$Z'tc$ coupling from $D^0 - \overline{D^0}$ mixing

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Abstract. We bound the $Z'tc$ coupling using the $D^0 - \overline{D^0}$ 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 $e^+e^- \to Z' \to tc$ 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 $Z' \to tc$ 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 ΔM_D of the $D^0 - \overline{D^0}$ 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 $SU_C(3) \times SU_L(2) \times U_Y(1) \times U'(1)$ group is given by

$$\mathcal{L}_{NC} = -eJ^\mu_{EM} A_\mu - g_1 J^\mu_1 Z_{\mu,1} - g_2 J^\mu_2 Z_{\mu,2}. \quad (1)$$

J^μ_1 is the weak neutral current and J^μ_2 represents the new weak neutral current given as

$$J^\mu_2 = \sum_{i,j} \overline{\psi'_i}\, \gamma^\mu (\epsilon^\psi_{Lij}\, P_L + \epsilon^\psi_{Rij}\, P_R)\, \psi'_j. \quad (2)$$

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 $\epsilon^u_{L,Rij}$ 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

$$\Omega_{Lij} = g_2\, (V_L\, \epsilon^u_L\, V^\dagger_L)_{ij}, \;\; \Omega_{Rij} = g_2\, (V_R\, \epsilon^u_R\, V^\dagger_R)_{ij}. \quad (3)$$

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

The Lagrangian containing the relevant information is

$$\begin{aligned}\mathcal{L}_{NC}^{Z'q_iq_j} =& -\big[\overline{u}\,\gamma^\mu(\Omega_{Luc}\,P_L + \Omega_{Ruc}\,P_R)\,c + \overline{c}\,\gamma^\mu(\Omega_{Lcu}\,P_L + \Omega_{Rcu}\,P_R)\,u \\ &+ \overline{u}\,\gamma^\mu(\Omega_{Lut}\,P_L + \Omega_{Rut}\,P_R)\,t + \bar{t}\,\gamma^\mu(\Omega_{Ltu}\,P_L + \Omega_{Rtu}\,P_R)\,u \\ &+ \overline{c}\,\gamma^\mu(\Omega_{Lct}\,P_L + \Omega_{Rct}\,P_R)\,t + \bar{t}\,\gamma^\mu(\Omega_{Ltc}\,P_L + \Omega_{Rtc}\,P_R)\,c\big]\,Z'_\mu. \end{aligned} \tag{4}$$

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

$$|\Omega_{uc}| \approx |\Omega_{ut}\Omega_{ct}|, \tag{5}$$

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

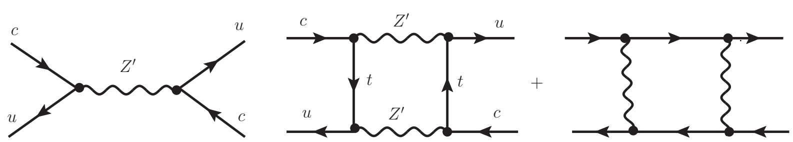
$$\mathcal{M}_{\text{tree}} = -\frac{i\Omega_{uc}^2}{m_{Z'}^2}\;\overline{u}\gamma^\alpha c\;\overline{u}\gamma_\alpha c. \tag{6}$$

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

$$\mathcal{L}_{eff}^{\text{tree}} = -\frac{\Omega_{uc}^2}{4m_{Z'}^2}\,(Q_1 + 2Q_2 + Q_6)\,, \tag{7}$$

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:



(a) (b)

Figure 1. (a) Tree diagram;(b) Box diagrams for $D^0 - \overline{D^0}$ mixing.

$$\mathcal{M}_{\text{box}} = 2\,\Omega_{tu}^2\,\Omega_{tc}^2 \int \frac{d^4k}{(2\,\pi)^4}\,\frac{[\overline{u}\,\gamma^\lambda\,(k^\alpha\gamma_\alpha + m_t)\,\gamma^\nu\,c]\,[\overline{u}\,\gamma_\nu\,(k^\alpha\gamma_\alpha + m_t)\,\gamma_\lambda\,c]}{(k^2 - m_t^2)^2(k^2 - m_{Z'}^2)^2}. \tag{8}$$

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

$$\mathcal{L}_{eff}^{\text{box}} = -\frac{\Omega_{tu}^2\,\Omega_{tc}^2}{64\pi^2 m_t^2}\,\big[f(x)\,(4Q_1 + 32Q_2 + 4Q_6) + g(x)\,(8Q_3 + 4Q_4 + Q_5 + 4Q_7 + Q_8)\big], \tag{9}$$

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

$$f(x) = \frac{1}{2}\,\frac{1}{(1-x)^3}\,[1 - x^2 + 2\,x\,\log x], \quad g(x) = \frac{2}{(1-x)^3}\,[2(1-x) + (1+x)\,\log x]. \tag{10}$$

with $x = m_{Z'}^2/m_t^2$. The mass difference ΔM_D provided by the $D^0 - \overline{D^0}$ meson-mixing system is $\Delta M_D = \frac{1}{M_D} Re\langle \overline{D^0}|\mathcal{H}_{eff} = -\mathcal{L}_{eff}|D^0\rangle$. The effective Lagrangian is $\mathcal{L}_{eff} = \mathcal{L}_{eff}^{\rm tree} + \mathcal{L}_{eff}^{\rm box}$ and M_D is the D^0 meson mass. Using the modified vacuum saturation approximation [4] we have:

$$\Delta M_D = \frac{\Omega_{uc}^2 f_D^2 M_D B_D}{12 m_{Z'}^2}\left[1 + \frac{x}{8\pi^2}\left(32f(x) - 5g(x)\right)\right], \qquad (11)$$

We used the relation in (5), 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 ΔM_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 ΔM_D does not exceed the experimental uncertainty

$$|\Omega_{uc}| < \frac{3.6\times 10^{-7} m_{Z'} \mathrm{GeV}^{-1}}{\sqrt{1 + \frac{x}{8\pi^2}\left(32f(x) - 5g(x)\right)}}, \qquad (12)$$

Taking $m_{Z'} = 1$ TeV we obtain a bound $|\Omega_{tc}\Omega_{tu}| < 3.31 \times 10^{-4}$, moreover, we assume that

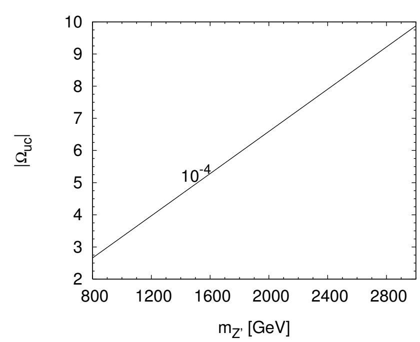


Figure 2. Behavior of $|\Omega_{uc}|$ coupling as a function of Z' boson mass.

$\Omega_{tc} = 10\,\Omega_{tu}$, 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 $|\Omega_{tu}| < 5.75\times 10^{-3}$, which are of the same order of magnitude approximately than those obtained in Ref. [3].

4. The process $e^+e^- \to Z' \to tc$ at ILC collider.

We only take the average of the chiral charges; the different values for the charges are: $Q_L^u = 0.3456$, $Q_R^u = -0.1544$, $Q_L^d = -0.4228$, $Q_R^d = 0.0772$, $Q_L^e = -0.2684$, $Q_R^e = 0.2316$ and $Q_L^\nu = 0.5$ for the Sequential Z model; $Q_L^u = \frac{1}{\sqrt{24}}$, $Q_R^u = \frac{-1}{\sqrt{24}}$, $Q_L^d = \frac{1}{\sqrt{24}}$, $Q_R^d = \frac{-1}{\sqrt{24}}$, $Q_L^e = \frac{1}{\sqrt{24}}$, $Q_R^e = \frac{-1}{\sqrt{24}}$ and $Q_L^\nu = \frac{1}{\sqrt{24}}$ for E_6 model; $Q_L^u = 0.2749$, $Q_R^u = -0.1793$, $Q_L^d = -0.1093$, $Q_R^d = -0.0635$, $Q_L^e = -0.0321$, $Q_R^e = 0.0137$ and $Q_L^\nu = 0.3521$ for Average model [4].

The Breit-Wigner resonant cross section is $\sigma(e^+e^- \to Z' \to tc) = \frac{12\,\pi\, m_{Z'}^2}{s}\frac{\Gamma(Z'\to e^+e^-)\,\Gamma(Z'\to tc)}{(s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2}$.

For the decay width $\Gamma(Z' \to tc)$ we obtain $\Gamma(Z' \to tc) = \frac{\left(2m_{Z'}^4 - m_t^4 - m_{Z'}^2 m_t^2\right)\Omega_{tc}^2}{12\,\pi\, m_{Z'}^3}$.

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 10^4 tc events predicted in Ref. [3], or similar results in Ref. [5],

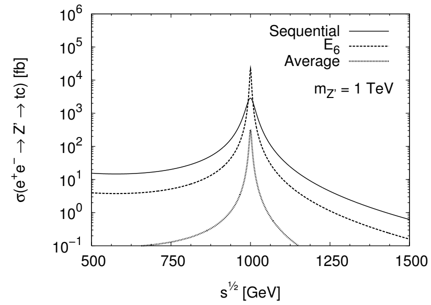


Figure 3. Cross section for $e^+e^- \to Z' \to tc$ process as a function of $\sqrt{s}$ for $m_{Z'} = 1$ TeV.

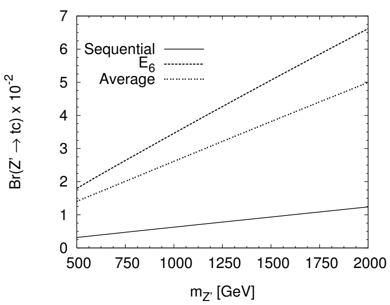


Figure 4. The branching ratio for $Z' \to tc$ decay.

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 $Br(Z' \to tc) \sim 10^{-2}$ and $Br(Z' \to tu) \sim 10^{-4}$ 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 $D^0 - \overline{D^0}$ 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 $e^+e^- \to Z' \to tc$ 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 $Z' \to tc$ decay.

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