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 \( ep \to t\bar{v} + X \) 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 \( e^+e^- \to Wtb \) has been discussed below and above \( tt \) threshold [1,2] and for the process \( e^+e^- \to e\bar{v}tb \) at CERN \( e^+e^- \) collider LEP2 [3] and linear \( e^+e^- \) collider(LC) [4,5] energies. Investigations for \( Wtb \) vertex have been done at \( \gamma e \) mode of LC [6], Fermilab \( pp \) 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

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

where

\[ W_{\mu\nu} \equiv g_{\mu\nu} W_{\mu
u} \]

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\[ W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu, \quad D_\mu = \partial_\mu - ieA_\mu \]
\[ P_\perp = \frac{1}{2} (1 \mp \gamma_5), \quad \sigma^{\mu\nu} = \frac{i}{2} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu) \]

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 \( b \to s\gamma \) 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 \([17]\). The magnetic type anomalous couplings are related to the coefficients \( C_{1W\Phi} \) and \( C_{2W\Phi} \) \([12]\) in the general effective lagrangian by

\[ F_{2L} = \frac{C_{1W\Phi} \sqrt{2} v m_w}{\Lambda^2 g}, \quad F_{2R} = \frac{C_{2W\Phi} \sqrt{2} v m_w}{\Lambda^2 g} \]

where \( \Lambda \) is the scale of new physics. Natural values of the couplings \( F_{2L(R)} \) are in the region \([10]\) of

\[ \sqrt{m_b m_t} / v \sim 0.1 \]

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 \( eb \to t\bar{\nu} \) and W-gluon fusion process \( eg \to t\bar{b}\nu \). Differential cross section for the subprocess \( eb \to t\bar{\nu} \) in terms of Mandelstam invariants \( \hat{s} \) and \( \hat{t} \) has been obtained as given below

\[ \frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi \alpha^2}{4 \sin^4 \theta_W \hat{s}^2 m_w^2 (\hat{t} - m_w^2)^2} \times \]
\[ [F_{2L}^2 (- (\hat{s} - m_t^2)^2 + \hat{t} (m_t^2 - \hat{s})) + 2 F_{2L} |V_{tb}| m_t m_w \hat{t} (\hat{s} + \hat{t} - m_t^2) - F_{2R}^2 \hat{t} (\hat{s} + \hat{t}) + |V_{tb}| m_w^2 (\hat{s} + \hat{t} + (\hat{s} + \hat{t})^2)] \]

where \( m_t, m_w, V_{tb} \) and \( \theta_W \) are top quark mass, W boson mass, CKM matrix element and Weinberg angle respectively.

If the second process \( eg \to t\bar{b}\nu \) is combined with \( eb \to t\bar{\nu} \) one should avoid double counting. The two subprocesses have a region of overlap when \( g \to bb \) 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 \( eb \to t\bar{\nu} \). In order to take care of this double counting we use the method proposed in ref. \([17]\). So, combined cross section becomes

\[ [\sigma(eb \to t\bar{\nu}) + \sigma(eg \to t\bar{b}\nu) - \sigma(g \to b\bar{b} + eb \to t\bar{\nu})] \]

where the subtracted term is the gluon splitting piece of the cross section for \( eg \to t\bar{b}\nu \) 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

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

where

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

with

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

Here, \( \alpha_s(Q^2) \) is the energy dependent QCD coupling whose expression is given in ref. \([15]\). \( \sigma_{ex} \) is the integrated total cross section over the parton distributions for the subprocess.
where gluon splitting piece is subtracted. The cross section for the subprocess $eg \rightarrow t\bar{t}ν$ is still to be added to $σ_{xx}$ for the combined cross section. QCD scale, $Q^2$, dependence of these cross sections is presented in Table III in the region $m_W/2 < Q < 2m_t$ for SM values of the couplings at $√s = 1.6$ TeV. It is seen that as $Q$ increases $σ_{eh}$ increases while $σ_{eg}$ decreases. Then, the combined cross section $σ$ is slightly changed by the variation of $Q^2$.

Table [I] 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) [13] have been used and total cross section for second process $eg \rightarrow t\bar{t}ν$ has been calculated using CompHEP package [14]. 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 $σ_{eh}$ 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 $√s$ of $ep$ system is shown in Fig. 1 for SM and $F_{2L} = −0.2$. From Tables [I] [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 $t\bar{t}ν$ are plotted in Fig. 3.

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

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

(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

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

$$y^- = \frac{2E_e m_T e^{-y} - m_t^2}{s - 2E_p m_T e^y}.$$  

(11)

(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

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

(13)

The behaviour of $p_T$ spectrum of top quark is shown in Fig. 3 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

$$χ^2 = \sum_{i=bin,s} \frac{(X_i - Y_i)^2}{\Delta X_{exp}}$$

(14)
\[ X_i = \int_{z_i}^{z_i+1} d\sigma^{SM} dz, \quad Y_i = \int_{z_i}^{z_i+1} d\sigma^{NEW} dz \]  

\[ \Delta_i^{exp} = X_i \sqrt{\delta_{stat}^2 + \delta_{sys}^2}, \quad z = \cos \theta. \]

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 \( N_i = \epsilon L_{int} \sigma_i \text{BR}(W \rightarrow \ell + \nu) \) where \( \epsilon \) 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 VI 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 \( \gamma e \) 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       | \( \sqrt{s_{ep}} \) (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 \( \sigma_{eb} \) from the subprocesses \( eb \rightarrow \bar{t} \bar{\nu} \), \( \sigma_{eg} \) from \( eg \rightarrow \bar{t} b \bar{\nu} \) and combined cross section \( \sigma \) 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.

| \( Q \)       | \( \sigma_{eb} \) | \( \sigma_{eg} \) | \( \sigma \) |
|---------------|-------------------|-------------------|---------|
| \( 2m_t \)    | 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 \( ep \to t\bar{v} + X \) in pb for \( \sqrt{s} = 1.6 \) TeV, TESLA+HERAp collider and for \( Q = m_w \). Cross sections \( \sigma_{eb} \) and \( \sigma_{eg} \) are contributions from the subprocesses \( eb \to t\bar{v} \) and \( eg \to t\bar{b}\bar{\nu} \). \( \sigma \) is combined cross section where on-shell b-quark contribution was subtracted from \( eb \to t\bar{v} \) before combination to avoid double counting.

| \( F_{2L} \) | \( F_{2R} \) | \( \sigma_{eb} \) | \( \sigma_{eg} \) | \( \sigma \) |
|---|---|---|---|---|
| 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 III but for \( \sqrt{s} = 5 \) TeV, CLIC+LHC energy.

| \( F_{2L} \) | \( F_{2R} \) | \( \sigma_{eb} \) | \( \sigma_{eg} \) | \( \sigma \) |
|---|---|---|---|---|
| 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.

| \( \sqrt{s}_{ep} \) (TeV) | \( \int L dt (fb^{-1}) \) | \( \delta^{95\%} \) | \( F_{2L} \) | \( F_{2R} \) |
|---|---|---|---|---|
| 1 | 20 | 0.05 | -0.075, 0.558 | -0.100, 0.100 |
| 1 | 20 | 0.10 | -0.084, 0.603 | -0.105, 0.105 |
| 1.6 | 20 | 0.05 | -0.099, 0.636 | -0.112, 0.112 |
| 1.6 | 20 | 0.10 | -0.072, 0.072 |
| 1.6 | 20 | 0.05 | -0.079, 0.079 |
| 1.6 | 20 | 0.10 | -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.

| \( \sqrt{s}_{ep} \) (TeV) | \( \int L dt (fb^{-1}) \) | \( \delta^{95\%} \) | \( F_{2L} \) | \( F_{2R} \) |
|---|---|---|---|---|
| 5 | 20 | 0.05 | -0.015, 0.016 | -0.038, 0.038 |
| 5 | 20 | 0.10 | -0.024, 0.029 | -0.044, 0.044 |
| 5 | 20 | 0.05 | -0.035, 0.303 | -0.051, 0.051 |
| 6.5 | 50 | 0.05 | -0.007, 0.008 | -0.026, 0.026 |
| 6.5 | 50 | 0.10 | -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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FIG. 1. Energy dependence of the total cross section for the single top quark production in the process $ep \rightarrow t\bar{t} + X$. 
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 $t\bar{t}$. 

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