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CP–violating asymmetries in top–quark production and decay in e^+e^- annihilation within the MSSM

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Abstract

We obtain analytic formulae for the cross section of the sequential processes of $e^+e^- \to t\bar{t}$ and $t \to bl^+\nu$ / $\bar{t} \to \bar{b}l^-\bar{\nu}$ in the laboratory frame, where the dependence on triple product correlations of the type $(\hat{\mathbf{q}}_1 \times \hat{\mathbf{q}}_2 \cdot \hat{\mathbf{q}}_3)$, induced by CP violation both in the production and the decay are explicitely shown. Different observables sensitive to CP violation are defined and calculated in the Minimal Supersymmetric Standard Model (MSSM). The observables sensitive to CP violation are of the order of 10^{-3}. The dependence on the masses of the supersymmetric particles is also shown.

1. Introduction

Precision measurements of various production and decay modes of the top quark are expected to provide also information about physics beyond the Standard Model (SM). Testing new physics in observables which are sensitive to CP violation seems especially promising. As the top quark does not mix with other generations, the GIM mechanism of unitarity constraints leads to negligibly small effects of CP violation in the SM. Thus, observation of CP noninvariance in top–quark physics would definitely be a signal for physics beyond the SM [1, 2, 3, 4, 5].

Here we shall consider CP violation induced by supersymmetry (SUSY). In the Minimal Supersymmetric Standard Model (MSSM) [6], there are more possibilities to introduce complex couplings than in the SM. Even without generation mixing, nonzero complex phases can occur in the Lagrangian that cannot be rotated away by a suitable redifinition of the fields. They give rise to CP violation within a single generation, free of the unitarity supression of the GIM mechanism.

In top–quark production and decay CP violation is due to radiative corrections. The magnitude is determined by the ratio of the masses of the top quark and the SUSY particles in the loop. Having in mind the large top–quark mass, $m_t = 175 GeV$ [7], we may expect that the CP–violating effects are only moderately suppressed. Thus, testing SUSY through CP–violating observables in top–quark physics is a promising task for future colliders.

Here, as possible evidence of CP violation we consider T–odd triple product correlations of the type

$$(\mathbf{q_1 q_2 q_3}) \equiv (\mathbf{q_1} \times \mathbf{q_2} \cdot \mathbf{q_3}) \tag{1}$$

where $\mathbf{q_{1,2,3}}$ can be any one of the 3–momenta in $e^+e^- \to t\bar{t}$ or of the t $(\bar{t})$– decay products $t \to b l^+ \nu$ $(\bar{t} \to \bar{b} l^- \bar{\nu})$. This method has been proposed in [1, 2] for a general study of CP violation in $t\bar{t}$ production in e^+e^- annihilation and in pp collisions. The correlations (1) are called T–odd as they change sign under a flip of the 3–momenta involved. However, this does neither imply time–reversal noninvariance nor CP violation if CPT is assumed. When loop corrections are included, T–odd correlations can arise either from absorptive parts in the amplitude (so-called final state interactions [8]), or from CP violation. The former effect is a consequence of the unitarity of the S–matrix, and it can be eliminated either by taking the difference between the process we are interested in and its CP conjugate [9] or by direct estimates. T–odd correlations in the SM due to gluon or Higgs boson exchange in the final states have recently been considered in [10].

Note that in collider experiments top–antitop quark pairs will be copiously produced and the decay modes $t \to bl^+\nu$ and $\bar{t} \to \bar{b}l^-\bar{\nu}$ will occur simultaneously. Therefore, it will be possible to form the difference between the two conjugate processes in the same experiment.

The appearance of triple product correlations of the type (1) can also be explained by the fact that the top–quark polarization has non–vanishing transverse components both in the production plane and perpendicular to it. Because of the large mass of the top quark the produced t and $\bar{t}$ can be regarded as free quarks with definite momenta and polarizations that are not affected by hadronization. Thus their polarization state can be infered from the distribution of their decay products.

In the $t\bar{t}$ production process

$$e^+(q_{\bar{l}}) + e^-(q_l) \to t(p_t) + \bar{t}(p_{\bar{t}})\,, \tag{2}$$

a T–odd correlation in the c.m.system is $(\xi \mathbf{q_l} \mathbf{p_t})$ [3], where ξ is the top–quark polarization vector. Evidently, this correlation is different from zero only if ξ has a component *normal to the production plane.*

In the semileptonic t and $\bar{t}$ decays:

$$t \to b(p_b)l^+(p_{l^+})\nu(p_\nu) \tag{3}$$

$$\bar{t} \to \bar{b}(p_{\bar{b}})l^-(p_{l^-})\bar{\nu}(p_{\bar{\nu}}) \tag{4}$$

a triple product correlation in the rest frame of the top quark is $(\xi \mathbf{p_b} \mathbf{p_{l^+}})$ [4]. Here it is the polarization of the top quark *normal to the decay plane* that contributes. In the production as well as in the decay we shall only consider correlations due to CP violation.

As the polarization of the top quark is not a directly observable quantity, we obtain information about the above spin–momenta correlations by triple product correlations of type (1) among the 3-momenta of the particles in the sequential processes:

$$e^+ \;\; + \;\; e^- \to t + \bar{t} \;\to \bar{t}\, b\, l^+\, \nu \tag{5}$$

$$e^+ \;\; + \;\; e^- \to t + \bar{t} \;\to t\, \bar{b}\, l^-\, \bar{\nu}. \tag{6}$$

In this paper we shall calculate the contribution to different triple product correlations of type (1) due to CP violation in (2) and in (3) or (4). We shall obtain analytic expressions for the sequential reactions (5) and (6) in which the triple product correlations (1), sensitive to CP violation in the production and in the decay, explicitely appear. The problem of distinguishing CP violation in $t\bar{t}$ production and t decay was considered previously in [1] . We shall use the triple product correlations to investigate CP violation induced by SUSY. However, our method is completely general and can also be applied to study other sources of CP violation.

In section 2 we obtain general expressions of processes (5) and (6) using the formalism developed in [11]. We write them in a form in which CP–violation manifests itself in triple product correlations. In section 3 we obtain the expressions for the polarization vectors of the top and antitop quarks, when the electric and weak dipole–moment couplings are taken into account. Formulae for the cross section of (5) and (6) in the c.m.system with the explicit dependence on the triple products of type (1) are given in section 4. In section 5 we formulate the CP – violating observables. In section 6 we obtain numerical results for these effects in the MSSM.

2. The Cross Section

Here we obtain analytic expression for the cross section of the sequential processes (5) and (6), in terms of the top/antitop polarization vectors. CP violation in both the production and the $t(\bar{t})$-decay processes are taken into account.

We write the amplitudes of (5) and (6) in the form:

$$\begin{aligned} \mathcal{M}^{t,\bar{t}} &= \frac{g}{2\sqrt{2}}\,\bar{u}(p_\nu)\gamma_\alpha(1\mp\gamma_5)u(-p_{l^+})\frac{-g^{\alpha\beta}+\frac{p_W^\alpha p_W^\beta}{m_W^2}}{p_W^2-m_W^2+im_W\Gamma_W} \\ &\times\bar{u}(p_b)V_\beta^{t,\bar{t}}\frac{\not{p}_t+m_t}{p_t^2-m_t^2+im_t\Gamma_t}\,A^{t,\bar{t}}\,u(-p_{\bar{t}})\,. \end{aligned} \tag{7}$$

Here $A^{t,\bar{t}}$ enters the amplitude M for the production process (2) which we write in the two equivalent forms:

$$M=\bar{u}(p_t)A^t u(-p_{\bar{t}})=\bar{u}_c(p_{\bar{t}})A^{\bar{t}}u_c(-p_t)\,. \tag{8}$$

A^t and $A^{\bar{t}}$ are given by s–channel γ and Z^0 exchange,

$$\begin{aligned} A^{t,\bar{t}} &= i\frac{e^2}{s}\,\bar{u}(-q_{\bar{l}})\,\gamma_\alpha\,u(q_l)(\mathcal{V}_\gamma^{t,\bar{t}})^\alpha \\ &-i\frac{g_Z^2}{s-m_Z^2}\,\bar{u}(-q_{\bar{l}})\,\gamma_\alpha(c_V+c_A\gamma_5)\,u(q_l)(\mathcal{V}_Z^{t,\bar{t}})^\alpha, \end{aligned} \tag{9}$$

where $c_V = -1/2 + 2\sin^2\theta_W$, $c_A = 1/2$ are the SM couplings of Z^0 to the electron, and $\sqrt{s}$ is the total c.m.energy. The quantities $(\mathcal{V}_i^{t,\bar{t}})$ describe the $t\bar{t}\gamma$ and $t\bar{t}Z^0$ vertices:

$$
\begin{aligned}
(\mathcal{V}_\gamma^{t,\bar{t}})_\alpha &= \frac{2}{3}\gamma_\alpha \mp \frac{d^\gamma}{m_t}\mathcal{P}_\alpha\gamma_5, \\
(\mathcal{V}_Z^{t,\bar{t}})_\alpha &= \gamma_\alpha(g_V \pm g_A\gamma_5) \mp \frac{d^Z}{m_t}\mathcal{P}_\alpha\gamma_5,
\end{aligned} \tag{10}
$$

with $\mathcal{P} = p_t - p_{\bar{t}}$. $g_V = 1/2 - 4/3\,\sin^2\theta_W$ and $g_A = -1/2$ in eq. (10) are the SM top–quark couplings to the Z^0, d^γ and d^Z are the electric and weak dipole moments of the t-quark, which in the limit of vanishing electron mass present the whole effect of CP violation. They can be induced only by CP–violating interaction and have in general both real and imaginary parts.

The $t(\bar{t})$–decays (3), (4) are treated as a sequence of the two–body decays $t \to bW^+(p_W)$ and $W^+ \to l^+\nu$, ($\bar{t} \to \bar{b}W^-(p_W)$ and $W^- \to l^-\bar{\nu}$). We write the tbW and $\bar{t}\bar{b}W$ vertices in the form:

$$
V_\alpha^t = \frac{g}{2\sqrt{2}}\left(\gamma_\alpha(1-\gamma_5) + f_L^t\gamma_\alpha(1-\gamma_5) + \frac{g_R^t}{m_W}P_\alpha^t(1+\gamma_5)\right), \tag{11}
$$

$$
V_\alpha^{\bar{t}} = \frac{g}{2\sqrt{2}}\left(\gamma_\alpha(1+\gamma_5) + f_L^{\bar{t}*}\gamma_\alpha(1+\gamma_5) + \frac{g_R^{\bar{t}*}}{m_W}P_\alpha^{\bar{t}}(1-\gamma_5\right) \tag{12}
$$

with g the weak coupling constant and $P^t = p_t + p_b$, $P^{\bar{t}} = p_{\bar{t}} + p_{\bar{b}}$. In eqs. (11) and (12) we have kept only the terms that do not vanish in the approximation $m_b = 0$. The form factors $f_L^{t,\bar{t}}$ and $g_R^{t,\bar{t}}$ get contributions both from the CP–invariant absorptive parts of the amplitudes and from CP–violating interactions, and can have real and imaginary parts. Furthermore, CPT is assumed. Neglecting the absorptive parts we then have [1]:

$$
f_L^t = \left(f_L^{\bar{t}}\right)^* \equiv f_L, \qquad g_R^t = \left(g_R^{\bar{t}}\right)^* \equiv g_R \tag{13}
$$

and CP invariance implies

$$
f_L = f_L^*, \qquad g_R = g_R^* \tag{14}
$$

For the $Wl\nu$–vertices we take the SM tree level expressions.

The amplitude $\mathcal{M}^{\bar{t}}$ for process (6) is obtained from (7) when also the spinors $\bar{u}(p_\nu)$, $u(-p_{l^+})$, $\bar{u}(p_b)$ and $u(-p_{\bar{t}})$ are replaced by $\bar{u}_c(p_{\bar{\nu}})$, $u_c(-p_{l^-})$, $\bar{u}_c(p_{\bar{b}})$ and $u_c(-p_t)$, respectively, which describe the charge conjugate particles.

In order to obtain the general expression for the cross sections of (5) and (6) we use the formalism developed in [11].

In the narrow width approximation for the top and the W ($\Gamma_t \ll m_t, \Gamma_W \ll m_W$) we obtain the cross section of reaction (5) in the form:

$$d\sigma = d\sigma_{e^+e^-} \cdot d\Gamma_{\vec{t}} \cdot \frac{p_{t_0}}{m_t \Gamma_t} \cdot d\Gamma_{\vec{W}} \frac{p_{W_0}}{m_W \Gamma_W} \, . \tag{15}$$

Here $d\sigma_{e^+e^-}$ is the differential cross section for $t\bar{t}$ production (2) in the c.m.s., $d\Gamma_{\vec{t}}$ is the decay rate for $t \to bW$, with the polarization state of the top quark determined in the production process $e^+e^- \to t\bar{t}$, and $d\Gamma_{\vec{W}}$ is the partial decay rate of $W \to l\nu$, with the polarization state of the W determined in the preceding t decay. $d\Gamma_{\vec{t}}$ and $d\Gamma_{\vec{W}}$ are the decay distributions in the c.m.s. of the initial e^+e^-. As $m_t\Gamma_t/p_{t_0}$ ($m_W\Gamma_W/p_{W_0}$) is the total decay width of t (W) in a frame in which the momentum of the top (W) equals $\mathbf{p}_t$ ($\mathbf{p}_W$), $d\Gamma_{\vec{t}} \cdot p_{t_0}/m_t\Gamma_t$ ($d\Gamma_{\vec{W}} \cdot p_{W_0}/m_W\Gamma_W$) is the branching ratio of the decay $t \to b\,W$ ($W \to l\nu$) in the laboratory frame, with the polarization of $t(W)$ determined in the preceding process.

Now we are interested only in triple product correlations in reactions (5) and (6) induced by CP violation in $\mathcal{V}^i_\alpha$ and/or V_α. First we consider process (5). Possible triple product correlations are $(\mathbf{q}_l\mathbf{p}_t\mathbf{p}_b)$, $(\mathbf{q}_l\mathbf{p}_t\mathbf{p}_{l^+})$, $(\mathbf{q}_l\mathbf{p}_{l^+}\mathbf{p}_b)$, and $(\mathbf{p}_t\mathbf{p}_{l^+}\mathbf{p}_b)$. These correlations follow from the covariant quantities $\varepsilon(p_1p_2p_3p_4)$, where p_i can be any one of the 4–vectors q_l, $q_{\bar{l}}$, p_t, p_b, p_{l^+} , when written in the laboratory frame. (The symbol $\varepsilon(p_1p_2p_3p_4)$ means $\varepsilon_{\alpha\beta\gamma\delta}\, p_1^\alpha\, p_2^\beta\, p_3^\gamma\, p_4^\delta$ with $\varepsilon_{0123} = -1$.)

The top–quark polarization normal to the production plane, ξ_N, which is induced by the CP–violating dipole couplings, gives rise to T–odd triple product correlations in $e^+e^- \to t\bar{t}$ which are proportional to $\Im m d^i$ [3]. CP–violating triple product correlations in the decay $t \to b\,l^+\,\nu$ arise from the top polarization *transverse to the decay plane* and are induced by $\Im m\, g_R$ in the tbW–vertex [4]. Both types of couplings d^i and g_R are generated by loop corrections.

We write the polarization 4–vector ξ^t and $\xi^{\bar{t}}$ as the sum

$$\xi^{t,\bar{t}} = \xi^{t,\bar{t}}_{SM} + \xi^{t,\bar{t}}_N, \tag{16}$$

where ξ_{SM} is the tree level SM contribution that lies in the production plane, and ξ_N is the component normal to the production plane, which can arise in general either from final-state interactions or from CP–violating interactions. Neglecting $\Re e g_R$ we obtain the following expression for the cross sections of (5) and (6) in terms of the top/antitop quark polarization vectors:

$$d\sigma^{t,\bar t} = \frac{96(4\pi)^2}{s}\alpha^2\left(\frac{g}{2\sqrt{2}}\right)^4\left(m_t^2 - 2(p_t p_{l^+})\right) N\left\{A^{t,\bar t}_{SM} + A^{t,\bar t}_{d} + A^{t,\bar t}_{g_R}\right\} d\Gamma^{t,\bar t} \qquad (17)$$

Here α is the finestructure constant and

$$\begin{aligned}
A^{t,\bar t}_{SM} &= (p_t p_{l^+}) \mp m_t(\xi^{t,\bar t}_{SM} p_{l^+})\,, && (18)\\
A^{t,\bar t}_{d} &= \mp m_t\,(\xi^{t,\bar t}_{N} p_{l^+})\,, && (19)\\
A^{t,\bar t}_{g_R} &= \mp 2\frac{\Im m g_R}{m_W}\varepsilon(\xi^{t,\bar t}_{SM} p_t p_{l^+} p_b)\,, && (20)\\
N &= \left(1+\beta^2\cos^2\theta\right)F_1 + \frac{4m_t^2}{s}F_2 + 2\beta\cos\theta F_3 && (21)\\
F_1 &= \left(\frac{2}{3}\right)^2 + h_Z^2(c_V^2+c_A^2)(g_V^2+g_A^2) - \frac{4}{3}h_Z c_V g_V\\
F_2 &= \left(\frac{2}{3}\right)^2 + h_Z^2(c_V^2+c_A^2)(g_V^2-g_A^2) - \frac{4}{3}h_Z c_V g_V\\
F_3 &= 4h_Z c_A g_A\left(h_Z c_V g_V - \frac{1}{3}\right) && (22)
\end{aligned}$$

$A^{t,\bar t}_{SM}$ is the SM contribution with the first terms describing the contribution where the produced top and antitop are unpolarized, while the second one takes into account $\xi^{t,\bar t}_{SM}$.

The terms $A^{t,\bar t}_{d}$ and $A^{t,\bar t}_{g_R}$ contain the T–odd CP–violating correlations induced by $\Im m d^\gamma$ and $\Im m d^Z$ via $\xi^{t,\bar t}_{N}$, and by $\Im m g_R$, respectively. (Note that the form factor f_L of eqs.11 and 12 does not appear.) The complete expressions for $\xi^{t,\bar t}$ will be given in the next section. The invariant phase space element $d\Gamma$ is

$$\begin{aligned}
d\Gamma^t &= \frac{1}{(2\pi)^8}\delta(q_l + q_{\bar l} - p_{l^+} - p_\nu - p_b - p_{\bar t})\cdot\frac{\pi}{m_t\Gamma_t}\delta(p_t^2 - m_t^2)\\
&\quad\times\frac{\pi}{m_W\Gamma_W}\delta(p_W^2 - m_W^2)\frac{d\mathbf{p}_{l^+}}{2p_{l\,0}}\,\frac{d\mathbf{p}_\nu}{2p_{\nu\,0}}\,\frac{d\mathbf{p}_b}{2p_{b\,0}}\,\frac{d\mathbf{p}_{\bar t}}{2p_{\bar t\,0}}\,. && (23)
\end{aligned}$$

Here $\beta = \sqrt{1-4m_t^2/s}$ is the velocity factor of the t–quark in the c.m.system, θ is the angle between the momenta of the initial electron and the t–quark, and

$$h_Z = \frac{s}{s-m_Z^2}\cdot\frac{g_Z^2}{e^2}\,,\qquad g_Z = \frac{e}{\sin 2\theta_W}\,, \qquad (24)$$

In order to obtain the cross section for reaction (6), in the expressions (17) – (20) and(23) the following replacements must be made:

$$p_t \to p_{\bar t},\qquad p_b \to p_{\bar b},\qquad p_{l^+} \to p_{l^-},\qquad p_\nu \to p_{\bar\nu}\,. \qquad (25)$$

3. The top–quark polarization vector

First we calculate the polarization vector ξ^t_α of the top quark. It is determined in the production process, and it is given by the expression [11]:

$$
\begin{aligned}
\xi^t_\alpha &= \left(g_{\alpha\beta} - \frac{p_{t\alpha}p_{t\beta}}{m_t^2}\right) \cdot Tr\ \left(A^t(-\Lambda(-p_{\bar{t}}))\bar{A}^t\Lambda(p_t)\gamma^\beta\gamma_5\right) \\
&\quad \times \left\{Tr\left[A^t(-\Lambda(-p_{\bar{t}}))\bar{A}^t\Lambda(p_t)\right]\right\}^{-1} . \qquad (26)
\end{aligned}
$$

ξ^t_α can be decomposed along three vectors which are independent and orthogonal to p_t: two of them, Q_l and $Q_{\bar{l}}$

$$
Q_l = q_l - \frac{p_t q_l}{m_t^2} \cdot p_t \qquad Q_{\bar{l}} = q_{\bar{l}} - \frac{p_t q_{\bar{l}}}{m_t^2} \cdot p_t \qquad (27)
$$

are in the production plane, and the third, $\varepsilon^{\alpha\beta\gamma\delta}p_{t\beta}q_{l\gamma}q_{\bar{l}\delta}$, is normal to it. We then have:

$$
(\xi^t_{SM})^\alpha = P^t_l(Q_l)^\alpha + P^t_{\bar{l}}(Q_{\bar{l}})^\alpha \qquad (\xi^t_N)^\alpha = D^t\varepsilon^{\alpha\beta\gamma\delta}p_{t\beta}q_{l\gamma}q_{\bar{l}\delta}. \qquad (28)
$$

We neglect contributions of $\Im m d^\gamma$ and $\Im m d^Z$ to P^t_l and $P^t_{\bar{l}}$ as they are much smaller than the SM contributions. Together with eqs. (9) and (10), up to first order in $\Im m d^\gamma$ and $\Im m d^Z$, eq. (26) implies the following expressions for the three components of the polarization vector as defined above:

$$
\begin{aligned}
P^t_l &= \frac{2m_t}{s}\left\{(1-\beta\cos\theta)\ G_1 + (1+\beta\cos\theta)\ G_2\right. \\
&\quad \left. -(3-\beta\cos\theta)\ G_3\right\}/N\,, \qquad (29) \\
P^t_{\bar{l}} &= -\frac{2m_t}{s}\left\{(1+\beta\cos\theta)\ G_1 + (1-\beta\cos\theta)\ G_2\right. \\
&\quad \left. +(3+\beta\cos\theta)\ G_3\right\}/N\,, \qquad (30) \\
D^t &= \frac{8}{sm_t}\ \left\{D_1 + \beta\cos\theta D_2\right\}/N. \qquad (31)
\end{aligned}
$$

Here

$$
\begin{aligned}
G_1 &= 2h_Z^2\, c_V c_A \left(g_V^2 + g_A^2\right) - \frac{4}{3}h_Z\, c_A g_V\,, \qquad (32) \\
G_2 &= 2h_Z^2\, c_V c_A \left(g_V^2 - g_A^2\right) - \frac{4}{3}h_Z\, c_A g_V\,, \qquad (33) \\
G_3 &= 2h_Z^2\, \left(c_V^2 + c_A^2\right) g_V g_A - \frac{4}{3}h_Z\, c_V g_A\,, \qquad (34) \\
D_1 &= 2h_Z^2\, c_V c_A g_V\, \Im m\, d^Z - h_Z\, c_A\left(g_V \Im m\, d^\gamma + \frac{2}{3}\Im m\, d^Z\right)\,, \qquad (35) \\
D_2 &= h_Z^2\,(c_V^2 + c_A^2) g_A\, \Im m\, d^Z - h_Z\, c_V g_A \Im m\, d^\gamma \qquad (36)
\end{aligned}
$$

As can be seen from eqs. (28),(31),(36),(37), $\Im m d^\gamma$ and $\Im m d^Z$ enter only in the polarization component transverse to the production plane.

In an analogous way we write the polarization vector $\xi^{\bar t}_{SM}$ of the antitop quark as

$$(\xi^{\bar t}_{SM})^\alpha = P^{\bar t}_l \bar Q^\alpha_l + P^{\bar t}_{\bar l} \bar Q^\alpha_{\bar l}, \qquad (\xi^{\bar t}_N)^\alpha = D^{\bar t} \varepsilon^{\alpha\beta\gamma\delta} p_{\bar t\beta} q_{l\gamma} q_{\bar l\delta}\,, \tag{37}$$

where

$$\bar Q_{l(\bar l)} = Q_{l(\bar l)}(p_t \to p_{\bar t})\,. \tag{38}$$

Then we obtain

$$P^{\bar t}_l = -P^t_{\bar l}, \qquad P^{\bar t}_{\bar l} = -P^t_l, \qquad D^{\bar t} = D^t\,. \tag{39}$$

In the c.m.system, the expressions (27) – (31) and (37) – (39) for $\xi^{t,\bar t}$ lead to the following relations between the space components of the polarization vectors of the top and the antitop:

$$\vec\xi^{\,\bar t}_{SM} = \vec\xi^{\,t}_{SM} \tag{40}$$

$$\vec\xi^{\,\bar t}_N = -\vec\xi^{\,t}_N\,. \tag{41}$$

This result can be readily understood by applying the CP operator (and is also a check of our results): CP invariance implies $\vec\xi^{\,t} = \vec\xi^{\,\bar t}$ which is nothing but the result (40) for the tree level SM (i. e. CP conserving) contribution. Evidently, eq. (41) violates CP, being induced by d^γ and d^Z.

Eq. (39) implies:

$$A^{\bar t}_{SM}(p_{\bar t}, p_{l^-}, p_{\bar b}) = A^t_{SM}(p_t, p_{l^+}, p_b), \tag{42}$$

$$A^{\bar t}_d(p_{\bar t}, p_{l^-}, p_{\bar b}) = -A^t_d(p_t, p_{l^+}, p_b), \tag{43}$$

$$A^{\bar t}_{g_R}(p_{\bar t}, p_{l^-}, p_{\bar b}) = -A^t_{g_R}(p_t, p_{l^+}, p_b). \tag{44}$$

4. Triple product correlations

Now we obtain the explicit dependence of the cross section of processes (5) and (6) on triple product correlations of type (1) in the c.m.system, the laboratory frame of the initial e^+e^- beams.

From (17), (26) and (37) we obtain the cross section $d\sigma^{t,\bar t}$ in the c.m. system.

$$\begin{aligned} d\sigma^{t,\bar t} = \sigma^{t,\bar t}_{SM}\,\{1 \;&+\; \frac{1}{1-\beta(\hat{\mathbf p}_t\hat{\mathbf p}_{l^+})}\left[(\hat{\mathbf q}_l\hat{\mathbf p}_t\hat{\mathbf p}_{l^+})\,A^{t,\bar t}_1 + (\hat{\mathbf q}_l\hat{\mathbf p}_t\hat{\mathbf p}_b)\,A^{t,\bar t}_2\right.\\ &+\; \left.(\hat{\mathbf p}_t\hat{\mathbf p}_{l^+}\hat{\mathbf p}_b)\,A^{t,\bar t}_3 + (\hat{\mathbf q}_l\hat{\mathbf p}_{l^+}\hat{\mathbf p}_b)\,A^{t,\bar t}_4\right]\Big\}\,d\Omega_t d\Omega_b d\Omega_l \end{aligned} \tag{45}$$

where $\hat{q}_e, \hat{p}_t$, etc. denote the corresponding unit 3-vectors.

We have

$$\sigma_{SM}^{t,\bar{t}} = \frac{\alpha^2}{4\pi^4}\left(\frac{g}{2\sqrt{2}}\right)^4 \frac{\beta}{s}\frac{[m_t^2 - 2(p_t p_{l^+})]}{m_t\Gamma_t\, m_W\Gamma_W}\frac{E_b^2}{m_t^2 - m_W^2}\frac{E_l^2}{m_W^2} N A_{SM}^{t,\bar{t}} \tag{46}$$

which is the expression for the SM cross sections of (5) and (6). Here E_b and E_l are the energies of the the b-quark and the final lepton in the c.m.s.

$$E_b = \frac{m_t^2 - m_W^2}{2E}\frac{1}{1-\beta(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b)} \tag{47}$$

$$E_l = \frac{m_W^2}{2\left[E(1-\beta(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_{l^+})) - E_b(1-(\hat{\mathbf{p}}_b\hat{\mathbf{p}}_{l^+}))\right]} \tag{48}$$

and $E = \sqrt{s}/2$. For the asymmetries A_i we obtain:

$$\begin{aligned}
A_1^{t,\bar{t}} &= \mp\beta\left[\frac{D}{2} - \frac{m_t}{\sqrt{s}}E_b P_- \frac{\Im m g_R}{m_W}\right] && (49)\\
A_2^{t,\bar{t}} &= \mp\beta\frac{m_t}{\sqrt{s}}E_b P_- \frac{\Im m g_R}{m_W} && (50)\\
A_3^{t,\bar{t}} &= -\,\beta\frac{m_t}{\sqrt{s}}E_b P_+ \frac{\Im m g_R}{m_W} && (51)\\
A_4^{t,\bar{t}} &= \pm\frac{m_t}{\sqrt{s}}E_b P_- \frac{\Im m g_R}{m_W} && (52)
\end{aligned}$$

where

$$\begin{aligned}
P_- &= \frac{4}{N}\left[G_1 + G_2 + \beta\cos\theta\, G_3\right]\\
P_+ &= -\frac{4}{N}\left[3G_3 + \beta\cos\theta\,(G_1 - G_2)\right]\\
D &= \frac{8}{N}\left[D_1 + \beta\cos\theta\, D_2\right]\,, && (53)
\end{aligned}$$

N was defined in eq.(21).

In order to obtain the expressions (45) – (52) for the reaction (6) (with the upper index $\bar{t}$) also the replacements (25) have to be made.

Notice, that only the correlation $(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l)$ gets a CP violating contribution from both the production and the decay, whereas the other correlations are sensitive only to CP violation in the decay. From eqs. (49) – (52) one expects that the triple product correlations discussed above are less sensitive to CP violation in top–decay then in $t\bar{t}$ production, because $\Im m g_R$ is multiplied by the SM–polarization $P_\pm$ and by $E_b/\sqrt{s}$.

We want to remark that $(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l)$, $(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b)$ and $(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b)$ do not change sign under the replacements (25) when calculating $d\sigma^{\bar{t}}$ in the c.m.s., while $(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b)$ changes sign. Together with eqs. (49)–(52) this implies that a nonzero value of the difference of $d\sigma^t$ and $d\sigma^{\bar{t}}$ would be the genuine signal for a triple product correlation induced by CP violation.

5. Observables

We consider two types of observables:

(i) If $N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) > 0(<0)\right]$ is the number of events in which $(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) > 0(<0)$, with analogous definitions for the other triple products, we define the following T–odd asymmetries:

$$O_1 = \frac{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) > 0\right] - N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) < 0\right]}{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) > 0\right] + N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l) < 0\right]} \tag{54}$$

$$O_2 = \frac{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b) > 0\right] - N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b) < 0\right]}{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b) > 0\right] + N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b) < 0\right]} \tag{55}$$

$$O_3 = \frac{N\left[(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) > 0\right] - N\left[(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) < 0\right]}{N\left[(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) > 0\right] + N\left[(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) < 0\right]} \tag{56}$$

$$O_4 = \frac{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) > 0\right] - N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) < 0\right]}{N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) > 0\right] + N\left[(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b) < 0\right]} \tag{57}$$

(ii) The other T–odd observables we consider are the mean values of the triple product correlations:

$$M_1 = \langle(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l)\rangle \tag{58}$$

$$M_2 = \langle(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_t\hat{\mathbf{p}}_b)\rangle \tag{59}$$

$$M_3 = \langle(\hat{\mathbf{p}}_t\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b)\rangle \tag{60}$$

$$M_4 = \langle(\hat{\mathbf{q}}_l\hat{\mathbf{p}}_l\hat{\mathbf{p}}_b)\rangle \tag{61}$$

The truly CP–violating effect would be a nonzero value of the differences:

$$\mathcal{O}_i = O_i - \bar{O}_i \tag{62}$$

$$\mathcal{M}_i = M_i - \bar{M}_i \tag{63}$$

where O_i and M_i refer to (5) and $\bar{O}_i$ and $\bar{M}_i$ refer to reaction (6).

Some of these correlations ($\mathcal{M}_1$ and $\mathcal{M}_4$) have been considered previously in [1]

6. Minimal Supersymmetric Standard Model

In this section we shall give numerical predictions in the MSSM [6] for the observables defined in the preceding section as well as for the quantities d^γ, d^Z, $\Im m g_R$, and $\xi_N^{t,\bar{t}}$.

The SM contribution is too small to be of any interest to be measured. Due to flavour mixing of the three generations of quarks d^i is a two–loop effect. The contribution to $\Im m g_R$ has been estimated in [12].

In the MSSM d^γ, d^Z and $\Im m g_R$ are generated at one–loop order, irrespectively of generation mixing. The main contribution comes from diagrams with gluino and scalar quarks in the loop, as shown in Fig. 1. The CP–violating phases ϕ_A and $\phi_{\tilde{g}}$ appear in the stop– squark mixing matrix and in the Majorana mass term of the gluino, respectively [13].

The dipole moments are determined by the gluino – stop exchange loops in the $t\bar{t}\gamma$ and $t\bar{t}Z^0$ vertices (see Fig. 1) and are given by the following expressions:

$$\begin{aligned}
\frac{d^\gamma}{m_t} &= \frac{\alpha_s}{3\pi}\frac{2}{3}\tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) \left[I_{11} - I_{22} - 2\left(I'_{11} - I'_{22}\right)\right] && (64)\\
\frac{d^Z}{m_t} &= \frac{\alpha_s}{3\pi}\tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) \sum_n \left(|a_n^L|^2 - \frac{4}{3}\sin^2\theta_W\right) \\
&\quad \times \left[I_{1n} - I_{2n} - 2\left(I'_{1n} - I'_{2n}\right)\right] && (65)
\end{aligned}$$

The CP–violating phases enter only in the combination $\phi_A - \phi_{\tilde{g}}$. $\tilde{\theta}$ is the stop – mixing angle which transforms the stop mass eigenstates $\tilde{t}_n$, $n = 1, 2$, with masses $m_{\tilde{t}_n}$, to the weak eigenstates $\tilde{t}_L$ and $\tilde{t}_R$:

$$\begin{aligned}
\tilde{t}_L &= exp(-i\phi_A/2)\left(\cos\tilde{\theta}\,\tilde{t}_1 + \sin\tilde{\theta}\,\tilde{t}_2\right) \equiv a_n^L \cdot \tilde{t}_n && (66)\\
\tilde{t}_R &= exp(i\phi_A/2)\left(-\sin\tilde{\theta}\,\tilde{t}_1 + \cos\tilde{\theta}\,\tilde{t}_2\right) \equiv a_n^R \cdot \tilde{t}_n\,. && (67)
\end{aligned}$$

We have also used the notation:

$$\begin{aligned}
I_{n,m} &= \int \frac{d^4k}{\pi^2}\frac{1}{k^2 - \tilde{m}_g^2}\frac{1}{(p_t - k)^2 - \tilde{m}_n^2}\frac{1}{(p_{\bar{t}} + k)^2 - \tilde{m}_m^2} && (68)\\
\mathcal{P}_\alpha I'_{n,m} + \mathcal{Q}_\alpha I''_{n,m} &= \int \frac{d^4k}{\pi^2}k_\alpha\frac{1}{k^2 - \tilde{m}_g^2}\frac{1}{(p_t - k)^2 - \tilde{m}_n^2}\frac{1}{(p_{\bar{t}} + k)^2 - \tilde{m}_m^2} && (69)
\end{aligned}$$

where $\mathcal{Q} = p_t + p_{\bar{t}}$ and $\tilde{m}_n \equiv m_{\tilde{t}_n}$, $m, n = 1, 2$.

The CP–violating contribution to $\Im m g_R$ from the gluino–stop–sbottom loop (see Fig.1) reads:

$$\frac{\Im m g_R}{m_W} = -\frac{\alpha_s}{3\pi}\tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) \left[I_1 - I_2 - 2\left(I'_1 - I'_2\right)\right] \qquad (70)$$

Here I_n and I'_n are obtained from (68) and (69) by replacing $p_{\bar{t}} \to -p_b$ and $\tilde{m}_m \to m_{\tilde{b}_L}$, $m_{\tilde{b}_L}$ being the $\tilde{b}_L$ mass. In obtaining (70) we have neglected the mixing of the scalar–bottom eigenstates.

We have studied the dependence of $\Im m d^\gamma$, $\Im m d^Z$, $\Im m g_R$, $\xi_N^{t,\bar{t}}$ and the CP violating quantities O_i and M_i on $\sqrt{s}$, the top–quark mass m_t, and the SUSY parameters $m_{\tilde{g}}$, $m_{\tilde{t}_1}$ and $m_{\tilde{b}_L}$. In our numerical analysis we have assumed maximal mixing, $\sin 2\tilde{\theta} = 1$, and maximal CP –violation, $\sin(\phi_A - \phi_{\tilde{g}}) = 1$. In the presentation of our results we choose the following set of reference values: $\sqrt{s} = 500$ GeV, $m_t = 175$ GeV, $m_{\tilde{g}} = 200$ GeV, $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 400$ GeV, and $m_{\tilde{b}_L} = 200$ GeV. In the figures below we show the dependence of $\Im m d^\gamma$, $\Im m d^Z$, $\Im m g_R$ and the quantities O_i and M_i on one of the parameters, with the other parameters being fixed at their reference values.

We first show in Figs. 2a, b, and c the dependence of the $\Im m d^\gamma$ and $\Im m d^Z$ on the beam energy $\sqrt{s}$, and on $m_{\tilde{g}}$ and $m_{\tilde{t}_1}$, respectively. Typically they have values in the range $10^{-3} - 10^{-2}$.

Figs. 3a and b show the dependence of $\Im m g_R$ on the SUSY parameters $m_{\tilde{g}}$ and $m_{\tilde{b}_L}$. Roughly, $\Im m g_R$ is an order of magnitude smaller then the dipole moments ($\Im m g_R \approx 10^{-4} - 10^{-3}$). As can be seen, the dipole moments $\Im m d^{\gamma,Z}$ and $\Im m g_R$ exhibit a rather strong dependence on $m_{\tilde{t}_1}$, changing sign at $m_{\tilde{t}_1} = 400$ GeV. (For our particular set of chosen parameters $m_{\tilde{t}_1} = 400$ GeV corresponds to $m_{\tilde{t}_1} = m_{\tilde{t}_2}$. At this point eqs. (64) and (70) immediately lead to $\Im m d^\gamma = 0$ and $\Im m g_R = 0$; eq. (65) implies $\Im m d^Z = 0$, but only for the considered case of maximal mixing.)

Figs. 4a, b, c and 5a, b, c exhibit the dependence of the CP – violating quantities M_i, and O_i, i=1,...,4, on $\sqrt{s}$, $m_{\tilde{g}}$ and $m_{\tilde{t}_1}$. Note that the observables $\mathcal{O}_i$ and $\mathcal{M}_i$ as defined in eqs. (62) and (63) are $\mathcal{O}_i = 2O_i$ and $\mathcal{M}_i = 2M_i$. Above the threshold region and up to $\sqrt{s} \approx 1$ TeV the M_i and the O_i are only weakly dependent on s. O_2, O_4 and M_4 are the largest. Their values are of the order of 10^{-3}. The dependence on $m_{\tilde{g}}$ and $m_{\tilde{t}_1}$ reflects the dependence of $\Im m d^{\gamma,Z}$ and $\Im m g_R$ on these parameters, changing sign at $m_{\tilde{t}_1} = m_{\tilde{t}_2} = 400$ GeV.

7. Concluding remarks

Here we have considered T–odd triple product correlations and corresponding asymmetries for $t\bar{t}$ production in e^+e^- annihilation with subsequent semileptonic decays of t or $\bar{t}$.

The contribution to the T–odd correlations induced by possible CP–violating interactions have been studied. T–odd CP–violating observables $\mathcal{O}_i$, eq. (62), and $\mathcal{M}_i$, eq. (63), have been defined. Numerical predictions within the MSSM have been given, and their dependence on the SUSY parameters and $\sqrt{s}$ has been presented. Our analysis shows:

1. Above threshold there is only a weak dependence on $\sqrt{s}$. The quantities $\mathcal{O}_2$, $\mathcal{O}_4$ and $\mathcal{M}_4$ are larger than the others. Their values at $\sqrt{s} = 500$ GeV are of the order of 10^{-3} for $m_{\tilde{t}_1} \leq 200$ GeV and $m_{\tilde{g}} \lesssim 500$ GeV. Note that the observables $\mathcal{O}_4$ and $\mathcal{M}_4$ have also the advantage that they involve only the momenta of the t and $\bar{t}$ decay products.

2. There is a marked dependence on $m_{\tilde{t}_1}$. At $m_{\tilde{t}_1} = m_{\tilde{t}_2}$ both $\mathcal{O}_i$ and $\mathcal{M}_i$ change sign.

3. The observables $\mathcal{O}_i$ and $\mathcal{M}_i$ considered exhibit less sensitivity to CP violation in top decay. This is due to the fact that i) $\Im m g_R$ is smaller than $d^{\gamma,Z}$, and ii) the contribution of $\Im m g_R$ to $\mathcal{O}_i$ and $\mathcal{M}_i$ is proportional to the degree of $t(\bar{t})$ polarization induced by the SM.

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Figure Captions

Fig. 1: Diagrams inducing CP violation in top production and decay.

Fig. 2: The imaginary parts of the dipole moments $\Im m d^\gamma$ and $\Im m d^Z$ as a function of (a) $\sqrt{s}/2$, (b) $m_{\tilde{g}}$, and (c) $m_{\tilde{t}_1}$, for $m_t = 175$ GeV, $m_{\tilde{t}_2} = 400$ GeV, $m_{\tilde{b}_L} = 200$ GeV. We have taken $\sqrt{s} = 500$ GeV in (b) and (c), $m_{\tilde{g}} = 200$ GeV in (a) and (c), $m_{\tilde{t}_1} = 150$ GeV in (a) and (b).

Fig. 3: $\Im m g_R$ as a function of (a) $m_{\tilde{g}}$, and (b) $m_{\tilde{b}_L}$, for $\sqrt{s} = 500$ GeV, $m_t = 175$ GeV, $m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 400$ GeV, with $m_{\tilde{b}_L} = 200$ GeV in (a) and $m_{\tilde{g}} = 200$ GeV in (b).

Fig. 4: The CP violating contribution to the observables M_i, $i = 1,..,4$, as a function of (a) $\sqrt{s}$, (b) $m_{\tilde{g}}$, and (c) $m_{\tilde{t}_1}$, for $m_t = 175$ GeV, $m_{\tilde{t}_2} = 400$ GeV, $m_{\tilde{b}_L} = 200$ GeV. We have taken $\sqrt{s} = 500$ GeV in (b) and (c), $m_{\tilde{g}} = 200$ GeV in (a) and (c), $m_{\tilde{t}_1} = 150$ GeV in (a) and (b). M_1(full line), M_2(long-dashed), M_3(short-dashed), M_4(dashed-dotted).

Fig. 5: The CP violating contribution to the asymmetries O_i, $i = 1,..,4$, as a function of (a) $\sqrt{s}$, (b) $m_{\tilde{g}}$, and (c) $m_{\tilde{t}_1}$, for $m_t = 175$ GeV, $m_{\tilde{t}_2} = 400$ GeV, $m_{\tilde{b}_L} = 200$ GeV. We have taken $\sqrt{s} = 500$ GeV in (b) and (c), $m_{\tilde{g}} = 200$ GeV in (a) and (c), $m_{\tilde{t}_1} = 150$ GeV in (a) and (b). O_1(full line), O_2(long-dashed), O_3(short-dashed), O_4(dashed-dotted).