Top-Charm Associated Production at High Energy $e^+e^-$ Colliders in Standard Model

Chao-Shang Huang $^a$, Xiao-Hong Wu $^a$ and Shou-Hua Zhu $^{b,a}$

$^a$ Institute of Theoretical Physics, Academia Sinica, P. O. Box 2735, Beijing 100080, P. R. China

$^b$ CCAST (World Lab), P.O. Box 8730, Beijing 100080, P.R. China

Abstract

The flavor changing neutral current $t c V (V=\gamma,Z)$ couplings in the production vertex for the process $e^+e^- \rightarrow t \bar{c}$ or $\bar{t} c$ in the standard model are investigated. The precise calculations keeping all quark masses non-zero are carried out. The total production cross section is found to be $1.84 \times 10^{-9}$ fb at $\sqrt{s}=200$ Gev and $0.572 \times 10^{-9}$ fb at $\sqrt{s}=500$ Gev respectively. The result is much smaller than that given in ref. [6] by a factor of $10^{-5}$. 
Top quark physics has been extensively investigated [1]. The advantage of examining top quark physics than other quark physics is that one can directly determine the properties of top quark itself and does not need to worry about non-perturbative QCD effects which are difficult to attack because there exist no top-flavored hadron states at all. The properties of top quark could reveal information on flavor physics, electroweak symmetry breaking as well new physics beyond the standard model (SM).

One of important fields in top physics is to study flavor changing neutral current (FCNC) couplings. There are no flavor changing neutral currents at tree-level in the SM. FCNC appear at loop-levels and consequently offer a good place to test quantum effects of the fundamental quantum field theory on which SM based. Furthermore, they are very small at one loop-level due to the unitary of Cabbibo-Kobayashi-Maskawa (CKM) matrix. In models beyond SM new particles beyond the particles in SM may appear in the loop and have significant contributions to flavor changing transitions. Therefore, FCNC interactions give an ideal place to search for new physics. Any positive observation of FCNC couplings deviated from that in SM would unambiguously signal the presence of new physics. Searching for FCNC is clearly one of important goals of high energy colliders, in particular, $e^+e^-$ colliders [2].

The flavor changing transitions involving external up-type quarks which are due to FCNC couplings are much more suppressed than those involving external down-type quarks in SM. The effects for external up-type quarks are derived by virtual exchanges of down-type quarks in a loop for which GIM mechanism [3] is much more effective because the mass splittings between down-type quarks are much less than those between up-type quarks. Therefore, the tc transition which is studied in the latter opens a good window to search for new physics.

The FCNC vertices $tcV(V=\gamma, Z)$ can be probed either in rare decays of t quark or via top-charm associated production. A lot of works have been done in the former case [4]. And a number of papers on the latter case have also appeared [5-7]. In this letter we shall investigate the latter case in the process
\[ e^+e^- \rightarrow t\bar{c} \text{ or } \bar{t}c. \] (1)

Comparing t quark rare decays where the momentum transfer \( q^2 \) is limited, i.e., it should be less or equal to mass square of t quark \( m_t^2 \), the production process (1) allows the large (time-like) momentum transfer, which is actually determined by the energies available at \( e^+e^- \) colliders. The reaction (1) has some advantages because of the ability to probe higher dimension operators at large momenta and striking kinematic signatures which are straightforward to detect in the clean environment of \( e^+e^- \) collisions. In particular, in some extensions of SM which induce FCNC there are large underlying mass scales and large momentum transfer so that these models are more naturally probed via \( t\bar{c} \) associated production than t quark rare decays.

The production cross sections of the process (1) in SM have been calculated in refs. [6,7]. In the early references [7] a top quark mass \( m_t \leq m_Z \) is assumed and the on-shell Z boson dominance is adopted. The reference [6] considered a large top quark mass and abandoned the on-shell Z boson dominance. However, the "self energy" diagrams have been omitted in ref. [6]. This is not legal because the one-loop contribution for FC transitions is of the leading term of the FC transitions and must be finite, i.e., although there are some divergences for some diagrams they should cancel each other in the sum of contributions of all diagrams. Furthermore, the order of values of cross sections given in ref. [6] is not correct.

The order of values of cross sections for the process (1) in SM can easily be estimated. The differential cross section can be written as

\[
\frac{d\sigma}{d\cos\theta} = \frac{N_c}{32\pi s} (1 - \frac{m_t^2}{s}) \frac{1}{4} \sum_{\text{spins}} |M|^2
\] (2)

Where \( N_c \) is the color factor, \( \theta \) is the the angle between incoming electron \( e^- \) and outgoing top quark \( t \) and \( M \) is the amplitude of the process. In eq.(2) the charm quark mass in kinetic factors has been omitted. Due to the GIM mechanism, one has

\[
\sum_{\text{spins}} |M|^2 = e^8 \left| \sum_{j=d,s,b} V_{jt}^* V_{jc} f(x_j, y_j) \right|^2
\]

\[
= e^8 |V_{tb}^* V_{cb} \frac{m_b^2 - m_s^2}{m_w^2} \frac{\partial f}{\partial x_j} |_{x_j, y_j=0 + \ldots} |^2,
\] (3)
where $x_j = m_j^2/m_w^2$, $y_j = m_j^2/s$, and "..." denote the less important terms for $\sqrt{s} \geq 200$ Gev. Assuming $\frac{\partial \sigma}{\partial x_j} |_{x_j,y_j=0} = O(1)$, one obtains from eqs. (2),(3)

$$\sigma \sim 10^{-8} - 10^{-9} fb$$

at $\sqrt{s} = 200$ Gev. However, the results given in ref. [6] are

$$\sigma = 0.71 \times 10^{-2} fb$$

for $m_t=165$ Gev and

$$\sigma = 4.1 \times 10^{-4} fb$$

for $m_t=190$ Gev, which are much larger than the above estimation by a factor of $10^5$. In order to test SM and search for new physics from observations of some process one needs to know what are the precise results for the relevant observables of the process in SM. Therefore, it is necessary to calculate precisely the cross sections in the SM. In this letter we calculate the differential and total cross sections of the process (1) in SM.

In SM for the process (1) there are three kinds of Feynman diagram at one loop, "self energy" (actually it is a FC transition, not a usual self energy diagram), triangle and box diagram, which are shown in Fig.1. We carry out calculations in the Feynman-t’Hooft gauge. The contributions of the neutral Higgs H and Goldstone bosons $G^{0,\pm}$ which couple to electrons are neglected since they are proportional to the electron mass and we have put the mass of electron to zero.

We do the reduction using FeynCalc and keep all masses non-zero except for the mass of electron. To control the ultraviolet divergence, the dimensional regularization is used. As a consistent check, we found that all divergences are canceled in the sum. The calculations are carried out in the frame of the centre of mass system (CMS) and Mandelstam variables have been employed:

$$s = (p_1 + p_2)^2 = (k_1 + k_2)^2 \quad t = (p_1 - k_1)^2 \quad u = (p_1 - k_2)^2,$$

\((4)\)
where $p_1, p_2$ are the momenta of electron and positron respectively, and $k_1, k_2$ are the momenta of top quark $t$ and anti-charm quark $\bar{c}$ respectively.

The amplitude of process $e^+e^- \rightarrow t\bar{c}$ can be expressed as

$$M = \sum_{j=d,s,b} 16\pi^2\alpha^2 V_{ij}^* V_{lj} [g_1 \bar{u}_t \gamma^\mu P_L v_c \bar{v}_e \gamma_\mu P_R u_e + g_2 \bar{u}_t \gamma^\mu P_L v_c \bar{v}_e \gamma_\mu P_L u_e + g_3 \bar{u}_t P_L v_c \bar{v}_e \not{k}_1 P_R u_e + g_4 \bar{u}_t P_L v_c \bar{v}_e \not{k}_1 P_L u_e + g_5 \bar{u}_t \not{P}_L v_c \not{u}_e \not{k}_1 P_R u_e + g_6 \bar{u}_t \gamma^\mu P_L v_c \bar{v}_e \gamma_\mu P_L u_e + g_7 \bar{u}_t \gamma^\mu P_R v_c \bar{v}_e \gamma_\mu P_L u_e + g_8 \bar{u}_t \gamma^\mu P_R v_c \bar{v}_e \gamma_\mu P_L u_e + g_9 \bar{u}_t P_R v_c \bar{v}_e \not{k}_1 P_R u_e + g_{10} \bar{u}_t P_R v_c \bar{v}_e \not{k}_1 P_L u_e + g_{11} \bar{v}_e \gamma^\mu P_L u_e \bar{u}_t \gamma_\mu \not{P}_R u_c]$$

(5)

where $\alpha$ is fine structure constant, $V_{ij}$ is CKM matrix element, $P_L$ is defined as $(1 - \gamma^5)/2$, and $P_R$ is defined as $(1 + \gamma^5)/2$. The exact expressions of the coefficients $g_j (j = 1, 2, \ldots, 11)$ are too long to be given. Instead, in order to show the essential points, we give them in the limit of $m_i/m$ (i=d,s,c, m=m_w, m_t, s) approach to zero. In the limit $g_j (j = 7, 8, 9, 10, 11)$ is zero, and the others are given as follows.

$$g_1 = a_3 m^2 - 2 a_4 m^2 s_w^4 + 6 a_4 C^c_2 m_j^2 m_t^4 + 6 m^2_w (2 C^d_{11} m^2 + 2 C^d_{22} s + 2 C^d_{12} (m^2 + s)) (a_3 + 2 a_4 c_w^2 s_w^2) + 12 m^2_w C^d_{22} (a_3 (m^2 + s) + a_4 (2 s c_w^2 + m^2 c_w s_w - m^2 s_w^4)) - B^b_0 (m^2_4 - m^2_2 m^2 + m^2_3 m^2 + m^2_4 m^2 - 2 m^2_4 m^2 - m^2_4 m^2 (a_1 + 2 a_2 s_w^2 (3 - 4 s_w^2)) + 12 C^d_{00} (a_3 (m^2 + 6 m^2_w) + a_4 s_w^2 (c_w^2 m^2 + 12 c_w^2 m^2 - m^2 s_w^2)) + 6 C^d_{11} m^2_w (2 a_3 (m^2 + s) + 2 a_4 s_w^2 (c_w^2 m^2 + 2 c_w^2 s - m^2 s_w^2)) - 6 C^d_{11} m^2_w (2 a_3 (m^2 + s) - m^2 s_w^2)) + 2 a_4 s_w^2 (2 c_w^2 m^2 + 2 c_w^2 s + 2 m^2 s_w^2 - m^2 s_w^2 - 3 m^2 c_w^2)) + 2 C^c_0 m^2_j (a_3 (m^2 + 2 m^2 - m^2) + a_4 s_w^2 (3 m^2 - 2 m^2 s_w - 4 m^2 s_w^2 + 2 m^2 s_w^2)) - 2 (2 C^c_0 + C^c_{11} m^2 + C^c_{22} s + C^c_0 s + C^c_{12} (m^2 + s)) (a_3 (m^2 + 2 m^2 + 2 a_4 s_w^2 (3 m^2_w - m^2 s_w^2 - 2 m^2 s_w^2)) + B^b_0 (a_1 (m^2_j - 2 m^2_w) (m^2 + 2 m^2_w) - 2 a_1 m^2 m^2 + 2 a_2 s_w^2 (3 m^2 - m^2 m^2 + 3 m^2 s_w - 2 m^2 s_w)) - 4 m^2 s_w^2 - 4 m^2 s_w^2 s_w^2 + 8 m^2 s_w^2 + 8 m^2 s_w^2 s_w^2)) - 2 C^c_1 (a_3 (m^2 + 2 m^2 + m^2)) - a_4 s_w^2 (3 m^2 m^2 + 2 m^2 m^2 s_w - 2 m^2 s_w + 4 m^2 s_w^2))$$

(6)

$$g_2 = a_3 m^2 + a_4 m^2 (1 - 2 s_w^2)(s_w^2 - 3 C^c_2 m^2) + a_5 (8 D^c_0 + u (D^c_6 + D^c_2 + 2 D^c_6 + 2 D^c_{12} + 4 D^c_{13} +$$

4
\[ 2D_{23}^{c} + 2D_{33}^{c} + (2m_t^2 D_3^c + 2sD_{13}^c + 2D_{33}^c m_t^2)) + 6m_w^2 (2C_{11}^d m_t^2 + 2C_{22}^d s +
2C_{12}^d (m_t^2 + s))(a_3 - a_4 C^2_w(1 - 2s_w^2)) + 6m_w^2 C^d_2 (2a_3 (m_t^2 + s) - a_4 (1 - 2s_w^2)(m_t^2 C^2_w - m_t^2 s_w^2 +
2s^2_w)) - B^b_0 (m_j^4 - m_j^2 m_t^2 + m_j^2 m_w^2 + 2m_t^2 m_w^2 - 2m^4_w)(a_1 - a_2 (3 - 4s^2_w)(1 - 2s^2_w)) +
6C^d_{00} (2a_3 (m_t^2 + 6m_w^2) - a_4 (1 - 2s_w^2)(s^2_w m_t^2 + 12c_w^2 m_w^2 - m_t^2 s_w^2)) + 6C^d_1 m_w^2 (2a_3 (m_t^2 + s) -
a_4 (1 - 2s_w^2)(s^2_w m_t^2 + 2c_w^2 s_w^2 - m_t^2 s_w^2)) - 6C^d_0 m_w^2 (2a_3 (m_t^2 - s) + a_4 (1 - 2s_w^2)(s^2_w m_t^2 + 2c_w^2 s_w^2 +
m_j^2 s_w^2 - m_t^2 s_w^2) + C^d_0 m_w^2 (2a_3 (m_t^2 + 2m_w^2 - m_j^2) - a_4 (1 - 2s_w^2)(3m_j^2 - 2m_j^2 s_w^2 - 4m_w^2 s_w^2 +
m_j^2 s_w^2)) - 2(2C^c_{00} + C^c_{11} m_t^2 + C^c_{22} s + C^c_5 s + C^c_{12} (m_t^2 + s))(a_3 (m_t^2 + 2m_w^2) -
a_4 (1 - 2s_w^2)(3m^2_w - m_j^2 s_w^2 - 2m_w^2 s_w^2)) + B^a_0 (a_1 (m_j^2 - m_w^2)(m_j^2 + 2m_w^2) - 2a_1 m_j^2 m_j^2 -
a_2 (1 - 2s_w^2)(3m_j^4 - 6m_j^2 m_t^2 + 3m^2_j m_w^2 - 6m^4_w - 4m_j^2 s_w^2 - 4m^2_j m_w^2 s_w^2 + 8m^4_j s_w^2 + 8m^2_j m_j^2 s_w^2)) -
C^c_1 (2a_3 (m_j^2 m_t^2 + 2m_j^2) + a_4 (1 - 2s_w^2)(3m^2_j m_t^2 - 6m^2_j s_w^2 + 4m^2_j s_w^2 + 2m^2_j m_j^2 s_w^2)) \]

\[ g_3 = 12a_4 s_w^2 m_t (2C^d_1 m_w^2 - C^c_2 m_j^2) + 4m_t C^c_0 m_j^2 (a_3 - 2a_4 s^4_w) + 24m_t m_w^2 (2C^d_1 + C^d_0) (a_3 + 2a_4 s^2_w m_t s_w) +
8C^c_1 m_t (a_3 m_j^2 - 2a_4 s^4_w m_j^2) + 12m_t (C^d_1 + C^d_{12}) (a_3 (m_j^2 + 2m_w^2) + a_4 s_w^2 (s^2_w m_j^2 + 4c_w^2 m_w^2 - m_j^2 s_w^2)) +
4m_t (C^c_{11} + C^c_{12}) (a_3 (m_j^2 + 2m_w^2) + a_4 s_w^2 (3m^2_w - m_j^2 s_w^2 - 2m^2_w s_w^2)) \]

\[ g_4 = -2a_5 m_t (2D_{23}^c + D_2^c + 2D_{33}^c + 2D_3^c) + 6a_4 m_t (C^c_2 m_j^2 - 2C^d_2 m_j^2)(1 - 2s_w^2) + 4C^c_0 m_t m_j^2 (a_3 +
a_4 s_w^2 (1 - 2s_w^2)) + 24m_t m_w^2 (2C^d_1 + C^d_0) (a_3 - a_4 s^2_w (1 - 2s_w^2)) + 8C^c_1 m_t (a_3 m_j^2 +
a_4 s^2_w m_j^2 (1 - 2s_w^2)) + 6(C^d_1 + C^d_{12}) m_t (2a_3 (m_j^2 + 2m_w^2) - a_4 (1 - 2s_w^2)(s^2_w m_j^2 + 4c_w^2 m_w^2 -
m_j^2 s_w^2)) + 4m_t (C^c_1 + C^c_{12}) (a_3 (m_j^2 + 2m_w^2) - a_4 (1 - 2s_w^2)(3m^2_w - m_j^2 s_w^2 - 2m^2_w s_w^2)) \]

\[ g_5 = -4a_5 (D_{12}^c + D_{13}^c) \]

\[ g_6 = a_5 m_t (2D_{12}^c + 2D_{13}^c + 2D_{23}^c + 2D_2^c + 2D_{33}^c + 2D_3^c) \]

with \( m_j^2 = m_h^2 \) (since \( m_s, m_d \) have been omitted in the above expressions of \( g \)'s),

where \( a_i (i = 1, 2, ..., 5) \) are defined by

\[
a_1 = \frac{1}{96s^2 m^2 t s^2 w m_t^2 m_w^2}, \quad a_2 = \frac{1}{768\pi^2 c_w^2 s^4_w m_t^2 m_w^2 (m^2_w - im_s \Gamma z - s)}, \quad a_3 = \frac{1}{192 s^2 t^2 w^2 m^2_w} \]
\[
a_4 = \frac{1}{384\pi^2 c_w^2 s_w^4 m_w^2 (m_z^2 - i m_z \Gamma_z - s)}; \quad a_5 = \frac{1}{32\pi^2 s_w^4}
\]

with \(c_w = \cos \theta_w\) and \(s_w = \sin \theta_w\). In the presentation of \(g_j\) above, we have used the definition of scalar integrals \(B_s, C_s,\text{and } D_s\) \[\text{[8]},\]
and these functions, \(B_s, C_s,\text{and } D_s\), with superscripts a,b,...,e have the arguments

\((0, m_j^2, m_w^2), \quad (m_j^2, m_j^2, m_w^2), \quad (m_t^2, 0, s, m_j^2, m_w^2, m_j^2), \quad (m_t^2, 0, s, m_w^2, m_j^2, m_w^2)\)

\((0, s, m_t^2, u, 0, 0, 0, m_w^2, m_w^2, m_j^2)\)

respectively. Here \(m_j\) denotes the mass of down-type quark b.

In the numerical calculations the following values of the parameters have been used \[\text{[9]}:\]

\[
m_e = 0, \quad m_c = 1.4 Gev, \quad m_t = 175 Gev, \quad m_d = 0.005 Gev, \quad m_s = 0.17 Gev, \quad m_b = 4.4 Gev, \quad m_w = 80.41 Gev, \quad m_z = 91.187 Gev, \quad \Gamma_z = 2.5 Gev, \quad \alpha = \frac{1}{128}
\]

In order to keep the unitary condition of CKM matrix exactly, we employ the standard parametrization and take the values \[\text{[9,10]}:\]

\[
s_{12} = 0.220, \quad s_{23} = 0.039, \quad s_{13} = 0.0031, \quad \delta_{13} = 70^\circ.
\]

Numerical results are shown in Figs. 2, 3. In Fig. 2, we show the total cross section \(\sigma_{tot}\) of the process \(e^+e^- \rightarrow t \bar{c}\) as a function of the centre of mass energy \(\sqrt{s}\). One can see from the figure that the total cross section is the order of \(10^{-10} \sim 10^{-9} \text{ fb}\), as expected, and decreases when center-of-mass energy increases and is large enough (\(\geq 250 \text{ Gev}\)). We fixed the centre of mass energy \(\sqrt{s}\) at 200 Gev. Differential cross section of the process at the energy as a function of \(\cos \theta\) is shown in Fig. 3.

To summarize, we have calculated the production cross sections of the process \(e^+e^- \rightarrow t \bar{c}\) in SM. We found that the total cross section is \(1.84 \times 10^{-9} \text{ fb}\) at \(\sqrt{s} = 200 \text{ Gev}\) and \(0.572 \times 10^{-9} \text{ fb}\) at \(\sqrt{s} = 500 \text{ Gev}\). It is too small to be of experimental relevance. Therefore, this is a remarkable situation that allows for a precise test of the SM and, in particular, of the GIM mechanism in SM. Even a small number of \(t \bar{c}\) events, detected at LEP II or a NLC running with a yearly integrated luminosity of \(\mathcal{L} \geq 10^2 [\text{fb}]^{-1}\), will unambiguously indicate new FCNC dynamics beyond SM.
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FIG. 1. Feynman diagrams of process $e^+e^- \rightarrow t\bar{c}$
FIG. 2. Cross section of the process $e^+e^- \rightarrow t\bar{c}$ as a function of $\sqrt{s}$. 
FIG. 3. Differential cross section of the process $e^+e^- \rightarrow t\bar{c}$, where $\sqrt{s} = 200$ GeV.