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Constraints on top-quark flavor changing neutral couplings from electroweak precision measurements

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We study the one-loop contributions of the effective flavor changing neutral couplings (FCNC) tcZ, tcH, and $tc\gamma$ on the electroweak precision observables Γ_Z, R_c, R_b, R_ℓ, A_c, and A_c^{FB}, as well as the oblique parameters S and T. Using the known experimental limits on these observables, we may place 95% C.L. bounds on these FCNC couplings which in turn translate into the following limits for the branching ratios $\mathrm{BR}(t \to cZ) \leq 1.6 \times 10^{-2}$ and $\mathrm{BR}(t \to cH) \leq (0.09 - 2.8) \times 10^{-3}$ for $114 \leq m_H \leq 170$ GeV.

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As soon as it was confirmed that the flavor changing neutral couplings (FCNC) of the top quark are highly suppressed in the standard model (SM) [1], it was realized that some of its FCNC decay modes can be enhanced by several orders of magnitude in scenarios beyond the SM [2–4]. Top-quark FCNC decays have been studied in models with supersymmetry [5], in two Higgs doublet models [6], in models with extra quark singlets [7], in technicolor models with a dynamical breakdown of the electroweak symmetry [8], as well as in left-right symmetric models [9]. Direct searches for FCNC decays by CDF have set the bounds $\mathrm{BR}(t \to q\gamma) < 0.032$ and $\mathrm{BR}(t \to qZ) < 0.33$ at 95% C. L. [10]. Indirect searches at HERA and LEP have set similar limits [11].

On the other hand, the use of effective Lagrangians in parametrizing physics beyond the SM has been exploited extensively in FCNC top-quark couplings and decays [12,13]. This formalism generates a model-independent parametrization of any new physics characterized by higher dimension operators. The use of this method has proved to be effective in the study of anomalous couplings of vector gauge bosons [14] and the top quark [15,16]. Also, the effective Lagrangian technique has been used to get limits on the new-physics scale Λ from the oblique parametersS, T, U [13,17]. Under this approach several FCNC transitions have been significantly constrained like $\ell_i \to \ell_j \gamma$ [16] and $H \to \ell_i \ell_j$ [18]. Of particular interest for the subject matter of the present paper is that known data on the low-energy decays $Z \to b\bar{b}$, and $b \to s\gamma$ were used to get the FCNC top-quark constraints $\mathrm{BR}(t \to c\gamma) \leq 1.3 \times 10^{-3}$, $\mathrm{BR}(t \to cg) \leq 3.4 \times 10^{-2}$, and $\mathrm{BR}(t \to cZ) \leq 5.0 \times 10^{-2}$ [13,14,16,19] .

In the present paper we are interested in getting the constraints imposed by the electroweak precision observables $\Gamma_Z, R_c, R_b, R_\ell, A_c$ on the FCNC transitions $t \to cZ, cH, c\gamma$. In order to perform a χ^2 fit at 95% C. L., we will compute the one-loop contributions of the $tcZ(\gamma)/H$ couplings to $Z \to c\bar{c}, b\bar{b}$ partial widths which in turn will induce corrections to the above observables. We will find that the known values of these observables place constraints on the FCNC transitions $t \to cZ$ and $t \to cH$, but not so much on the $t \to c\gamma$ decay. We will also analyze the constraints on $t \to cZ$ coming from the experimental fit of the S and T parameters.

We will use the following effective Lagrangian to parametrize the FCNC of the top quark [20]:

$$\begin{aligned}\mathcal{L} = \bar{t}\Big\{&\frac{ie}{2m_t}(\kappa_{tq'\gamma} + i\tilde{\kappa}_{tq'\gamma}\gamma_5)\sigma_{\mu\nu}F^{\mu\nu} \\ &+ \frac{i}{2m_t}(\kappa_{tq'Z} + i\tilde{\kappa}_{tq'Z}\gamma_5)\sigma_{\mu\nu}Z^{\mu\nu} \\ &+ \frac{g}{2c_w}\gamma_\mu(v_{tq'Z} + a_{tq'Z}\gamma_5)Z^\mu \\ &+ \frac{g}{2\sqrt{2}}(h_{tq'H} + i\tilde{h}_{tq'H}\gamma_5)H\Big\}q'. \end{aligned} \quad (1)$$

The one-loop contributions of the $tcZ(\gamma)$ and tcH couplings to the decay mode $Z \to c\bar{c}$ are shown in Fig. 1. The operator tcZ also contributes to $Z \to b\bar{b}$; its contribution is taken from Ref. [13]. Even though the anomalous vertices enter in the Feynman diagrams in Fig. 1(a)–1(c) as a second order perturbation, the known limits on the precision observables impose some constraints on the couplings $tcZ(\gamma)/tcH$. However, this is not the case for the magnetic-dipole type couplings $tcZ(\gamma)$ since their respective contributions are suppressed by an additional $1/m_t$ factor.

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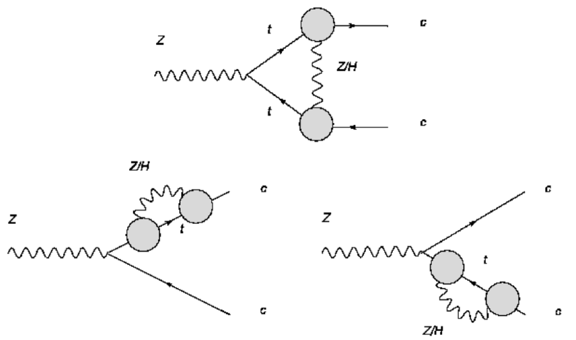

FIG. 1. Feynman diagrams for the one-loop contribution of the FCNC $tcZ(\gamma)/H$ vertices to the decay modes $Z \to c\bar{c}$.

The partial width for the decay mode $Z \to c\bar{c}$ may be expressed in the following form after including the one-loop corrections induced by the $tcZ(\gamma)/tcH$ couplings,

$$\Gamma(Z \to c\bar{c}) = \Gamma(Z \to c\bar{c})_{\mathrm{SM}}(1 + \delta_{NP}^{Z/H}), \tag{2}$$

where the Z and H one-loop corrections are given by

$$\delta_{NP}^{Z/H} = 2\left[\frac{g_V^{\mathrm{SM}}\delta g_V^{Z/H} + g_A^{\mathrm{SM}}\delta g_A^{Z/H}}{(g_V^{\mathrm{SM}})^2 + (g_A^{\mathrm{SM}})^2}\right], \tag{3}$$

with $g_{V/A}^{\mathrm{SM}}$ the SM couplings of the Z gauge boson to the c quark and

$$\begin{aligned} \delta g_{V,A}^Z &= \mathrm{Re}[g_l^2 F_L \pm g_r^2 F_R], \\ \delta g_{V,A}^H &= \mathrm{Re}[h_l h_r (H_L \pm H_R)]. \end{aligned} \tag{4}$$

In the above expressions, we have used the definitions

$$g_{r/l} = \frac{i}{2c_W}(v_{tcZ} \pm a_{tcZ}), \qquad h_{r/l} = \frac{1}{2\sqrt{2}}(h_{tcH} \mp i\tilde{h}_{tcH}), \tag{5}$$

and the functions $F_{L/R}$ and $H_{L/R}$ are given in terms of Veltman-Passarino functions and the dimensionless variables $x_t = m_t/m_Z$ and $x_H = m_H/m_Z$,

$$\begin{aligned} F_L = \frac{g^2}{12\pi^2}\bigg\{&(-3 + 4s_w^2)\bigg[-3B_o(0, m_t, m_Z) \\ &+ 2B_o(m_Z^2, m_t, m_t) + B_1(0, m_t, m_Z) \\ &+ B_1(m_Z^2, m_t, m_t) + x_t(B_o(0, m_t, m_Z) \\ &- B_o(m_Z^2, m_t, m_t)) - \frac{1}{2}\bigg] + x_t(12 - 12s_W^2 \\ &- x_t(3 - 4s_W^2))C_o(x_t)\bigg\}, \\ F_R = \frac{g^2}{12\pi^2}\{&s_W^2[1 + 2B_1(0, m_t, m_Z) - 2B_1(m_Z^2, m_t, m_t) \\ &+ 2x_t(B_o(m_Z^2, m_t, m_t) - B_o(0, m_t, m_Z))] \\ &+ (2s_W^2(3 + 2x_t - x_t^2) - 3x_t)C_o(x_t)\}, \end{aligned} \tag{6}$$

$$\begin{aligned} H_L = \frac{g^2}{96\pi^2 c_W}\bigg\{&(3 - 4s_W^2)[B_0(0, m_t, m_Z) \\ &- B_0(m_Z^2, m_t, m_t) + B_1(m_Z^2, m_t, m_t) - B_1(0, m_t, m_Z) \\ &+ (x_t - x_H - 1)(B_o(0, m_t, m_Z) - B_o(m_Z^2, m_t, m_t)) \\ &+ (x_t - x_H)^2 C_o(x_H) - \frac{1}{2}\bigg] + \frac{4}{3}x_t s_W^2 C_o(x_H)\bigg\}, \\ H_R = \frac{g^2}{96\pi^2 c_W}\{&-4s_W^2[B_o(0, m_t, m_Z) - B_o(m_Z^2, m_t, m_t) \\ &- B_1(m_Z^2, m_t, m_t) - B_1(0, m_t, m_Z) \\ &+ (x_t - x_H - 1)(B_o(0, m_t, m_Z) - B_o(m_Z^2, m_t, m_t)) \\ &+ ((x_t - x_H)^2 - x_t)C_o(x_H)] + 3x_t C_o(x_H)\}. \end{aligned} \tag{7}$$

The direct correction to $\Gamma(Z \to b\bar{b})$ induced by the dimension 4 tcZ coupling has been considered by Han *et al.* [13]. Even though this diagram has only one FCN vertex, its contribution is suppressed by the V_{cb} matrix element, and as a result, it will be of similar importance as that coming from the diagrams in Fig. 1(a)–1(c). The SM values of the electroweak observables adquire the following deviations:

$$\begin{aligned} \Gamma_Z &= \Gamma_Z^{\mathrm{SM}}[1 + \mathrm{BR}^{\mathrm{SM}}(Z \to c\bar{c})\delta_{NP}^{Z/H} \\ &\quad + \mathrm{BR}^{\mathrm{SM}}(Z \to b\bar{b})\delta_{NP}^{Z,b}], \\ \Gamma_{\mathrm{had}} &= \Gamma_{\mathrm{had}}^{\mathrm{SM}}[1 + R_c^{\mathrm{SM}}\delta_{NP}^{Z/H} + R_b^{\mathrm{SM}}\delta_{NP}^{Z,b}], \\ R_c &= R_c^{\mathrm{SM}}[1 + (1 - R_c^{\mathrm{SM}})\delta_{NP}^{Z/H} - R_b^{\mathrm{SM}}\delta_{NP}^{Z,b}], \\ R_b &= R_b^{\mathrm{SM}}(1 - R_c^{\mathrm{SM}}\delta_{NP}^{Z/H} - (1 - R_b^{\mathrm{SM}})\delta_{NP}^{Z,b}), \\ R_\ell &= R_\ell^{\mathrm{SM}}(1 + R_c^{\mathrm{SM}}\delta_{NP}^{Z/H} + R_b^{\mathrm{SM}}\delta_{NP}^{Z,b}), \\ A_c &= A_c^{\mathrm{SM}}\left(1 + \frac{\delta g_V^{Z/H}}{g_V^{\mathrm{SM}}} + \frac{\delta g_A^{Z/H}}{g_A^{\mathrm{SM}}} - \delta_{NP}^{Z/H}\right), \\ A_{FB}^c &= A_{FB}^{c,\mathrm{SM}}\left(1 + \frac{\delta g_V^{Z/H}}{g_V^{\mathrm{SM}}} + \frac{\delta g_A^{Z/H}}{g_A^{\mathrm{SM}}} - \delta_{NP}^{Z/H}\right). \end{aligned} \tag{8}$$

We have taken for $\delta_{Np}^{Z,b}$ the contribution obtained in Ref. [13] to the partial decay width $Z \to b\bar{b}$ by the Ztc vertex, which modifies only the terms proportional to g_ℓ in $\Gamma(Z \to b\bar{b})$. On the other hand, we have calculated the contribution of the dimension 5 $tcZ(\gamma)$ operators. They induce corrections to $\Gamma(Z \to c\bar{c})$ but these are suppressed by a factor of the order of $(m_z/m_t)^4$ with respect to the corrections arising from the dimension 4 operators (see Eq. (1)). One $1/m_t^2$ factor is coming from the mass scale factor of the dimension-5 operator. The other $1/m_t^2$ comes from the chirality flip in the triangle diagram when the dimension-4 operator is used. There is no chirality flip when the dimension-5 one is taken into account. In other processes, like $b \to s\gamma$, the contributions of the dimension 5 operator are of the same order as those of the dimension 4 operator. In contrast to $Z \to c\bar{c}$, in $b \to s\gamma$ another Feynman diagram appears where the photon is coming

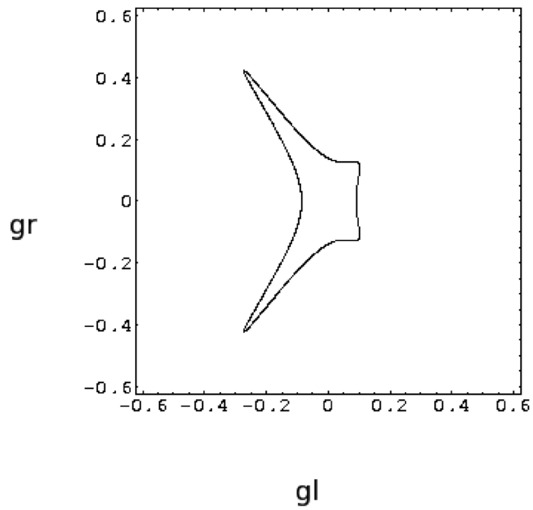

FIG. 2. A 95% C. L. fit on the bounds of the dimension 4 tcZ coupling obtained from the current values for the electroweak precision observables shown in Eq. (8).

from an internal boson line. For this diagram there is chirality flip when dimension 5 operator is used [21].

We now use the values given by the Particle Data Group [22] for the observables of Eq. (8). By doing a χ^2 fit, and taking into account the correlation matrix [23] we obtain the 95% C. L. limits for the tcZ and the tcH couplings. In Fig. 2 the allowed parameter region in the g_l–g_r plane is shown. We can compare with the recent limits obtained by the DELPHI Collaboration [24] on the tcZ coupling coefficient $\kappa_Z = 2c_w\sqrt{g_r^2 + g_l^2}$. For $\kappa_\gamma = 0$ DELPHI's upper limit $\kappa_Z \leq 0.4$ is the same as ours. On the other hand, a similar analysis based on the tcZ contribution to FCNC processes like $B \rightarrow l^+ l^- X$ has put a stringent constraint on g_l ($\kappa_L \leq 0.05$) [13]. Not so much for g_r ($\kappa_R \leq 0.29$), for which the constraint comes from its contribution to the oblique parameters [13]. When computing the contribution of tcZ to $b \rightarrow l^+ l^- X$ one single triangle diagram is considered (in the unitary gauge) where the FCNC coupling appears only once, and this makes this process more sensitive to the anomalous vertex. Our analysis puts similar bounds on the right handed tcZ coupling and it is based on a different set of variables than the ones considered by Ref. [13].

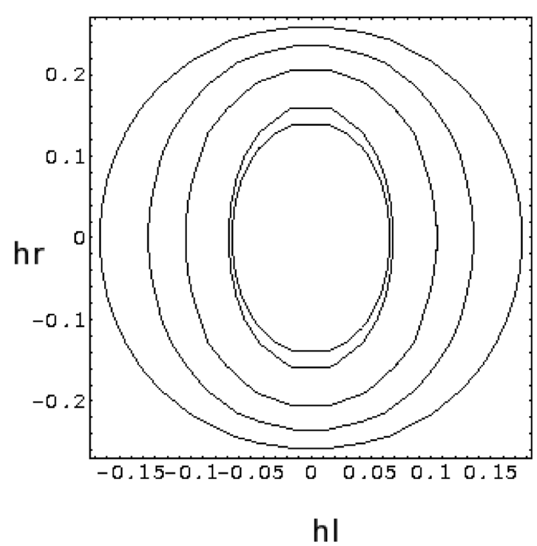

FIG. 3. A 95% C. L. fit on the bounds of the dimesion 4 tcH coupling obtained from the current values of the electroweak precision observables shown in Eq. (8). Upper limits from inner to outer contour line correspond to the following values of the Higgs boson mass: 114, 130, 145, 160, and 170 GeV.

In Fig. 3 we depict the contours for the 95% C. L. upper limits on the tcH coupling for a selection of intermediate Higgs boson masses. The upper limits obtained for the tcZ/tcH couplings can be translated into constraints on the respective branching ratios of the FCNC decay modes using the expressions

$$\Gamma(t \rightarrow cZ) = \frac{\alpha m_t (1 - x_Z^2)^2 (1 + 2x_Z^2)[g_l^2 + g_r^2]}{8 s_W^2 x_Z^2},$$
$$\Gamma(t \rightarrow cH) = \frac{\alpha m_t}{8 s_W^2}(1 - m_H^2/m_t^2)^2 [h_l^2 + h_r^2] \quad (9)$$

where $x_Z = m_Z/m_t$.

Finally, using the known expression for the SM decay width of the top quark $\Gamma_t \cong \Gamma(t \rightarrow bW) = 1.6$ GeV, and the limits of Figs. 2 and 3 we obtain the following bounds on the FCNC decay modes of the top quark:

$$\mathrm{BR}(t \rightarrow cZ) \leq 6.7 \times 10^{-2},$$
$$\mathrm{BR}(t \rightarrow cH) \leq 0.9 \times 10^{-4}, \qquad (m_H = 170 \text{ GeV})$$
$$\mathrm{BR}(t \rightarrow cH) \leq 2.9 \times 10^{-3}, \qquad (m_H = 114 \text{ GeV}). \quad (10)$$

Let us now consider the corrections to the S and T oblique parameters. According to Ref. [13] the contributions of tcZ to both S and T are negative:

$$\Delta\rho = \alpha(M_Z^2) T = -\frac{3c_w^2}{2\pi^2}(g_l^2 + g_r^2)\frac{m_t^2}{v^2}\ln\frac{\Lambda^2}{m_t^2},$$
$$\frac{\alpha(M_Z^2)}{4s_w^2 c_w^2} S = -\frac{g^2}{4\pi^2}(g_l^2 + g_r^2)\ln\frac{\Lambda^2}{m_t^2}. \quad (11)$$

By taking $\ln\Lambda^2/m_t^2 = 4$, and the 95% C. L. limits on $S \geq -0.4$ and $T \geq -0.3$ for $m_H = 300$ GeV [22], we obtain

$$\sqrt{g_l^2 + g_r^2} \leq 0.11, \qquad \mathrm{BR}(t \rightarrow cZ) \leq 1.6 \times 10^{-2}. \quad (12)$$

As mentioned above, the upper limit on $\mathrm{BR}(t \rightarrow cZ)$ based on the observables $\Gamma_Z, R_c, R_b, R_\ell, A_c$ and A_c^{FB}, is similar to the recently reported by the DELPHI collaboration. This limit is further improved when we consider the corrections to the oblique parameters S and T. On the other hand, the limit on tcH can be used as a test against some possible beyond the SM contributions that could be of order 10^{-3} to 10^{-1} [3]. Some extensions of the SM with nonuniversal couplings to fermions can give sizeable tcH couplings [2]. Alternative left-right symmetric models with extra isosinglet heavy fermions may generate branching ratios for the $t \to cH$ mode as high as 2×10^{-3} [9]. In the two higgs doublet model it is found that $\text{BR}(t \to cH) \approx 10^{-4}$ [25], whereas in R-parity violating SUSY it is of the order of 10^{-5} [26].

Our bounds given in Eq. (10) may point towards significant constraints on the parameters of this kind of models. However, we should bear in mind that in general other new-physics effects may give additional contributions to these observables. These contributions could weaken the severity of the constraints.

These bounds are also similar in size to the ones obtained for other FCNC top-quark decay modes: $\text{BR}(t \to c\gamma) \leq 1.3 \times 10^{-3}$ and $\text{BR}(t \to cg) \leq 3.4 \times 10^{-2}$. Both obtained from the observed $b \to s\gamma$ rate [14,16].

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