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ANOMALOUS Wtb VERTEX IN TOP QUARK PRODUCTION IN e^+e^- COLLIDERS* **

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The potential of high energy e^+e^- collisions to detect an anomalous Wtb coupling is discussed. The anomalous Wtb coupling is implemented in the calculation of cross sections of four fermion reactions containing a single on-mass-shell top quark and numerical results for $e^+e^- \to t\bar{b}\mu^-\bar{\nu}_\mu$ are presented.

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1. Introduction

The Standard Model (SM) of strong and electroweak interactions has been phenomenologically very successful. However, it does not seem to be an ultimate fundamental theory, because of, *e.g.*, too many arbitrary parameters, or missing explanation for the observed number of families. Therefore, it is commonly believed that the SM will have to be extended if experiments in future e^+e^- colliders bring evidence for new physical phenomena beyond its scope.

As the most massive particle ever observed, top quark is believed to be more sensitive to the effects of new physics than other particles. Therefore, in the past decade growing interest concerning many aspects of the top quark physics could be observed. New interactions with a scale Λ larger than the Fermi scale $G_{\rm F}^{-1/2}$ will manifest themselves at energies below Λ through small

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deviations from the SM. Any discrepancies between theoretical predictions based on the SM and experimental measurements can be a possible signal of the new physical phenomena beyond the SM.

Investigations of the top quark properties at a TeV energy scale can provide us with important indications towards better understanding of the actual mechanism of electroweak symmetry breaking in nature. The properties of the top quark are determined by its couplings to the gauge boson fields and to the Higgs sector. Therefore, the top quark couplings should be measured as precisely as possible and compared with the SM predictions. In the following, we will discuss effects related to existence of an anomalous Wtb interaction. To this end, we consider processes:

$$e^+e^- \to t\bar{b}f\bar{f}' \,, \tag{1}$$

where $f = e^-, \mu^-, \tau^-, d, s$ and $f' = \nu_e, \nu_\mu, \nu_\tau, u, c$, respectively, taking into account the complete set of the Feynman graphs which contribute to the specific final state at the tree level in the framework of the SM extended by a linear effective Lagrangian containing the anomalous Wtb vertex.

In Section 2, we discuss the effective Lagrangian which leads to the anomalous Wtb vertex used in the calculations. Then, in Section 3, we present results for total cross sections of (1) and discuss the sensitivity of future linear colliders to 'magnetic' form factors which are used to parameterize the anomalous Wtb coupling. We finish with presenting conclusions and outlook in Section 4.

2. The effective Wtb Lagrangian

Low energy effects of new physical phenomena which may arise at the energy scale Λ, where Λ is typically of the order of a few TeV, are usually described in terms of effective Lagrangians with heavy fields integrated out. At low energies of the order m_W, the effective Lagrangian can be expanded in terms of $(1/\Lambda)$ as:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0 + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{1}{\Lambda^2}\mathcal{L}_2 + \ldots \,, \tag{2}$$

where $\mathcal{L}_0$ is the SM Lagrangian and $\mathcal{L}_1$, $\mathcal{L}_2, \ldots$ are terms of dimension 5, 6, and higher. Eq. (2) is quite general and does not depend on specific properties of new interactions at the scale Λ. If the $\mathrm{SU(3)}_c \times \mathrm{SU(2)_L} \times \mathrm{U(1)}_Y$ invariance is imposed it is not possible to construct the term $\mathcal{L}_1$ of dimension 5 in Eq (2) consisting of fermion and/or gauge boson fields [1]. An interested reader is referred to [2] for a complete list of the $\mathrm{SU(3)}_c \times \mathrm{SU(2)_L} \times \mathrm{U(1)}_Y$ conserving dimension six terms $\mathcal{L}_2$ of Eq. (2).

Departures of the Wtb interaction from the SM Wtb coupling, caused by the new fundamental interactions at the scale Λ, are often described in terms of the low energy effective Lagrangian containing terms of dimension 6 [3,4]

$$L = \frac{g}{\sqrt{2}} \Big[W_\mu^- \bar{b} \gamma^\mu \left(f_{1\mathrm{L}} P_\mathrm{L} + f_{1\mathrm{R}} P_\mathrm{R}\right) t - \frac{1}{m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_{2\mathrm{L}} P_\mathrm{L} + f_{2\mathrm{R}} P_\mathrm{R}\right) t \Big] + \mathrm{h.c.} \tag{3}$$

In Eq. (3), $P_{\mathrm{L,R}}$ are chirality projectors given by

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

the anomalous couplings $f_{1\mathrm{L}}, f_{1\mathrm{R}}, f_{2\mathrm{L}}$ and $f_{2\mathrm{R}}$ are assumed to be real, and W_μ^- should be regarded as an effective vector field. The SM Wtb coupling is reproduced if we assume $f_{1\mathrm{R}} = f_{2\mathrm{L}} = f_{2\mathrm{R}} = 0$ and identify $f_{1\mathrm{L}}$ with the real Cabibbo–Kobayashi–Maskawa (CKM) matrix element V_{tb}. According to the present experimental data, V_{tb} is very close to 1 [5] and $f_{1\mathrm{R}}$ is strongly constrained by the CLEO $b \to s\gamma$ data which give $f_{1R} \approx 0$ [6]. The couplings $f_{2\mathrm{L}}$ and $f_{2\mathrm{R}}$ are at present only weakly constrained, see *e.g.* [2].

Typical values of couplings $|f_{2\mathrm{L(R)}}|$ are of the order of $\sqrt{m_b m_t}/v \sim 0.1$ [4]. Unitarity limit from $t\bar{t}$ scattering at the TeV energy scale gives the constraint $f_{2\mathrm{L(R)}} \leq 0.65$. Expected limits on $|f_{2\mathrm{L(R)}}|$ from upgraded Tevatron are of order 0.2. Therefore, in Section 3, we will analyze effects of the nonzero anomalous couplings $f_{2\mathrm{L}}$ and $f_{2\mathrm{R}}$ on the cross sections of reaction (1) taking into account those weak constraints.

3. Numerical results

In this section, we illustrate possible effects caused by the anomalous Wtb interaction of Eq. (3) in reactions (1). To this end we present numerical results for the total cross sections of $e^+e^- \to t\bar{b}\mu^-\bar{\nu}_\mu$ for several different values of the anomalous couplings $f_{2\mathrm{L(R)}}$.

We have implemented the anomalous Wtb vertex resulting from (3) into the calculation of total cross sections of (1), which were obtained and discussed in the framework of SM in our previous work [7]. The helicity amplitude method introduced in [8] and [9] for calculating matrix elements and the multichannel Monte Carlo for the space integration have been used. The specific values of physical parameters used in the calculation are the same as in [7] except for the top quark width which is now replaced with the two body top quark decay width $\Gamma_t\,(t \to W^-b)$ calculated to the lowest order with the effective Lagrangian (3).

Results for total cross sections of $e^+e^- \to t\bar{b}\mu^-\bar{\nu}_\mu$ at a few centre of mass energies typical for linear colliders and different values of the anomalous couplings $f_{2\mathrm{L}}$ and $f_{2\mathrm{R}}$ are shown in Table I. The large numerical change in the tree level matrix elements caused by the anomalous Wtb coupling of Eq. (3) is almost completely compensated by the corresponding change in the top quark width. The latter is introduced through the substitution

$$M_t = m_t - i\frac{\Gamma_t}{2} \tag{4}$$

in the top quark propagator. Substitution (4) is used in order to avoid the on-mass-shell pole in the propagator of the unstable top quark in the lowest order. This corresponds to resumation of some higher order corrections. Although, for fermions, substitution (4) is not theoretically justified in the framework of quantum field theory, at present it is the only known way to treat production and decay of an unstable fermion. The change in Γ_t directly affects the cross section, because the total cross section of reaction (1) is almost exactly proportional to $\sim 1/\Gamma_t$ in the energy range from the $t\bar{t}$-pair production threshold up to 2 TeV, as it has been shown in [7].

TABLE I

Cross sections σ in fb of $e^+e^- \to t\bar{b}\mu^-\bar{\nu}_\mu$

$f_{2\mathrm{L}}$	$f_{2\mathrm{R}}$	340 GeV	360 GeV	500 GeV	800 GeV	2000 GeV
0.2	−0.2	0.646(1)	40.90(4)	58.92(8)	28.62(3)	5.541(6)
0.2	0.2	1.032(1)	39.58(4)	58.67(9)	28.71(4)	5.601(6)
0.0	0.2	0.806(1)	40.31(4)	58.76(8)	28.62(3)	5.544(6)
0.2	0.0	1.011(1)	39.66(4)	58.66(9)	28.68(4)	5.561(7)
0.0	0.0	0.783(1)	40.39(4)	58.78(8)	28.59(3)	5.505(6)
−0.2	0.0	0.620(1)	41.00(5)	58.93(9)	28.59(3)	5.501(6)
0.0	−0.2	0.823(1)	40.28(4)	58.78(8)	28.63(3)	5.547(6)
−0.2	−0.2	0.658(1)	40.86(4)	58.92(8)	28.62(3)	5.545(6)
−0.2	0.2	1.052(1)	39.55(4)	58.68(9)	28.72(4)	5.604(6)

Effects of the anomalous couplings shown in Table I are typically of the order of $\mathcal{O}(1\%)$ for energies above the $t\bar{t}$ threshold. The effects are relatively bigger below the threshold, however, the cross section is much smaller there and detection of possible anomalous effects will be certainly obscured by background contributions, see *e.g.* [10, 11]. We do not present numerical result for other channels, as the relative size of the anomalous effects is practically independent of the light fermion masses in reactions (1).

4. Conclusions and outlook

We have analyzed the top quark production in e^+e^- annihilation at linear colliders in the presence of the anomalous Wtb interaction given in terms of the effective Lagrangian (3). Numerical effects of the considered values of the 'magnetic' couplings, $|f_{2\mathrm{L(R)}}| \sim 0.2$, are not big, typically of the order of $\mathcal{O}(1\%)$. Whether such small effects will be detectable or not depends obviously on luminosity of the future collider.

The anomalous Wtb coupling has been implemented in a program package `ee4f`γ which has been developed for calculating any process $e^+e^- \to 4f, 4f\gamma$ with nonzero fermion masses [12].

It would be desirable to implement the anomalous Wtb vertex together with other anomalous couplings of the top quark into the more realistic framework of the top quark pair production and decay into 6 fermions [10], which will be done in the near future. A more refined analyses of the anomalous effects, which would take into account a possible numerical conspiracy between the effects caused by $f_{2\mathrm{L}}$ and $f_{2\mathrm{R}}$, is also planned.

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