Year: 2011

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Search for anomalous top quark production at the early LHC

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We present a detailed study of the anomalous top quark production with subsequent decay at the LHC induced by model-independent flavor-changing neutral-current couplings, incorporating the complete next-to-leading order QCD effects. Our results show that, taking into account the current limits from the Tevatron, the LHC with $\sqrt{s} = 7$ TeV may discover the anomalous coupling at 5σ level for a very low integrated luminosity of 61 pb^{-1}. The discovery potentials for the anomalous couplings at the LHC are examined in detail. We also discuss the possibility of using the charge ratio to distinguish the *tug* and *tcg* couplings.

The CERN Large Hadron Collider (LHC) is currently operating at a center-of-mass (c.m.) energy of 7 TeV. Even with a relatively low integrated luminosity ($\sim 40\,\mathrm{pb}^{-1}$), it has already delivered many interesting results, including new tests on the standard model (SM) in both electroweak and strong interacting sectors, as well as constraints on new physics models beyond the SM. In particular, both the ATLAS and the CMS collaborations have measured the cross section for top quark pair production with a precision of around 10%. With more data being collected, it can be expected that the top quark properties will be well measured in the near future, and exotic physics in the top quark sector can also be potentially probed.

In the SM, flavor-changing neutral-currents (FCNC) in the top quark sector are strongly suppressed. However, many new physics models can induce large FCNC couplings of the top quark with a light up-type quark and a gluon, which can be possibly detected at the LHC [1]. Such couplings can be incorporated into the model-independent effective Lagrangian [2]

$$\mathcal{L} = g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R)q G_{\mu\nu}^a + h.c.,$$

where κ_{tqg}/Λ are real numbers representing the strength of the couplings, and $f_q^{L,R}$ are chiral parameters normalized to $|f_q^L|^2 + |f_q^R|^2 = 2$. Both the CDF and D0 collaborations at the Tevatron have searched for processes induced by these operators and provided constraints on the anomalous couplings [3, 4]. The most stringent one-dimensional exclusion limit (assuming only one coupling is non-zero) is given by [4]

$$\kappa_{tug}/\Lambda < 0.013\,\mathrm{TeV}^{-1}, \quad \kappa_{tcg}/\Lambda < 0.057\,\mathrm{TeV}^{-1}, \quad (1)$$

at the 95% confidence level (C.L.). The above anomalous couplings can induce various rare processes at hadron colliders. Among them, the most interesting one is direct top quark production, where a single top quark is produced without any additional particle. The signature of this process is different from the single top production in the SM (where the top quark is always accompanied by other particles). Given the couplings allowed by the

Tevatron search, the production rate for this process can still be large at the LHC, which makes it a promising channel to search for new physics in the flavor sector. Any observation of this characteristic process definitely indicates the existence of the *tqg* anomalous couplings, and the underlying new physics.

There have been several analyses in the literature of direct top quark production at the LHC at the leading order (LO) [1, 2, 5]. The next-to-leading order (NLO) QCD correction to the total cross section of this process has also been calculated in [6]. However, there is no detailed phenomenological study based on the NLO result. Also, the previous LO studies [1, 2] only focused on the LHC with $\sqrt{s} = 14$ TeV. Moreover, they did not include the SM single top quark production in the background processes, and therefore underestimated the background rate. The SM single top quark production can mimic the signal process if the additional jet is not reconstructed. At the NLO, the signal process can also emit an additional jet which makes the single top background more prominent. With these considerations, it is therefore very important to perform an analysis taking into account the NLO QCD effects and all the SM backgrounds for the early LHC search of the anomalous couplings with $\sqrt{s} = 7$ TeV. Besides, in order to provide a more complete NLO prediction, the QCD effects in the top quark decay process should also be included. While the QCD correction to the decay process does not alter the inclusive rate, it may change the signal acceptance significantly when kinematic cuts are applied. In this Letter, we present a detailed study of the direct top quark production with subsequent decay at the LHC, including NLO QCD corrections for both the production part and decay part. The SM backgrounds and the LHC discovery potential of the anomalous couplings are also examined in detail.

The NLO QCD corrections to the direct top quark production with subsequent decay can be factorized into two independent gauge invariant parts, i.e., the top quark production at NLO with subsequent decay at LO, and production at LO with subsequent decay at NLO, by using the modified narrow width approximation incorpo-

rating the finite width effects as in the previous studies of the SM single top quark production [7, 8]. Note that if we only consider the inclusive rate of the process, the NLO QCD corrections to the decay part will have no influence since the branching ratio of the top quark decay into W boson is always 100% at both the LO and the NLO (the branching ratios of the rare decays $t \rightarrow gq$ [9] are negligible here considering the Tevatron limits). But for the production rate after applying final state kinematic cuts, the NLO QCD corrections to the decay part can have significant contributions as we will show below.

In the following analysis we only consider the leptonic decay (with two lepton flavors) of the top quark since the hadronic decay mode suffers from large QCD backgrounds. And also we need to use b-tagging to suppress the large W+jet backgrounds. We use the following basic selection cuts

$$p_{Tl} > 20\,\text{GeV}\,, \quad p_{Tb} > 50\,\text{GeV}\,, \quad \slashed{E}_T > 30\,\text{GeV}\,,$$
$$|\eta_l| < 2.4\,, \quad |\eta_b| < 2.0\,, \quad \Delta R_{bl} > 0.7\,, \qquad (2)$$

and the anti-k_T jet algorithm with the jet radius parameter $D = 0.7$. We also demand $\Delta R_{jl} > 0.7$ if there is an additional jet with $p_T > 20\,\text{GeV}$ and $|\eta| < 3$. The large transverse momentum cut of the b-jet can suppress the W+jet backgrounds efficiently while has small influence on the signal process. To further reduce the W+jet backgrounds we require the reconstructed top quark to satisfy

$$160\,\text{GeV} < m_{\text{r,top}} < 185\,\text{GeV}\,, \quad |y_{\text{r,top}}| > 0.3\,. \qquad (3)$$

With all the above selection conditions, we can get a stable b-tagging efficiency of 50% while the misidentification rates for other jets are, 8% for charm quark, 0.2% for gluon and other light quarks [10]. Another main background of the signal process is the SM t-channel single top quark production, where the associated jet prefers to be in the forward region. In order to suppress its contribution we will use a jet veto just as in the case of SM Higgs boson search in the WW channel [11]. Here we require the final state contains exact one charged lepton and one b-jet, and events containing additional jets with $p_T > 30\,\text{GeV}$ and $|\eta| < 3$ will be vetoed. Moreover, to account for the resolution of the detectors, we use the following smearing parameters for lepton, jets and missing transverse momentum [10]

$$\Delta E_l/E_l = 0.1/\sqrt{E_l/\text{GeV}} \oplus 0.007\,,$$
$$\Delta \eta_l = \Delta \phi_l = 0.001\,,$$
$$\Delta E_{b(j)}/E_{b(j)} = 0.5/\sqrt{E_{b(j)}/\text{GeV}} \oplus 0.02\,,$$
$$\Delta \eta_{b(j)} = \Delta \phi_{b(j)} = 0.01\,,$$
$$\Delta \slashed{E}_{T,x(y)} = 0.46\sqrt{H_T/\text{GeV}}\,, \qquad (4)$$

where H_T is the scalar sum of the transverse energy of all the lepton and jets.

We now present the numerical results of our study. First, we give the total cross sections for the signal process of the direct top quark production. The CTEQ6L1 (CTEQ6.6) [12] parton distribution function (PDF) and the corresponding running QCD coupling constant are used in the LO (NLO) calculations. We choose the anomalous couplings $\kappa_{tug}/\Lambda = \kappa_{tcg}/\Lambda = 0.01\,\text{TeV}^{-1}$, and the renormalization and factorization scales to be the top quark mass $m_t = 173.1\,\text{GeV}$, unless otherwise specified. We use L and R to denote the pure left-handed couplings ($f_g^R = 0$) and pure right-handed couplings ($f_g^L = 0$), respectively. Table I shows the inclusive cross sections for the top (anti-top) quark production with subsequent leptonic decay, without applying any kinematic cuts. The scale uncertainties shown are calculated by varying the renormalization and factorization scales between $m_t/2$ and $2m_t$. It can be seen that the NLO corrections reduce the scale uncertainties from about 10% to about 7%. We have also estimated the PDF uncertainties by using the 44 error sets of the CTEQ6.6 PDFs, and the values are within $\pm 4\%$ for the NLO inclusive cross sections.

	σ_{LO} [pb]	σ_{NLO} [pb]
tug (L/R)	$1.12^{+0.10}_{-0.09}$ ($0.202^{+0.020}_{-0.018}$)	$1.48^{+0.10}_{-0.09}$ ($0.285^{+0.018}_{-0.017}$)
tcg (L/R)	$0.105^{+0.011}_{-0.011}$ (—)	$0.159^{+0.012}_{-0.012}$ (—)

TABLE I. The total cross sections for the direct top quark production with subsequent leptonic decay at the LHC ($\sqrt{s} = 7\,\text{TeV}$) without applying any kinematic cuts. The numbers in brackets correspond to anti-top quark production. The b-tagging efficiency is not included here.

		σ_{LO} [fb]	K_{pro}	K_{tot}	K_{veto}
tug	(L)	148 (40.5)	1.36 (1.32)	1.27 (1.23)	0.91 (0.96)
	(R)	164 (41.3)	1.34 (1.32)	1.24 (1.22)	0.90 (0.94)
tcg	(L)	21.7 (—)	1.37 (—)	1.27 (—)	0.96 (—)
	(R)	21.8 (—)	1.36 (—)	1.26 (—)	0.95 (—)

TABLE II. The LO cross sections and K-factors of the direct top quark production at the LHC ($\sqrt{s} = 7\,\text{TeV}$) with the kinematic cuts Eqs. (2) and (3) applied, and jet veto in addition for K_{veto}. The b-tagging efficiency is not included here.

When constraints on the final state kinematics are imposed, we need to include the NLO QCD corrections to the decay process as well. We find that these corrections will reduce the cross sections by 10%. This can be understood since the emission of an extra gluon can broaden the reconstructed top quark mass distribution, and can also make the b-jet softer. The corresponding results are shown in Table II, where the K-factors are defined as the ratio of the NLO cross sections to the LO ones. Here the kinematics cuts Eqs. (2) and (3) are always imposed.

$K_{\rm pro}$ includes only the NLO corrections to the production part , $K_{\rm tot}$ includes also the corrections to the decay part, and $K_{\rm veto}$ has in addition jet veto applied. The differences between the results of the left-handed and the right-handed couplings are due to the spin effects of the top quark. After applying the jet veto, the complete NLO QCD corrections are further reduced to $-4\% \sim -10\%$ as shown in Table II since most of the contributions from the real corrections are dropped. The scale uncertainties of the NLO cross sections are within $\pm4\%$ of the center values. By comparing the results in Table I and II, we can see that the differences of the K-factors between the inclusive rate and the one with the kinematic cuts and jet veto can be over 40%. Finally, after taking into account all the cuts and the b-tagging efficiency, the NLO cross sections of the signal process can be written as

$$\sigma_{\rm signal} = \sum_{q=u,c} \left(\frac{\kappa_{tqg}}{\Lambda}\right)^2 \left(b_{qL}|f_q^L|^2 + b_{qR}|f_q^R|^2\right), \qquad (5)$$

with the coefficients $b_{qL(R)}$ given in Table III.

[pb·TeV^2]		b_{uL}	b_{uR}	b_{cL}	b_{cR}
7 TeV	l^+	338	368	52.5	51.8
	l^-	97.0	96.8		
14 TeV	l^+	588	625	167	164
	l^-	272	272		

TABLE III. Values of the coefficients $b_{qL(R)}$.

We now turn to the SM backgrounds, which are calculated with a modified version of the MCFM [8] package and crosschecked with MadGraph [13]. The PDF choice here is the same as in the signal process while the scale is set to m_Z and m_t for the W boson and top quark related processes, respectively. The main contributions arise from the SM t-channel single top quark production, the W+jet production and $W + bb(bq)$ production as shown in Table IV, where for the sum in the last column the b-tagging efficiency and misidentification rates have been taken into account. The t-channel single top and $W + c$ processes are calculated up to the NLO in QCD. Other contributions from $W + cc(cq)$ production, the top quark pair production, the vector boson pair production and other single top quark production channels can all be neglected according to our calculation.

[pb]		$Wu(d,s,g)$	Wc	$Wbb(bq)$	single top	total
7 TeV	l^+	33	2.67	0.14	0.632	0.666
	l^-	18	2.81	0.077	0.320	0.460
14 TeV	l^+	69	7.60	0.28	2.27	2.02
	l^-	47	8.16	0.18	1.33	1.50

TABLE IV. The cross sections for the SM background processes.

In Fig. 1 we show the reconstructed top quark mass distribution from the signal and background processes. Here and below we have added the positive and negative charged lepton contributions together. It can be seen that the SM t-channel single top quark production contributes over 40% of the total backgrounds and is hard to be further suppressed since it has almost the same kinematics as the signal process (both from top quark decay).
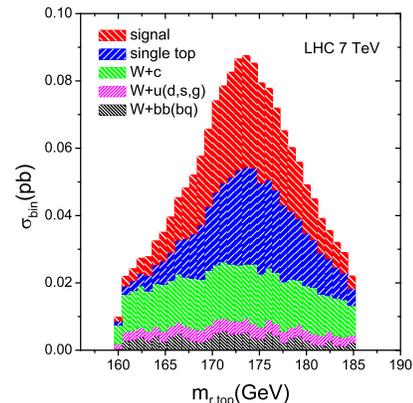

FIG. 1. The reconstructed top quark mass distribution from the signal and background processes, assuming $f_q^L = 0$ and $\kappa_{tcg}/\Lambda = 0.05\,{\rm TeV}^{-1}$, $\kappa_{tug}/\Lambda = 0$.

To further study the LHC discovery potential of the anomalous couplings, we choose $f_q^L = f_q^R = 1$ as in the previous experimental analysis at the Tevatron. If we take the anomalous couplings equal to the one-dimensional upper limits in Eq. (1), we find that, for the LHC with $\sqrt{s} = 7\,{\rm TeV}$, the needed integrated luminosity for a 5σ discovery ($N_S/\sqrt{N_B} = 5$) of the signal process is $61\,{\rm pb}^{-1}$ ($1.22\,{\rm fb}^{-1}$) for the tcg (tug) coupling, which means that we may expect the observation of this rare process at the early stage of the LHC. Moreover, in Fig. 2 we show the 5σ discovery limits of the anomalous couplings for the LHC with different integrated luminosities and c.m. energies. We find that with a luminosity of $2\,(10)\,{\rm fb}^{-1}$ and $\sqrt{s} = 7\,{\rm TeV}$, the LHC can detect the anomalous couplings down to $0.0115\,(0.0077)\,{\rm TeV}^{-1}$ and $0.024\,(0.016)\,{\rm TeV}^{-1}$ for the tug and tcg couplings, respectively, assuming only one coupling is non-zero. The increase of the c.m. energy will raise the discovery potential for the tcg coupling significantly. Assuming that the LHC could reach its designed energy of $14\,{\rm TeV}$ and collect an integrated luminosity of $100\,{\rm fb}^{-1}$, we can see that the one-dimensional discovery limits of the anomalous couplings can be as low as $0.0041\,{\rm TeV}^{-1}$ and $0.0067\,{\rm TeV}^{-1}$. The LHC shows a great improvement for the detection of the tcg anomalous coupling as compared to the Tevatron due to the large enhancement of the charm quark PDF.

Once the direct top quark production is observed, it is important to determine whether it comes from the up quark or charm quark initiated process for the under-
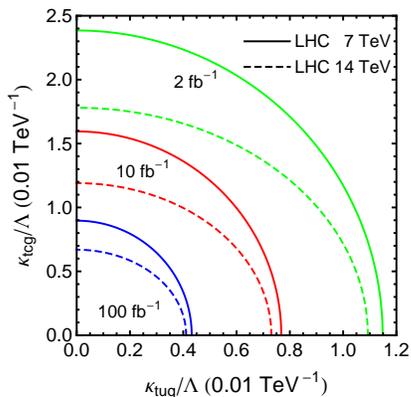
FIG. 2. The 5σ discovery limits of the anomalous couplings for the LHC with different c.m. energies and luminosities.
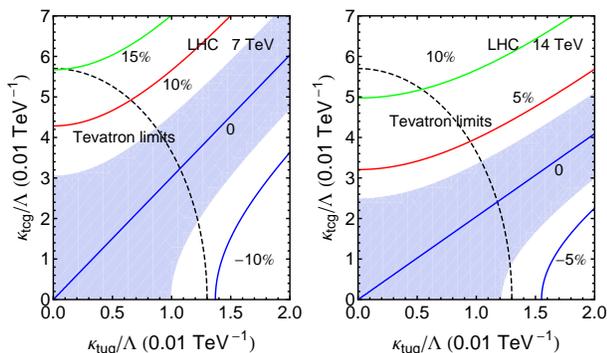

FIG. 3. Contour plot for the relative deviation of the ratio $\sigma(l^-)/\sigma(l^+)$ induced by the anomalous couplings, the shadow regions indicate the $\pm 3\sigma$ statistic fluctuation of the SM background values assuming an integrated luminosity of $10\,\text{fb}^{-1}$.

standing of the underlying new physics. In Fig. 3 we plot the relative deviation of the charge ratio $\sigma(l^-)/\sigma(l^+)$ induced by the anomalous couplings as compared to the SM backgrounds. The shadowed regions indicate the $\pm 3\sigma$ statistic fluctuation of the SM background values assuming an integrated luminosity of $10\,\text{fb}^{-1}$ and the dashed lines represent the current two-dimensional exclusion limits from Tevatron [4]. Since the *tcg* coupling contributes equally to the top and anti-top quark production, it prefers a larger value of the ratio as compared to the SM backgrounds. When the LHC collects enough data, a precision measurement of the charge ratio can be expected, which can be used to distinguish the *tug* and *tcg* couplings together with the total cross section measurements. Furthermore, we also emphasize that if the anomalous couplings are pure left(right)-handed, the top quark spin direction is parrel (opposite) to the incident quark direction, which can be determined through the boost direction of the reconstructed top quark only for the *tug* coupling. Thus it may be possible to determine the chiral structure of the *tug* anomalous coupling by

studying the angular distribution of the charged lepton, which will be discussed in detail elsewhere.

In conclusion, we have performed a detailed study of the direct top quark production with subsequent decay including the complete NLO QCD effects at the LHC. We show that after using the kinematic cuts and jet veto in the final states, the QCD corrections of the signal process become negative while the one for the inclusive rate is large and positive, which may have significant influence to the precision measurement of the anomalous couplings at the LHC. Assuming the anomalous couplings equal to the current experimental limits, for the LHC with $\sqrt{s} = 7\,\text{TeV}$, we find that the integrated luminosity needed for a 5σ discovery of the anomalous top quark production is as low as $61\,\text{pb}^{-1}$, and can be easily accomplished at the early stage of the LHC. Besides, with an integrated luminosity of $10\,\text{fb}^{-1}$ and $\sqrt{s} = 7\,\text{TeV}$ the LHC can probe the anomalous couplings down to $0.0077\,\text{TeV}^{-1}$ and $0.016\,\text{TeV}^{-1}$ for the *tug* and *tcg* couplings, respectively, assuming only one coupling is nonzero. Moreover, we also study the lepton charge ratio in the final states, which may be further used to distinguish the *tug* and *tcg* couplings.

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