Z′tc coupling from D^0 – D^0̅ mixing

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Abstract. We bound the Z′tc coupling using the D^0 – D^0̅ meson mixing system. We obtained such coupling which is less than 5.75 × 10^{-2}. We have studied the Z′ boson resonance considering single top production in the e^+e^- → Z′ → tc process. We obtained the number of events which is expected to be less than 10^7 at the International Linear Collider scenario. We get a branching ratio of the order of 10^{-2} for the Z′ → tc decay.

1. Introduction.
Many extensions of the Standard Model (SM) predict the existence of an extra U′(1) gauge symmetry group and its associated Z′ boson which has been object of extensive phenomenological studies [1]. This boson can induce flavor changing neutral currents (FCNC) at tree level through Z′q_iq_j couplings where q_i and q_j are up or down-type quarks. The flavor-violating parameters must fulfill experimental constraints on FCNC [2]. We focus on the Z′ virtual effects we may analyze the impact of the FCNC through the single top quark production. We can use the mass difference ∆M_D of the D^0 – D^0̅ mixing observed by the Babar and Belle collaborations to bound the strength of these couplings.

2. The Z′tu_i couplings.
The FCNC Lagrangian contained in the SU_C(3) × SU_L(2) × U_Y(1) × U′(1) group is given by

\[ \mathcal{L}_{NC} = -eJ_{EM}^\mu A_\mu - g_1 J_1^\mu Z_{\mu,1} - g_2 J_2^\mu Z_{\mu,2}. \]  

(1)

J_1^\mu is the weak neutral current and J_2^\mu represents the new weak neutral current given as

\[ J_2^\mu = \sum_{i,j} \bar{\psi}_i^\prime \gamma^\mu (\epsilon_{L ij} P_L + \epsilon_{R ij} P_R) \psi_j^\prime. \]  

(2)

Since the interaction between the bosons Z_1 and Z_2 is too weak to be considered, there is no mixing between them, consequently their mass eigenstates are Z^0 and Z′ respectively. Let us consider the \( \epsilon_{L,R ij} \) matrix for the sector of quarks type up. Some models assume this matrix as flavor diagonal and non-universal. The FCNC couplings in the mass eigenstates basis can be read off as

\[ \Omega_{L ij} = g_2 (V_L \epsilon_{L}^i V_L^\dagger)_{ij}, \quad \Omega_{R ij} = g_2 (V_R \epsilon_{R}^i V_R^\dagger)_{ij}. \]  

(3)
3. Bounding the $Z' tc$ couplings from $D^0 - \bar{D}^0$.

The Lagrangian containing the relevant information is

$$L_{NC}^{Z'q_iq_j} = -\overline{u}\gamma^\mu(\Omega_{Lac}P_L + \Omega_{Ruc}P_R)c + \overline{c}\gamma^\mu(\Omega_{Lcu}P_L + \Omega_{Rtu}P_R)u$$
$$+ \overline{u}\gamma^\mu(\Omega_{Ldt}P_L + \Omega_{Rct}P_R)t + \overline{t}\gamma^\mu(\Omega_{Ltc}P_L + \Omega_{Rtc}P_R)c$$

(4)

From the unitary property of the $V_{L,R}$ matrices

$$|\Omega_{uc}| \approx |\Omega_{ut}| \Omega_{ct},$$

(5)

provided that $\epsilon_{tt} \ll 1$. For simplicity we assume $\Omega$'s as real and $\Omega_{L,Rq_iq_j} = \Omega_{Rq_iq_j} \equiv \Omega_{q_iq_j}$. The tree-level amplitude can be written as

$$M_{\text{tree}} = -\frac{i\Omega_{uc}^2 m_{Z'}^2}{m_{Z'}^2} \overline{u}\gamma^\alpha c \overline{c}\gamma^\alpha c.$$

(6)

$M_{\text{tree}}$ amplitude can be related to a four-quark effective vertex accounted by the effective Lagrangian:

$$L_{\text{tree}}^{\text{eff}} = -\frac{\Omega_{uc}^2}{4m_{Z'}^2} (Q_1 + 2Q_2 + Q_6),$$

(7)

where a 1/4 factor has been introduced to compensate Wick contractions. The $Q_i$ are dimension-six effective operators.

Analogously, the one-loop level amplitude is given by:

$$M_{\text{box}} = 2\Omega_{tu}^2 \Omega_{tc}^2 \int \frac{d^4k}{(2\pi)^4} \frac{[\overline{u}\gamma^\lambda (k^\alpha \gamma_\alpha + m_t) \gamma^\nu c][\overline{c}\gamma_\nu (k^\alpha \gamma_\alpha + m_t) \gamma_\lambda c]}{(k^2 - m_t^2)^2(k^2 - m_{Z'}^2)^2}.$$  

(8)

After some algebra we arrive at the $M_{\text{box}}$ amplitude which can be related to a four-quark effective vertex accounted by the effective Lagrangian:

$$L_{\text{eff}}^{\text{box}} = -\frac{\Omega_{tu}^2 \Omega_{tc}^2}{64\pi^2 m_t^4} \left[f(x) (4Q_1 + 32Q_2 + 4Q_6) + g(x) (8Q_3 + 4Q_4 + Q_5 + 4Q_7 + Q_8)\right],$$

(9)

where a 1/4 factor has been introduced to compensate Wick contractions; $f(x)$ and $g(x)$ are loop functions given as

$$f(x) = \frac{1}{2} \frac{1}{(1-x)^3} [1 - x^2 + 2x \log x], \quad g(x) = \frac{2}{(1-x)^4} [2(1-x) + (1+x) \log x].$$

(10)
with \( x = m^2_{Z'}/m^2_1 \). The mass difference \( \Delta M_D \) provided by the \( D^0 - \bar{D}^0 \) meson-mixing system is \( \Delta M_D = \frac{1}{M_D} \text{Re}(\overline{D}D) |H_{eff}| = -\mathcal{L}_{eff} |D^0| \). The effective Lagrangian is \( \mathcal{L}_{eff} = \mathcal{L}_{eff}^{tree} + \mathcal{L}_{eff}^{box} \) and \( M_D \) is the \( D^0 \) meson mass. Using the modified vacuum saturation approximation \[3\] we have:

\[
\Delta M_D = \frac{\Omega_{uc}^2 f_D^2 M_D B_D}{12 m^2_{Z'}} \left[ 1 + \frac{x}{8\pi^2} \left( 32 f(x) - 5g(x) \right) \right],
\]

(11)

We used the relation in \[4\], \( B_D \) is the bag model parameter and \( f_D \) represents the \( D^0 \) meson decay constant. We can see from Eqs. (7), (9) and (11) that the main contribution to \( \Delta M_D \) comes from the tree-level amplitude while the contribution coming from the box amplitude is of approximately 17%-19% in the range of 800 GeV \( \leq m_{Z'} \leq 3000 \) GeV. Taking \( B_D \sim 1 \), \( f_D = 222.6 \) MeV and \( M_D = 1.8646 \) GeV and considering that \( \Delta M_D \) does not exceed the experimental uncertainty

\[
|\Omega_{uc}| < \frac{3.6 \times 10^{-7} m_{Z'} \text{GeV}^{-1}}{\sqrt{1 + \frac{x}{8\pi^2} (32 f(x) - 5g(x))}},
\]

(12)

Taking \( m_{Z'} = 1 \) TeV we obtain a bound \( |\Omega_{uc} \Omega_{ta}| < 3.31 \times 10^{-4} \), moreover, we assume that

\[\Omega_{tc} = 10 \Omega_{ta},\]

as it occurs for the absolute values of \( U_{ts}, U_{td} \) elements in the CKM matrix. We found that \( |\Omega_{tc}| < 5.75 \times 10^{-2} \) and \( |\Omega_{ta}| < 5.75 \times 10^{-3} \), which are of the same order of magnitude approximately than those obtained in Ref. \[5\].

4. The process \( e^+e^- \rightarrow Z' \rightarrow tc \) at ILC collider.

We only take the average of the chiral charges; the different values for the charges are: \( Q^L_u = 0.3456, Q^u_R = -0.1544, Q^d_L = -0.4228, Q^d_R = 0.0772, Q^e_L = 0.2684, Q^e_R = 0.2316 \) and \( Q^\nu_R = 0.5 \) for the Sequential Z model; \( Q^L_u = \frac{1}{\sqrt{24}}, Q^u_R = \frac{1}{\sqrt{24}}, Q^d_L = \frac{1}{\sqrt{24}}, Q^d_R = \frac{1}{\sqrt{24}}, Q^e_L = \frac{1}{\sqrt{24}}, Q^e_R = \frac{1}{\sqrt{24}} \) and \( Q^{\nu_R} = \frac{1}{\sqrt{24}} \) for the \( E_6 \) model; \( Q^L_u = 0.2749, Q^u_R = -0.1793, Q^d_L = -0.1093, Q^d_R = -0.0635, Q^e_L = -0.0321, Q^e_R = 0.0137 \) and \( Q^{\nu_R} = 0.3521 \) for Average model \[4\].

The Breit-Wigner resonant cross section is \( \sigma(e^+e^- \rightarrow Z' \rightarrow tc) = \frac{12 \pi m^2_{Z'} \Gamma(Z' \rightarrow e^+e^-) \Gamma(Z' \rightarrow tc)}{(s - m^2_{Z'})^2 + m^2_{Z'} \Gamma^2_{Z'}} \).

For the decay width \( \Gamma(Z' \rightarrow tc) \) we obtain \( \Gamma(Z' \rightarrow tc) = \frac{(2m^2_{Z'} - m^2_1 - m^2_2) \Omega_{uc}^2}{12 \pi m^2_{Z'}} \).

We can predict around \( 10^7 \) events just at the resonance for the \( E_6 \) model. For the sequential Z model it is expected to obtain around \( 10^6 \) events. For the average of the two models, it is expected around \( 10^5 \) events. We obtain that the associated branching ratio is of the order of \( 10^{-2} \). The production of around \( 10^5 \) \( tc \) events predicted in Ref. \[3\], or similar results in Ref. \[5\],

![Figure 2](image-url)
Figure 3. Cross section for $e^+e^- \rightarrow Z' \rightarrow tc$ process as a function of $\sqrt{s}$ for $m_{Z'} = 1$ TeV.

Figure 4. The branching ratio for $Z' \rightarrow tc$ decay.

predicted for the Compact Linear Collider calculated at the resonance, can be compared with our predictions and find that ours are bigger in 1 and 3 orders of magnitude for the average and the $E_6$ model, respectively. We found that it will be produced around $10^3$ $tc$ events for a Higgs mass of the order of top quark mass, which is two orders of magnitude less than the average prediction, calculated at the resonance. In relation to the values we have found for the branching ratios $Br(Z' \rightarrow tc) \sim 10^{-2}$ and $Br(Z' \rightarrow tu) \sim 10^{-4}$ calculated at the resonance, we can mention that these values are one order of magnitude less restrictive than corresponding branching ratios obtained in the model 3-3-1 [6].

5. Conclusions.
We have bounded the strength of the flavor-violating $Z'tc$ coupling using the experimental results coming from the $D^0 - \bar{D}^0$ meson mixing system. For a $m_{Z'} = 1$ TeV we found that $|\Omega_{tc}| < 5.75 \times 10^{-2}$. We have calculated the cross section for the $e^+e^- \rightarrow Z' \rightarrow tc$ process in the ILC collider scenario; where we found an estimation around $10^7$ events for a luminosity of 500 fb$^{-1}$ in the context of $Z'$ boson predicted by the $E_6$ model. According to our results the $tc$ flavor violation effect mediated by a $Z'$ boson from the $E_6$ model is more favorable of being observed than that predicted in the sequential model one. This behavior is also repeated for the branching ratio of the $Z' \rightarrow tc$ decay.

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