Constraints on top-quark FCNC from electroweak precision measurements

F. Larios\textsuperscript{a,}\*, R. Martínez\textsuperscript{b}, and M.A. Pérez\textsuperscript{c}

\textsuperscript{a} Departamento de Física Aplicada, CINVESTAV-Mérida, A.P. 73, 97310 Mérida, Yucatán, México
\textsuperscript{b} Departamento de Física, Universidad Nacional, Apartado aéreo 14490, Bogotá, Colombia
\textsuperscript{c} Departamento de Física, CINVESTAV, A.P. 14-740, 07000 México, D.F., México

March 26, 2022

Abstract

We study the one-loop contributions of the effective flavor changing neutral couplings (FCNC) $tcZ$ and $tcH$ on the electroweak precision observables $\Gamma_Z$, $R_c$, $R_b$, $R_\ell$, $A_c$ and $A_F^{FB}$. Using the known experimental limits on these observables, we may place 95% CL bounds on these FCNC couplings which in turn translate into the following limits for the branching ratios $BR(t \to cZ) \leq 6.7 \times 10^{-2}$ and $BR(t \to cH) \leq (0.09 - 2.9) \times 10^{-3}$ for $114 \leq m_H \leq 170 GeV$.

PACS numbers 14.65.Ha;12.60.C;12.15.M;12.15.L

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), it was realized that some of its FCNC decay modes can be enhanced by several orders of magnitude in scenarios beyond the SM, and some of them

\*Also at Dept. of Physics and Astronomy, Michigan State University.
falling within the LHC’s reach\cite{2,3,4}. 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\cite{5,6,7}. This formalism generates a model-independent parametrization of any new physics characterized by higher dimension operators. In particular, the use of this method to place limits on new physics effects by studying their one-loop contributions to precisely measured observables has been proved to be effective in the study of anomalous couplings of vector gauge bosons\cite{8,9,10}, the top quark\cite{6,11} and the tau neutrino\cite{12}. Under this approach, several FCNC transitions have been also significantly constrained: $t \to c \gamma$\cite{9,13}, $t \to cg$\cite{13,14}, $\ell_i \to \ell_j \gamma$\cite{12,15} and $H \to \ell_i \ell_j$\cite{16}. The effective Lagrangian technique has also been used to get limits on the scale $\Lambda$ associated to the new physics from the oblique parameters $S,T,U$\cite{7,17}.

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 $t \to cZ$ and $t \to cH$. In order to perform a $\chi^2$ fit at 95\% CL, we will compute the one-loop contributions of the $tcZ/H$ couplings to $Z \to c\bar{c}$ which in turn will induce corrections to these observables.

We will use the following effective Lagrangian to parametrize the FCNC of the top quark\cite{18}:

\[
\mathcal{L} = \bar{t} \left\{ \frac{ie}{2m_t}(\kappa_{tq}\gamma + i\tilde{\kappa}_{tq}\gamma_5)\sigma_{\mu\nu}F^{\mu\nu} + \frac{ig_s}{2m_t}(\kappa_{tq}g + i\tilde{\kappa}_{tq}g\gamma_5)\sigma_{\mu\nu}\lambda^a G_a^{\mu\nu} + \frac{i}{2m_t}(\kappa_{tq}Z + i\tilde{\kappa}_{tq}Z\gamma_5)\sigma_{\mu\nu}Z^{\mu\nu} + \frac{g}{2c_w}(v_{tq}Z + a_{tq}Z\gamma_5)Z^\mu + \frac{g}{2\sqrt{2}}(h_{tq}H + i\tilde{h}_{tq}H\gamma_5)H \right\} q'
\]

(1)

The one-loop contributions of the FCNC $tcZ$ and $tcH$ to the decay mode $Z \to c\bar{c}$ are shown in Fig. 1. Even though the anomalous vertices enter in these Feynman diagrams as a second order perturbation, we will see that the known limits on the precision observables impose stringent constraints on the couplings $tcZ/tcH$. This is not the case for the magnetic-dipole type couplings since their respective contributions are suppressed by an additional $1/m_t$ factor.
The width for the decay model $Z \rightarrow c\bar{c}$ may be expressed in the following form after including the one-loop corrections.

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

(2)

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

$$\delta_{NP}^{Z/H} = 2 \left[ \frac{g_{V}^{SM} \delta g_{V}^{Z/H} + g_{A}^{SM} \delta g_{A}^{Z/H}}{(g_{V}^{SM})^2 + (g_{A}^{SM})^2} \right],$$

(3)

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

$$\delta g_{V,A}^{Z} = Re\left[ g_2 F_L \pm g_2 F_R \right],$$

$$\delta g_{V,A}^{H} = Re\left[ h_t h_r (H_L \pm H_R) \right].$$

(4)

In the above expressions, we have used the definitions

$$g_{r/l} = \frac{i}{2c_W}(v_{tcZ} \pm a_{tcZ}),$$

$$h_{r/l} = \frac{1}{2\sqrt{2}}(h_{tCZ} \mp i\tilde{h}_{tCZ}),$$

(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 $x_H = m_H/m_Z$,

$$F_L = \frac{g_2}{12\pi^2} \left[ (-3 + 4s_w^2) \left[ -3B_o(0, m_t, m_Z) + 2B_o(m_Z^2, m_t, m_t) 
+ B_1(0, m_t, m_Z) + B_1(m_Z^2, m_t, m_t) 
+ x_t(B_o(0, m_t, m_Z) - B_o(m_Z^2, m_t, m_t)) - \frac{1}{2} \right] 
+ x_t(12 - 12s_w^2 - x_t(3 - 4s_w^2))C_o(x_t) \right],$$

$$F_R = \frac{g_2}{12\pi^2} \left[ s_w^2 \left[ 1 + 2B_1(0, m_t, m_Z) - 2B_1(m_Z^2, m_t, m_t) 
+ 2x_t(B_o(m_Z^2, m_t, m_t) - B_o(0, m_t, m_Z)) \right] 
+ (2s_w^2(3 + 2x_t - x_t^2) - 3x_t)C_o(x_t) \right],$$

(6)
\begin{align}
H_L & = \frac{g^2}{96\pi^2c_W} \{(3 - 4s_W^2) \left[ B_0(0, m_t, m_Z) - B_0(m_Z^2, m_t, m_t) \right]
+ 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} \right] + \frac{4}{3} x_t s_W^2 C_o(x_H) \}, \\
H_R & = \frac{g^2}{96\pi^2c_W} \{-4s_W^2 \left[ 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 \right] C_o(x_H) \}. \tag{7}
\end{align}

We will use the above results to obtain 95% CL limits on each individual anomalous coupling $t c Z/ t c H$. As mentioned before, from their contribution to the effective $Z c \bar{c}$ vertex shown in Fig. 1 we can compute the deviation from the SM value of the following electroweak observables:

\begin{align}
\Gamma_Z & = \Gamma_{ZSM} [1 + BR_{ZSM} (Z \rightarrow c \bar{c}) \delta_{Z/SM}^{Z/H}], \\
R_c & = R_{cSM} [1 + (1 - R_{cSM}) \delta_{c/SM}^{Z/H}], \\
R_b & = R_{bSM} [1 - R_{cSM} \delta_{b/SM}^{Z/H}], \\
R_\ell & = R_{\ell SM} [1 + R_{cSM} \delta_{\ell/SM}^{Z/H}], \\
A_c & = A_{cSM} [1 + \frac{\delta g_{VZ/SM}}{g_{VSM}} + \frac{\delta g_{AZ/SM}}{g_{ASM}} - \delta_{c/SM}^{Z/H}], \\
A_F & = A_{FB} [1 + \frac{\delta g_{VZ/SM}}{g_{VSM}} + \frac{\delta g_{AZ/SM}}{g_{ASM}} - \delta_{c/SM}^{Z/H}]. \tag{8}
\end{align}

We now use the values given by the Particle Data Group [20] for the observables of Eq. (8) and obtain the 95% CL limits for the $t c Z$ and the $t c H$ couplings. We will neglect possible interference effects and consider each coupling separately. In Fig. 2 the allowed parameter region in the $g_\ell - g_r$ plane is shown. We can compare with the recent limits obtained by the DELPHI collaboration [19], from their definition of the $t c Z$ coupling coefficient $\kappa_Z$. We obtain $\kappa_Z = 2c_w \sqrt{g_r^2 + g_t^2}$, and for $\kappa = 0$ DELPHI’s upper limit $\kappa Z \leq 0.4$ is equivalent to ours. On the other hand, years ago a similar study on the $t c Z$
contribution to FCNC processes like $B \to l^+l^-X$ put a stringent constraint on $g_t$ ($\kappa_L \leq 0.05$)\textsuperscript{[6]}; but not so much for $g_r$ ($\kappa_R \leq 0.29$) for which the constraint came from its contribution to the oblique parameters\textsuperscript{[6]}. When computing the contribution of $tcZ$ to $b \to l^+l^-X$ 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. \textsuperscript{[6]}. In Fig. 3 we depict the contours for the 95\% CL 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

$$
\Gamma(t \to cZ) = \frac{\alpha m_t (1 - x_Z^2)^2 (1 + 2 x_Z^2) [g_l^2 + g_r^2]}{8 s_W^2 x_Z^2}
$$

$$
\Gamma(t \to cH) = \frac{\alpha m_t}{8 s_W^2} (1 - m_H^2/m_t^2)^2 [h_l^2 + h_r^2]
$$

(9)

where $x_Z = m_Z/m_t$.

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

$$
BR(t \to cZ) \leq 6.7 \times 10^{-2},
$$

$$
BR(t \to cH) \leq 0.9 \times 10^{-4}, \quad (m_H = 170$GeV$)
$$

$$
BR(t \to cH) \leq 2.9 \times 10^{-3}, \quad (m_H = 114$GeV$).
$$

(10)

As mentioned above, the upper limit on $BR(t \to cZ)$ is equivalent to the recently reported by the DELPHI collaboration. 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 $10^{-1}$\textsuperscript{[3]}. Some extensions of the SM with non-universal couplings to fermions can give sizeable $tcH$ couplings \textsuperscript{[2, 14]}. In particular, it was found recently \textsuperscript{[21]} that alternative Left-Right symmetric models with extra isosinglet heavy fermions may generate branching ratios for the $t \to cH$ mode as high as $2 \times 10^{-3}$. Our bounds given in Eq. (10) clearly point to severe constraints on the parameters of this kind of models.

These bounds are also similar in size to the ones obtained within the same approach for other FCNC top-quark decay modes: $BR(t \to c\gamma) \leq 1.3 \times 10^{-3}$
and \( BR(t \to cg) \leq 3.4 \times 10^{-2} \). Both obtained from the observed \( b \to s\gamma \) rate \[9, 11, 13\].

In conclusion, in this paper we have performed a systematic analysis of the radiative corrections induced on electroweak precision observables by the effective FCNC vertices \( tcZ \) and \( tcH \). We have found that at the 95\% CL the known values of these observables place significant constraints on the branching ratios allowed for the decay modes \( t \to cZ, cH \) within the framework of the effective Lagrangian approach.

Acknowledgments

We would like to thank CONACyT (México), Colciencias and Fundación del Banco de la República (Colombia) for support.

References

[1] J.L. Díaz-Cruz, R. Martínez, M.A. Pérez, A. Rosado, *Phys. Rev. D* **41** (1990) 891; G. Eilam, J.L. Hewett, A. Soni, *Phys. Rev. D* **44** (1991) 1473; *erratum* Phys. Rev. D59 (1999)039901.

[2] For reviews see, D. Chakaraborty, J. Konigsberg, D. Rainwater, *Annu. Rev. Part. Nucl. Sci.* **53** (2003) 301; M. Beneke, I. Efthymiopoulos, M. Mangano, J. Womersley, et. al., *Top quark Physics: 1999 CERN Workshop on the SM Physics (and more) at the LHC.* [hep-ph/0003033]

[3] J.M. Yang, *Probing new physics from the top quark FCNC processes at the linear colliders: a mini review* Talk given at APPI2004, Iweta, Japan, [arXiv:hep-ph/0409351] J. Cao, G. Liu and J.M. Yang [arXiv:hep-ph/0311166]

[4] J.A. Aguilar-Saavedra, *Top FCNC interactions: theoretical expectations and experimental detection* Talk given at the final meeting of the European Network “Physics at Colliders”, Montpellier, September 2004, [arXiv:hep-ph/0409342] J.A. Aguilar-Saavedra and G.C. Branco, *Phys. Lett. B* **495** (2000) 347.

[5] S. Weinberg, *Physica A* **96** (1979) 327; H. Georgi, *Nucl. Phys. B* **361** (1991) 339.

[6] T. Han, R.D. Peccei and X. Zhang, *Nucl. Phys. B* **454** (1995) 527.
[7] R.D. Peccei S. Peris and X. Zhang, *Nucl. Phys. B* 349 (1991) 305; R.D. Peccei and X. Zhang, *Nucl. Phys. B* 337 (1990) 269.

[8] C. Artz, M.B. Einhorn. J. Wudka, *Phys. Rev. D* 49 (1994) 1370.

[9] R. Martínez, M.A. Pérez, J.J. Toscano, *Phys. Lett. B* 340 (1994) 91.

[10] S. Alam, S. Dawson, R. Szalapski, *Phys. Rev. D* 57 (1998) 1577; J. Bagger, S. Dawson, G. Valencia, *Nucl. Phys. B* 399 (1993) 364.

[11] R. Martínez, J.A. Rodríguez, *Phys. Rev. D* 55 (1997) 3212; ibid. *Phys. Rev. D* 60 (1999) 077504; *Phys. Rev. D* 65 (2002) 017301; F. Larios, M.A. Pérez, C.P. Yuan, *Phys. Lett. B* 457 (1999) 334; U. Baur et al., arXiv:hep-ph/0412021.

[12] F. Larios, R. Martínez, M.A. Pérez, *Phys. Lett. B* 345 (1995) 259.

[13] T. Han, K. Whisnant, B.L. Young, X. Zhang, *Phys. Rev. D* 55 (1997) 7241.

[14] A. Cordero-Cid, M.A. Pérez, G. Tavares-Velasco, J.J. Toscano, *Phys. Rev. D* 70 (2004) 074003.

[15] R.A. Díaz, R. Martínez, J.A. Rodríguez, *Phys. Rev. D* 64 (2001) 033004.

[16] J.L. Díaz-Cruz, J.J. Toscano, *Phys. Rev. D* 62 (2000) 116005.

[17] G. Sánchez-Colón, J. Wudka, *Phys. Lett. B* 432 (1998) 383; P. Bamert et al., *Phys. Rev. D* 54 (1996) 4275.

[18] T. Han, J.L. Hewett, *Phys. Rev. D* 60 (1999) 074015.

[19] Abdallah, J. et al, *Phys.Lett. B* 590 (2004) 21.

[20] Particle Data Group, *Phys.Lett. B* 592 (2004) 1; G. Altarelli, arXiv:hep-ph/0405182.

[21] R. Gaitán, O.G.Miranda, L.G. Cabral-Rosetti, arXiv:hep-ph/0410268.
Figure 1: Feynman diagrams for the one-loop contribution of the FCNC tcZ/H vertices to the decay mode $Z \to c\bar{c}$
Figure 2: A 95% CL fit of the \( tcZ \) coupling bounds obtained from the current values for the electroweak precision observables shown in Eq. (8).
Figure 3: A 95% CL fit of the $tcH$ coupling bounds 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.