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TOP QUARK PAIR PRODUCTION  
AT A LINEAR COLLIDER IN THE PRESENCE  
OF AN ANOMALOUS  $Wtb$  COUPLING\* \*\*

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Angular distributions of a  $\mu^+$  and a  $b$ -quark resulting from the decay of a top quark produced at the  $e^+e^-$  linear collider with unpolarized and 100% longitudinally polarized electron beam are presented. The results of the standard model are compared with the results obtained in the presence of the anomalous  $Wtb$  coupling.

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## 1. Introduction

Future high luminosity  $e^+e^-$  linear collider with its very clean experimental environment will be the most suitable tool for searching for the effects of physics beyond the standard model (SM). In particular, such effects may manifest themselves in deviations of the top quark properties and interactions from those predicted by SM. Therefore, experimental studies of the top quark pair production belong to the research program of any future linear collider [1]. Due to its large decay width, the top quark decays even before it hadronizes. As the dominant top decay mode is

$$t \rightarrow bW^+, \tag{1}$$

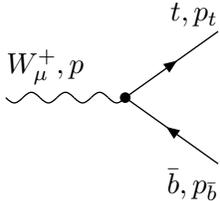
it is interesting to look at extensions of the pure left-handed  $Wtb$  coupling that governs reaction (1) in the lowest order of SM.

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Such extensions of SM can be best parametrized in terms of the effective lagrangian that has been written down in Eq. (3) of [2]. The corresponding modification of the SM Feynman rule for the  $Wtb$ -vertex is the following



$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}}V_{tb} \left[ \gamma^\mu (f_1^- P_- + f_1^+ P_+) - \frac{i\sigma^{\mu\nu} p_\nu}{m_W} (f_2^- P_- + f_2^+ P_+) \right]. \quad (2)$$

In Eq. (2),  $V_{tb}$  is the element of the Cabibbo–Kobayashi–Maskawa matrix,  $P_\pm = (1 \pm \gamma_5)/2$  are chirality projectors,  $p$  is the four momentum of the incoming  $W^+$  and  $f_i^\pm$ ,  $i = 1, 2$ , are the  $Wtb$  vertex form factors. The SM vertex is reproduced with  $f_1^- = 1$  and  $f_1^+ = f_2^- = f_2^+ = 0$ .

As the experimental value of  $|V_{tb}|$  is 0.9990–0.9993 [3] and deviation of the  $(V + A)$  coupling  $f_1^+$  from zero is severely constrained by the CLEO data on  $b \rightarrow s\gamma$  [4], in the following we set  $V_{tb} = 1$ ,  $f_1^- = 1$  and  $f_1^+ = 0$  and consider modifications of the  $Wtb$  vertex by nonzero values of the other two anomalous form factors  $f_2^+$  and  $f_2^-$  which are often referred to as the magnetic type anomalous couplings. Typical values of the couplings  $f_2^\pm$  discussed in this talk are [6]

$$|f_2^\pm| \sim \frac{\sqrt{m_b m_t}}{v} \sim 0.1. \quad (3)$$

They contradict neither the unitarity limit obtained from the  $t\bar{t}$  scattering at the TeV energy scale that gives the constraint  $|f_2^\pm| \leq 0.6$  [7], nor the limits that are expected from the upgraded Tevatron, which are of order 0.2.

In practice, the measurement of the form factors of Eq. (2) through decay (1) does not take place in the rest frame of the top quark. At the linear collider, the top quark pair is produced in the process

$$e^+e^- \rightarrow t\bar{t} \quad (4)$$

and, as  $t$  and  $\bar{t}$  almost immediately decay into 3 fermions each, what one actually observes are reactions of the form

$$e^+e^- \rightarrow 6f, \quad (5)$$

where  $6f$  denotes a 6 fermion final state that is possible in SM. Reactions (5) receive contributions typically from several hundred Feynman diagrams, whereas there are only two  $\gamma$  and  $Z$  exchange signal diagrams in the annihilation channel that contribute to (4). Fortunately, the signal diagrams

dominate the cross section over a wide range of the centre of mass system (CMS) energies, see [8]. This justifies the simplified approach used in this talk, in which only the two signal diagrams that contribute to (5) are kept and all other, non-doubly resonant diagrams, are neglected. In the next section, we present our numerical results for one specific semileptonic channel of (5)

$$e^+e^- \rightarrow t^*\bar{t}^* \rightarrow b\nu_\mu\mu^+\bar{b}\bar{u} \quad (6)$$

in the double resonance approximation for the  $t$  and  $\bar{t}$ . In particular, we address the issue of determining the spin of the top-quark produced in reaction (6) by measuring the angular distribution of the  $\mu^+$  resulting from its decay, the method first proposed in [9].

## 2. Numerical results

In this section, we present numerical results on the angular distributions of the  $b$ -quark and  $\mu^+$  of reaction (6) at  $\sqrt{s} = 360$  GeV and  $\sqrt{s} = 500$  GeV, typical for a future linear collider.

The matrix elements corresponding to Eq. (2) have been programmed with the helicity amplitude method of [10] and [11] and then implemented into `eett6f`, a Monte Carlo program for top quark pair production and decay into 6 fermions at linear colliders [12]. The calculation has been performed in the fixed width scheme with the top quark mass  $m_t = 174.3$  GeV and the 3 body top quark decay width calculated to lowest order of the perturbation series, taking into account the modified  $Wtb$  coupling given by Eq. (2) and assuming  $\mathcal{CP}$  conservation. Other physical parameters used in the calculation have been taken from [3].

In Fig. 1, we plot the angular distributions of a  $\mu^+$  at  $\sqrt{s} = 360$  GeV (left) and  $\sqrt{s} = 500$  GeV (right). The plots show the differential cross section  $d\sigma/d\cos\theta_\mu$  for the unpolarized and for 100% longitudinally polarized left-handed and right-handed electron beam. The slant of the histograms representing unpolarized cross section both at  $\sqrt{s} = 360$  GeV and  $\sqrt{s} = 500$  GeV is caused solely by the Lorentz boost of the corresponding flat angular distribution of the  $\mu^+$  resulting from the decay of unpolarized top quark at rest. The slants of the histograms representing polarized cross sections at  $\sqrt{s} = 360$  GeV, on the other hand, reflect proportionality of the angular distribution of  $\mu^+$  to  $(1 + \cos\theta)$ , if the spin of the decaying top-quark points in the positive direction of the  $z$  axis (spin up), and to  $(1 - \cos\theta)$ , if the spin of the decaying top-quark points in the negative direction of the  $z$  axis (spin down), see [13] for illustration. With 100% left-handedly (right-handedly) polarized electron beam that goes in the direction of negative  $z$ -axis, the top quark is produced preferably with the spin up (down). The corresponding

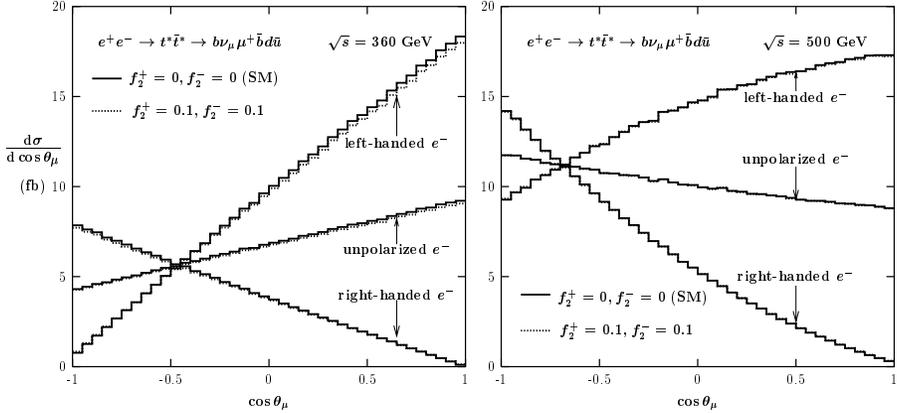


Fig. 1. Angular distributions of a  $\mu^+$  at  $\sqrt{s} = 360$  GeV (left) and  $\sqrt{s} = 500$  GeV (right).

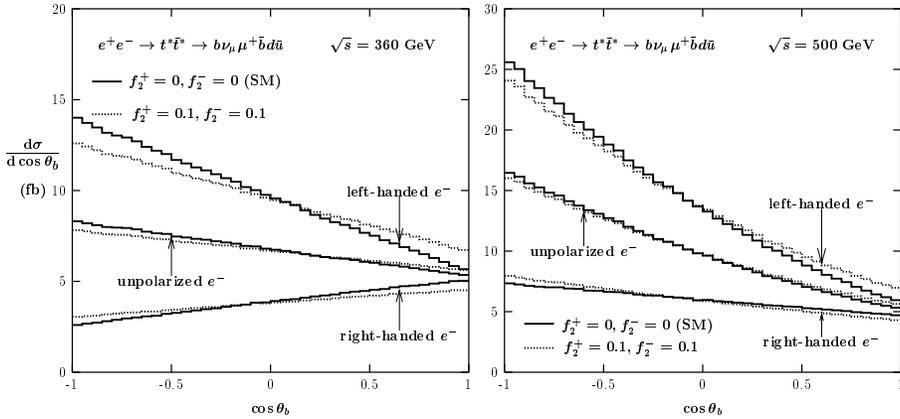


Fig. 2. Angular distributions of a  $b$ -quark at  $\sqrt{s} = 360$  GeV (left) and  $\sqrt{s} = 500$  GeV (right).

$(1 \pm \cos\theta)$  behaviour of the  $\mu^+$  angular distribution is somewhat changed by the Lorentz boost, in particular at  $\sqrt{s} = 500$  GeV. The dotted histograms in Fig. 1 represent the angular distributions of  $\mu^+$  in the presence of anomalous  $Wtb$  coupling (2) with  $f_1^\pm$  set to their SM values,  $f_1^+ = 0$ ,  $f_1^- = 1$ , and  $f_2^+ = f_2^- = 0.1$ . Except for a rather small effect in case of the left-handed electron beam at  $\sqrt{s} = 360$  GeV, the change in the  $\mu^+$  angular distributions is hardly visible. This nicely confirms the decoupling theorem discussed in [14].

The angular distributions of a  $b$ -quark at  $\sqrt{s} = 360$  GeV and  $\sqrt{s} = 500$  GeV are plotted in Fig. 2. Again the dotted histograms represent the angular distributions of a  $b$ -quark in the presence of anomalous  $Wtb$  coupling (2) with  $f_1^\pm$  set to their SM values,  $f_1^+ = 0$ ,  $f_1^- = 1$ , and  $f_2^+ = f_2^- = 0.1$ . The numerical effect of the anomalous coupling is bigger than in Fig. 1. It is visible in particular for the longitudinally polarized electron beams.

### 3. Summary

We have computed angular distributions of a  $\mu^+$  and a  $b$ -quark resulting from the decay of a top quark produced in reaction (6) at a linear collider. The results have been obtained with the unpolarized and 100% longitudinally polarized electron beam. Analysis of the  $\mu^+$  distributions obtained with the longitudinally polarized beam shows that they are a very sensitive probe of the top quark polarization, as expected. We have also illustrated how the anomalous  $Wtb$  coupling modifies the  $b$ -quark angular distributions while it practically does not affect the angular distributions of  $\mu^+$ .

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