Anomalous single top quark production at the CERN LHC

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Abstract. Production of single top quarks via the anomalous interaction $u(c)g \rightarrow t$, and its decay to $W + b$ are studied for the CERN LHC ATLAS experiment. The sensitivity to anomalous coupling κ/Λ down to 0.024 TeV^{-1} can be achieved.

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1. Introduction

Recently, there have been intensive studies to test possible deviations from the standard model (SM) at present and future colliders. Due to the large mass close to the electroweak symmetry breaking scale, the top quark is a good candidate for probing new physics beyond the SM. The top quark, being heavy and having poorly measured couplings, could have different dynamics than other quarks. This motivates the study of resonant single top quark production by flavour changing neutral current (FCNC) couplings at future hadron colliders. These anomalous couplings can lead to different signatures than those of SM processes of single top production, including potentially interesting polarization observables [1]. However in this work, we consider only the anomalous production mechanism.

The effective Lagrangian for the anomalous $t - u(c) - \gamma(g, Z)$ interaction is given by

$$\begin{aligned} L = & \frac{\kappa_\gamma^{qi}}{\Lambda} e_q g_e \bar{t} \sigma_{\mu\nu} (A_\gamma^{qi} + B_\gamma^{qi} \gamma_5) q_i F^{\mu\nu} + \frac{\kappa_Z^{qi}}{2\Lambda} g_Z \bar{t} \sigma_{\mu\nu} (A_Z^{qi} + B_Z^{qi} \gamma_5) q_i Z^{\mu\nu} \\ & + \frac{\kappa_g^{qi}}{\Lambda} g_s \bar{t} \sigma_{\mu\nu} (A_g^{qi} + B_g^{qi} \gamma_5) T^a q_i G_a^{\mu\nu} + H.c. \end{aligned} \quad (1)$$

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where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the photon, Z boson and gluons, respectively; T^a are Gell-Mann matrices; e_q is the charge of the quark; g_e , g_Z and g_s are the electroweak and the strong coupling constants, respectively; $g_Z = g_e / \cos \theta_W \sin \theta_W$ where θ_W is the Weinberg angle; $A_{\gamma,Z,g}^q$ and $B_{\gamma,Z,g}^q$ are the magnitudes of the neutral currents; κ_γ , κ_Z and κ_g define the strengths of the anomalous couplings for the neutral currents mediated by a photon, Z boson and gluon, respectively; Λ is the new physics scale. The investigation of these couplings at hadron colliders has been studied in [2, 3].

In this study, we assume all the neutral current magnitudes in Eq. (1) satisfy the constraint $|A|^2 + |B|^2 = 1$. Hence, using the above Lagrangian, the anomalous decay widths can be expressed as

$$\Gamma(t \rightarrow qg) = \left(\frac{\kappa_g^q}{\Lambda} \right)^2 \frac{2\alpha_s}{3} m_t^3 \quad (2)$$

$$\Gamma(t \rightarrow q\gamma) = \left(\frac{\kappa_\gamma^q}{\Lambda} \right)^2 e_q^2 \frac{\alpha}{2} m_t^3 \quad (3)$$

$$\Gamma(t \rightarrow qZ) = \left(\frac{\kappa_Z^q}{\Lambda} \right)^2 \frac{\alpha}{4 \sin^2 2\theta_W} m_t^3 \left(1 - \frac{m_Z^2}{m_t^2} \right)^2 \left(2 + \frac{m_Z^2}{m_t^2} \right) \quad (4)$$

where q denotes u or c quarks, $\alpha_s = g_s^2/4\pi$ and $\alpha = g_e^2/4\pi$ are the coupling constants for strong and electromagnetic interactions. We consider a definition for the anomalous couplings leading to the factor of $2/3$ in eq. (2). This can be compared with the definitions given in [4] and [5]. The decay width for SM decay mode is given by

$$\begin{aligned} \Gamma(t \rightarrow bW) &= \frac{\alpha |V_{tb}|^2}{16 \sin^2 \theta_W} \frac{m_t^3}{m_W^2} \left(1 - \frac{m_W^2}{m_t^2} \right) \left(1 + \frac{m_W^2}{m_t^2} - \frac{2m_W^4}{m_t^4} \right) \\ &\times \left[1 - 2 \frac{\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2} \right) \right] \end{aligned} \quad (5)$$

which equals $\simeq 1.4$ GeV for the input parameters $m_t = 175$ GeV, $m_W = 80$ GeV and $\alpha = 1/128$, $V_{tb} = 1$ and $\sin^2 \theta_W = 0.23$.

The experimental limits by the CDF collaboration for the anomalous decay channels of top quarks are [6]:

$$BR(t \rightarrow c\gamma) + BR(t \rightarrow u\gamma) < 0.032 \quad (6)$$

$$BR(t \rightarrow cZ) + BR(t \rightarrow uZ) < 0.33 \quad (7)$$

Using these branching ratio limits (6) and (7) of the CDF on FCNC, and assuming the $\Lambda = m_t$, we can derive the following model-dependent limits: $\kappa_\gamma < 0.28$, $\kappa_Z < 0.78$ and $\kappa_g < 0.34$. In our notation, a model-dependent anomalous coupling for tgq interaction translates into $\kappa_g/\Lambda < 2$ TeV $^{-1}$.

The OPAL results improve the limits on the anomalous coupling for tqZ , but not on $tq\gamma$ [7]. However, one should note that translation of these branching ratios into the parameter κ/Λ (see Eq. (1)) is model dependent.

Table 1. The cross sections for anomalous single top events for various coupling values (results are obtained from PYTHIA implementation). Total decay widths and $t \rightarrow Wb$ branching ratios are also given.

$\kappa/\Lambda(\text{TeV}^{-1})$	$\sigma_{ug \rightarrow t}(\text{pb})$	$\sigma_{cg \rightarrow t}(\text{pb})$	$\Gamma_{\text{tot}}(\text{GeV})$	BR_{Wb}
1×10^0	4.07×10^4	7.19×10^3	2.264	0.612
8×10^{-1}	2.64×10^4	4.74×10^3	1.947	0.711
6×10^{-1}	1.42×10^4	3.04×10^3	1.701	0.814
4×10^{-1}	6.48×10^3	1.33×10^3	1.525	0.908
2×10^{-1}	1.64×10^3	3.15×10^2	1.420	0.975
1×10^{-1}	3.89×10^2	8.27×10^1	1.393	0.994
1×10^{-2}	4.09×10^0	7.94×10^{-1}	1.385	1.000
1×10^{-3}	4.08×10^{-2}	7.69×10^{-3}	1.385	1.000

Figure 1. Feynman diagram of $u(c)g \rightarrow t \rightarrow Wb \rightarrow l v b$, where $l=e$ or μ .

The H1 results on the anomalous top production put an upper limit of 0.27 on the $tu\gamma$ coupling at 95% confidence level [8].

The FCNC decays of the top quark were considered in ATLAS TDR [10] and the reach for $t \rightarrow qZ$, $t \rightarrow q\gamma$ and $t \rightarrow qg$ were given as $\text{BR}(t \rightarrow qZ)=\text{BR}(t \rightarrow q\gamma)=10^{-4}$ at 5σ level and $\text{BR}(t \rightarrow qg)=7.4 \times 10^{-3}$ (or $\kappa_g/\Lambda = 0.091 \text{ TeV}^{-1}$) at 95% C.L.

The top quark decay width would be slightly increased by the anomalous interactions. In our calculations, we assume $\kappa = \kappa_\gamma^q = \kappa_g^q = \kappa_Z^q$ and $\kappa^u = \kappa^c$ in order to restrict the number of parameters. The anomalous decay $t \rightarrow u(c)g$ will give a small contribution to the decay width i.e. $\Gamma(t \rightarrow u(c)g) \simeq 3 \times 10^{-2} \text{ GeV}$ for $\kappa/\Lambda = 0.2 \text{ TeV}^{-1}$. Since the top quark anomalous interactions don't exist in PYTHIA [9], we have modified the code and implemented the corresponding couplings. Hence, the resulting $u(c) \rightarrow t$ cross sections, total decay widths and $t \rightarrow Wb$ branching ratios for different κ/Λ values are given in Table 1. One can see from Table 1 how the presence of anomalous couplings affects the standard top quark decay branching ratio $\text{BR}(t \rightarrow W^+b)$.

Here, single top quark production in the resonance channel, through the anomalous process $qg \rightarrow t \rightarrow Wb$ as shown in Fig. 1, will be investigated.

2. Analysis

In order to simulate the anomalous top quark signal and relevant backgrounds, and also take into account the experimental conditions prevailing at LHC for the ATLAS detector [10], the PYTHIA event generator and ATLFAST [11] detector simulation packages were used. We have implemented the process of anomalous single top production in PYTHIA. Since the dominant decay mode for top quark is $t \rightarrow Wb$, and the leptonic decay of W gives a clear signal, we search for a signal in the detector through the presence of a b-tagged jet, an isolated lepton and missing transverse momentum. We have used CTEQ5L parton distribution functions [12] in PYTHIA to calculate the cross sections for anomalous single top production at LHC.

In our analysis, we reconstructed top quark mass from the relation

$$p_t = p_b + p_l + p_\nu \quad (8)$$

$$m_{bl\nu} = \sqrt{(E_b + E_l + E_\nu)^2 - (\vec{p}_b + \vec{p}_l + \vec{p}_\nu)^2} \quad (9)$$

requiring the W boson mass constraint $m_{l\nu} = m_W$ in order to calculate the longitudinal component of the neutrino momentum as

$$p_{L\nu} = \frac{v p_{Ll} \pm \sqrt{\vec{p}_l^2 (v^2 - p_{Tl}^2 p_{T\nu}^2)}}{p_{Tl}^2} \quad (10)$$

where $v = m_W^2/2 + \vec{p}_{Tl} \cdot \vec{p}_{T\nu}$. The neutrino is not directly observed, but its transverse momentum can be deduced from the missing transverse momentum. From the two alternatives given in Eq. (10), we choose the one that results in reconstructed invariant mass closer to m_t .

In Fig. 2, we present the fraction of the signal events lost as a function of the p_T cuts. For the selection of the anomalous single top events, we require one single isolated lepton, a single b-jet and missing p_T . The b-tagging efficiency is taken as 60%, leading to rejection factors of 93 for light quarks and 7 for c quarks. For proper particle reconstruction, and to satisfy the trigger requirements, additional p_T cuts are applied:

$$p_T^e > 25\text{GeV}, \quad p_T^\mu, p_T^{miss} > 20\text{GeV}, \quad p_T^b > 50\text{GeV} \quad (11)$$

In Fig. 3, the reconstructed invariant mass of the signal before and after p_T cuts is presented in arbitrary units. The anomalous single top events are suppressed about 50% by the p_T cuts.

The most important backgrounds to the signal are $W + j$ and single production of top quarks. However, there are also relatively small contributions from $t\bar{t}$, $Wb\bar{b}$ and ZW/WW processes as shown in Fig. 4. We have generated $Wb\bar{b}$ events using the Madgraph ME [13] routines interfaced to PYTHIA and ATLFAST. At the LHC, top quarks are mostly produced in pairs via the process $gg \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ with a total cross section $\sigma \simeq 800$ pb. However, the top quarks will be produced singly with a significant number at the LHC: t-channel production has the largest cross section ~ 250 pb, s-channel has ~ 10 pb and the Wt process has a cross section of ~ 50 pb. The first

Figure 2. Fraction of signal events lost with the p_T cuts applied

Figure 3. Invariant mass distribution of single top events without (solid line) and with (dashed line) p_T cuts.

Figure 4. The invariant mass distributions $m_{jl\nu}$ of all the background processes. Solid line - without p_T cuts and b -tagging, dashed line - with p_T cuts and b -tagging.

two processes are suppressed by the requirement of a single b -tagged jet, since a bottom quark is produced in association with the top quark in these cases. PYTHIA accounts for the t -channel exchange of a W via a $2 \rightarrow 2$ process, but does not include the full $2 \rightarrow 3$ process of Wg fusion. We have therefore scaled the cross section to include contributions from the latter process, according to [14]. When we apply the above cuts, these backgrounds are reduced to a lower level.

The cross sections for the relevant backgrounds in the mass window of top quark ($m_t \pm 2\sigma$, the expected mass resolution being $\sigma \simeq 12$ GeV) are shown in Table 2 before and after the cuts. The p_T cuts are effective on $W + j$ background. Requiring only one b -jet and no other jet reduces the $t\bar{t}$ and $Wb\bar{b}$ backgrounds considerably and suppresses the SM single top production by a factor 2. The resulting backgrounds are dominated by $W + j$ and single- t processes (see Fig. 4).

The reconstructed signal+background is given in Fig. 5 for $\kappa/\Lambda = 0.4$ TeV $^{-1}$. The resulting $S/\sqrt{B}$ values in the mass window of top quark are given in Table 3.

Due to the statistical errors, uncertainties on parton distribution functions and the scale used in calculations the expected theoretical error on the production cross

Table 2. The background cross sections (in the mass window) relevant to FCNC top quark production at the LHC as seen in ATLFAST.

Process	$ZW + WW$	Wbb	single- t	$t\bar{t}$	Wj	All
no-cuts(pb)	2.43×10^{-2}	6.03×10^{-1}	1.26×10^0	4.18×10^{-2}	5.70×10^1	5.90×10^1
with-cuts(pb)	6.90×10^{-3}	9.15×10^{-2}	6.43×10^{-1}	4.18×10^{-2}	2.86×10^0	3.64×10^0

Figure 5. The signal+background events for $L_{int} = 100 \text{ fb}^{-1}$ and $\kappa/\Lambda = 0.4 \text{ TeV}^{-1}$. The background alone is also shown for comparison.**Table 3.** Statistical significance for the anomalous top quark production at the CERN LHC at an integrated luminosity of 10^5 pb^{-1} , where the total number of background events is $B = 3.6 \times 10^5$.

$\kappa/\Lambda(\text{TeV}^{-1}) \rightarrow$	0.4	0.2	0.1	0.01	0.001
S	3.4×10^6	8.6×10^5	2.5×10^5	2.3×10^3	2.3×10^1
$S/\sqrt{B}$	5.6×10^3	1.4×10^3	4.1×10^2	3.9×10^0	4.0×10^{-2}

sections of the single top processes is 11% for Wg fusion as given in [10]. However, since background from SM single top production is about 20% of the total background (see Fig. 4) this uncertainty is manageable in our case, even if the background has a shape similar to the signal, as can be seen in Fig. 4. It is likely that the theoretical uncertainties arising from the structure functions will be considerably reduced when the LHC turns on. The uncertainties in the luminosity measurement of the LHC is expected to be $\sim 5 - 10\%$.

To evaluate the discovery potential, we assume that the systematic uncertainty in the SM single top background cross section remains 11%, or 7100 events for an integrated luminosity of 100 fb^{-1} . From table 2, one then concludes that discovery

at 95% C.L. (2σ) is possible if $\kappa/\Lambda = 0.024$. We can translate this value of κ/Λ to $\text{BR}(t \rightarrow ug) = 5.22 \times 10^{-3}$. For this value of the parameters, the expected number of anomalous single top events is 15443.

3. Conclusion

In the effective Lagrangian description of FCNC interactions there are various models assuming different structure of the couplings. We have calculated the discovery limits for the anomalous couplings $u(c)gt$ at LHC using the resonant production of top quarks. Taking into account the systematic uncertainty in the single top production cross sections the sensitivity to anomalous coupling κ/Λ can be achieved down to 0.024 TeV^{-1} in the ATLAS experiment.

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