Search for anomalous couplings via single top quark production in association with a photon at LHC

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Introduction

- The FCNC processes are forbidden at tree level in the SM due to the GIM mechanism. The observation of the FCNC-induced couplings of the type $tq\gamma$ and tqg would indicate the existence of new physics beyond the Standard Model.
- Searches for FCNCs might be done using specific models or in a model-independent way. The effective operators will simplify multiple free parameters of specific models to estimate these new physics contributions.
- Among FCNC top quark decays, $t \to qg$ is very difficult to distinguish from generic multijet production via quantum chromodynamics (QCD). It has therefore been suggested to search for FCNC couplings in anomalous single top-quark production.

- Many works about the $t\gamma$ production exist. We focus on an analysis of signal and backgrounds based on a fast simulation of the CMS.

- Our work gives the constraints to the FCNC anomalous coupling strength by considering the productions of single top by using effective operators. In addition, we discuss the 14 TeV LHC detection potential bounds on the $tq\gamma$ and tqg couplings.

$t\gamma$ production

The effective Lagrangian of $tq\gamma$ and tqg

$$
\begin{aligned}
\mathcal{L}_{eff} \;=\;& -eQ_t\bar{u}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}(\kappa^L_{tu\gamma}P_L+\kappa^R_{tu\gamma}P_R)tA_\mu \\
&- eQ_t\bar{c}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}(\kappa^L_{tc\gamma}P_L+\kappa^R_{tc\gamma}P_R)tA_\mu \\
&- g_s\bar{u}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}(\kappa^L_{tug}P_L+\kappa^R_{tug}P_R)T^a tG_{a\mu} \\
&- g_s\bar{c}\frac{i\sigma^{\mu\nu}q_\nu}{\Lambda}(\kappa^L_{tcg}P_L+\kappa^R_{tcg}P_R)T^a tG_{a\mu} + h.c.
\end{aligned}
$$

- Where $\Lambda = m_{top}$, $T^a = \frac{1}{2}\lambda_a$, q is the momentum of the gauge boson and $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu,\gamma^\nu]$ as a tensor under the Lorentz group.
- $\kappa^L_{tq\gamma} = \kappa^R_{tq\gamma} = \kappa_{tq\gamma}$ and $\kappa^L_{tqg} = \kappa^R_{tqg} = \kappa_{tqg}$.
  (In the SM, the values of $\kappa_{tq\gamma}$ and κ_{tqg} are zero at tree level.)

- The production of a single top quark in association with a photon

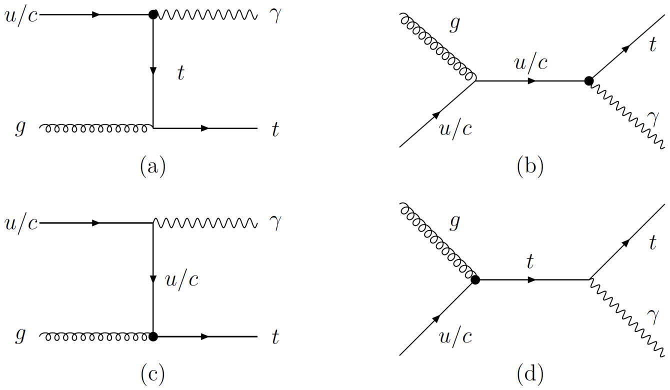

FIG. 1: Representative Feynman diagrams leading to the production of a single top quark in association with a photon. Flavor violation (the dots) occurs either in the weak (top) or strong (bottom) sector.

Leading order cross section

$$\sigma_{t\gamma}(\kappa_{tu\gamma}) = 208.9 \, \left|\kappa_{tu\gamma}\right|^2 \, (pb) \; ,$$
$$\sigma_{t\gamma}(\kappa_{tc\gamma}) = 16.2 \, \left|\kappa_{tc\gamma}\right|^2 \, (pb) \; ,$$
$$\sigma_{t\gamma}(\kappa_{tug}) = 2549.5 \, \left|\kappa_{tug}\right|^2 \, (pb) \; ,$$
$$\sigma_{t\gamma}(\kappa_{tcg}) = 283.5 \, \left|\kappa_{tcg}\right|^2 \, (pb) \; .$$

(Assuming a single non-vanishing anomalous coupling with $p_T^\gamma > 15$GeV for LHC at 14 TeV)

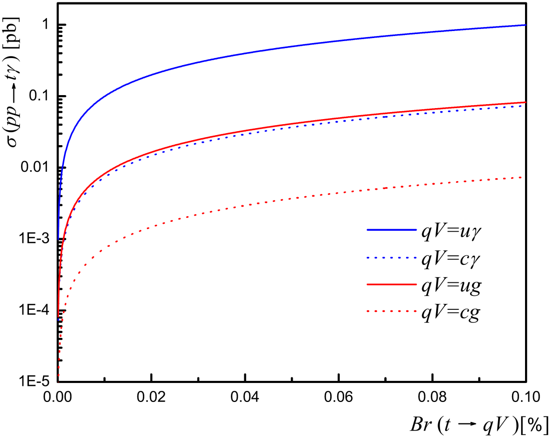

FIG. 2: The cross sections of anomalous $t\gamma$ production versus the FCNC branching ratios $\mathcal{BR}(t \to u\gamma)$, $\mathcal{BR}(t \to c\gamma)$, $\mathcal{BR}(t \to ug)$ and $\mathcal{BR}(t \to cg)$.

Experimental limits

TABLE I: The most stringent experimental upper bounds on the top quark FCNC branching ratios at 95% CL obtained in CDF, D0, ATLAS and CMS from different channels.

EXP	$\sqrt{s}$ TeV	$\mathcal{L}(fb^{-1})$	$\mathcal{B}$	$(q=u)\%$	$(q=c)\%$	Ref
CDF	1.8	0.11	$t \to q\gamma$	3.2		[30]
CMS	8	19.1	$t \to q\gamma$	0.0161	0.182	[31]
CDF	1.96	2.2	$t \to qg$	0.039	0.57	[32]
D0	1.96	2.3	$t \to qg$	0.02	0.39	[33]
CMS	7	4.9	$t \to qg$	0.56	7.12	[34]
CMS	7	4.9	$t \to qg$	0.035	0.34	[35]
ATLAS	8	14.2	$t \to qg$	0.0031	0.016	[36]

The upper limits on the strengths of the anomalous couplings from the CMS results :

- $\kappa_{tu\gamma} < 0.028$, $(Br(t \to u\gamma) < 1.61 \times 10^{-4})$
- $\kappa_{tc\gamma} < 0.094$, $(Br(t \to u\gamma) < 1.82 \times 10^{-3})$
- $\kappa_{tug} < 0.036$, $(Br(t \to ug) < 3.55 \times 10^{-4})$
- $\kappa_{tcg} < 0.112$. $(Br(t \to cg) < 3.44 \times 10^{-3})$

(CMS-PAS-TOP-14-003; CMS-PAS-TOP-14-007;)

Signal and background simulation

Signal and background

1. Two kinds of signals
   - $pp \to \gamma t \to \gamma W^+ b \to l\nu b\gamma$,
   - $pp \to \gamma t \to \gamma W^+ b \to jjb\gamma$,

2. The signal of FCNC $t\gamma$ production might suffer more realistic experimental issues of fake photon and mis-tagged b jet.

   Several SM background processes are considered, W+jets, $W\gamma$+jet , $Z\gamma$+jets, $t\bar{t}$, $t\bar{t}\gamma$, $t\gamma + X$ and QCD background ($4j$, $bjjj$) for hadronic mode.

Signal and background simulation

1. We use MadGraph5aMC@NLO to generate events in a collision energy $\sqrt{s} = 14$ TeV;
2. Parton showering and fast detector simulations are performed by PYTHIA6 and Delphes3.
3. For multijet background events, the MLM merging/matching is used with matching scale Qcut=30 GeV and $x_q = 15$ GeV to avoid double-counting between ME and PS;
4. For numerical estimation, we take coupling constants $\kappa_{tu\gamma} = 0.01$, $\kappa_{tc\gamma} = 0.02$, $\kappa_{tug} = 0.01$ and $\kappa_{tcg} = 0.03$;
5. Higher order correction is taken into account for signal by K factor ($K = \sigma_{NLO}/\sigma_{LO}$), which is equal to 1.8.[1]

[1] Y. Zhang, B. H. Li, C. S. Li *et al.*, Phys.Rev.D 83, 094003 (2011).

	σ (fb)	Expected number of events at $100\,\mathrm{fb}^{-1}$	Number of events generated
$t\gamma$	5.234×10^2	5.2×10^4	100,000
W+jets	3.066×10^7	3.1×10^9	8,000,000
$W\gamma$+jets	1.1×10^5	1.1×10^7	1,000,000
$Z\gamma$+jets	7.44×10^4	7.4×10^6	1,000,000
$t\bar{t}$	5.969×10^5	6.0×10^7	4,000,000
$t\bar{t}\gamma$	2.447×10^3	2.5×10^5	500,000
single-top+γ	1.705×10^3	1.7×10^5	400,000
$4j$(QCD)	2.058×10^{10}	2.06×10^{12}	5,000,000
$bjjj$(QCD)	2.217×10^8	2.2×10^{10}	4,000,000

TABLE II: The expected number of events with 100 fb^{-1} integrated luminosity at $\sqrt{s} = 14$ TeV and the generated events for all processes are displayed.

Preselection Cuts	Description
1	$N(\gamma) = 1$ and $N(b) = 1$ $N(\ell) = 1$ or $N(j) < 4$
2	$p_t(\gamma) > 50$ GeV, $p_t(b/j) > 30$ GeV, $\lvert\eta\rvert \leq 2.5$, $\Delta R(\ell/j, \gamma) > 0.7$, $p_t(\ell) > 10$ GeV , $\not{E}$ >30 GeV.

TABLE III: The preselection cuts in our analysis are tabulated.

reconstruction of $\ell\nu b\gamma$

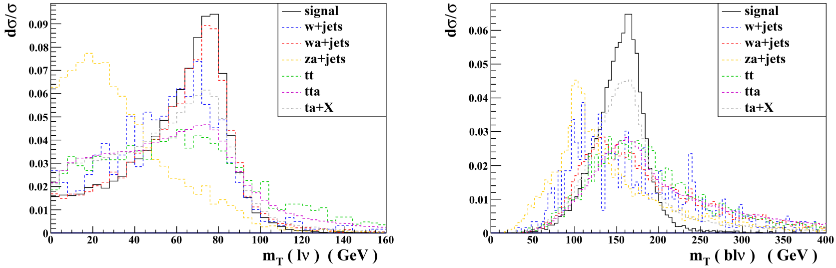

FIG. 3: Normalized transverse mass distributions of the $m_T(\ell\nu)$ (left) and $m_T(\ell\nu b)$ (right) signal and backgrounds before kinematical cuts at 14 TeV LHC.

kinematical cuts

1. 45 GeV $< m_T(\ell\nu) < 85$ GeV,
2. 130 GeV $< m_T(\ell\nu b) < 190$ GeV.

reconstruction of $\ell\nu b\gamma$

TABLE IV: The event numbers of the $\ell\nu b\gamma$ signal and backgrounds with $\mathcal{L} = 100\text{fb}^{-1}$ and $\sqrt{s} = 14$ TeV.

	$\ell\nu b\gamma$	W+jets	$W\gamma$+jets	$Z\gamma$+jets	$t\bar{t}$	$t\bar{t}\gamma$	$t\gamma + X$
preselection cut 1	5736.3	18640	19920	2492.9	149752	19973	9481.2
preselection cut 2	1084.0	2189.3	2378.0	74.60	38655	5459.5	1683.7
45 GeV $< m_T(\ell\nu) <$ 85GeV	670.7	1282.3	1471.2	34.43	15028	2271.6	852.7
130 GeV $< m_T(\ell\nu b) <$ 190 GeV	515.4	375.3	454.5	11.48	6696.2	990.8	539.0
$S/\sqrt{S+B}$	5.265						
S/B	5.684×10^{-2}						

It is most promising to observe anomalous top couplings via leptonic mode of $t\gamma$ production at the LHC.

reconstruction of $jjb\gamma$

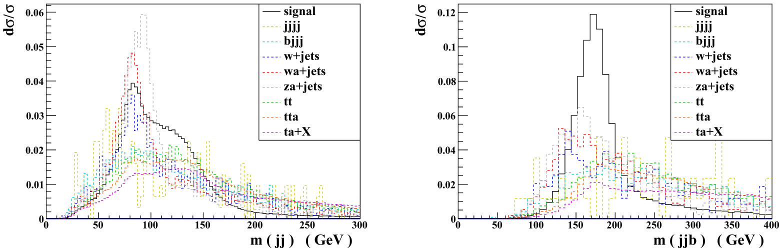

FIG. 4: Normalized invariant mass distributions of the $m(jj)$ (left) and $m(jjb)$ (right) in sig

and backgrounds before kinematical cuts at 14 TeV LHC.

kinematical cuts

1. $m(jj)$ will not be very effective in improving the significance of the signal.
2. $|m(jjb) - m(top)| < 35\text{GeV}$.

reconstruction of $jjb\gamma$

TABLE V: The event numbers of the $jjb\gamma$ signal and backgrounds with $\mathcal{L} = 100\text{fb}^{-1}$ at 14 TeV LHC.

	Signal γjjb	W+jets	$W\gamma$+jets	$Z\gamma$+jets	$t\bar{t}$	$t\bar{t}\gamma$	$t\gamma + X$	$4j$ (QCD)	$bjjj$ (QCD)
preselection cut 1	14071	114996	104115	76843	167330	9418.7	15571	159114715	13745400
preselection cut 2	3974.5	29137	15652	11635	63690	3089.3	3564.5	42088408	2660400
$\lvert m(jjb) - m_t \rvert < 35$ GeV	1619.7	4532.5	2458.4	1375.9	11261	455.9	271.2	5132732	370711
$S/\sqrt{S+B}$	0.6891								
S/B	2.93×10^{-4}								

With less than 1σ level statistical significance, it is challenging to discover the FCNC $t\gamma$ production via the hadronic mode explored at LHC.

The contribution of photon radiation to signal

- The additional Feynman diagrams [1] for $qg \to f\bar{f}b\gamma$

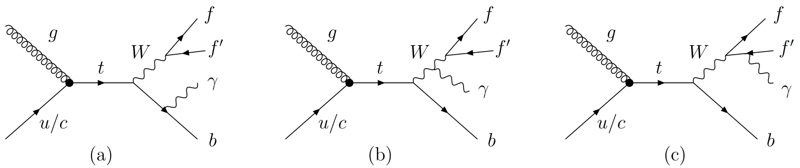

FIG. 5: Additional Feynman diagrams contributing to the signal of top decay products in association with a photon through tqg vertices.

[1] J. A. Aguilar Nucl.Phys.B **837**, 122 (2010).

- As a probe to research the top-quark FCNC, radiation processes could help us to further understand whether it is induced by strong interactions. In this case, it is necessary to consider the final state particles reconstructing a top quark.

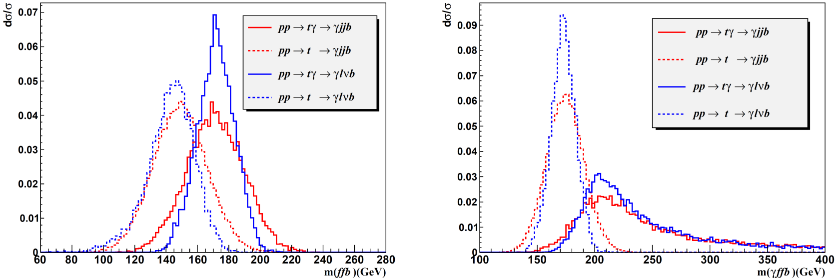

FIG. 7: Normalized distributions of $m(f\bar{f}b)$(left) and $m(f\bar{f}b\gamma)$(right) via different processes with $p_T^\gamma > 15$ GeV. The $f\bar{f}$ here denotes W decay products jj or $\ell\nu$.

Sensitivity of anomalous top couplings at LHC-RunII

The sensitivity of the 14 TeV LHC run to the top anomalous couplings define as statistical significance, $S/\sqrt{S+B}$. Fig. 8 is presented for four anomalous coupling parameters in the case we assume a single non-vanishing coupling at a time.

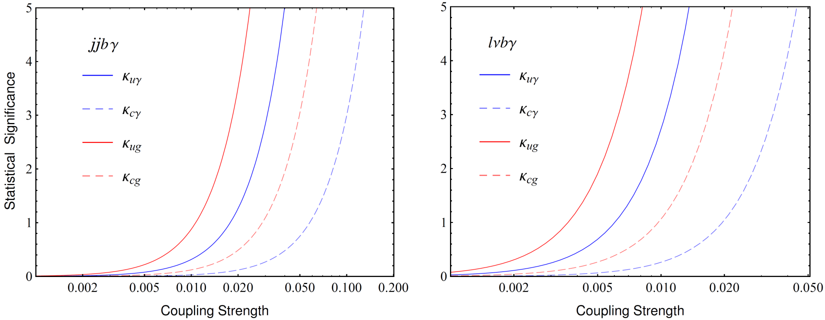

FIG. 8: LHC sensitivity to the considered anomalous top couplings as a function of the coupling strengths after applying the kinematical cuts and event selection.

As shown in Table VI, the overwhelming QCD multijet backgrounds make the FCNC coupling constants in hadronic mode looser. The $\ell\nu b\gamma$ signal is more sensitive to search for anomalous couplings at 14 TeV LHC.

TABLE VI: 5σ (3σ) discovery lower limits on top-quark FCNC anomalous couplings.

Signal	$\kappa_{tu\gamma}$	$\kappa_{c\gamma}$	κ_{tug}	κ_{tcg}
$\ell\nu b\gamma$	0.0136(0.0105)	0.0442(0.0341)	0.0082(0.0063)	0.0219(0.0169)
$jjb\gamma$	0.0398(0.0308)	0.1292(0.1001)	0.0239(0.0185)	0.0641(0.0496)

Actually, we allow for a set of non-vanishing couplings simultaneously, either in the weak sector (non-vanishing $\kappa_{tu\gamma}$ and $\kappa_{tc\gamma}$) or in the strong sector (non-vanishing κ_{tug} and κ_{tcg}).

- 3σ and 5σ discovery ranges for top anomalous interactions in $\kappa_{tuX} - \kappa_{tcX}$ $(X = \gamma, gluon)$ planes for $\ell\nu b\gamma$.

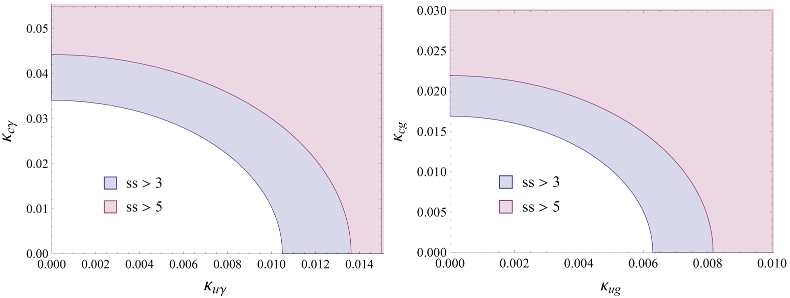

FIG. 9: 3σ and 5σ detection potential regions for the $\ell\nu b\gamma$ signal in weak (left) and strong (right) sector at 14 TeV LHC.

- Since both $tq\gamma$ and tqg operators contribute to the same final state, the interference effects should be considered.
- If $\kappa_{tu\gamma} = \kappa_{tc\gamma} = \kappa_{tq\gamma}$, $\kappa_{tug} = \kappa_{tcg} = \kappa_{tqg}$, the total $t\gamma$ cross section is

$$\sigma_{t\gamma} = 158.2\ \left|\kappa_{tq\gamma}\right|^2 + 457.3\ \left|\kappa_{tqg}\right|^2 + 153\ \kappa_{tq\gamma} \cdot \kappa_{tqg}\ (pb)\ .$$

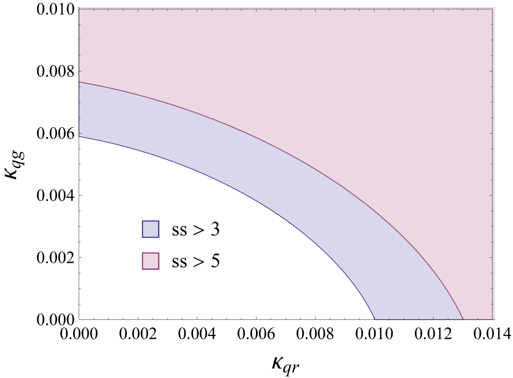

FIG. 10: 3σ and 5σ discovery ranges at 14 TeV LHC in the $\kappa_{tq\gamma} - \kappa_{tqg}$ plane.

Summary

- The FCNC coupling $tq\gamma$ and tqg can be studied by $t\gamma$ production in a model independent way. Due to the overwhelming QCD multijet backgrounds, it is hard to discover the FCNC $t\gamma$ production via the hadronic mode explored at LHC. It is most promising to observe anomalous top couplings via leptonic mode of $t\gamma$ production at the LHC.
- The contribution of radiation signal would be experimentally detectable within relatively small photon momenta. If top FCNC processes are eventually detected, these relations will allow to test whether the origin of the FCNC interactions is in the strong sector or not.
- With an integrated luminosity of 100 fb^{-1} and $\sqrt{s} = 14$ TeV, for a 5σ discovery, the needed strengths of $tq\gamma$ and tqg couplings of order are down to 0.001-0.01. We hope our results can motivate a further investigation by the ATLAS and CMS collaborations in the context of LHC RunII.

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Thank You!