Study of anomalous top quark flavor-changing neutral current interactions via the tW channel of single-top-quark production

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The potential of the LHC for investigation of anomalous top quark interactions with gluon (tug, tcg) through the production of tW channel of single top quarks is studied. In the standard model, the single top quarks in the tW-channel mode are charge symmetric, meaning that $\sigma(pp \to t + W^-) = \sigma(pp \to \bar{t} + W^+)$. However, the presence of anomalous flavor-changing neutral current (FCNC) couplings leads to charge asymmetry. In this paper, a method is proposed in which this charge asymmetry may be used to constrain anomalous FCNC couplings. The strength of resulting constraints is estimated for the LHC for the center of mass energies of 7 and 14 TeV.

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I. INTRODUCTION

Several properties of the top quark have been measured ever since its discovery [1–5]. However, there are still open questions whether the top quark couplings obey the standard model (SM) or there exist contributions from beyond SM physics. One tool that is often used to describe the effects of new physics at an energy scale of Λ, much higher than the electroweak scale, is the effective Lagrangian method. If the underlying extended theory under consideration only becomes important at a scale of Λ, then it makes sense to expand the Lagrangian in powers of Λ^{-1} [6–8]:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum \frac{c_i}{\Lambda^{n_i - 4}} O_i, \tag{1}$$

where $\mathcal{L}_{\rm SM}$ is the SM Lagrangian, O_i's are the operators containing *only* the SM fields, n_i is the dimension of O_i, and c_i's are dimensionless parameters. In the top quark sector, the lowest dimension operators that contribute to flavor-changing neutral current (FCNC) with the tcg, tug vertex can be written as [2]

$$g_s \frac{\kappa_u}{\Lambda} (\bar{c}) \bar{u} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu} + \text{H.c.}, \tag{2}$$

where g_s is the strong coupling constant, $\kappa_{u,c}$ are free parameters determining the strength of these anomalous couplings, and $G^a_{\mu\nu}$ is the gauge field tensor of the gluon. λ_a are Gell-Mann matrices. u, c, and t are Dirac spinors for up, charm, and top quarks and $\sigma_{\mu\nu} = i(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)/2$. The presence of such anomalous FCNC vertices leads to additional processes in the tW-channel mode of single top production at hadron colliders such as the LHC. Figure 1 shows the Feynman diagrams for the production of the tW channel of single top in the SM framework and the new diagrams which are introduced in Eq. (2) because of the new anomalous FCNC interactions.

Single top quark in the tW mode is not observable at Tevatron because of its very small cross section. However, at the LHC the cross section of the tW channel at leading order is around 62 pb. It has been shown that this process is observable at the LHC using the fully simulated data at the CMS and ATLAS detectors [9,10]. Recently, this process has been studied carefully in [11].

There are many experimental and phenomenological studies about FCNC anomalous couplings, of which some can be found in [12–28]. In the SM framework, the tW mode of single top is charge symmetric, meaning that $\sigma(pp \to t + W^- + X) = \sigma(pp \to \bar{t} + W^+ + X)$. The reason is that the parton distribution functions (PDFs) of b quark and $\bar{b}$ quark in proton are the same. According to Fig. 1, in the presence of anomalous couplings, the d quark contributes to the production of top quark and $\bar{d}$ quark contributes to the production antitop quark. Since the

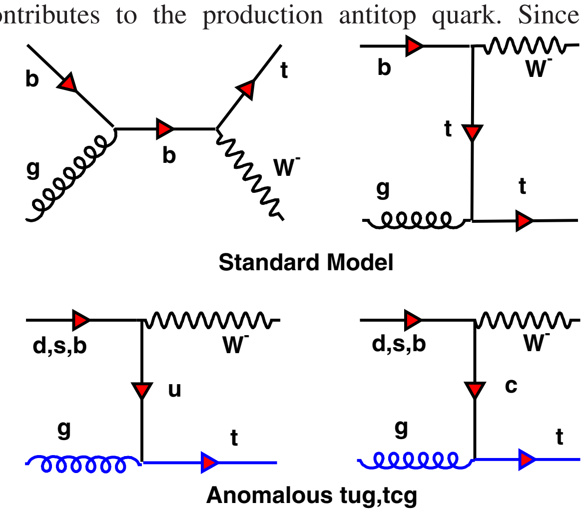

FIG. 1 (color online). Feynman diagrams for the tW-channel single top production at the LHC, including anomalous FCNC vertices.

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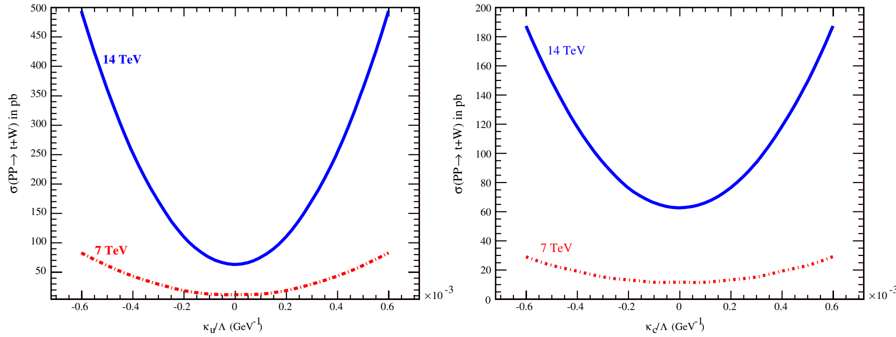

FIG. 2 (color online). The tW–cross section dependence on the anomalous couplings at the LHC with the center of mass energies of 7 and 14 TeV when $\kappa_c = 0$ in the left side and when $\kappa_u = 0$ in the right side.

parton distribution function of d quark in the proton is more than the parton distribution function of $\bar{d}$ quark, the presence of anomalous FCNC vertices described by Eq. (2) leads to an asymmetry of charge in the tW channel production. It is worth mentioning that the charge asymmetry in the tW channel can also be generated by non-SM values of V_{td} and V_{ts} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [29].

The aim of this article is to benefit the charge asymmetry to estimate the limits for such anomalous couplings. Since the two main backgrounds in the study of the tW channel ($t\bar{t}$, QCD events, and WW) are charge symmetric, using the charge asymmetry method is considered as a powerful tool to obtain the limits on anomalous FCNC couplings.

II. tW-CHANNEL CROSS SECTION AND CHARGE ASYMMETRY SENSITIVITIES TO ANOMALOUS COUPLINGS

The dependency of the tW channel of single top quark cross sections on the anomalous FCNC couplings ($\kappa_{u,c}$) at the LHC with center of mass energies of 7 and 14 TeV are presented in Fig. 2. This figure has been obtained using the COMPHEP package [30]. In calculating the cross section, it is assumed that $m_{\rm top} = 175$ GeV$/c^2$ and$m_b = 4.8$ GeV$/c^2$, and CTEQ6L1 is used as the proton parton distribution function. The CKM mixing angles are taken as $c_{12} = 0.974\,84$, $c_{23} = 1.0$, $c_{13} = 1.0$.

According to the CMS Collaboration's full simulation results, the relative statistical uncertainty on measurement of the cross section ($\frac{\Delta\sigma}{\sigma}$) of the tW channel, taking into account 10 fb^{-1} of integrated luminosity, is 9.9% [9]. ATLAS Collaboration predicted 2.8% statistical uncertainty on the measurement of the cross section with 30 fb^{-1} of data [10]. Therefore, the cross section of the tW channel will be measured precisely by the LHC experiments.

In the SM, the cross section of single top quark and single antitop quark in the tW-channel mode are equal. Therefore,

$$R_{\rm SM} = \frac{\sigma(pp \to t + W^-)}{\sigma(pp \to \bar{t} + W^+)} = 1. \qquad (3)$$

However, when the anomalous FCNC vertices are taken into account, the above ratio is not equal to one anymore, and $R = R(\kappa_u, \kappa_c)$. Figure 3 presents the dependency of R on κ_u, κ_c at the LHC with the center of mass energies of 10 and 14 TeV when $\kappa_c = 0$ in the left side and when $\kappa_u = 0$ in the right side. Because of the higher PDF contributions of the valence quarks with regard to sea quarks in the

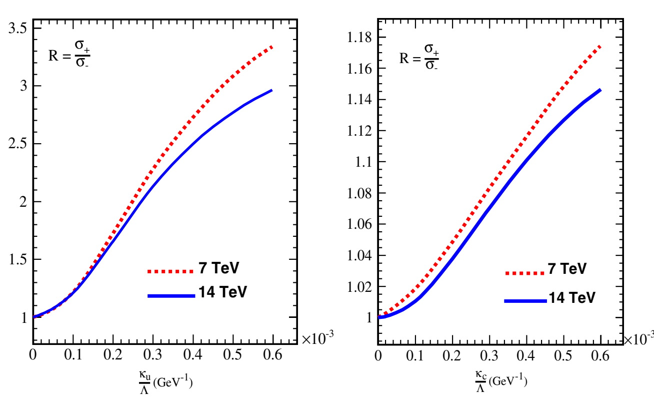

FIG. 3 (color online). The ratio of cross section of top to antitop in the tW channel versus κ_u, κ_c, at the LHC with the center of mass energies of 7 TeV and 14 TeV when $\kappa_c = 0$ in the left side and when $\kappa_u = 0$ in the right side.

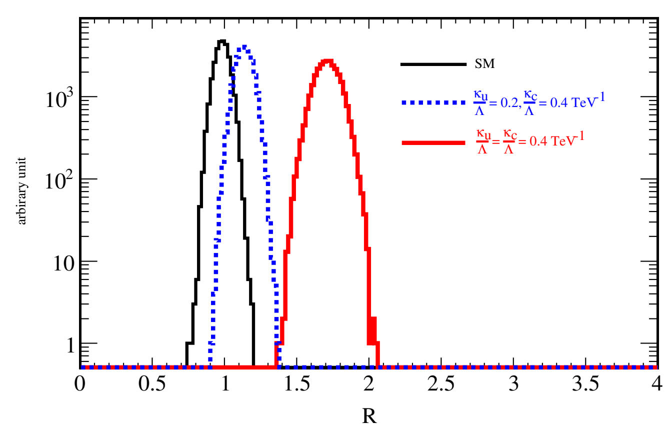

FIG. 4 (color online). The outcome of the pseudoexperiments for $R = \frac{N_+}{N_-}$ calculated from Eq. (5), including 5% systematic uncertainty for the SM and for the presence of anomalous couplings.

proton and the size of the involved CKM matrix elements in the new additional processes in the production of tW-channel single top, R is more sensitive to κ_u with respect to κ_c. For example, at the center of mass energy of 14 TeV:

$$\begin{aligned} R(\kappa_u/\Lambda = 0.2\ \mathrm{TeV}^{-1}, \kappa_c/\Lambda = 0.0) &= 1.67 \\ R(\kappa_u/\Lambda = 0.0, \kappa_c/\Lambda = 0.2\ \mathrm{TeV}^{-1}) &= 1.04. \end{aligned} \tag{4}$$

Therefore, any observable deviation of R from the SM expectation (charge asymmetry) can be exploited to predict the sensitivity to anomalous tug, tcg couplings. One should note that the advantage of using the ratio of R is that the uncertainties coming from parton distribution function, luminosity, etc. will cancel.

III. MONTE CARLO SIMULATION

In order to predict the sensitivity to the anomalous tug, tcg couplings, we perform Monte Carlo event generation and a very raw detector simulation (no specific detector is considered). One has to take into account backgrounds, realistic detector effects, and selection cuts. Obviously, a comprehensive analysis of all reducible backgrounds and detector effects is beyond the scope of this study and must be performed by the experimental collaborations. In this study, the anomalous single top signal events have been generated by the COMPHEP package [30]. The COMPHEP-PYTHIA interface package [31] was used to pass the generated events through PYTHIA [32]. PYTHIA performs fragmentation, parton showering, and hadronization.

The detector simulation is performed by smearing energies for stable particles deposited into proper segmentation of calorimeter geometry. A jet is clustered by the PYCELL routine in PYTHIA with the cone size of 0.5. b tagging is simulated with the efficiency of 60%. The missing transverse energy is calculated by the vector summation of the lepton and jets.

IV. EVENT SELECTION AND SENSITIVITY STUDY

In this section, we predict the bounds after event selection on the anomalous FCNC vertices (tug, tcg) using the *semileptonic* reconstructed events of tW channel. One should note that by semileptonic, we mean that the W boson coming from the top decays to leptons and another W boson decays to two jets. The final state consists of a charged lepton, missing energy, and three hadronic jets.

To help reduce the backgrounds, we follow the strategy which the ATLAS experiment proposed [2,10]. In this strategy, one isolated lepton (electron-muon) is required with transverse momentum[1] greater than 20 GeV$/c$ and $|\eta| < 2.5$.[2] The number of jets in the central region ($\eta < 2.5$) is required to be exactly three, each with $p_T >$ 50 GeV$/c$. One of the jets should be tagged as a b jet. The requirement of at least one b jet is necessary to reduce W + jets background events.

To ensure that the other two untagged jets come from the W boson (which is not from top), it is required that the invariant mass of the two jets should satisfy $65 < m_{jj} < 95$ GeV$/c^2$. It is noticeable that this cut and the cut on the number of jets are very useful to suppress the W + jets background [2]. It is also required that $m_{l\nu b} < 300$ GeV$/c^2$, which helps suppress the W + jets background. In contrast to the $t\bar{t}$ background, the W + jets background is not charge symmetric. However, according to the proposed strategy by the ATLAS Collaboration [2,10], which was followed in the current analysis, the applied cuts mentioned above are powerful in suppressing W + jets background events. These cuts reduce the W + jets background to a negligible level.

Since the charge asymmetry measurement is used in the analysis, the decays of $tW^- \to W^+ bW^- \to l^+ \nu_l bjj'$ and $tW^- \to W^+ bW^- \to jj'bl^- \nu_l$ must be kinematically distinguished. To guarantee that it is required: $m_{bjj'} < 125$ or $m_{bjj'} > 225$ GeV$/c^2$.

The *pseudoexperiments* are used for the evaluation of the statistical significance of the signal and include the systematic uncertainties. For the signal process, 30 000 random numbers are drawn from a Gaussian distribution centered on the number of selected events. Further Gaussian smearing is applied in order to take into account the overall systematic uncertainty. Calling $G(m, \sigma)$ a random number belonging to a Gaussian distribution with mean m and standard deviation σ, each pseudoexperiment gives

$$N^{\pm} = G(N^{\pm}_{\mathrm{sel}}, \sqrt{N^{\pm}_{\mathrm{sel}}}) \times G(1, \Delta_{\mathrm{syst}}), \tag{5}$$

where $N^{\pm}_{\mathrm{sel}}$ is the selected number of events after all cuts with positively and negatively charged electrons or muons in the top quarks decay. As discussed before, several uncertainties will resolve when we use the ratio of R for the analysis. However, a few sources of uncertainties may not resolve. Therefore, Δ_{syst}, which is defined as an overall systematic uncertainty, is included in the analysis to get more realistic results.

Figure 4 shows the outcome of the pseudoexperiments, including 5% systematic uncertainty for $R = \frac{N_+}{N_-}$ with center of mass energy of 14 TeV and 10 fb^{-1} of integrated luminosity. The signal significance is defined as

$$S = \frac{M(\kappa_u, \kappa_c) - M_{\mathrm{SM}}}{\sqrt{\sigma^2(\kappa_u, \kappa_c) + \sigma^2_{\mathrm{SM}}}}, \tag{6}$$

where M is the peak position and σ is the standard deviation of the distributions. M and σ (for the SM case and the presence of anomalous couplings case) are extracted by Gaussian fits on the pseudoexperiments distribution in Fig. 4. To determine the maximum allowed values of $\frac{\kappa_u}{\Lambda}$ and $\frac{\kappa_c}{\Lambda}$ that could be reached at the LHC, it is required that

[1] $p_T = \sqrt{p_x^2 + p_y^2}$.
[2] $\eta = -\ln(\tan(\frac{\theta}{2}))$.

TABLE I. Limits on anomalous couplings obtained from various experiments and methods.

	Tevatron 1.96 TeV, 2.2 fb^{-1}	LHC 7 TeV, 1 fb^{-1}	LHC 14 TeV, 10 fb^{-1}
$\kappa_u/\Lambda(2\to 1)$ TeV^{-1}	0.018	$\cdots$	0.003
$\kappa_u/\Lambda(2\to 2)$ TeV^{-1}	0.037	$\cdots$	0.006
$\kappa_u/\Lambda(tW)$ TeV^{-1}	$\cdots$	0.1	0.08
$\kappa_c/\Lambda(2\to 1)$ TeV^{-1}	0.069	$\cdots$	0.008
$\kappa_c/\Lambda(2\to 2)$ TeV^{-1}	0.15	$\cdots$	0.013
$\kappa_c/\Lambda(tW)$ TeV^{-1}	$\cdots$	0.38	0.35

$S > 5$, which is corresponding to approximately 68% confidence level. This requirement leads to the bounds on $\frac{\kappa_u}{\Lambda}$ and $\frac{\kappa_c}{\Lambda}$ separately presented in Table I. It is noticeable that when the limit on κ_u is calculated, κ_c is set to zero, and vice versa.

The FCNC tqg vertex has been studied via other processes such as the quark-gluon fusion process $u(c) + g \to t(2\to 1)$ or $qq \to tq$, $gg \to t\bar{q}$, $qg \to tg(2\to 2)$ processes. The resulting limits from the studies of $2\to 1$ and $2\to 2$ processes with Tevatron data and LHC simulated data have been presented in Table I [25,26]. One should note that the Tevatron bounds are at 95% confidence level. The estimated bounds from $2\to 1$ and $2\to 2$ are tighter than those obtained in this study. This is because of the larger cross sections and more statistics of these processes.

V. CONCLUSION

The tW-channel single-top-quark production at the LHC was considered as a probe for non-SM couplings at the LHC. In the SM, the cross section of single top quark and single antitop quark in the tW-channel mode are equal. Therefore, $R_{\mathrm{SM}} = \frac{\sigma(pp\to t+W^-)}{\sigma(pp\to \bar{t}+W^+)} = 1$. However, when the anomalous FCNC vertices are taken into account the above ratio is not equal to one anymore, and $R = R(\kappa_u, \kappa_c)$. This interesting aspect was used to extract the 68% C.L. bounds on the anomalous couplings $\frac{\kappa_{u(c)}}{\Lambda}$. We find that at 14 TeV center of mass energy and with 10 fb^{-1} integrated luminosity of data, $\frac{\kappa_{u(c)}}{\Lambda} = 0.08\ \mathrm{TeV}^{-1}$ (0.35). The upper limits for 7 TeV center of mass energy with 1 fb^{-1} are $\frac{\kappa_{u(c)}}{\Lambda} = 0.1\ \mathrm{TeV}^{-1}$ (0.38).

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