Effects of Top-Quark Anomalous Decay Couplings at $\gamma\gamma$ Colliders

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Most general $tbW$ couplings were investigated in the process $\gamma\gamma \to t\bar{t} \to \ell^\pm X$ for unpolarized photon beams. The double angular and energy distribution of the lepton was calculated and an optimal-observable analysis on it was carried out for the SM $t\bar{t}$ production mechanism. It was also shown that the leptonic angular distribution is insensitive to non-standard $tbW$ vertex. That means that observation of non-standard effects indicates existence of some new physics in the production part.

1. INTRODUCTION

The standard model (SM) is extremely successful in particle-physics phenomenology. However, since there are still several unsolved problems in the SM, it is believed that the new physics beyond the SM is necessary to solve them. Therefore, it is very important to search for signals of new physics beyond the SM at forthcoming collider experiments.

Top-quark interactions could prove to be a reach source of information on the new physics. Since the mass of the top quark is much larger than the masses of the other quarks and leptons, and couplings of the top quark are still not strongly constrained, it is very interesting to investigate contribution from possible new physics in the top-quark sector. In addition, the top quark has some advantageous properties for searching new physics beyond the SM. Therefore, in this work, we will discuss effects from possible anomalous $tbW$ couplings in the process $\gamma\gamma \to t\bar{t} \to \ell^\pm X$, which will be observed at future photon-photon colliders, by performing a model-independent form-factor analysis.

2. FRAMEWORK

We will adopt the Kawasaki-Shirafuji-Tsai formula, assuming that both decaying top quarks and $W$ bosons are on-shell particles. In this formula, production and decay part are factorized as follows:

$$
\frac{d\sigma}{d\mathbf{p}_\ell}(\gamma\gamma \to \ell^\pm X) = 4 \int d\Omega_t \frac{d\sigma}{d\Omega_t}(n_t,0) \times \frac{1}{\Gamma_t} \frac{d\Gamma}{d\mathbf{p}_\ell}(t \to b\ell^+\nu),
$$

where $\Gamma$ and $\Gamma_t$ are the leptonic and total widths of the top quark, respectively, i.e., $\Gamma = B_t \Gamma_t$, using $B_t$ as the branching ratio for $t \to b\ell^+\nu$ ($\approx 0.22$). $d\Gamma/d\mathbf{p}_t$ means the differential decay rate for the top quark. $d\sigma(n_t,0)/d\Omega_t$ is obtained from $d\sigma(s_t,s_t)/d\Omega_t$, which is the angular distribution of $t\bar{t}$ with spin $s_t$ and setting $s_t \to 0$. Since we will perform a model-independent analysis we should use the most general couplings of $t\gamma$ and $tbW$. However, since top-quark pair is produced via $t$- and $u$-channel processes in $\gamma\gamma$ collisions differently from the case of $e^+e^-$ collisions in which top-quark pair is produced via $s$-channel one, there are two $tt\gamma$ couplings, and each $tt\gamma$ coupling includes one virtual top quark. Thus, without some assumptions or choice of specific models, it is not possible to estimate momentum dependence of form factors of $tt\gamma$ coupling, and consequently we cannot perform the $d\Omega_t$ integration in this framework.

On the other hand, in top-quark decay processes, since top quarks, bottom quarks and $W$ bosons can be treated as on-shell particles, we can fix momentum dependence of form factors and parameterize non-standard effects in terms of constant parameters. For these reasons, in this work, we will focus on the possibilities of new physics in the decay part assuming the SM pro-
duction of the top quark.

We will adopt the following most general form of the $t\bar{b}W$ vertex suitable for the $t \to W^+ b$ decays:

$$
\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} \bar{u}(p_b) \left[ \gamma^\mu (f_1^L P_L + f_1^R P_R) - i\sigma^{\mu\nu}k_\nu \frac{G_\mu}{M_W} (f_2^L P_L + f_2^R P_R) \right] u(p_t), \quad (2)
$$

where $P_{L/R} = (1 \mp \gamma_5)$ and $k$ is the momentum of $W$ boson. $f_{1,2}^{L/R}$ parameterize non-standard decay effects. Because $W$ boson is on-shell in the narrow-width approximation, the two additional form factors do not contribute. In the SM, $f_{1}^L = 1$ and the other form factors vanish.

Eq. (2) allows us to perform global analysis of the non-standard effects in the top-quark decay if the decay is described by the sequential chain: $t \to W^+ b \to b\ell^+\nu_\ell$.

### 3. Final Lepton Distribution

In the following calculation, we neglected masses of final leptons, bottom quarks and quadratic terms of non-standard form factors.

#### 3.1. Angular and Energy Distribution

Adopting the SM production of $tt$ and the form factors of the top-quark decay in eq. (2), we can calculate the angular and energy distribution of final leptons as

$$
\frac{d\sigma}{dx d\cos \theta}\gamma\to \ell^+ X = \frac{3(cQ_\ell)^4 \beta}{64\pi^2 s} \times \left[ f_1(x, \cos \theta_\ell) + \text{Re}(f_2^R f_2(x, \cos \theta_\ell)) \right],
$$

where

$$
f_1(x, \cos \theta_\ell) = x\left[ -2\pi G_{00} + \left(1 + \frac{4m_\ell^2}{s} - \frac{8m_\ell^4}{s^2} \right) G_{01} - \frac{8m_\ell^4}{s^2} G_{02} \right],
$$

$$
f_2(x, \cos \theta_\ell) = 2\sqrt{x} \left[ -2\pi G_{10} + \left(1 + \frac{4m_\ell^2}{s} - \frac{8m_\ell^4}{s^2} \right) G_{11} - \frac{8m_\ell^4}{s^2} G_{12} \right],
$$

with

$$
G_{00}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell \omega,
$$

$$
G_{01}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell (I_+ + I_-),
$$

$$
G_{02}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell (J_+ + J_-),
$$

$$
G_{10}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell \omega \left( \frac{1}{1 - \omega} - \frac{3}{1 + 2r} \right),
$$

$$
G_{11}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell \omega \left( \frac{1}{1 - \omega} - \frac{3}{1 + 2r} \right) \times (J_+ + J_-),
$$

$$
G_{12}(x, \theta_\ell) \equiv C \int_{c_+}^{c_-} d\cos \theta_\ell \omega \left( \frac{1}{1 - \omega} - \frac{3}{1 + 2r} \right) \times (J_+ + J_-),
$$

$$
I_\pm \equiv \int_0^{2\pi} dx \frac{1}{A_\pm \cos x + B_\pm} = 2\pi / \sqrt{B_\pm^2 - A_\pm^2},
$$

$$
J_\pm \equiv \int_0^{2\pi} dx \frac{1}{(A_\pm \cos x + B_\pm)^2} = 2\pi B_\pm / \sqrt{(B_\pm^2 - A_\pm^2)^3}.
$$

In the above integration, $c_{\pm}$ express the kinematical upper/lower bounds of $\cos \theta_\ell$ (see ref. [3]), $x$ is the rescaled energy of the final lepton defined in terms of its CM-frame energy $E_\ell$ and the top-quark velocity $\beta = \sqrt{1 - 4m_t^2/s}$ as $x = 2E_\ell / (m_t \sqrt{(1 - \beta)/(1 + \beta)})$, and $\theta_\ell$ is the angle between the initial beam direction and the final-lepton momentum. This result shows that the angular and energy distribution enables us to investigate non-standard decay via $\text{Re}(f_2^R)$ exclusively.

Performing an optimal-observable analysis for $t$ decay, we have determined the following size of anomalous coupling that would guarantee a signal at 1σ level: $\delta(\text{Re}(f_2^R)) = 8.58 \times 10^{-3}$ with integrated luminosity $L = 500$ fb$^{-1}$ and one-lepton-detection efficiency $\epsilon = 0.6$. Of course we can carry out an analogous calculation for $\bar{t}$ decay, and get the same result.
3.2. Angular Distribution

Performing further integration over \( x \) for \( r(1 - \beta)/(1 + \beta) \leq x \leq 1 \), we obtain the angular distribution of the final lepton:

\[
\frac{d\sigma}{d\cos\theta_\ell} = \frac{(eQ_1)^2}{128\pi^2s} (r - 1)^2 (1 + 2r) (\beta - 1)^2 \\
\times C \int_{c_-}^{c_+} \frac{d\cos\theta_\nu}{(1 - \beta \cos\theta_\ell)^2} \left[ -2\pi \\
+ \left( 1 + \frac{4m_e^2}{s} - \frac{8m_\nu^2}{s^2} \right)(I_+ + I_-) \\
- \frac{8m_\nu^2}{s^2}(J_+ + J_-) \right].
\]

Surprisingly, we found that \( f_R^B \) terms vanish after \( x \) integration. This is one typical example of the general decoupling theorem found in [7]. For \( d\sigma(\gamma\gamma \rightarrow \ell^-X)/d\cos\theta_\ell \), some calculations lead us to an analogous result. Thus, in this distribution, we should not observe any signal of non-standard top-quark decay.

This means: if non-standard effects are observed in this distribution, that is a signal of some physics beyond our assumptions. Let us recall what assumptions we have adopted in this work:

1. top-quark decay is described by sequential decays \( t \rightarrow W^+b \rightarrow b\ell^+\nu_\ell \),
2. narrow-width approximation is applicable for \( t \) and \( W \),
3. masses of \( b \) quarks and final leptons, and quadratic terms of non-standard form factors were neglected,
4. non-standard effects do not exist in the production.

The assumptions 1~3 are well justified in this process, therefore observation of non-standard effects in the angular distribution would be a signal of physics beyond the assumption 4, i.e. new physics in the production part.

4. SUMMARY

In the process \( \gamma\gamma \rightarrow t\bar{t} \rightarrow \ell^+\ell^-X \) for unpolarized photon beams\(^3\), the angular and energy distribution, and the angular distribution of the secondary lepton were calculated, assuming the standard top-quark production and the most general couplings for the decay. In addition, the masses of bottom quarks and final leptons have been neglected and only linear terms of non-standard form factors have been kept. To calculate distributions of final leptons, Kawasaki-Shirafuji-Tsai formula was adopted with narrow-width approximation for the top quark and \( W \) boson.

The double angular and energy distribution is sensitive to the non-standard contribution from the top-quark decay vertex. Thus this observable seems to be a useful tool to measure deviations from the standard top-quark decay. For the angular distribution of the final leptons, non-standard effects of \( tbW \) couplings completely vanish after integration of the energy dependence. Therefore, an observation of any non-standard signal in the angular distribution may be an indication of some new physics in the production mechanism.

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