Chapter 9
Probing Anomalous *tcZ* Couplings with Rare *B* and *K* Decays

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Abstract In this work, we study the effects of anomalous tcZ couplings. Such couplings would potentially affect several neutral current decays of K and B mesons via Z-penguin diagrams. Using constraints from relevant observables in K and B sectors, we calculate $\mathscr{B}(t \to cZ)$ and $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ in the presence of anomalous tcZ coupling. Further, we find that the complex tcZ coupling can also provide large enhancements in many CP violating angular observable in $B \to K^*\mu^+\mu^-$ decay.

9.1 Introduction

The measurement of several observables in B meson decays do not agree with their Standard Model (SM) predictions. These observables include the measurement of $R_{K^{(*)}}$, angular observables in $B \to K^*\mu^+\mu^-$ (in particular $P_5^{'}$), $\mathscr{B}(B_s \to \phi\mu^+\mu^-)$ in the neutral current sector and $R_{D^{(*)},J/\psi}$ in the charged current sector. These measurements can be considered as hints of physics beyond the SM.

Apart from the decays of B meson, the top quark decays are particularly important for hunting physics beyond the SM. As it is the heaviest of all the SM particles, it is expected to feel the effect of new physics (NP) most. Also, LHC is primarily a top factory producing abundant top quark events. Hence one expects the observation of possible anomalous couplings in the top sector at the LHC. The SM predictions for the branching ratios of the flavor changing neutral current (FCNC) top quark decays, such as $t \to uZ$ and $t \to cZ$ decays are $\sim 10^{-17}$ and 10^{-14}, respectively [1, 2], and are probably immeasurable at the LHC until NP enhances their branching ratios up to the detection level of LHC.

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In this work, we study the effects of anomalous tcZ couplings on rare B and K meson decays. Using these decays, we obtain constraints on anomalous $t \to cZ$ coupling. We then look for flavor signatures of anomalous tcZ coupling. In particular, we examine $\mathcal{B}(K_L \to \pi\,\nu\,\bar{\nu})$ and various CP violating angular observables in $B \to K^*\,\mu^+\,\mu^-$. We find that the complex tcZ coupling can give rise to large new physics effects in these CP violating observables.

9.2 Effect of Anomalous $t \to cZ$ Couplings on Rare B and K Decays

The effective tcZ Lagrangian can be written as [3]

$$\mathcal{L}_{tcZ} = \frac{g}{2\cos\theta_W}\bar{c}\gamma^\mu\left(g_{ct}^L P_L + g_{ct}^R P_R\right) t Z_\mu + \frac{g}{2\cos\theta_W}\bar{c}\frac{i\sigma^{\mu\nu}p_\nu}{M_Z}\left(\kappa_{ct}^L P_L + \kappa_{ct}^R P_R\right) t Z_\mu + \text{h.c.}, \quad (9.1)$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and $g_{ct}^{L,R}$ and $\kappa_{ct}^{L,R}$ are NP couplings. The anomalous tcZ couplings can provide additional contributions to $b \to s\,l^+\,l^-$, $b \to d\,l^+\,l^-$ and $s \to d\nu\bar{\nu}$ decays via Z penguin diagrams and hence have the potential to affect the decays of several B and K mesons.

Let us now consider the contribution of anomalous tcZ couplings to the rare B decays induced by the quark-level transition $b \to s\,\mu^+\,\mu^-$. The effective Hamiltonian for the quark-level transition $b \to s\,\mu^+\,\mu^-$ in the SM can be written as

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)\ , \quad (9.2)$$

where the form of the operators O_i are given in [4]. The effective tcZ vertices, given in (9.1), affect $b \to s\,\mu^+\,\mu^-$ transition. This contribution modifies the Wilson coefficients (WCs) C_9 and C_{10}. The NP contributions to these WCs are [5]

$$C_9^{s,NP} = -C_{10}^{s,NP} = -\frac{1}{8\sin^2\theta_W}\frac{V_{cs}^*}{V_{ts}^*}\left[\left(-x_t\ln\frac{M_W^2}{\mu^2} + \frac{3}{2} + x_t - x_t\ln x_t\right) g_{ct}^L\right], \quad (9.3)$$

with $x_t = \bar{m}_t^2/M_W^2$. Here the right-handed coupling, g_{ct}^R, is neglected as it is suppressed by a factor of $\bar{m}_c/M_W$. Here we have also neglected the contributions from CKM suppressed Feynman diagrams. The NP contributions to $C_{9,\,10}$ have been calculated in the unitary gauge with the modified minimal subtraction ($\overline{\text{MS}}$) scheme [5]. The effective Hamiltonian and the NP contributions to the WCs C_9 and C_{10} for the process $b \to d\,\mu^+\,\mu^-$ can be obtained from (9.2) to (9.3), respectively, by replacing s by d.

We now consider NP contribution to $s \to d\,\nu\bar{\nu}$ transition. The $K^+ \to \pi^+\,\nu\bar{\nu}$ decay is the only observed decay in this sector. The effective Hamiltonian for $K^+ \to \pi^+\,\nu\bar{\nu}$ in the SM can be written as

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} \left[V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_t) \right] \times (\bar{s}d)_{V-A} (\bar{\nu}_l \nu_l)_{V-A}\,, \tag{9.4}$$

where X_{NL}^l and $X(x_t)$ are the structure functions corresponding to charm and top sector, respectively [4, 6, 7]. The contribution of anomalous tcZ coupling to $\bar{s} \to \bar{d}\,\nu\bar{\nu}$ transition then modifies the structure function $X(x_t)$ in the following way:

$$X(x_t) \to X^{\rm tot}(x_t) = X(x_t) + X^{NP}, \tag{9.5}$$

where

$$X(x_t) = \eta_X \frac{x_t}{8} \left[\frac{2 + x_t}{x_t - 1} + \frac{3x_t - 6}{(1 - x_t)^2} \ln x_t \right], \tag{9.6}$$

$$X^{NP} = -\frac{1}{8} \left(\frac{V_{cd} V_{ts}^* + V_{td} V_{cs}^*}{V_{td} V_{ts}^*} \right) \left(-x_t \ln \frac{M_W^2}{\mu^2} + \frac{3}{2} + x_t - x_t \ln x_t \right) (g_{ct}^L)^*\,. \tag{9.7}$$

Here $\eta_x = 0.994$ is the NLO QCD correction factor.

9.3 Constraints on the Anomalous tcZ Couplings

In order to obtain the constraints on the anomalous tcZ coupling g_{ct}^L, we perform a χ^2 fit using all measured observables in B and K sectors. The total χ^2 is written as a function of two parameters: $\mathrm{Re}(g_{ct}^L)$ and $\mathrm{Im}(g_{ct}^L)$. The χ^2 function is defined as

$$\chi^2_{\rm total} = \chi^2_{b \to s\,\mu^+\mu^-} + \chi^2_{b \to d\,\mu^+\mu^-} + \chi^2_{s \to d\nu\bar{\nu}}\,. \tag{9.8}$$

In our analysis, we include all recent CP conserving data from $b \to s\mu^+\mu^-$ to obtain constraints on $C_{9,10}^{s,NP}$. Assuming the WCs C_i to be real, we obtain $C_9^{NP} = -C_{10}^{NP} = -0.51 \pm 0.09$ [8]. This is consistent with several global fit results such as [9–11]. For complex WCs, we get $C_9^{NP} = -C_{10}^{NP} = (-0.56 \pm 0.26) + i(0.55 \pm 1.36)$. The fit values thus obtained can be used to constrain g_{ct}^L. For real g_{ct}^L coupling, we have

$$\chi^2_{b \to s\mu^+\mu^-} = \left(\frac{C_9^{s,NP} + 0.51}{0.09} \right)^2. \tag{9.9}$$

For complex g_{ct}^L couplings, the χ^2 function can be written as

$$\chi^2_{b \to s\mu^+\mu^-} = \left(\frac{Re(C_9^{s,NP}) + 0.56}{0.26} \right)^2 + \left(\frac{Im(C_9^{s,NP}) - 0.55}{1.36} \right)^2. \tag{9.10}$$

From $b \to d\mu^+\mu^-$ sector the branching ratio of $B^+ \to \pi^+ \mu^+ \mu^-$ and $B_d \to \mu^+\mu^-$ decay are included in our analysis:

$$\chi^2_{b\to d\,\mu^+\mu^-} = \chi^2_{B^+\to\pi^+\mu^+\mu^-} + \chi^2_{B_d\to\mu^+\mu^-}. \tag{9.11}$$

For $B^+ \to \pi^+ \mu^+ \mu^-$ decay,

$$\chi^2_{B^+\to\pi^+\mu^+\mu^-} = \left(\frac{\mathscr{B}(B^+ \to \pi^+ \mu^+ \mu^-) - 2.3 \times 10^{-8}}{0.66 \times 10^{-8}}\right)^2, \tag{9.12}$$

where, following [12], a theoretical error of 15% is included in $\mathscr{B}(B^+ \to \pi^+ \mu^+ \mu^-)$. For $\mathscr{B}(B_d \to \mu^+\mu^-)$ decay,

$$\chi^2_{B_d\to\mu^+\mu^-} = \left(\frac{\mathscr{B}(B_d \to \mu^+ \mu^-) - 3.9 \times 10^{-10}}{1.6 \times 10^{-10}}\right)^2. \tag{9.13}$$

The branching ratio of $B_d \to \mu^+ \mu^-$ in the presence of anomalous tcZ coupling is given by

$$\mathscr{B}(B_d \to \mu^+ \mu^-) = \frac{G_F^2 \alpha^2 M_{B_d} m_\mu^2 f_{B_d}^2 \tau_{B_d}}{16\pi^3} |V_{td} V_{tb}^*|^2 \sqrt{1 - 4(m_\mu^2/M_{B_d}^2)} \left|C_{10} + C_{10}^{d,NP}\right|^2. \tag{9.14}$$

The branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$, the only measurement in $s \to d\,\nu\bar{\nu}$ sector, in the presence of anomalous tcZ coupling is given by

$$\frac{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})}{\kappa_+} = \left(\frac{\mathrm{Re}(V_{cd}V_{cs}^*)}{\lambda} P_c(X) + \frac{\mathrm{Re}(V_{td}V_{ts}^*)}{\lambda^5} X^{\mathrm{tot}}(x_t)\right)^2 + \left(\frac{\mathrm{Im}(V_{td}V_{ts}^*)}{\lambda^5} X^{\mathrm{tot}}(x_t)\right)^2, \tag{9.15}$$

where $P_c(X) = 0.38 \pm 0.04$ [13] is the NNLO QCD-corrected structure function in the charm sector and

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathscr{B}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8 . \tag{9.16}$$

Using $r_{K^+} = 0.901$, we estimate

$$\frac{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})}{\kappa_+} = 3.17 \pm 2.05. \tag{9.17}$$

Table 9.1 Values of anomalous tcZ couplings

Real coupling	Complex coupling
$g_L^{ct} = (-7.04 \pm 1.28) \times 10^{-3}$	$\mathrm{Re}(g_L^{ct}) = (-7.63 \pm 3.69) \times 10^{-3}$; $\mathrm{Im}(g_L^{ct}) = (1.87 \pm 1.02) \times 10^{-2}$

In order to include $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu})$ in the fit, we define

$$\chi^2_{K^+\to\pi^+\nu\bar{\nu}} = \left(\frac{\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})/\kappa_+ - 3.17}{2.05}\right)^2 + \left(\frac{P_c(X) - 0.38}{0.04}\right)^2. \quad (9.18)$$

Thus, the error on $P_c(X)$ has been taken into account by considering it to be a parameter and adding a contribution to χ^2_{total}.

The $\mathscr{B}(t \to cZ)$ in the presence of tcZ coupling is given as [14–16]

$$\mathscr{B}(t \to c\,Z) = \frac{\beta_Z^4(3 - 2\beta_Z^2)}{2\beta_W^4(3 - 2\beta_W^2)} \frac{|g_{ct}^L|^2 + |g_{ct}^R|^2}{|V_{tb}|^2}, \quad (9.19)$$

with $\beta_x = (1 - m_x^2/m_t^2)^{1/2}$, being the velocity of the $x = W, Z$ boson in the top quark rest frame.

The fit results for real and complex tcZ couplings are presented in Table 9.1. Using the fit results, we find that for real tcZ coupling, $\mathscr{B}(t \to c\,Z) = (0.90 \pm 0.33) \times 10^{-5}$. For complex tcZ coupling, 2σ upper bound on the branching ratio is 2.14×10^{-4}. Hence, any future measurement of this branching ratio at the level of 10^{-4} would imply the coupling to be complex.

9.4 Predictions for Various CP Violating Observables

We now see whether large deviation is possible in some of the flavor physics observables due to the anomalous tcZ coupling.

$\mathscr{B}(\mathbf{K_L} \to \pi^{\mathbf{0}}\,\nu\,\bar{\nu})$: The preset upper bound on $\mathscr{B}(K_L \to \pi^0\,\nu\,\bar{\nu})$ is 2.6×10^{-8} [17] at 90% C.L. which is about three orders of magnitude above the SM prediction. The branching ratio of $K_L \to \pi^0\,\nu\,\bar{\nu}$ is a purely CP violating quantity.The branching ratio of $K_L \to \pi^0\,\nu\,\bar{\nu}$ in the presence of tcZ coupling is given by

$$\mathscr{B}(K_L \to \pi^0\,\nu\,\bar{\nu}) = \kappa_L \left[\frac{\mathrm{Im}\left(V_{ts}^* V_{td} X^{\text{tot}}(x_t)\right)}{\lambda^5}\right]^2, \quad (9.20)$$

where $X^{\text{tot}}(x_t)$ is given in (9.5).

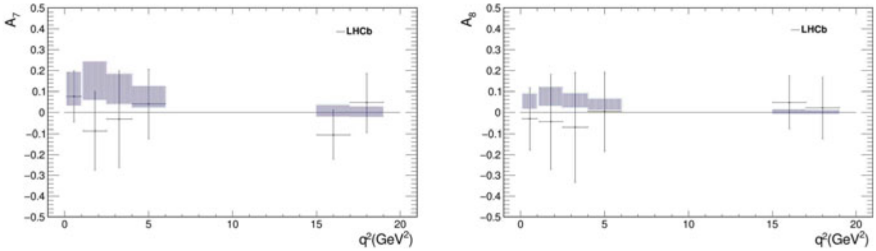

Fig. 9.1 (Color Online) The plots depicts various CP violating observables in $B \to K^* \mu^+ \mu^-$ decays

Using fit result for the complex tcZ coupling, we get $Br(K_L \to \pi^0 \nu\bar{\nu}) = (9.88 \pm 5.96) \times 10^{-11}$. The 2σ upper bound on $\mathscr{B}(K_L \to \pi^0\, \nu\, \bar{\nu})$ is obtained to be $\leq 2.18 \times 10^{-10}$, an order of magnitude higher than its SM prediction.

CP violating observables in B $\to$ K* $\mu^+ \mu^-$: We study various CP violating observables in $B \to K^* \mu^+ \mu^-$ decays in the presence of complex anomalous tcZ couplings.The CP-violating observables for these decays are defined as [18]

$$A_i = \frac{I_i - \bar{I}_i}{d(\Gamma + \bar{\Gamma})/dq^2}, \tag{9.21}$$

where $I_i s$ are given in [18]. These asymmetries are largely suppressed in SM because of the small weak phase of CKM and hence they are sensitive to complex NP couplings. These symmetries can get significant contribution from the NP in the presence of CP-violating phase [19–21].

The predictions for CP-violating asymmetries A_7 and A_8 in the presence of complex anomalous tcZ couplings are shown in Fig. 9.1. It can be seen from our results that the asymmetry A_7 can be enhanced up to 20% whereas enhancement in A_8 can be up to 10% in the low-q^2 region. For all other asymmetries, large enhancement is not possible.

References

1. G. Eilam, J.L. Hewett and A. Soni, Phys. Rev. D **44**, 1473 (1991) [Erratum-ibid. D **59**, 039901 (1999)]
2. J.A. Aguilar-Saavedra, Acta Phys. Polon. B **35**, 2695 (2004)
3. J.A. Aguilar-Saavedra, Nucl. Phys. B **812**, 181 (2009)
4. G. Buchalla, A.J. Buras, M.E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996)
5. X.Q. Li, Y.D. Yang, X.B. Yuan, JHEP **1203**, 018 (2012)
6. G. Buchalla, A.J. Buras, Nucl. Phys. B **412**, 106 (1994)
7. G. Buchalla, A.J. Buras, Nucl. Phys. B **548**, 309 (1999)
8. S. Kumbhakar, J. Saini, arXiv:1905.07690 [hep-ph]
9. A.K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar, D. London, Phys. Rev. D **96**(9), 095009 (2017)

10. A.K. Alok, A. Dighe, S. Gangal, D. Kumar, arXiv:1903.09617 [hep-ph]
11. M. Algueró, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias, J. Virto, arXiv:1903.09578 [hep-ph]
12. J.J. Wang, R.M. Wang, Y.G. Xu, Y.D. Yang, Phys. Rev. D **77**, 014017 (2008)
13. A.J. Buras, M. Gorbahn, U. Haisch, U. Nierste, JHEP **0611**, 002 (2006) [Erratum-ibid. **1211**, 167 (2012)]
14. T. Han, R.D. Peccei, X. Zhang, Nucl. Phys. B **454**, 527 (1995)
15. M. Beneke et al., hep-ph/0003033
16. W. Bernreuther, J. Phys. G **35**, 083001 (2008)
17. J.K. Ahn et al., E391a collaboration. Phys. Rev. D **81**, 072004 (2010)
18. W. Altmannshofer, P. Ball, A. Bharucha, A.J. Buras, D.M. Straub, M. Wick, JHEP **0901**, 019 (2009)
19. A.K. Alok, A. Dighe, S. Ray, Phys. Rev. D **79**, 034017 (2009)
20. A.K. Alok, A. Datta, A. Dighe, M. Duraisamy, D. Ghosh, D. London, JHEP **1111**, 122 (2011)
21. A.K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, S.U. Sankar, Phys. Rev. D **96**(1), 015034 (2017)