

Anomalous Wtb Coupling in ep Collision

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The potential of ep collision to prospect for anomalous Wtb vertex is discussed from the single top quark production process $ep \rightarrow t\bar{\nu} + X$ for TESLA+HERAp and CLIC+LHC energies. Sensitivities to anomalous couplings F_{2L} and F_{2R} , in the case of CLIC+LHC, are shown to be comparable with LHC.

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I. INTRODUCTION

After the observation of top quark with mass much heavier than the rest of the Standard Model(SM) fermions and gauge bosons, special attention to its couplings with gauge bosons has been drawn. Since the coupling Wtb is responsible for all top quark decays, it plays crucial role to help understand the nature of electroweak theory and "new physics" beyond. Therefore it is important to study Wtb vertex and measure the coupling parameters with high precision. Single top quark production processes provide unique possibility to search for this vertex due to their direct proportionality to the Wtb coupling. Deviations from the SM expectation in Wtb vertex would be a possible signal for the new physics beyond SM. Several collider experiment potentials have been examined to search for these coupling parameters through single top production. Single top cross section for the process $e^+e^- \rightarrow Wtb$ has been discussed below and above $t\bar{t}$ threshold [1,2] and for the process $e^+e^- \rightarrow e\bar{\nu}tb$ at CERN e^+e^- collider LEP2 [3] and linear e^+e^- collider(LC) [4,5] energies. Investigations for Wtb vertex have been done at γe mode of LC [6], Fermilab $p\bar{p}$ collider Tevatron and CERN pp collider LHC [7,8].

Additional option of linear e^+e^- collider would be an ep collider when LC is constructed on the same base as the proton ring. Linear collider design TESLA at DESY is the one that can be converted into TESLA+HERAp ep collider [9]. Similar option would be considered for CLIC+LHC at CERN. Estimations about the main parameters of these collider modes are shown in Table I for two different design values of linear electron beam energies.

In this paper, the potential of future high energy ep colliders to investigate anomalous Wtb couplings will be discussed.

II. LAGRANGIAN AND CROSS SECTIONS

In the model independent effective lagrangian approach [10–13] there are seven anomalous CP conserving operators of dimension six which contribute Wtb vertex [12]. This effective lagrangian contains four independent couplings whose explicit forms are given in ref. [12]. Effects of all seven operators will not be investigated here. We only consider following couplings to reveal the potential of ep collision

$$L = \frac{g_w}{\sqrt{2}} [W_\mu \bar{t} (\gamma^\mu F_{1L} P_- + \gamma^\mu F_{1R} P_+) b - \frac{1}{2m_w} W_{\mu\nu} \bar{t} \sigma^{\mu\nu} (F_{2L} P_- + F_{2R} P_+) b] + h.c. \quad (1)$$

where

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$$W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$P_\mp = \frac{1}{2}(1 \mp \gamma_5), \quad \sigma^{\mu\nu} = \frac{i}{2}(\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu) \quad (2)$$

In the SM, the (V-A) coupling F_{1L} corresponds Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{tb} which is very close to unity and F_{1R} , F_{2L} and F_{2R} are equal to zero. The (V+A) coupling F_{1R} is severely bounded by the CLEO $b \rightarrow s\gamma$ data [14] at a level such that it will be out of reach at expected future colliders. Therefore we set $F_{1L} = 0.999$ and $F_{1R} = 0$ as required by present data [15]. The magnetic type anomalous couplings are related to the coefficients $C_{tW\Phi}$ and $C_{bW\Phi}$ [12] in the general effective lagrangian by

$$F_{2L} = \frac{C_{tW\Phi} \sqrt{2} v m_w}{\Lambda^2 g} \quad F_{2R} = \frac{C_{bW\Phi} \sqrt{2} v m_w}{\Lambda^2 g} \quad (3)$$

where Λ is the scale of new physics. Natural values of the couplings $F_{2L(R)}$ are in the region [16] of

$$\frac{\sqrt{m_b m_t}}{v} \sim 0.1 \quad (4)$$

and do not exceed unitarity violation bounds for $|F_{2L(R)}| \sim 0.6$ [11].

In ep collision there are two subprocesses contributing to single top production $eb \rightarrow t\bar{\nu}$ and W-gluon fusion process $eg \rightarrow t\bar{b}\bar{\nu}$. Differential cross section for the subprocess $eb \rightarrow t\bar{\nu}$ in terms of Mandelstam invariants $\hat{s}$ and $\hat{t}$ has been obtained as given below

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi\alpha^2}{4\sin^4\theta_W \hat{s}^2 m_w^2 (\hat{t} - m_w^2)^2} \times$$

$$[F_{2L}^2 \hat{t}(-(\hat{s} - m_t^2)^2 + \hat{t}(m_t^2 - \hat{s})) + 2F_{2L}|V_{bt}|m_t m_w \hat{t}(\hat{s} + \hat{t} - m_t^2)$$

$$- F_{2R}^2 \hat{s} \hat{t}(\hat{s} + \hat{t}) + |V_{bt}|^2 m_w^2 (-m_t^2(\hat{s} + \hat{t}) + (\hat{s} + \hat{t})^2)] \quad (5)$$

where m_t , m_w , V_{bt} and θ_W are top quark mass, W boson mass, CKM matrix element and Weinberg angle respectively.

If the second process $eg \rightarrow t\bar{b}\bar{\nu}$ is combined with $eb \rightarrow t\bar{\nu}$ one should avoid double counting. The two subprocesses have a region of overlap when $g \rightarrow b\bar{b}$ in the W-gluon fusion is nearly collinear (close to on shell) so that b quark interacting with W boson is the same as the initial b sea quark in the first subprocess $eb \rightarrow t\bar{\nu}$. In order to take care of this double counting we use the method proposed in ref. [17]. So, combined cross section becomes

$$[\sigma(eb \rightarrow t\bar{\nu}) + \sigma(eg \rightarrow t\bar{b}\bar{\nu}) - \sigma(g \rightarrow b\bar{b} * eb \rightarrow t\bar{\nu})] \quad (6)$$

where the subtracted term is the gluon splitting piece of the cross section for $eg \rightarrow t\bar{b}\bar{\nu}$ and they are all integrated cross sections over the parton distributions. For the distribution function of b quark inside the gluon (splitting part) leading order approximation will be used defined below

$$\sigma_{ex}(ep \rightarrow t\bar{\nu} + X) = \int_{m_t^2/s}^1 \hat{\sigma}(xs) [f_{b/p}(x, Q^2) - f_{b/p}^{LO}(x, Q^2)] dx \quad (7)$$

where

$$f_{b/p}^{LO}(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{d\xi}{\xi} P_{b/g}(\frac{x}{\xi}) f_{g/p}(\xi, Q^2) \ln \frac{Q^2}{m_b^2} \quad (8)$$

with

$$P_{b/g}(z) = \frac{1}{2}[z^2 + (1-z)^2] \quad (9)$$

Here, $\alpha_s(Q^2)$ is the energy dependent QCD coupling whose expression is given in ref. [15]. σ_{ex} is the integrated total cross section over the parton distributions for the subprocess

$eb \rightarrow t\bar{\nu}$ where gluon splitting piece is subtracted. The cross section for the subprocess $eg \rightarrow t\bar{b}\bar{\nu}$ is still to be added to σ_{ex} for the combined cross section. QCD scale, Q^2 , dependence of these cross sections is presented in Table II in the region $m_w/2 < Q < 2m_t$ for SM values of the couplings at $\sqrt{s} = 1.6$ TeV. It is seen that as Q increases σ_{eb} increases while σ_{eg} decreases. Then, the combined cross section σ is slightly changed by the variation of Q^2 .

Table III and Table IV show the influence of the the anomalous couplings F_{2L}, F_{2R} on the integrated total cross sections and subtraction at TESLA+HERAp and CLIC+LHC energies for $Q^2 = m_w^2$ and $m_t = 175$ GeV. Parton distribution functions of Martin, Robert and Stirling (MRS A) [18] have been used and total cross section for second process $eg \rightarrow t\bar{b}\bar{\nu}$ has been calculated using CompHEP package [19]. As seen from tables subtracted terms are not negligible and the combined cross sections are slightly larger than the cross section of the first process σ_{eb} by a factor 1.1 for TESLA+HERAp and by a factor 1.2 for CLIC+LHC. From here on, we will consider only the first process because of its simplicity to investigate potential sensitivity of ep collision to anomalous Wtb vertex. Integrated total cross section as a function of center of mass energy $\sqrt{s}$ of ep system is shown in Fig. 1 for SM and $F_{2L} = -0.2$. From Tables III, IV and Fig. 1, it is clear that total cross sections in ep collision are much larger than the case of γe mode [6] of e^+e^- collider and Tevatron [8]. Furthermore, cross sections from CLIC+LHC are a few times larger than those of LHC [8] as expected. Fig. 2 shows the cross sections as functions of the anomalous couplings F_{2L} and F_{2R} for TESLA+HERAp and CLIC+LHC energies. A common feature of each figure is that deviation from the SM increases with increasing energy and cross sections grow as deviation gets large.

The influence of the deviation of anomalous couplings from the SM on the shape of the angular and p_T distribution of top quark is also important. Integrated differential cross sections as functions of the angle between top quark and incoming proton direction in the center of mass frame of $t\bar{\nu}$ are plotted in Fig. 3.

In order to get p_T distribution of top quark we use following standard procedure:

$$\frac{d\sigma}{dp_T} = 2p_T \int_{y_-}^{y_+} \frac{dy}{|s - 2E_p m_T e^y|} f_{q/p}(x, Q^2) \hat{s} \frac{d\hat{\sigma}}{d\hat{t}} \quad (10)$$

where y is the rapidity of the top quark whose lower and upper limits and momentum fraction x of the struck quark in the proton are given by

$$y^\mp = \ln \left[\frac{s + m_t^2}{4E_p m_T} \mp \left\{ \left(\frac{s + m_t^2}{4E_p m_T} \right)^2 - \frac{E_e}{E_p} \right\}^{1/2} \right] \quad (11)$$

$$x = \frac{2E_e m_T e^{-y} - m_t^2}{s - 2E_p m_T e^y}. \quad (12)$$

Here E_p and E_e are proton and electron beam energies and $\hat{s}$, $\hat{t}$ and m_T are defined as follows

$$\hat{s} = xs, \quad \hat{t} = m_t^2 - 2xE_p m_T e^y, \quad m_T^2 = m_t^2 + p_T^2. \quad (13)$$

The behaviour of p_T spectrum of top quark is shown in Fig. 4 for two different energy region and for some anomalous couplings. Clearly, angular and p_T distributions of top quark lead to deviations from the SM expectation.

III. SENSITIVITY TO ANOMALOUS COUPLINGS

We use simple χ^2 criterion from angular distributions of top quark to estimate sensitivity of ep collision to anomalous Wtb couplings

$$\chi^2 = \sum_{i=bins} \left(\frac{X_i - Y_i}{\Delta_i^{exp}} \right)^2 \quad (14)$$

$$X_i = \int_{z_i}^{z_{i+1}} \frac{d\sigma^{SM}}{dz} dz, \quad Y_i = \int_{z_i}^{z_{i+1}} \frac{d\sigma^{NEW}}{dz} dz \quad (15)$$

$$\Delta_i^{exp} = X_i \sqrt{\delta_{stat}^2 + \delta_{sys}^2}, \quad z = \cos \theta. \quad (16)$$

We have divided the range of $\cos \theta$ into 6 pieces for TESLA+HERAp and 10 pieces for CLIC+LHC and have considered at least 20 events in each bin. The expected number of events in the i -th bin which is used in statistical error has been calculated considering the leptonic channel of W boson as the signal $N_i = \epsilon L_{int} \sigma_i BR(W \rightarrow \ell + \nu)$ where ϵ is the overall efficiency and L_{int} is the integrated luminosity. The limits on the anomalous couplings F_{2L} and F_{2R} are provided in Table V at TESLA+HERAp and Table VI at CLIC+LHC energies for the deviation from the SM values at 95% confidence level. Only one of the couplings is assumed to deviate from the SM at a time. With integrated luminosities in Table V the potential sensitivities of TESLA+HERAp to both F_{2L} and F_{2R} are about $O(10^{-2})$ ($O(10^{-1})$ with 10% systematic) in the case of higher energy option $\sqrt{s} = 1.6$ TeV which improve the results obtained at Tevatron [8]. For possible CLIC+LHC energies from Table VI, sensitivities to F_{2L} and F_{2R} are about $O(10^{-2})$ ($O(10^{-1})$ with 10% systematic). For $\sqrt{s} = 6.5$ TeV region, CLIC+LHC will have higher potential to probe F_{2L} and F_{2R} than LHC [8]. In order to compare ep colliders with γe mode of linear e^+e^- collider [6], hadronic channels should be included with more reduced uncertainties.

Systematic uncertainties from V_{tb} , m_t , parton distribution functions, QCD scales, luminosity measurement are also important for accurate results. However, at this stage it is difficult to give a realistic estimate of systematics. Therefore, combined systematic errors of 0.05 and 0.10 are taken into account and $\epsilon = 0.5$ overall efficiency is assumed. For more precise results, further analysis needs to be supplemented by observables such as the distributions of the top decay products i.e., $ep \rightarrow \ell + b + \bar{\nu} + \nu_\ell + X$ with a more detailed knowledge of the experimental performances.

TABLE I. Main parameters of ep colliders where linear electron beams are allowed to collide protons from the ring for two different design values of linear electron beam energies. Luminosity values reflects the orders only.

Colliders	$\sqrt{s_{ep}}(\text{TeV})$	$L_{ep}(cm^{-2}s^{-1})$
CLIC+LHC	5	10^{32}
CLIC+LHC	6.5	10^{32}
TESLA+HERAp	1	10^{31}
TESLA+HERAp	1.6	10^{31}

TABLE II. Q^2 dependence of the cross sections σ_{eb} from the subprocesses $eb \rightarrow t\bar{\nu}$, σ_{eg} from $eg \rightarrow t\bar{b}\bar{\nu}$ and combined cross section σ where on-shell b-quark contribution was subtracted. Standard Model values of the couplings are considered only and cross sections are computed for $\sqrt{s} = 1.6$ TeV.

Q	σ_{eb}	σ_{eg}	σ
$2m_t$	3.78	1.88	3.28
m_t	3.55	2.13	3.38
m_w	3.20	2.53	3.59
$m_w/2$	2.79	3.00	3.88

TABLE III. Integrated total cross sections of the process $ep \rightarrow t\bar{\nu} + X$ in pb for $\sqrt{s} = 1.6$ TeV, TESLA+HERAp collider and for $Q = m_w$. Cross sections σ_{eb} and σ_{eg} are contributions from the subprocesses $eb \rightarrow t\bar{\nu}$ and $eg \rightarrow t\bar{b}\bar{\nu}$. σ is combined cross section where on-shell b-quark contribution was subtracted from $eb \rightarrow t\bar{\nu}$ before combination to avoid double counting.

F_{2L}	F_{2R}	σ_{eb}	σ_{eg}	σ
0	0	3.20	2.53	3.52
-0.1	0	3.33	2.60	3.63
0.1	0	3.13	2.51	3.48
0	0.1	3.28	2.61	3.63
0	0.2	3.51	2.88	3.97
-0.1	0.1	3.41	2.70	3.76

TABLE IV. The same as Table II but for $\sqrt{s} = 5$ TeV, CLIC+LHC energy.

F_{2L}	F_{2R}	σ_{eb}	σ_{eg}	σ
0	0	29.0	25.6	33.6
-0.1	0	30.2	26.1	34.4
0.1	0	28.7	25.6	33.5
0	0.1	29.7	26.2	34.4
0	0.2	32.1	29.6	38.5
-0.1	0.1	30.9	27.2	35.8

TABLE V. Sensitivity of TESLA+HERAp collider to anomalous Wtb couplings at 95% C.L. Only one of the couplings is assumed to deviate from the SM at a time.

$\sqrt{s_{ep}}(\text{TeV})$.	$\int Ldt(fb^{-1})$	δ^{sys}	F_{2L}	F_{2R}
1	20	0	-0.075, 0.558	-0.100, 0.100
1	20	0.05	-0.084, 0.603	-0.105, 0.105
1	20	0.10	-0.099, 0.636	-0.112, 0.112
1.6	20	0	-0.040, 0.051	-0.072, 0.072
1.6	20	0.05	-0.051, 0.069	-0.079, 0.079
1.6	20	0.10	-0.066, 0.465	-0.088, 0.088

TABLE VI. Sensitivity of CLIC+LHC collider to anomalous Wtb couplings at 95% C.L. Only one of the couplings is assumed to deviate from the SM at a time.

$\sqrt{s_{ep}}(\text{TeV})$.	$\int Ldt(fb^{-1})$	δ^{sys}	F_{2L}	F_{2R}
5	20	0	-0.015, 0.016	-0.038, 0.038
5	20	0.05	-0.024, 0.029	-0.044, 0.044
5	20	0.10	-0.035, 0.303	-0.051, 0.051
6.5	50	0	-0.007, 0.008	-0.026, 0.026
6.5	50	0.05	-0.015, 0.017	-0.034, 0.034
6.5	50	0.10	-0.024, 0.290	-0.041, 0.041

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- [1] S. Ambrosanio, B. Mele, Z. Phys. **C63**, 63 (1994).
 - [2] N.V. Dokholian, G.V. Jikia, Phys. Lett. **B336**, 251 (1994).
 - [3] K. Hagiwara, M. Tanaka and T. Stelzer, Phys. Lett. **B325**, 521 (1994); E. Boos *et al.*, Phys. Lett. **B336**, 190 (1994).
 - [4] E. Boos *et al.*, Z. Phys. **C70**, 255 (1996).
 - [5] A. Bienarchik, K. Cieckiewicz and K. Kolodziej, hep-ph/012253.
 - [6] E. Boos, A. Pukhov, M. Sachwitz, and H.J. Schreiber, Phys. Lett. **B404**, 119 (1997).
 - [7] D. Dicus and S. Willenbrock, Phys. Rev. **D34**, 155 (1986); C.-P. Yuan, Phys. Rev. **D41**, 42 (1990); G.V. Jikia and S.R. Slabospitsky, Phys. Lett. **B295**, 136 (1992); R.K. Ellis and S. Parke, Phys. Rev. **D46**, 3785 (1992); G. Bordes and B. van Eijk, Z. Phys. **C57**, 81 (1993); D.O. Carlson and C.-P. Yuan, Phys. Lett. **B306**, 386 (1993); G. Bordes and B. van Eijk, Nucl. Phys. **B435**, 23 (1995); S. Cortese and R. Petronzio, Phys. Lett. **B253**, 494 (1991); D.O. Carlson, E. Malkawi and C.-P. Yuan, Phys. Lett. **B337**, 145 (1994); T. Stelzer and S. Willenbrock, Phys. Lett. **B357**, 125 (1995); R. Pittau, Phys. Lett. **B386**, 397 (1996); M.C. Smith and S. Willenbrock, Phys. Rev. **D54**, 6696 (1996); D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, Phys. Rev. **D54**, 5412 (1996); C.S. Li, R. J. Oakes and J.M. Yang, Phys. Rev. **D55**, 5780 (1997); G. Mahlon and S. Parke, Phys. Rev. **D55**, 7249 (1997); A.P. Heinson, A.S. Belyaev, and E.E. Boos, Phys. Rev. **D56**, 3114 (1997); T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. **D56**, 5919 (1997); D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, Phys. Rev. **D57**, 2957 (1998); T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. **D58**, 094021 (1998); A.S. Belyaev, E.E. Boos and L.V. Dudko, Phys. Rev. **D59**, 075001 (1999);
 - [8] E. Boos, L. Dudko and T. Ohl, Eur. Phys. J **C11**, 473 (1999).
 - [9] H. Abramowicz *et al.*, THERA, A contribution to the TESLA Technical Design Report, TESLA TDR, Appendices, Chapter 2, DESY-01-011FB, (2001).
 - [10] W. Buchmuller and D. Wyler, Nucl. Phys. **B268**, 621 (1986); K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Rev. **D48**, 2182 (1993).
 - [11] G.J. Gounaris, F.M. Renard, and C. Verzegnassi, Phys. Rev. **D52**, 451 (1995); G.J. Gounaris, F.M. Renard, and N.D. Vlachos, Nucl. Phys. **B459**, 51 (1996).
 - [12] K. Whisnant, J. Yang, B. Young and X. Zhang, Phys. Rev. **D56**, 467 (1997); J.M Yang and B. Young, Phys. Rev. **D56**, 5907 (1997).
 - [13] G. Kane, G. Ladinsky and C.-P. Yuan, Phys. Rev. **D45**, 124 (1992).
 - [14] M.S. Alam *et al.*, CLEO, Phys. Rev. Lett. **74**, 2885 (1995); F. Larios, M.A. Perez and C.-P. Yuan Phys. Lett **B457**, 334 (1999).
 - [15] D.E. Groom, *et al.*, The European Physical Journal **C15**, 1 (2000).
 - [16] R.D. Peccei and X. Zhang, Nucl. Phys. **B337**, 269 (1990); R.D. Peccei, S. Peris and X. Zhang, Nucl. Phys. **B349**, 305 (1991).
 - [17] M. Aivazis, J.C. Collins, F. Olness and Wu-Ki Tung, Phys. Rev. **D50**, 3102 (1994); R.M. Barnett, H.E. Haber and D.E. Soper, Nucl. Phys. **B306**, 697 (1988); F.I. Olness and W.-K. Tung, Nucl. Phys. **B308**, 813 (1988).
 - [18] A.D. Martin, W.J. Stirling and R.G. Roberts Phys. Rev. **D51**, 4756 (1995).
 - [19] E. Boos, M. Dubinin, V. Ilyin, A. Pukhov, V. Savrin, INP MSU 94-36/358, 1994 (hep-ph/9503280); P. Baikov *et al.*, in: Proc. of X Workshop on High Energy Physics and Quantum Field Theory, ed. by B. Levtchenko, V. Savrin, Moscow, 1996, p.101 (hep-ph/9701412); A. Pukhov *et al.*, hep-ph/9908288; <http://theory.npi.msu.su/comphep>.

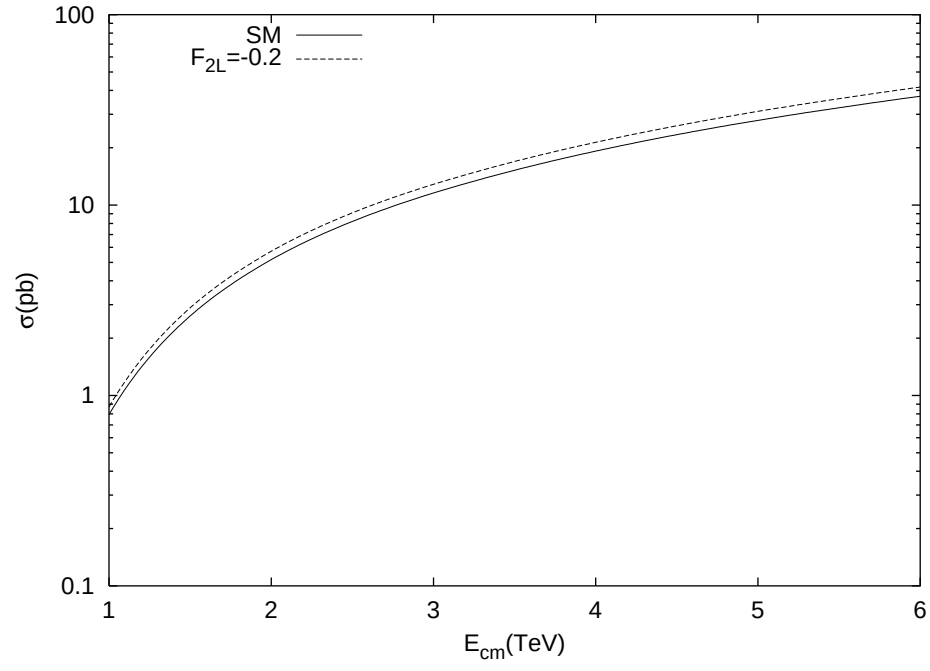


FIG. 1. Energy dependence of the total cross section for the single top quark production in the process $ep \rightarrow t\bar{\nu} + X$.

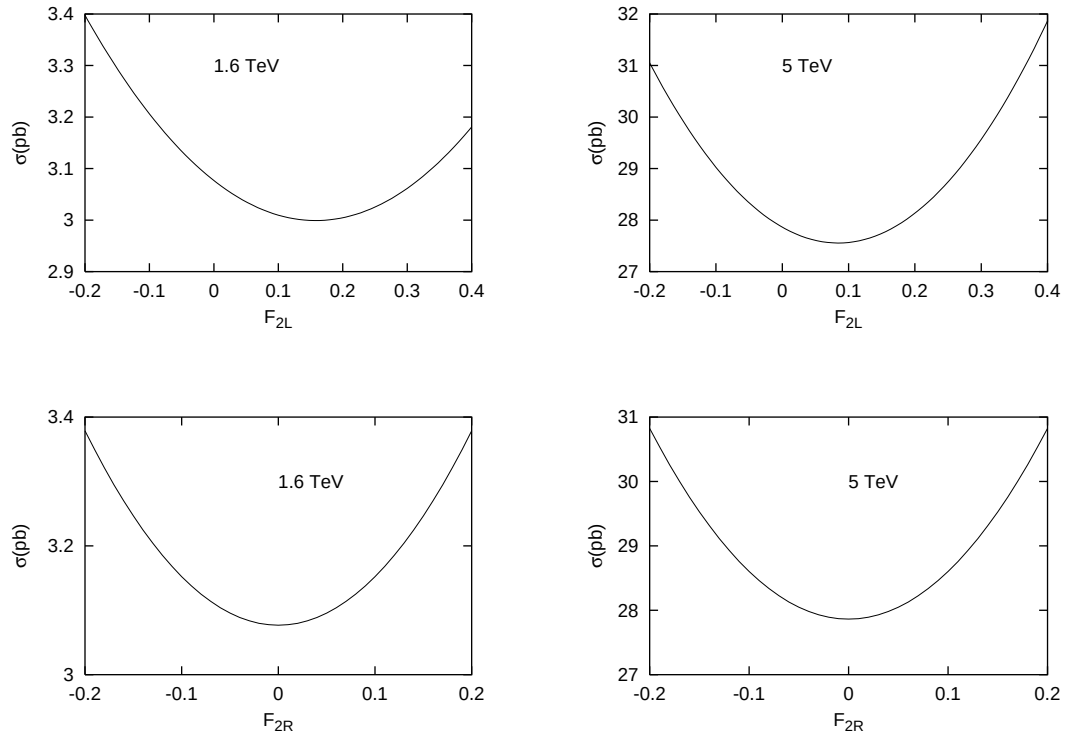


FIG. 2. Integrated total cross sections as functions of anomalous couplings at possible TESLA+HERAp (1.6 TeV) and CLIC+LHC (5 TeV) energies.

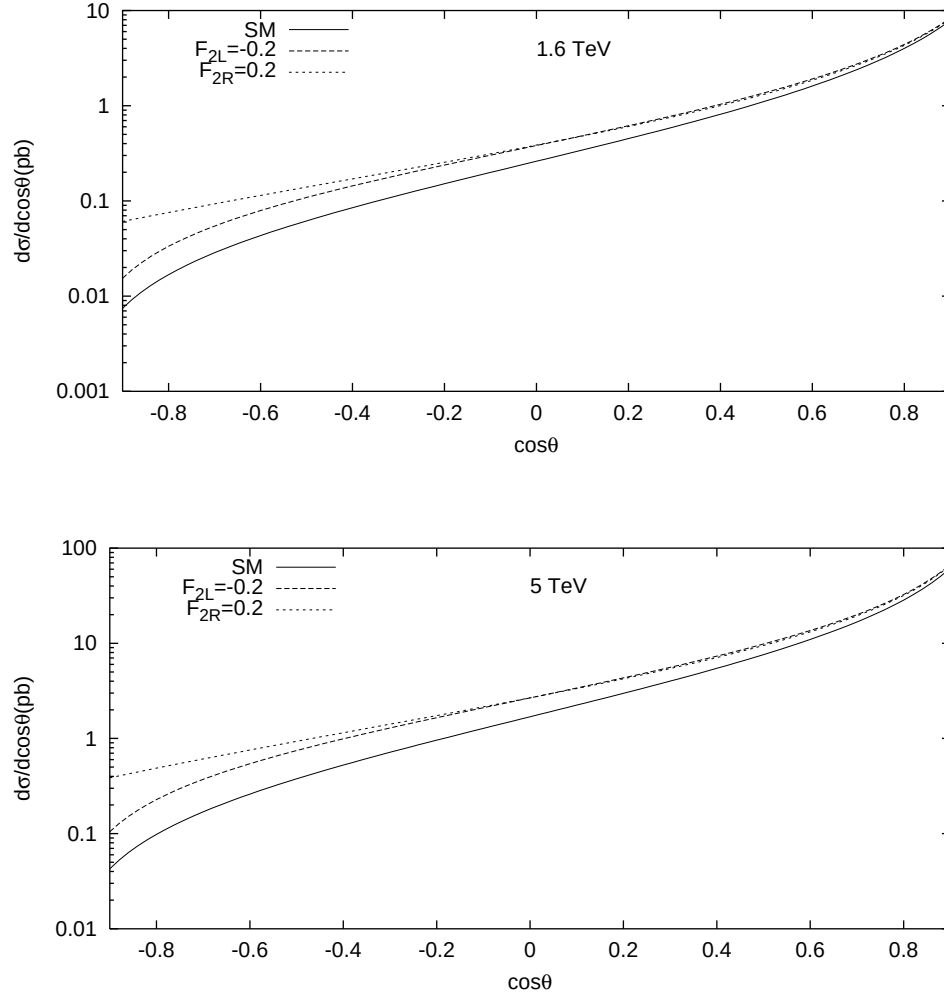


FIG. 3. Angular distributions of the top quark at TESLA+HERAp and CLIC+LHC energies in the center of mass frame of $t\bar{\nu}$.

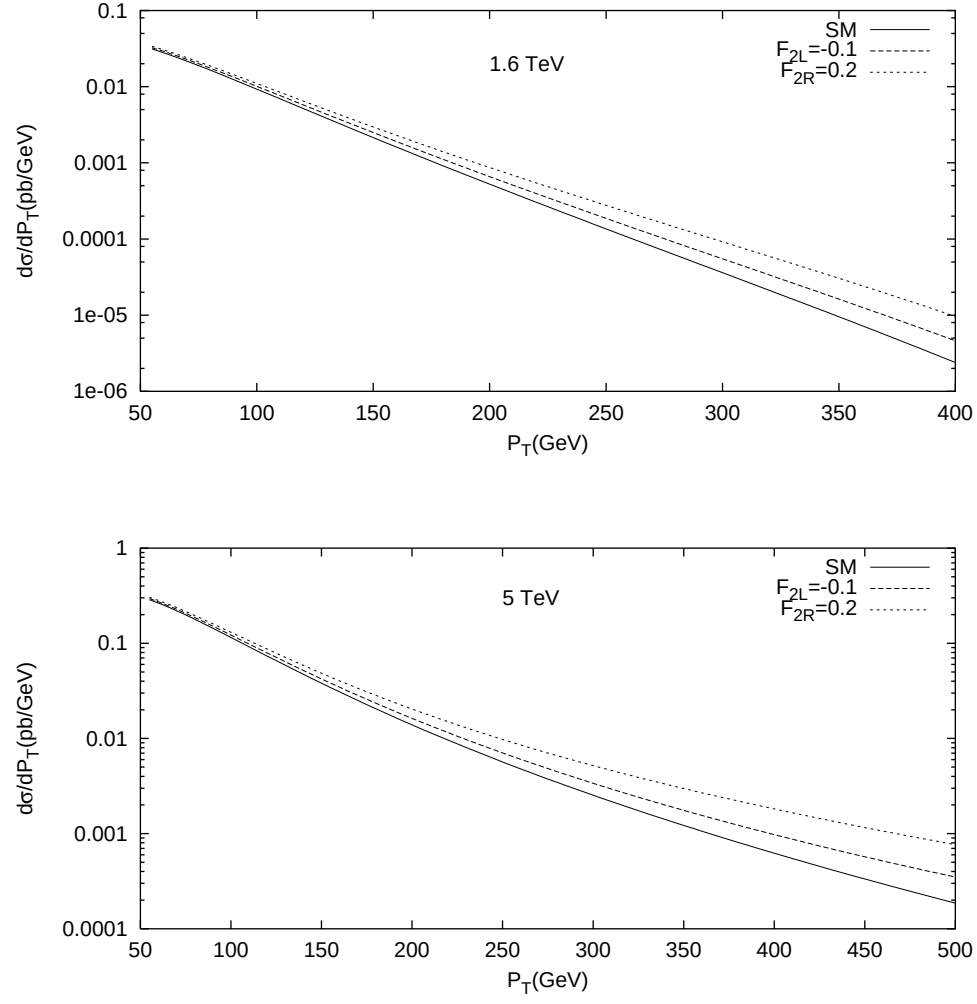


FIG. 4. p_T distributions of the top quark at TESLA+HERAp and CLIC+LHC energies.