{\ell\ell}>12GeV, |M_{\ell\ell}-m_Z|>10GeV.}$

  To remove contamination from hadron decay chains including dileptons and Z boson

- Cut 2: $N(j)\geq 2, M_{jj}<90GeV.$

  There are at least one pair of jets which could come from a *W* boson either on-shell or off-shell

- Cut 3: $M_{l_2jj}<120GeV.$

- Cut 4: $M_{bl_1}<140GeV.$ → The higher PT lepton is assumed to originate from the leptonically decaying top quark.

- Cut 5: $H_T<250GeV.$

  The scalar sum of transverse momenta.

TABLE I: The cut flow of the cross sections (in fb) for the signal and SM backgrounds for the SS2L channel. The coupling parameters are taken as $\kappa_{tuH} = 0.1$ or $\kappa_{tcH} = 0.1$ while fixing the other to zero.

Cuts	Signal			Backgrounds			
	ug	cg	$t\bar{t} \to tHq$	$t\bar{t}V$	$WWjj$	$WZjj$	$t\bar{t}$
Basic cuts	3.12	0.34	3.77	6.73	6.42	20.9	61004
Cut 1	0.48	0.056	0.69	0.85	0.21	0.25	6.52
Cut 2	0.225	0.027	0.34	0.27	0.04	0.046	2.54
Cut 3	0.18	0.022	0.28	0.092	0.016	0.011	1.7
Cut 4	0.15	0.019	0.24	0.058	0.009	0.0063	1.36
Cut 5	0.14	0.017	0.21	0.048	0.007	0.005	1.16

Recently, the CMS collaboration searched for SS2L signatures and found that the overall non-prompt backgrounds are about 1.5 times the ttW background after all cuts. For simplicity, we add a non-prompt background that is 1.5 times ttW after selection cuts to the overall background. A. M Sirunyan *et al.*, [CMS Collaboration], Eur. Phys. J. C 77 (2017) 578.

◆ Nonprompt leptons: electrons or muons from the dacay of heavy- or light-flavor hadrons, hadrons misidentified as leptons, or electrons from conversions of photons in jets.

3.2 3L Channel

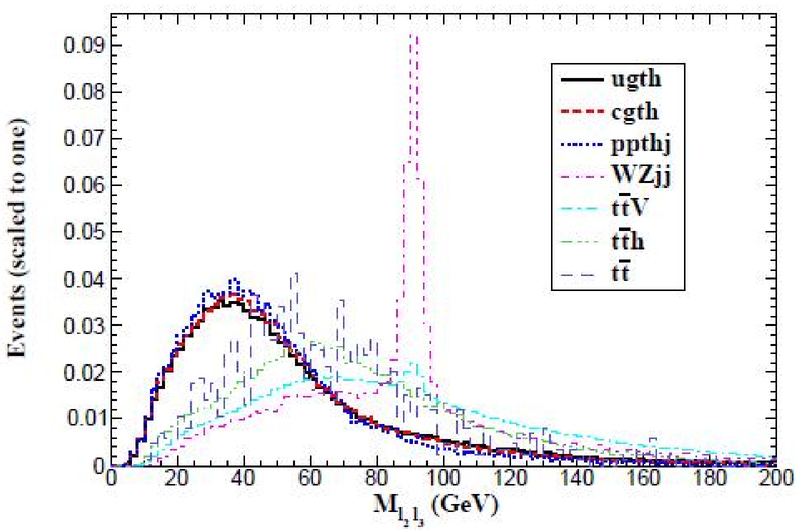
$$pp \to t(\to W^+ b \to \ell^+ \nu_\ell b) H(\to WW^* \to \ell^+ \nu j \ell^- \bar{\nu}),$$
$$pp \to t(\to W^+ b \to \ell^+ \nu_\ell b) \bar{t}(\to Hq \to WW^* q \to \ell^+ \nu \ell^- \bar{\nu} q),$$

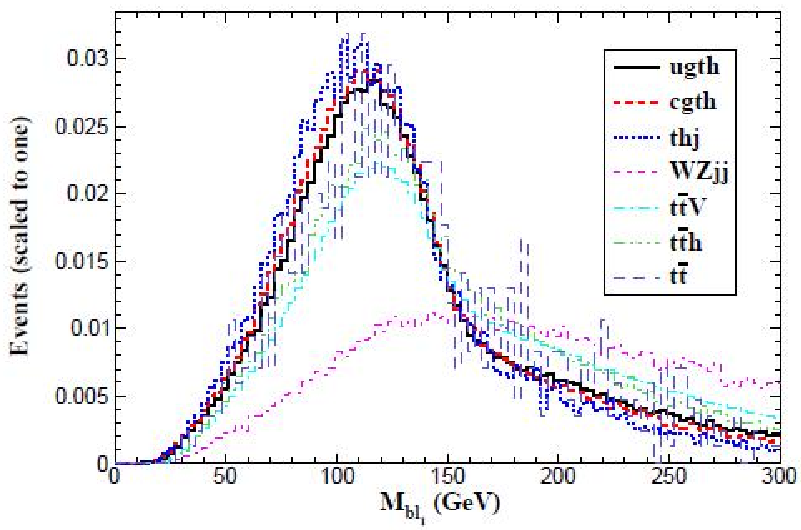
The dominant SM backgrounds: ttV, ttH, WZ+ jets, and top pair production processes.

Cut 1: $\boxed{N(l)=3, p_T(l_1)>20GeV, p_T(l_{2,3})>10GeV, N(b)=1, \not{E}_T>100GeV.}$

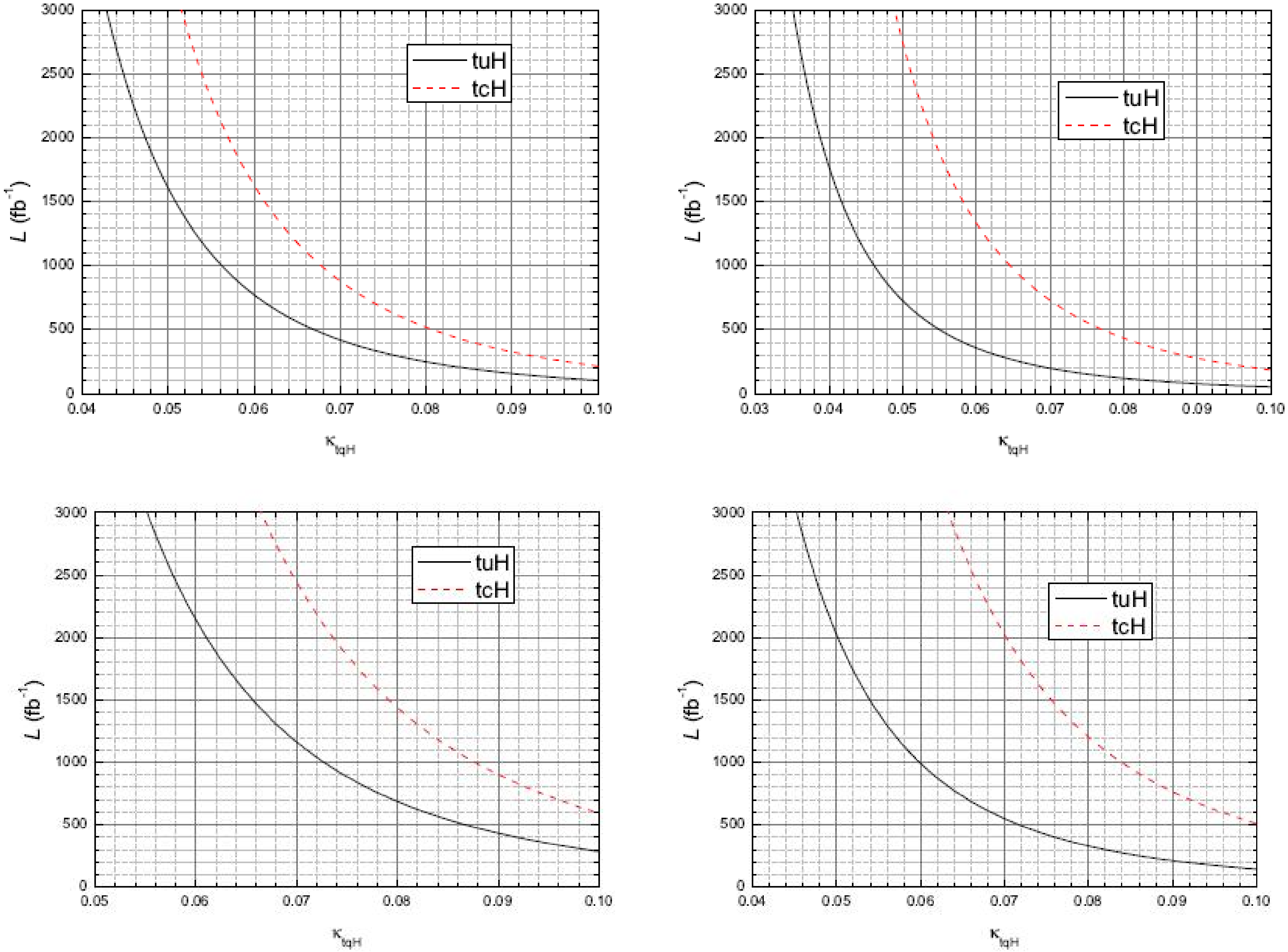
Cut 2: $12GeV < M(l_2 l_3) < 55GeV$

Cut 3: $M_{bl_1} < 140GeV.$





Using the Poisson formula $SS = \sqrt{2L_{\text{int}}[(S+B)\ln(1+S/B)-S]}$



3σ

5σ

TABLE III: The projected limits on $Br(t \to qH)$ from different channels. The last two lines of the table are the results of this work.

Channels	Data Set	Limits
$tH \to \ell\nu b\tau^+\tau^-$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br\ (t \to uH) < 0.15$ % [13]
$tH \to \ell\nu b\ell^+\ell^- X$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br\ (t \to uH) < 0.22$ % [13]
$t\bar{t} \to Wb + Hc \to jjb + \tau\tau c$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br\ (t \to cH) < 0.25$ % [14]
$tH \to jjbb\bar{b}$	LHC, 100 fb^{-1} @ 13 TeV, 95% CL	$Br\ (t \to uH) < 0.36$ % [13]
$Wt \to WHq \to \ell\nu b\gamma\gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br\ (t \to qH) < 0.24$ % [28]
$tH \to \ell\nu b\gamma\gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br\ (t \to uH) < 0.036$ % [29]
$t\bar{t} \to WbqH \to \ell\nu b\gamma\gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br\ (t \to uH) < 0.23$ % [30]
$e^- p \to \nu_e \bar{t} \to \nu_e H(\to b\bar{b})\bar{q}$	LHeC, 200 fb^{-1} @ 150 GeV $\oplus$ 7 TeV, 95% CL	$Br\ (t \to qH) < 0.013$ % [31]
$t\bar{t} \to tqH \to \ell\nu bb\bar{b}q$	ILC, 3000 fb^{-1} @ 500 GeV, 95% CL	$Br\ (t \to qH) < 0.112$ % [32]
$t\bar{t} \to tqH \to \ell\nu bb\bar{b}q$	ILC (unpolarized), 500 fb^{-1} @ 500 GeV, 3σ	$Br\ (t \to qH) < 0.119$ % [33]
$t\bar{t} \to tqH \to \ell\nu bb\bar{b}q$	ILC (polarized), 500 fb^{-1} @ 500 GeV, 3σ	$Br\ (t \to qH) < 0.088$ % [33]
$t\bar{t} \to Wb + Hq \to \ell\nu b + \gamma\gamma q$	LHC, 3000 fb^{-1} @ 14 TeV, 95% CL	$Br\ (t \to qH) < 0.02$ % [51]
$t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	LHC, 3000 fb^{-1} @ 14 TeV, 95% CL	$Br\ (t \to qH) < 0.05$ % [51]
This work for the SS2L channel	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br\ (t \to uH) < 0.117$ %, $Br\ (t \to cH) < 0.156$ %
This work for the 3L channel	LHC, 3000 fb^{-1} @ 14 TeV, 3σ	$Br\ (t \to uH) < 0.071$ %, $Br\ (t \to cH) < 0.139$ %

Our results are comparable with the sensitivity limits at the HL-LHC from other channels.

4. Conclusion

- The discovery of the 125 GeV Higgs boson opens the door to probe NP processes that involve Higgs boson associated production or decay.
- We focus on two processes with final states including SS2L and 3L signals from tH associated production and top pair production through the leptonic top quak decays and H $\rightarrow WW^*$. It is shown that, at the future HL-LHC, the branching ratios Br(t→uh) and Br(t→ch) can be respectively probed at 3σ sensitivity as:

$$Br(t \to uH) \leq 1.17 \times 10^{-3}$$
$$Br(t \to cH) \leq 1.56 \times 10^{-3}$$

SS2L channel

$$Br(t \to uH) \leq 7.1 \times 10^{-4}$$
$$Br(t \to cH) \leq 1.39 \times 10^{-3}$$

3L channel

Thank you!