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Probing Anomalous Wtb Coupling via Single Top Production at TeV Energy γe Colliders

E. Boos[1], A. Pukhov[1], M. Sachwitz[2] and H. J. Schreiber[2]

[1]Institute of Nuclear Physics, Moscow State University, 119899, Moscow, Russia
[2]DESY-Institut für Hochenergiephysik, Zeuthen, FRG

Abstract

Results of complete tree level calculations of the single top production reaction $\gamma e \longrightarrow \nu \bar{t} b$ at the Next Linear Collider, including the contribution of anomalous operators to the Wtb coupling are presented. The sensitivity for probing the structure of the Wtb coupling in a model independent way is analyzed and found to be significantly higher than for comparable measurements at the Tevatron.

The top quark, by far the heaviest established elementary particle, is not only a further manifestation of the Standard Model (SM)[1], it also poses new questions. One example is the spectacular numerical coincidence between the vacuum expectation value $v/\sqrt{2} = 175$ GeV and the t-quark mass, measured by the CDF and D0 collaborations [2] to be 175^{+6}_{-6} GeV, and extracted indirectly from fits of precision electroweak LEP data as 177^{+7+16}_{-7-19} GeV [3]. It is an open question whether or not this is due to fundamental physics relations or is only accidental. The heavy t-quark decays electro-weakly before hadronization [4] and therefore it could provide a first window to help understand the nature of the electroweak symmetry breaking [5]. In this context, reactions involving a light Higgs boson and t-quark production as intermediate states are extremely interesting. One example is the reaction $p\bar{p} \to W^{\pm} b\bar{b} + anything$, with the two subprocesses $p\bar{p} \to W^{\pm} H^0$ $(H^0 \to b\bar{b})$ and $p\bar{p} \to tb$ $(t \to Wb)$ [6], which - together with several other SM diagrams - contribute to the $Wb\bar{b}$ final state. Another example is the reaction $\gamma e \to \nu W b\bar{b}$ [7]. Here, three out of 24 SM diagrams involve associated Higgs boson production,

$$\gamma \quad e \longrightarrow \nu \quad W^- \quad H^0, \tag{1}$$

and four diagrams represent single top quark production,

$$\gamma \quad e \longrightarrow \nu \quad \bar{t} \quad b, \tag{2}$$

with subsequent decays of the Higgs boson $(H^0 \longrightarrow b\bar{b})$ and the t-quark $(t \longrightarrow Wb)$.

The associated Higgs production reaction (1) has a high sensitivity for probing anomalous WWH coupling structures [7], whereas the single top reaction (2) is a unique tool for measuring the $|V_{tb}|$ matrix element with very high precision [7, 8, 9].

In this study, we consider one of the most obvious and easily imagined scenarios in which the t-quark coupling to the W boson and the b-quark is altered with respect to the SM expectations. In order to probe such an anomalous Wtb coupling in a model independent way, we use the effective Lagrangian approach

[10] with notations in the unitary gauge as given in ref. [11]. The Lagrangian $\mathcal{L}$ contains only necessary vertices for the process (2):

$$\begin{aligned}\mathcal{L} \ = \tfrac{g}{\sqrt{2}}\Big[\ & W_\nu^- \bar{b}(\gamma_\mu F_1^L P_- + F_1^R P_+)t \\ & - \frac{1}{2M_W} W_{\mu\nu}\bar{b}\sigma^{\mu\nu}(F_2^L P_- + F_2^R P_+)t\Big] + \text{h.c.}\end{aligned} \qquad (3)$$

with $W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu, D_\mu = \partial_\mu - ieA_\mu, P_\pm = 1/2(1 \pm \gamma_5)$ and $\sigma^{\mu\nu} = i/2(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$. The similarity of the $\sigma^{\mu\nu}$-connected operators with the QED anomalous magnetic moments prompts the name 'magnetic type' for the operators and their associated vertices. Within the Standard Model, $F_1^L = |V_{tb}|$ and $F_1^R = F_2^{L,R} = 0$. Terms containing $\partial_\mu W^\mu$ are omitted in the Lagrangian. They can be recovered by applying the quantum equation of motion through operators of the original Lagrangian [10]. We assume CP conservation with $F_i^{L,R} = F_i^{*L,R}$.

The corresponding Feynman rules, obtained from the effective Lagrangian $\mathcal{L}$ (eq. 3), are listed in the Appendix. These rules for the new vertices have been implemented in the program package CompHEP 3.2 [12]. Effects of the anomalous couplings are simulated by varying the $F_i^{L,R}$ parameters from their SM values. Input parameters used in the calculations were either taken from the Particle Data Group report [13] or are as listed below: m_t = 170 GeV, m_b = 4.3 GeV, α_{EW} =1/128, $|V_{tb}|$ = 0.9984, M_Z = 91.187 GeV, $\sin^2\Theta_W$ = 0.23, $M_W = M_Z \cdot \cos\Theta_W$, Γ_Z=2.50 GeV and Γ_W=2.09 GeV.

The SM tree-level diagrams contributing to the reaction $\gamma e \longrightarrow \nu\bar{t}b$ are shown in Fig. 1. The t-channel singularities, occurring in the variables $t_{\gamma b}$ and $t_{\gamma\nu}$, have to be handled with care. In order to select the proper kinematic scheme for

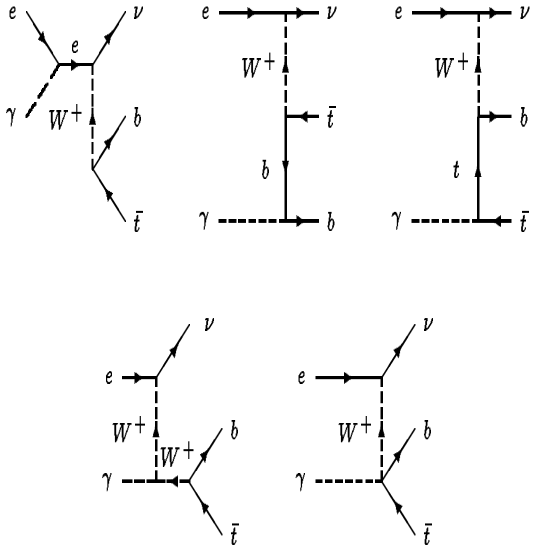

Figure 1: Feynman diagrams for the reaction $\gamma e \longrightarrow \nu\bar{t}b$.

the process considered and to smooth the singular variables we applied special options offered by CompHEP [14] (for more details see ref. [7]). We ensure $\mathcal{U}(1)$ gauge invariance for the process $\gamma e \longrightarrow \nu \bar{t} b$ by adding the last diagram of Fig. 1 to the SM Feynman diagrams. This non-SM diagram with the four-point $\gamma W t b$ vertex is extracted from the Lagrangian (3) and contains the sole contribution from the magnetic type of operators.

The true photon beam spectrum produced by laser light backscattered from the incoming high energy electron beam is unknown, so we use, as a numerical illustration, the model-dependent photon spectrum as suggested in ref. [15]. The convolution of the cross section for reaction (2) with this photon spectrum leaves the basic physical properties of the reaction unaffected but lowers the effective cross sections by a factor of 2-3 [7].

Fig.2 shows the variation of the single top cross section as function of the anomalous couplings F_1^R , F_2^L , F_2^R , at four cm energies $\sqrt{s_{e^+e^-}} = 0.5$, 1.0, 1.5 and 2.0 TeV. Each of the figures 2a-c reflects a possible deviation of the different anomalous couplings around zero with the other F-parameters fixed to the SM-values. A common feature is an increasing sensitivity with growing energies and an enhancement of the cross section when the couplings deviate from the SM value. As expected from the operators' additional power of momentum (see Appendix) the $F_2^{L,R}$ couplings represent a much higher sensitivity to variations from the SM than the F_1^R .

With annual luminosities for the Next Linear Collider as anticipated in ref. [16] and an event detection efficiency of 30% for reaction (2) we calculate limits of the variation of F_1^R , F_2^L and F_2^R within two standard deviation of the SM cross section. As can be seen from Table 1 the limits of the anomalous couplings obtained are in the interesting region [5] of

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

and do not exceed the unitary violation bounds [17] in the one TeV scale of

$$F_2^{R,L} \sim 0.8 \quad \text{and} \quad F_1^R \sim 0.6. \qquad (5)$$

For comparison, recent studies of single top production rates including anomalous couplings at the Tevatron indicate the bounds -0.5 $\lesssim F_1^R \lesssim$ 0.5 [18, 19], -0.1 $\lesssim F_2^L \lesssim$ 0.2 and -0.2 $\lesssim F_2^R \lesssim$ 0.2 [20] which are comparable with our results expected at NLC energies of 0.5 TeV. At energies above 0.5 TeV we obtain significantly higher sensitivities (see Table 1).

The existence of anomalous couplings should also affect the production properties of the final state particles of reaction (2). As an example, Fig.3a-c show the differential cross sections $\mathrm{d}\sigma/\mathrm{dcos}\Theta_{\gamma b}$, $\mathrm{d}\sigma/\mathrm{d}p_\perp^t$ and $\mathrm{d}\sigma/\mathrm{d}p_\perp^b$ expected for $F_2^L =$

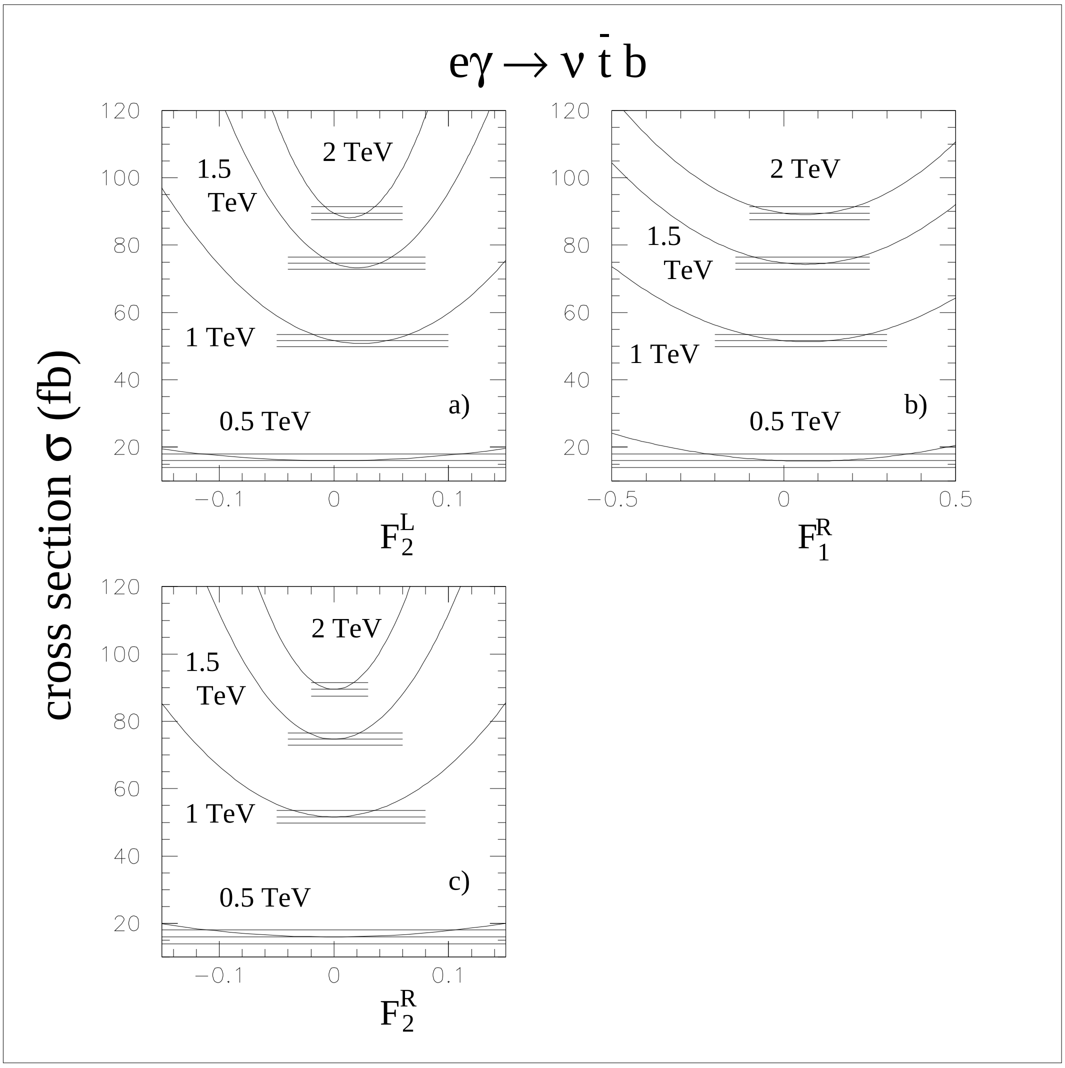

Figure 2: Cross sections of the reaction $\gamma e \longrightarrow \nu\bar{t}b$ as functions of the anomalous couplings F_2^L, F_1^R and F_2^R at $\sqrt{s_{e^+e^-}} = 0.5$, 1.0, 1.5 and 2.0 TeV. The horizontal lines show the SM values with the two standard deviation errors expected.

Table 1: Limits for the anomalous couplings $F_i^{L,R}$ obtained from the two standard devitation critera as described in the text for annual luminosities as indicated.

$\sqrt{s_{e^+e^-}}$, TeV	0.5	1.0	1.5	2.0
$\mathcal{L}$, fb^{-1}	50	200	300	500
δF_2^L	-.1/.1	-.020/.065	-.01/.05	-.008/.035
δF_2^R	-.1/.1	-.035/.035	-.022/.022	-.016/.016
δF_1^R	-.20/.35	-.12/.25	-.09/.22	-.08/.20

-0.1, F_2^R= F_1^R= 0 and F_1^L= SM value (open areas), compared with the SM predictions (hatched areas)[1]. In particular, the SM angular distribution $\mathrm{d}\sigma/\mathrm{d}\cos\Theta_{\gamma b}$

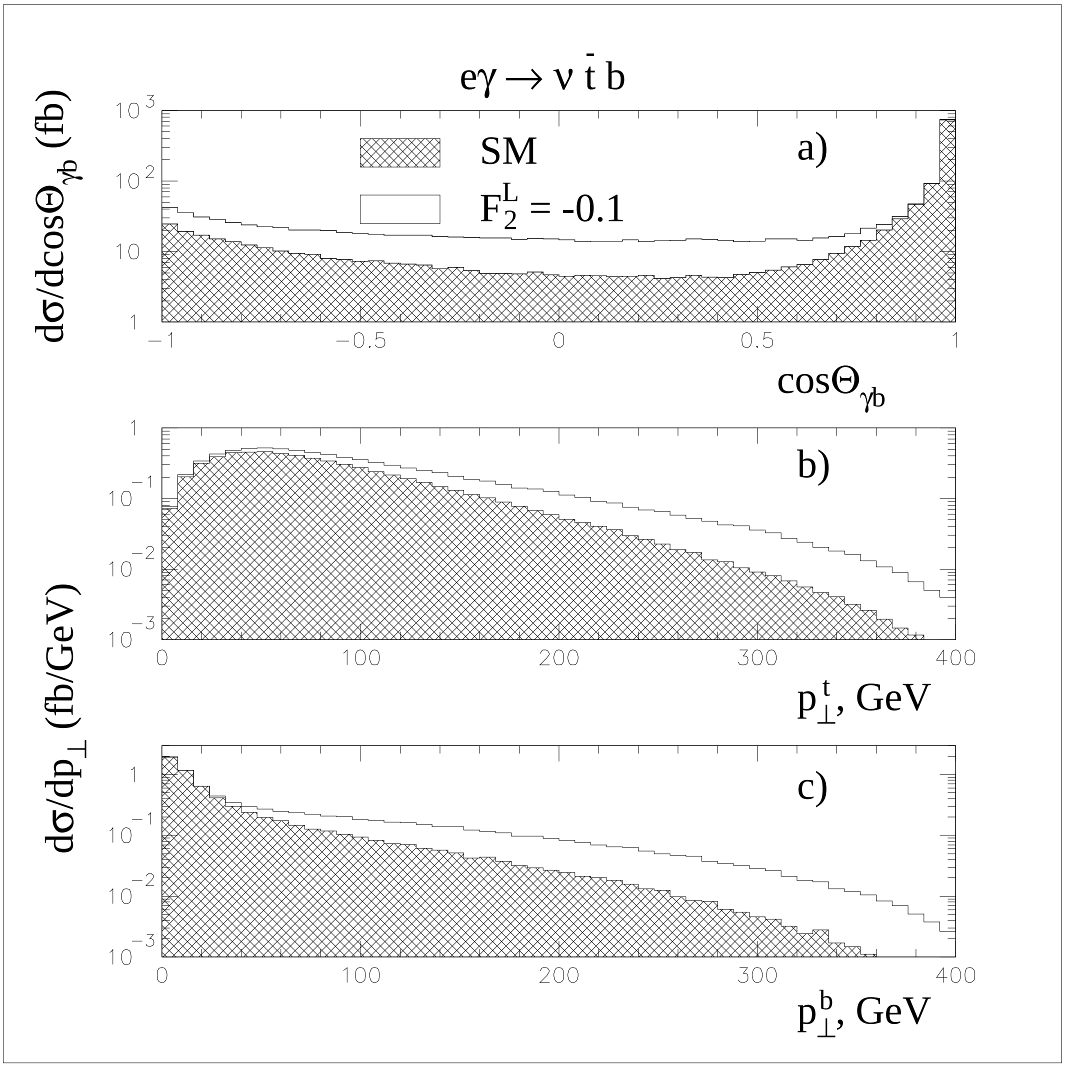

Figure 3: Cross sections of reaction $\gamma e \longrightarrow \nu\bar{t}b$ as function of cos$\Theta_{\gamma b}$, $p_\perp^t$ and $p_\perp^b$ at 1.0 TeV. Compared are the SM predictions (hatched areas) with expectations from an anomalous coupling F_2^L = -0.1.

in Fig. 3a has a broad minimum around $\cos\Theta_{\gamma b} \sim 0$ - 0.5. This behavior is due to the existence of the so called radiation zero of the 2-to-2 body process $q\,\bar{q} \longrightarrow W\gamma$ [21] and its time-reversed reaction $\gamma W \to \bar{t}b$ as the most important subreaction for our consideration. In our case, the incident γ spectrum and the off-shell character of the W-boson in addition to the contribution of the first diagram of Fig. 1 washed out this zero to a broad minimum. For anomalous coupling contributions the minimum becomes significantly higher.

In the Lagrangian (3), the (V+A) operator which is proportional to the F_1^R coupling has only an overall numerical factor and leads to a simple shift

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[1] The angle $\Theta_{\gamma b}$ is defined as the angle of the b-quark with respect to the incident photon direction in the e^+e^- rest frame.

of the $p_\perp$ distributions. On the other hand, the new anomalous magnetic type vertices (last diagram in Fig.1) contain an additional power of momentum (see Appendix) and therefore the transverse momentum distributions of the $t-$ and b-quark deviate from the SM expectations. As a consequence, such different behavior allows one to separate contributions of the (V+A) operator from the magnetic type ones. Fig. 3b and c show an excess at high $p_\perp$ for both, the $p^b_\perp$ and the $p^t_\perp$ distributions. Clearly, cuts in the tranverse momenta and angular distributions should lead to significantly more stringent constraints in $F_i^{R,L}$. For illustration purpose, we require $p^b_\perp > 40$ GeV, $p^t_\perp > 80$ GeV and $\Theta_{\gamma b} > 10^0$ for the cross section calculation at 1 TeV. Fig. 4 shows the cross section in dependence of the coupling parameter F_2^L while fixing the remaining F parameters to their SM values. The bounds are improved to -0.012 $< F_2^L <$ 0.058 which should be compared with -0.020 $< F_2^L <$ 0.065 (see Tab. 1).

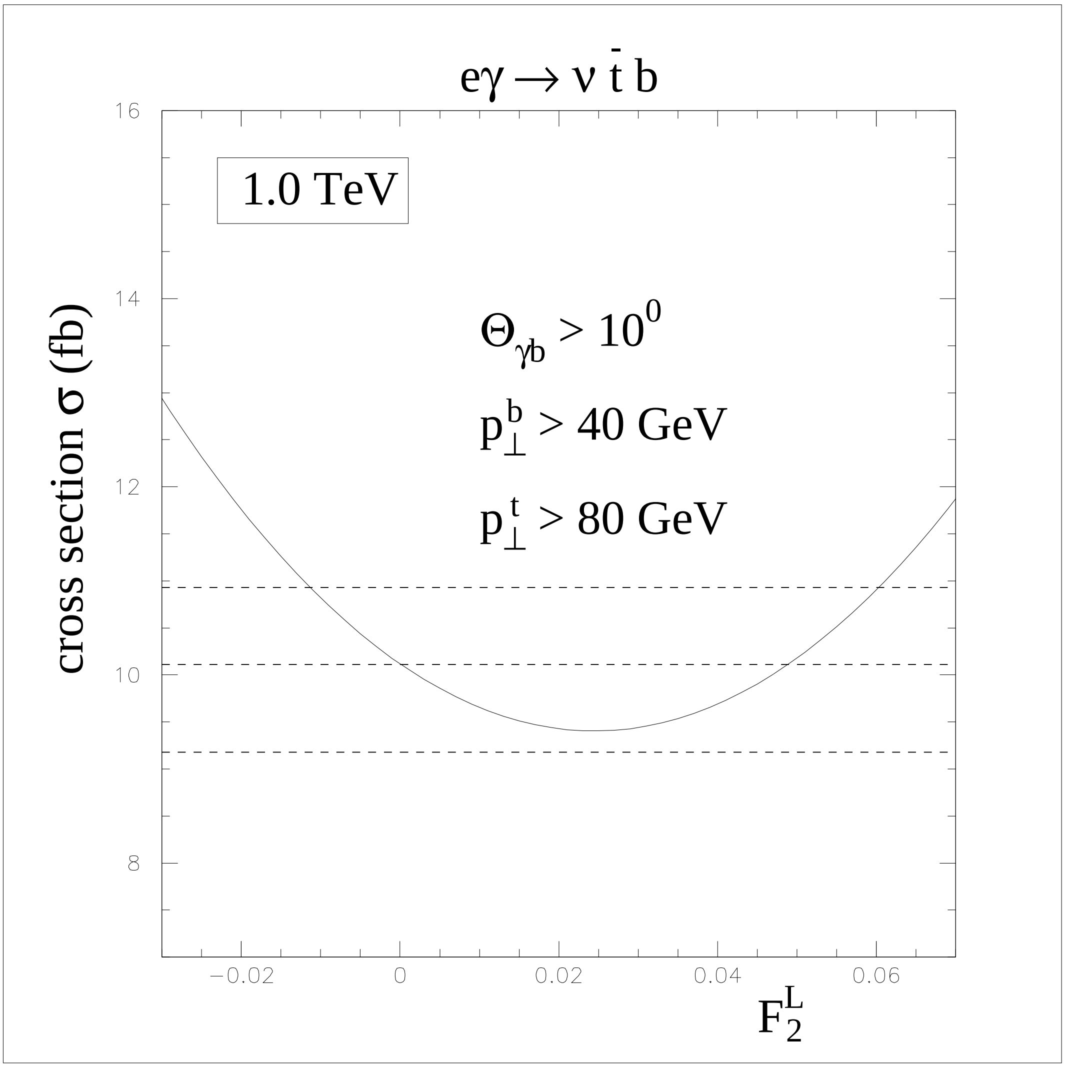

Figure 4: Cross section of reaction $\gamma e \longrightarrow \nu \bar{t} b$ at 1.0 TeV in dependence of the anomalous coupling parameter F_2^L with angular and $p_\perp$ cuts as indicated. The dashed lines show the SM expectation with the two standard deviation error.

A further possibility for studying anomalous couplings could be the measurement of the t-quark partial decay width [17] described by the same effective Lagrangian $\mathcal{L}$. Here, the partial decay width is extracted from the single top production rate [18] and therefore the measurement is not independent from the procedure given above.

A tt-pair production measurement would only deliver the branching ratios of the t-quark into W-boson and b-quark comparing the single and double b-tagging rates [22]. Calculations show that the branching ratio is very insensitive to variations of the F-parameters. Even for extreme values of the parameter in the range of ± 1 the branching fraction varies from 99.7% to 99.9%. Since the precision of the determination of the branching ratio is of the order of 10%, a deviation from the SM value of 99.8% due to the influence of anomalous couplings will not be visible.

Appendix

The Feynman rules for the vertices obtained from the Lagrangian (3) and implemented into the CompHEP package are as follows:

$$\Gamma_{\mu}^{\bar{t}bW^{+}}(p,q,k) = -\frac{e}{2\sqrt{2}s_W}\left[F_1^L\gamma_\mu(1-\gamma_5) + F_1^R\gamma_\mu(1+\gamma_5)\right.$$
$$\left. -\frac{F_2^L}{2M_W}(\hat{k}\gamma_\mu - \gamma_\mu\hat{k})(1-\gamma_5) - \frac{F_2^R}{2M_W}(\hat{k}\gamma_\mu - \gamma_\mu\hat{k})(1+\gamma_5)\right]$$

$$\Gamma_{\mu\nu}^{\bar{t}bW^{+}\gamma}(p,q,k,r) = \frac{e^2}{4\sqrt{2}s_W M_W}[F_2^L(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)(1-\gamma_5)$$
$$+F_2^R(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)(1+\gamma_5)]$$

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