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Anomalous single top production at the LHeC based γp collider

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ABSTRACT

The top quark could provide very important information for the Standard Model extensions due to its large mass close to the electroweak symmetry breaking scale. In this work, anomalous single top production is studied by using $\gamma p \to W^+ b$ process at the LHeC based γp collider. The sensitivity to anomalous coupling κ/Λ could be reached down to 0.01 TeV^{-1}.

The top quark is considered to be the most sensitive to the new physics beyond the Standard Model (BSM) since it is the heaviest available particle of the Standard Model (SM). If the BSM is associated with the mass generation, the top quark interactions will be sensitive to the mechanism of dynamical symmetry breaking. The precise measurement of the couplings between SM bosons and fermions provides powerful tool for the search of the BSM physics. As mentioned in [1], the effects of new physics on the top quark couplings are expected to be larger than that on any other fermions, and deviations with respect to the SM predictions might be detectable.

A possible anomalous tqV ($V = g, \gamma, Z$ and $q = u, c$) couplings can be generated through a dynamical mass generation [2]. They have a similar chiral structure as the mass terms, and the presence of these couplings would be interpreted as signals of new interactions. This motivates the study of top quarks' flavour changing neutral current (FCNC) couplings at present and future colliders.

Current experimental constraints at 95% C.L. on the anomalous top quark couplings are [3]: $BR(t \to \gamma u) < 0.0132$ and $BR(t \to \gamma u) < 0.0059$ from HERA; $BR(t \to \gamma q) < 0.041$ from LEP and $BR(t \to \gamma q) < 0.032$ from CDF. The HERA has much higher sensitivity to $u\gamma t$ than $c\gamma t$ due to more favorable parton density: the best limit is obtained from the ZEUS experiment.

The top quarks will be produced in large numbers at the Large Hadron Collider (LHC), therefore the couplings of the top quark can be probed with a great precision. For a luminosity of 1 fb^{-1} the expected ATLAS sensitivity to the top quark FCNC decay is $BR(t \to q\gamma) \sim 10^{-3}$ at 95% C.L. [4]. For $L_{int} = 100$ fb^{-1} the ATLAS sensitivity to $t\gamma q$ anomalous interactions has been estimated as $BR(t \to q\gamma) \sim 10^{-4}$ at 5σ level [5].

The production of top quarks by FCNC interactions at hadron colliders has been studied in [6], e^+e^- colliders in [2,7] and lepton–hadron collider in [2,8]. LHC will give an opportunity to probe $BR(t \to ug)$ down to 5×10^{-3} [9]; ILC/CLIC has the potential to probe $BR(t \to q\gamma)$ down to 10^{-5} [10].

It is known that linac-ring type colliders present the sole realistic way to TeV scale in lepton–hadron collisions [11]. An essential advantage of linac-ring type *ep* colliders is the opportunity to construct γp colliders on their basis [12]. Construction of linear e^+e^- collider or special linac tangential to LHC ring will give opportunity to utilize highest energy proton and nuclei beams for lepton–hadron collisions. Recently this opportunity is widely discussed in the framework of the LHeC project [13]. Two stages of the LHeC are considered: QCD Explorer ($E_e = 50$–100 GeV) and Energy Frontier ($E_e > 250$ GeV). First stage is mandatory for two reasons: to provide precision PDF's for adequate interpretation of LHC data and to enlighten QCD basics.

In this Letter, we investigate the potential of LHeC based γp collider to search for anomalous top quark interactions.

The effective Lagrangian involving anomalous $t\gamma q$ ($q = u, c$) interactions is given by [9]

$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q + h_q \gamma_5) q A_{\mu\nu} + \text{h.c.} \tag{1}$$

where $A_{\mu\nu}$ is the usual photon field tensor, $\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$, Q_q is the quark charge, in general f_q and h_q are complex numbers, g_e is electromagnetic coupling constant, κ_q is real and positive anomalous FCNC coupling and Λ is the new physics scale. The neutral current magnitudes in the Lagrangian satisfy

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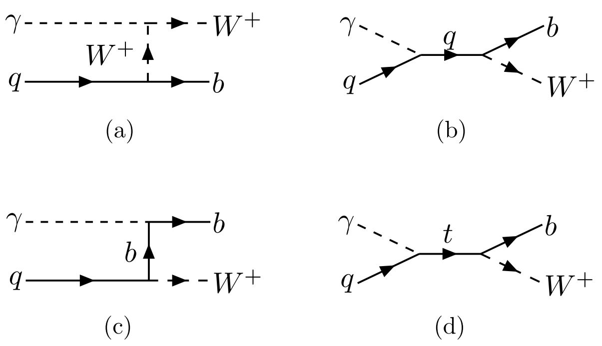
$|(f_q)^2 + (h_q)^2| = 1$ for each term. Using Eq. (1), the anomalous decay width can be calculated as

$$\Gamma(t \to q\gamma) = \left(\frac{\kappa_q}{\Lambda}\right)^2 \frac{2}{9}\alpha_{em} m_t^3. \tag{2}$$

Taking $m_t = 173$ GeV and $\alpha_{em} = 0.0079$, we find the anomalous decay width ≈ 9 MeV for $\kappa_q/\Lambda = 1$ TeV^{-1}, while the SM decay width is about 1.5 GeV. For numerical calculations we implemented anomalous interaction vertices from Lagrangian (1) into the CalcHEP package [14] and use PDF library CTEQ6M [15]. The Feynman diagrams for the subprocess $\gamma q \to W^+ b$, where $q = u, c$ are presented in Fig. 1. First three diagrams correspond to irreducible background and the last one to signal.

The main background comes from associated production of W boson and the light jets. Hereafter, for b-tagging efficiency we used the 60% and the mistagging factors for light jets ($d, s, \bar{u}$) and $\bar{c}$ quark are taken as 0.01 and 0.1, respectively.

The differential cross sections of the final state jets are given in Fig. 2 ($\kappa/\Lambda = 0.02$ TeV^{-1}) and Fig. 3 ($\kappa/\Lambda = 0.04$ TeV^{-1}) for $E_e = 70$ GeV and $E_p = 7000$ GeV. Here, we assume $\kappa_u = \kappa_c = \kappa$. The transverse momentum distribution of the signal has a peak around 70 GeV.



(a) (b)

(c) (d)

Fig. 1. Feynman diagrams for $\gamma q \to W^+ b$, where $q = u, c$.

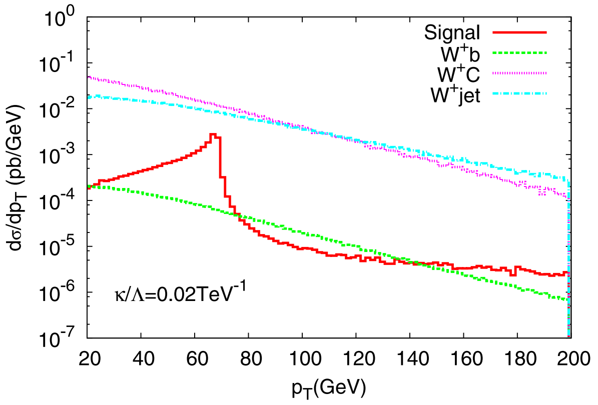


Fig. 2. The transverse momentum distribution of the final state jet for the signal and background processes, where C denotes $\bar{c}$ quark. The differential cross section includes the b-tagging efficiency and the rejection factors for the light jets. Here the center of mass energy $\sqrt{s_{ep}} = 1.4$ TeV and $\kappa/\Lambda = 0.02$ TeV^{-1}.

The pseudo-rapidity distribution of the jets in the signal ($\kappa/\Lambda = 0.01$ TeV^{-1}) and background processes are presented in Fig. 4, where we applied a cut $p_T > 20$ GeV. The maximum of the signal is around $\eta = 1$, while the main background shifted to $\eta \sim 2$. Nevertheless, one can see from Fig. 4 that η cut does not provide essential gain.

The cross sections for signal and background processes with different p_T cuts are presented in Table 1. It is seen that p_T cut slightly reduce the signal ($\sim 30\%$ for $p_T > 50$ GeV), whereas the background is essentially reduced (factor 4–6). In order to improve the signal to background ratio further one can use invariant mass (W + jet) cut around top mass. In Table 2, the cross sections for signal and background processes are given using both p_T and invariant mass cuts ($M_{Wb} = 150$–200 GeV).

In order to calculate the statistical significance (SS) we use following formula [16]:

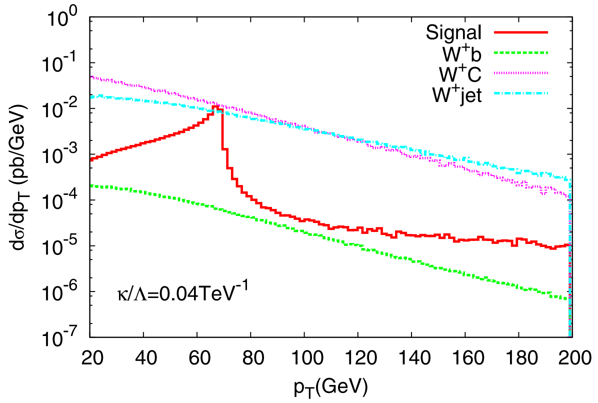


Fig. 3. The same as Fig. 2 but for $\kappa/\Lambda = 0.04$ TeV^{-1}.

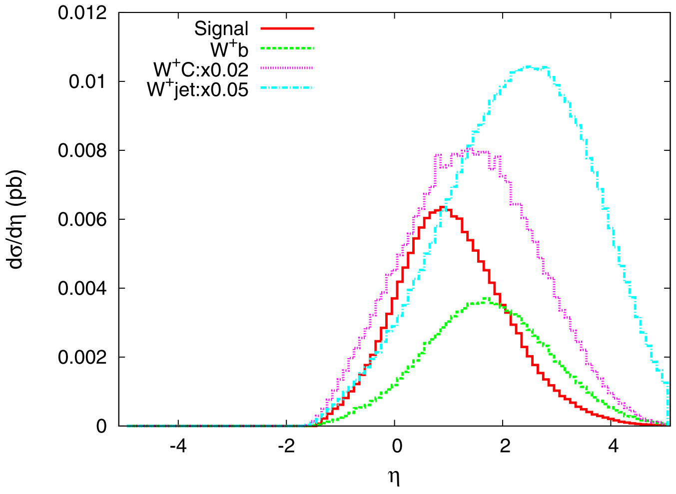


Fig. 4. Pseudo-rapidity distribution of the jets in the signal ($\kappa/\Lambda = 0.01$ TeV^{-1}) and background processes (C denotes $\bar{c}$ quark), where we applied a cut $p_T > 20$ GeV. Here, $E_e = 70$ GeV and $E_p = 7000$ GeV.

Table 1
The cross sections (in pb) according to the p_T cut for the signal and background at γp collider based on the LHeC with $E_e = 70$ GeV and $E_p = 7000$ GeV.

$\kappa/\Lambda = 0.01$ TeV^{-1}	No cut	$p_T > 20$ GeV	$p_T > 40$ GeV	$p_T > 50$ GeV
Signal	9.54×10^{-3}	9.16×10^{-3}	7.84×10^{-3}	6.66×10^{-3}
Background: W^+b	9.60×10^{-3}	6.18×10^{-3}	3.48×10^{-3}	2.55×10^{-3}
Background: $W^+\bar{c}$	3.11×10^{0}	1.27×10^{0}	6.85×10^{-1}	4.90×10^{-1}
Background: W^+jet	1.79×10^{0}	7.24×10^{-1}	4.79×10^{-1}	3.77×10^{-1}

Table 2
The cross sections (in pb) according to the p_T cut and invariant mass interval ($M_{Wb} = 150$–200 GeV) for the signal and background at γp collider based on the LHeC with $E_e = 70$ GeV and $E_p = 7000$ GeV.

$\kappa/\Lambda = 0.01$ TeV^{-1}	$p_T > 20$ GeV	$p_T > 40$ GeV	$p_T > 50$ GeV
Signal	8.86×10^{-3}	7.54×10^{-3}	6.39×10^{-3}
Background: W^+b	1.73×10^{-3}	1.12×10^{-3}	7.69×10^{-4}
Background: $W^+\bar{c}$	3.48×10^{-1}	2.30×10^{-1}	1.63×10^{-1}
Background: W^+jet	1.39×10^{-1}	9.11×10^{-2}	6.38×10^{-2}

Table 3
The signal significance (SS) for different values of κ/Λ and integral luminosity for $E_e = 70$ GeV and $E_p = 7000$ GeV (the numbers in parenthesis correspond to $E_e = 140$ GeV).

SS	$L = 2$ fb^{-1}	$L = 10$ fb^{-1}
$\kappa/\Lambda = 0.01$ TeV^{-1}	2.58 (2.88)	5.79 (6.47)
$\kappa/\Lambda = 0.02$ TeV^{-1}	5.26 (5.92)	11.78 (13.25)

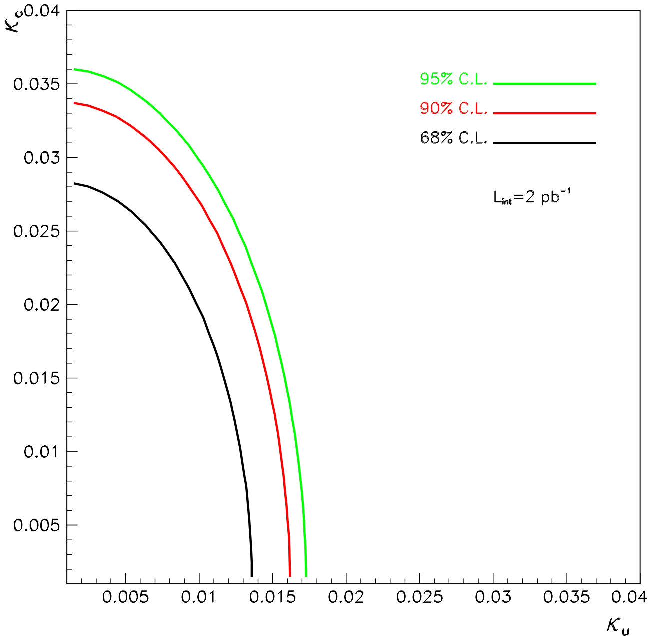


Fig. 5. Contour plot for the anomalous couplings reachable at the LHeC based γp collider with the ep center of mass energy $\sqrt{s_{ep}} = 1.4$ TeV and integrated luminosity $L_{int} = 2$ fb^{-1}.

$$SS = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]} \tag{3}$$

where S and B are the numbers of signal and background events, respectively. Results are presented in Table 3 for different κ/Λ and luminosity values. It is seen that even with 2 fb^{-1} the LHeC based γp collider will provide 5σ discovery for $\kappa/\Lambda = 0.02$ TeV^{-1}.

Up to now, we assume $\kappa_u = \kappa_c = \kappa$. However, it is a matter of interest to analyze the $\kappa_u \neq \kappa_c$ case. Being different from HERA where anomalous single top production is dominated by valence u-quarks, at LHeC energy region c-quark contribution becomes comparable with the u-quark contribution. Therefore, the sensitivity to κ_c will be enhanced at LHeC comparing to HERA. In Figs. 5–8 the contour plots for the anomalous couplings in κ_u–κ_c plane are presented. For this purpose, we perform a χ^2 analysis by using

$$\chi^2 = \sum_{i=1}^{N}\left(\frac{\sigma^i_{S+B} - \sigma^i_B}{\Delta\sigma^i_B}\right)^2 \tag{4}$$

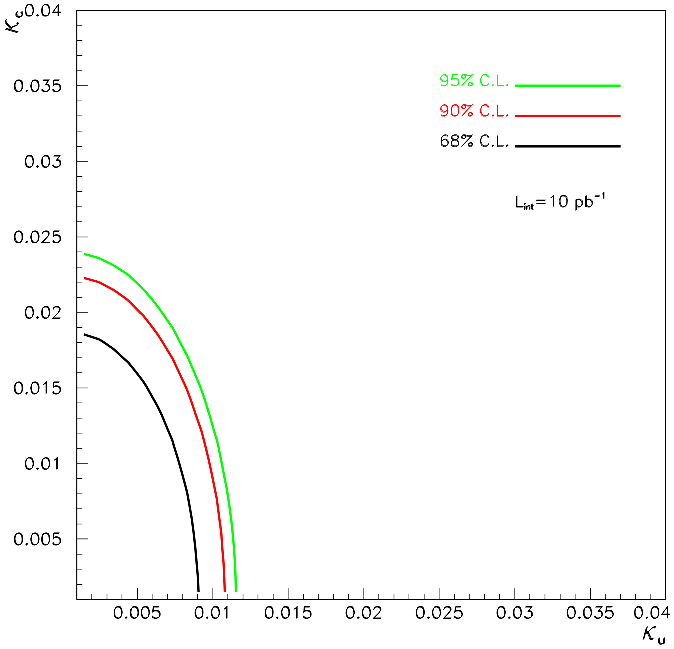


Fig. 6. The same as Fig. 5 but for $L_{int} = 10$ fb^{-1}.

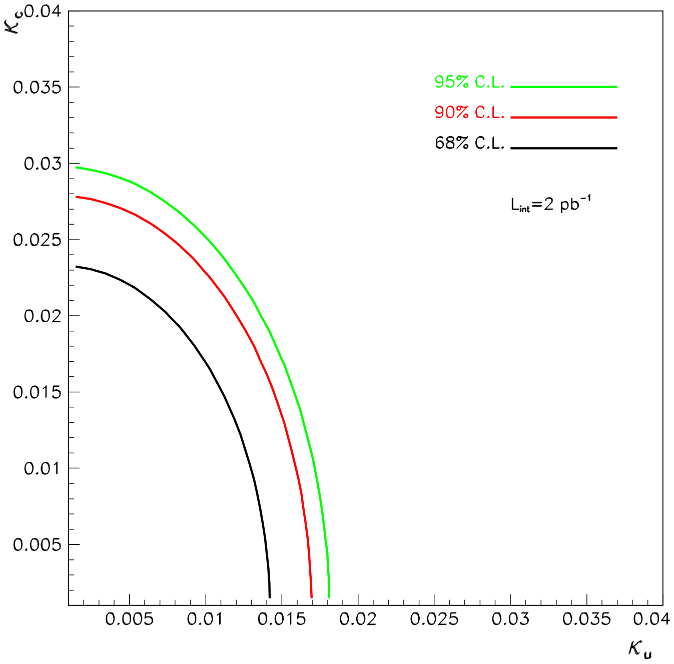


Fig. 7. Contour plot for the anomalous couplings reachable at the LHeC based γp collider with the ep center of mass energy $\sqrt{s_{ep}} = 1.9$ TeV and integrated luminosity $L_{int} = 2$ fb^{-1}.

where σ^i_B is the cross-section for the SM background in the ith bin. It includes both b-jet and light-jet contributions with the corresponding efficiency factors. In the σ_{S+B} calculations, we take into account κ_u different from κ_c case as well as signal-background interference. One can see from Figs. 5–8 that sensitivity is enhanced by a factor of 1.5 when the luminosity changes from 2 fb^{-1} to 10 fb^{-1}. Concerning the energy upgrade, increasing electron energy from 70 GeV to 140 GeV results in 20% improvement for κ_c. Increasing electron energy further (energy frontier ep collider) does not give essential improvement in sensitivity to anomalous couplings [17].

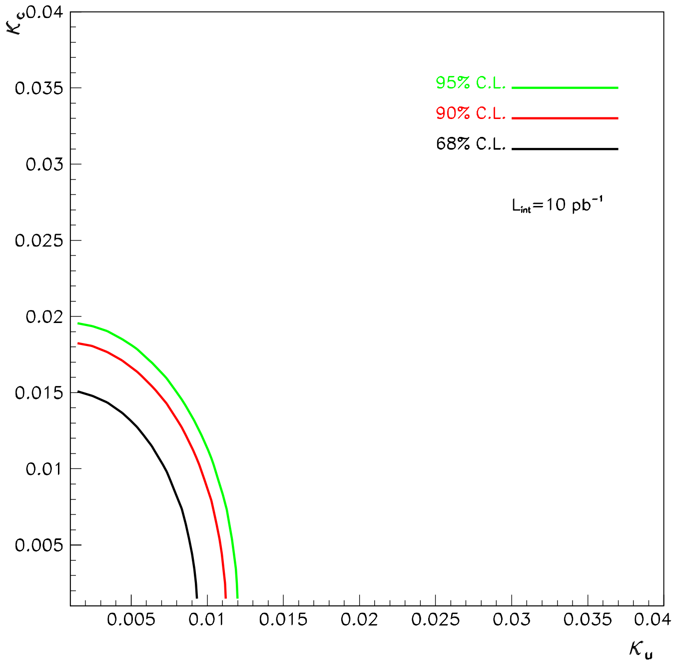


Fig. 8. The same as Fig. 7 but for the integrated luminosity $L_{int} = 10\ \text{fb}^{-1}$.

Finally, we compare our results with the LHC potential. The value of $\kappa/\Lambda = 0.01\ \text{TeV}^{-1}$ corresponds to $BR(t \to \gamma u) \approx 2 \times 10^{-6}$ which is two orders smaller than the LHC reach with 100 fb^{-1}. It is obvious that even upgraded LHC will not be competitive with LHeC based γp collider in the search for anomalous $t\gamma q$ interactions. Different extensions of the SM (supersymmetry, little Higgs, extra dimensions, technicolor, etc.) predict branching ratio $BR(t \to \gamma q) = O(10^{-5})$, hence the LHeC will provide opportunity to probe these models.

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