Secondary particles spectra in the decay of a polarized top quark with anomalous $tWb$ couplings

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Abstract

Analytic expression for energy and angular dependence of a secondary charged lepton in the decay of a polarized top quark with anomalous $tWb$ couplings in the presence of all anomalous couplings are derived. The angular distribution of the $b$-quark is derived as well. It is presented that the charged lepton spin correlation coefficient is not very sensitive to the anomalous couplings. However, the $b$-quark spin correlation coefficient is sensitive to anomalous couplings and could be used as a powerful tool for searching of non-SM coupling.

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1 Introduction

Studying top quark is particularly interesting for several practical reasons. Indeed due to its large mass the electroweak gauge symmetry is broken maximally by top quark and it may be the first place in which the non-SM effects could be appeared. Such a large mass leads to a very short life time for the top quark ($\tau_{\text{top}} \sim 4 \times 10^{-25} \, \text{s}$). This number is roughly one order of magnitude smaller than the typical QCD hadronization time scale ($3 \times 10^{-24} \, \text{s}$). The top quark therefore decay before it can hadronize unlike the other quarks. As a result, the spin information of the top quark is transferred to its decay products. In the case of having an appropriate choice of spin quantization axis the top quark spin can be utilized as a strong tool for investigation of new physics in the top quark interactions. But the rate of “polarized” top quark production at LHC and Tevatron is very small. For this reason, the existing correlations between top spin and anti-top spin in the $t\bar{t}$ production and the correlation between top spin and the direction of the light quark momentum in the single top t-channel production (which is the largest source of single top at the LHC) can be used to reconstruct the spin information of the top quark [1]. There have been some studies in probing of the anomalous $tWb$ couplings in the past, for example in [2],[3],[4]. The effect of anomalous $tWb$ couplings on angular distribution of secondary particles has been studied in [8],[9],[10]. However, in those studies all quadratic contributions of the anomalous couplings have been neglected and the narrow width approximation for the W-boson has been used.

In this paper, the effects of the anomalous $tWb$ couplings on the spectra of a secondary charged lepton and b-quark in the decay of a polarized top quark are shown by obtaining the analytic expression. The dependency of the top width on the anomalous couplings is presented too. In particular, the dependency of spin correlation coefficients (which are observables in top events at hadron colliders) on the anomalous couplings for the charged lepton and b-quark are derived. This calculation has been performed in the presence of the all anomalous couplings ($f_{R1}, f_{L2}, f_{R2}$) and quadratic contributions of anomalous couplings are kept. Regarding to the bounds obtained in [2] and [4] the quadratic terms seem to be really important. For instance, the 95\% C.L. estimated bounds on a ratio of anomalous couplings using $t\bar{t}$ events are [4]:

\[-0.93 < \frac{f_{R2}}{f_{L1}} < 0.57 \, \text{ (for 100 reconstructed events at Tevatron)}\]

\[-0.81 < \frac{f_{R2}}{f_{L1}} < -0.70 \, , \, \, -0.12 < \frac{f_{R2}}{f_{L1}} < 0.14 \, \text{ (for 1K reconstructed events at Tevatron)}\]

\[-0.74 < \frac{f_{R2}}{f_{L1}} < -0.72 \, , \, \, -0.01 < \frac{f_{R2}}{f_{L1}} < 0.01 \, \text{ (for 100K reconstructed events at the LHC)}\]
In obtaining these constraints the detector effects have been simulated taking into account the geometry and energy resolutions of CDF and ATLAS detectors for the Tevatron and the LHC, respectively. The above bounds are still optimistic values because only the statistical uncertainties have been taken into account and the systematic uncertainties neglected.

The 95% C.L. estimated bounds on the anomalous couplings using single top events with taking into account 10% of systematic uncertainties are [2]:

\[-0.24 < f_{R2} < 0.25, \quad -0.18 < f_{L2} < 0.55 \quad \text{Tevatron}\]
\[-0.17 < f_{R2} < 0.18, \quad -0.094 < f_{L2} < 0.34 \quad \text{LHC}\]

From measurements of the FCNC processes of rare B decays, \(b \to s\gamma\), the CP-violation is severely constrained [5], which means that the anomalous couplings can be taken as real values. The “right-handed” top quark coupling is strongly constrained [6]. However, it is kept in the calculations in this paper to have the most general expression and show its effect.

This paper is organized as follows: In section 2 the effective Lagrangian of \(tWb\) anomalous couplings is introduced. Section 3 is dedicated to present some results of two-body and three-body decay of the top quark with anomalous Lagrangian introduced in section 2 and finally section 4 concludes the paper.

## 2 The effective \(tWb\) Lagrangian

The Lagrangian of new physical phenomena which may occur at the energy scale of \(\Lambda\) can be expanded in terms of \((1/\Lambda)\) as:

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_{i} C_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right),
\]

where \(\mathcal{L}_{SM}\) is the SM Lagrangian and \(O_i\) are the SM-gauge-invariant dimension-six operators. \(C_i\) represent the coupling strengths of \(O_i\) [7][11]. Keeping the \(CP\) conserving terms in dimension six in the unitary gauge leads to the following Lagrangian [11]:

\[
L = \frac{g}{\sqrt{2}} [W_\mu \bar{b} \gamma^\mu (f_{L1} P_L + f_{R1} P_R) t - \frac{1}{2 M_W} W_{\mu \nu} \bar{b} \sigma^{\mu \nu} (f_{L2} P_L + f_{R2} P_R) t] + \text{h.c.},
\]

where \(W_{\mu \nu} = D_\mu W_\nu - D_\nu W_\mu, \quad D_\mu = \partial_\mu - ieA_\mu, \quad P_{R,L} = \frac{1 \pm \gamma_5}{2}\) and \(\sigma^{\mu \nu} = \frac{i}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)\).

The corresponding feynman rule is:
\[
\Gamma^\mu = -\frac{g}{\sqrt{2}} [\gamma^\mu (f_{L1} P_L + f_{R1} P_R) - i \sigma^{\mu \nu} (p_t - p_b)_{\nu} (f_{L2} P_L + f_{R2} P_R) / M_W ],
\]

where \( p_t \) is the four momentum of the incoming \( t \) quark and \( p_b \) is the four momentum of the outgoing \( b \)-quark. The couplings \( (f_{L1}, f_{R1}, f_{L2}, f_{R2}) \) are the vertex form factors. In order to keep the \( CP \) conservation, which is assumed in the rest of the work, we have the following relations among the form factors:

\[
f_{L1}^* = f_{L1}, \quad f_{R1}^* = f_{R1}, \quad f_{R2}^* = f_{R2}, \quad f_{L2}^* = f_{L2},
\]

In the SM case, the coupling \( f_{L1} \) is equal to one and the others are equal to zero. The natural values of couplings \( f_{L2}, f_{R2} \) are in the order of \( \sqrt{m_b m_t} / v \sim 0.1 \) [11].

### 3 Polarized top decay

In the frame of SM the dominant decay chain of the top quark is:

\[
t \to W^+ + b \to \begin{cases} l^+ \nu_l + b \\ u \bar{d} \end{cases}
\]

Because of the V-A structure of the weak interaction the decay products of the polarized top have a special angular correlation. In the top rest frame, the decay angular distribution of the top products can be written as:

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d(\cos \theta_i^t)} = \frac{1}{2} (1 + \alpha_i \cos \theta_i^t),
\]

where \( \theta_i^t \) is the angle between the spin quantization axis of the top and the direction of the momentum of the \( i \)-th top products and \( \alpha_i \) is called correlation coefficient or asymmetry. This correlation coefficient shows the degree of the correlation of each decay products to the spin of the parent top quark. In the frame of SM, it has been shown that [12]:

\[
\begin{align*}
\alpha_l &= 1.0, \quad \alpha_{\nu_l} \simeq -0.324, \\
\alpha_b &= -\frac{r^2 - 2}{r^2 + 2} \simeq -0.408, \\
\alpha_u &= -0.324, \quad \alpha_d = 1.0,
\end{align*}
\]

where \( r = \frac{m_t}{m_W} \). It is clear that the charged lepton is maximally correlated with its parent spin.
3.1 Two-body decay of top quark $t \to Wb$

The tree level $t \to W + b$ with anomalous vertex can be simply obtained by using the helicity amplitude method which is available in [13]:

$$
\Gamma_{t \to Wb} = \frac{G_F m_t m_W^2}{8\sqrt{2}\pi} \frac{(r^2 - 1)^2}{r^4} \left[ (r^2 + 2)(f_{L1}^2 + f_{R1}^2) + (2r^2 + 1)(f_{L2}^2 + f_{R2}^2) + 6r(f_{L1}f_{R2} + f_{R1}f_{L2}) \right],
$$

(3.8)

It is clear that the new effective Lagrangian can change the width of the top quark significantly if the anomalous couplings are sufficiently large. The variation of $\tau_t \propto 1/\Gamma_{t \to Wb}$ in terms of anomalous couplings are shown in two dimensional plots in Fig. 1. The Fig.(1b) and Fig.(1c) show that a small deviation in $f_{R1}$ and $f_{R2}$ leads to a non-negligible variation in the width of top quark.

![Figure 1](image-url)

Figure 1: $\tau_t \propto 1/\Gamma_{t \to Wb}$ in terms of different anomalous couplings.
The spin correlation coefficient in Eq. (3.6) for the b-quark could be calculated using the helicity amplitude approach. It has the following form in terms of anomalous couplings:

\[
\alpha_b = -\frac{(r^2 - 2)(f_{L1}^2 - f_{R1}^2) + (2r^2 - 1)(f_{L2}^2 - f_{R2}^2) + 2r(f_{R1}f_{L2} - f_{L1}f_{R2})}{(r^2 + 2)(f_{L1}^2 + f_{R1}^2) + (2r^2 + 1)(f_{L2}^2 + f_{R2}^2) + 6r(f_{L1}f_{R2} + f_{R1}f_{L2})},
\]

(3.9)

For example, \(\alpha_b(f_{L1} = 1, f_{R1} = f_{L2} = f_{R2} = 0.1) = -0.276\) and \(\alpha_b(f_{L1} = 1, f_{R1} = f_{L2} = f_{R2} = -0.1) = -0.548\). Comparing with the SM case in which \(\alpha_b = -0.408\) (see Eq. (3.7)), almost a big deviation is observed. This sensitivity could be utilized in the probe of \(tWb\) vertex in the experimental analyzes for obtaining bounds on the anomalous couplings in the \(t\bar{t}\) and single top events.

Applying the upper bounds (mentioned in the Introduction for the LHC case from [2]) on \(f_{L2}\) and \(f_{R2}\) in \(\alpha_b\) shows that the effect of quadratic terms could be important with 30% which is not negligible. In particular, one should note that the \(tWb\) vertex will be examined with high precision at the LHC in which 8 millions \(t\bar{t}\) events will be producing per year [1].

### 3.2 Three-body decay of top quark \(t \rightarrow l^+\nu_l b\)

The effective \(tWb\) vertex in Eq. (2.3) contains some terms proportional to \(\gamma_\mu, \sigma_{\mu\nu}(p_t - p_b)^\nu, p_t^\mu\) and \(p_b^\mu\). In order to simplify the calculation, we can use the Gordon identity:

\[
-ib(\sigma_{\alpha\beta}(p_t - p_b)^\beta P_{R,L})t = \bar{b}(m_t\gamma_\alpha P_{L,R} - (p_t + p_b)_\alpha P_{R,L})t,
\]

(3.10)

In this calculation it is assumed that \(m_b \sim 0, m_l \sim 0\). Using the following definitions:

\[
x_l \equiv \frac{2E_l}{m_t} = \frac{2p_t.p_l}{m_t^2}, \quad x_l \cos \theta_l = -\frac{2p_l.s}{m_t}, \quad \gamma_w \equiv \frac{\Gamma_W}{m_W},
\]

\[
S_1 \equiv \tan^{-1}\left[\frac{\gamma_w r^2 x_l}{1 - r^2 x_l^2 + \gamma_w^2}\right], \quad S_2 \equiv \log\left[\frac{1 + \gamma_w^2}{(1 - r^2 x_l^2 + \gamma_w^2)}\right],
\]

(3.11)

where \(s\) is the spin four-vector of the top quark, \(p_l\) is the four-momentum of the charged lepton, \(\theta_l\) is the angle between top quark spin and the momentum of the charged lepton in the top rest frame and \(\Gamma_W\) is the full width of W-boson. After following the same method which has been used in [14] in obtaining the lepton spectra in the polarized top quark decay the following
expression is derived:

\[
\frac{d^2T_{\ell\to\nu b}}{dxd\cos\theta}\ =
\begin{align*}
C_0 &= \frac{G_F^2m_W^5}{64\pi^3}r_f, \\
T_0 &= I_{R1}^{(0)}f_{R1}^2 + I_{R2}^{(0)}f_{R2}^2, \\
T_1 &= I_{R1}^{(1)}f_{R1}^2 + I_{R2}^{(1)}f_{R2}^2 + J_1^{(1)}f_{R1}f_{L2} + J_2^{(1)}f_{R2}f_{L1}, \\
T_2 &= I_{R1}^{(2)}f_{R1}^2 + I_{R2}^{(2)}f_{R2}^2 + I_{L1}^{(2)}f_{L1}^2 + I_{L2}^{(2)}f_{L2}^2 + J_1^{(2)}f_{R1}f_{L2} + J_2^{(2)}f_{R2}f_{L1}, \\
T_3 &= I_{R1}^{(3)}f_{R1}^2 + I_{R2}^{(3)}f_{R2}^2 + I_{L1}^{(3)}f_{L1}^2 + I_{L2}^{(3)}f_{L2}^2,
\end{align*}
\]

(3.12)

where,

\[
\begin{align*}
I_{R1}^{(0)} &= 4\cos\theta_l(S_2 - \gamma_wS_1 + S_1/\gamma_w), \\
I_{R2}^{(0)} &= 4\cos\theta_l(S_2 + \gamma_wS_1 - S_1/\gamma_w)r^2, \\
I_{R1}^{(1)} &= -2\gamma_wS_1 - (2 + r^2)S_2 + 2S_1(1 + r^2)/\gamma_w + \cos\theta_l(4r^2 + S_2(2 + 3r^2) \\
&+ 2\gamma_wS_1 - 2S_1(1 + 3r^2)/\gamma_w), \\
I_{R2}^{(1)} &= 2\gamma_wS_1r^2 + (2 + r^2)r^2S_2 - 2(1 + r^2)r^2S_1/\gamma_w + \cos\theta_l(-4r^4 - S_2r^2(r^2 + 6) \\
&- 6r^2\gamma_wS_1 + 2r^2S_1(3 + r^2)/\gamma_w), \\
J_1^{(1)} &= (-4r\gamma_wS_1 - 4rS_2 + 4rS_1/\gamma_w)(1 + \cos\theta_l), \\
J_2^{(1)} &= (2r^3S_2 - 4r^3S_1/\gamma_w)(1 + \cos\theta_l), \\
I_{R1}^{(2)} &= (2(S_2 + 1)r^2 - 2S_1r^2(2 + r^2)/\gamma_w)(1 - \cos\theta_l), \\
I_{R2}^{(2)} &= -(S_2 + 2)r^4 - r^2(2 + r^2)S_2 - 2r^2\gamma_wS_1 + 2S_1r^2(1 + r^2)/\gamma_w \\
&+ \cos\theta_l(6r^4 + 2r^2S_2(1 + r^2) + 2r^2\gamma_wS_1 - 2r^2S_1(1 + 2r^2)/\gamma_w), \\
I_{L1}^{(2)} &= 2r^4S_1(1 + \cos\theta_l)/\gamma_w, \\
I_{L2}^{(2)} &= (-2r^3S_2 - 2r^2\gamma_wS_1 + 2r^2S_1/\gamma_w)(1 + \cos\theta_l), \\
J_1^{(2)} &= (2r^3(2 + S_2) - 4r^3S_1/\gamma_w)(1 + \cos\theta_l), \\
J_2^{(2)} &= (-2r^3S_2 + 4r^3S_1/\gamma_w)(1 + \cos\theta_l), \\
I_{R1}^{(3)} &= 2r^4S_1(1 - \cos\theta_l)/\gamma_w, \\
I_{R2}^{(3)} &= (r^4(2 + S_2) - 2r^4S_1/\gamma_w)(1 - \cos\theta_l), \\
I_{L1}^{(3)} &= 2r^4S_1(1 + \cos\theta_l)/\gamma_w, \\
I_{L2}^{(3)} &= (r^4(2 + S_2) - 2r^4S_1/\gamma_w)(1 + \cos\theta_l),
\end{align*}
\]

(3.13)

If one sets \(f_{L1} = V_{tb} \simeq 1, f_{R1} = f_{R2} = f_{L2} = 0\) in Eq. (3.12) and Eq. (3.13), the SM result is
obtained:

\[
\left. \frac{d^2 \Gamma_{t \rightarrow l\nu b}}{dx_l d\cos \theta_l} \right|_{SM} = \frac{G_f^2 m_W^5 r^3 x_l (1 - x_l) S_1}{32 \pi^3 \gamma_l} (1 + \cos \theta_l),
\]

which coincides with the expression which has been obtained in [14].

Figure 2: Energy dependence of the top quark width in terms of different anomalous couplings. Solid curve shows the SM case and dashed curve is for the case of \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = 0.1 \) and dash-dotted curve is for \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = -0.1 \).

In order to have a feeling of the effect of the anomalous couplings, the energy and angular dependence of the top quark width are plotted by substitution of the following values in Eq. (3.12) and Eq. (3.13):

\[
G_f = 1.166 \times 10^{-5} \text{ GeV}^{-2}, \quad m_W = 80.2 \text{ GeV}/c^2,
\]
\[
m_t = 175 \text{ GeV}/c^2, \quad \Gamma_W = 2.06 \text{ GeV},
\]

(3.15)

In Fig. 2 the energy dependence of top width in SM case (solid curve) and \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = 0.1 \) (dashed curve) and \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = -0.1 \) (dash-dotted curve) are plotted. The positive values for anomalous couplings lead to increment from the SM and vice versa for using negative values. But these deviations are mostly appeared in the range of \( 0.2 < x_l < 0.8 \).

Fig. 3 shows three different lines with distinct slopes corresponding to SM case (solid curve) and \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = 0.1 \) (dashed curve) and \( f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = -0.1 \) (dash-dotted curve). The correlation coefficient \( \alpha_l \) has been represented in Tab. 1. It is clear that \( \alpha_l \) receives a negligible deviation from the SM case.
Figure 3: Angular dependence of the top quark width in terms of different anomalous couplings. Solid curve shows the SM case and dashed curve is for the case of $f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = 0.1$ and dash-dotted curve is for $f_{L1} = 1, f_{R1} = f_{R2} = f_{L2} = -0.1$.

Table 1: Correlation coefficients for different values of the anomalous couplings.

| combination          | $\Gamma(t \rightarrow l\nu b)$ | $\alpha_l$ | $\alpha_b$ |
|---------------------|---------------------------------|-----------|-----------|
| $f_{L1} = 1.0, f_{R1} = f_{L2} = f_{R2} = 0.0$ | 0.168             | 1.0       | -0.408    |
| $f_{L1} = 1.0, f_{R1} = f_{L2} = f_{R2} = 0.1$ | 0.210             | 0.986     | -0.276    |
| $f_{L1} = 1.0, f_{R1} = f_{L2} = f_{R2} = -0.1$ | 0.146             | 0.981     | -0.548    |

It is well known that top quarks produced in hadron colliders are scarcely polarized. As a result, the correlations between top spin and anti-top spin in the $t\bar{t}$ is considered [1], [16]. In order to illustrate we consider the decay of the $t\bar{t}$ events in hadron colliders:

$$PP, P\bar{P} \rightarrow t\bar{t} \rightarrow 6\text{-body final state}$$ (3.16)

The double differential angular distribution of the $i$th and $i'$th product coming from the top and anti-top in the SM is [1], [16]:

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos \theta_i d\cos \theta_{i'}} = \frac{1}{4} (1 + \kappa_{ii'} \cos \theta_i \cos \theta_{i'}) \times \frac{N_{\parallel} - N_{\times}}{N_{\parallel} + N_{\times}}$$ (3.17)

where $\theta_i(\bar{\theta}_{i'})$ is the angle between the direction of the $i$th($i'$th) product in the rest frame of the $t$($\bar{t}$) and the direction of the momentum of the $t$($\bar{t}$) in the $t\bar{t}$ center of mass. $N_{\parallel}$ is the number
of top pair events where both quarks have spin up or spin down and $N_x$ is the number of top pair events where one quark is spin up and the other is spin down. Eq. (3.17) shows the strong dependence of the experimental observable, $\kappa_{ii}$, to the spin correlation coefficient ($\alpha_i$). For the $t\bar{t}$ production at the Tevatron and the LHC, the SM predicts $(N_\parallel - N_x)/(N_\parallel + N_x) = 0.88, 0.33$, respectively. Since the $\alpha_b$ is very sensitive to anomalous couplings, for instance the measurement of $\kappa_{i\bar{i}}$ with $i = b, \bar{i} = l$ might give some valuable information concerning the non-SM couplings in hadron colliders.

4 Conclusion

An effective Lagrangian approach to new physics in the top quark sector was used and the effect of the anomalous couplings on the energy and angular dependence of a secondary charged lepton produced by a polarized top quark was investigated by obtaining the analytic expression. We found that a small variation in the anomalous couplings gives a noticeable deviation in the width of top quark. The correlation coefficient of a secondary charged lepton, which is maximally correlated with the top quark spin, receives a negligible contribution from anomalous $tWb$ couplings. However the correlation coefficient of the b-quark receives a remarkable deviation from SM. Within the current estimated bounds using the simulation techniques the effect of quadratic terms of the anomalous couplings is not negligible. The b-quark spin correlation coefficient could be used in the experimental analyzes in $t\bar{t}$ events to obtain better constraints on the anomalous couplings, specially at the LHC in which we are not restricted by statistics.

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