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ScienceDirect

Nuclear Physics B 906 (2016) 321–341

NUCLEAR PHYSICS B

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Flavor signatures of isosinglet vector-like down quark model

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Received 7 October 2015; received in revised form 19 February 2016; accepted 7 March 2016

Available online 14 March 2016

Editor: Tommy Ohlsson

Abstract

We consider a model where the standard model is extended by the addition of a vector-like isosinglet down-type quark b'. We perform a χ^2 fit to the flavor physics data and obtain the preferred central values along with errors of all the elements of the measurable 3×4 quark mixing matrix. The fit indicates that all the new-physics parameters are consistent with zero and the mixing of the b' quark with the other three is constrained to be small. The current flavor physics data rules out possibility of detectable new physics signals in most of the flavor physics observables. We also investigate possible deviations in the standard model Wtb couplings and bottom quark coupling to Higgs boson. We find that these deviations are less than a percent level which is too small to be observed at the LHC with current precision.

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http://dx.doi.org/10.1016/j.nuclphysb.2016.03.012

1. Introduction

The standard model (SM) consists of three generations of quarks, with two quarks in each generation. However, there is no *a priori* reason for the number of quarks to be restricted to six. It may be possible to have heavier quarks whose effects have not been detected yet. The minimal extension of the SM in this direction can be obtained by adding a vector-like isosinglet quark, either up-type or down-type, to the SM particle spectrum [1–15]. Such exotic fermions can appear in E_6 grand unified theories as well in models with large extra dimensions. Since these quarks are vector-like, they do not lead to chiral anomalies. Here we consider the extension of SM by adding an isosinglet vector-like down-type quark b'.

As of now there are no direct evidences of exotic quarks. The additional chiral quarks, such as perturbative SM with fourth generation are excluded at the level of 5σ by the recent LHC data on Higgs searches, when combined with electroweak precision data and direct searches at the LHC [16]. As vector like fermions do not receive their mass from a Higgs doublet, they are still allowed by the existing experimental data and hence keep us interested.

The ordinary quarks with charge $(-1/3)$ mix with the b'. Because the b'_L has a different I_{3L} from d_L, s_L and b_L, Z-mediated flavor changing neutral current (ZFCNC) appears at the tree level in the left-handed sector. Thus the quark level transitions such as $b \to s$, $b \to d$, $s \to d$ can occur at the tree level. The addition of a b' quark to the SM leads to a quark mixing matrix which is the 3×4 upper submatrix of a 4×4 quark-mixing matrix CKM4, which is an extension of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix in the SM. This model thus provides a self-consistent framework to study deviations of 3×3 unitarity of the CKM matrix as well as flavor changing neutral currents at tree level.

Not all the elements of the CKM matrix are measured directly; the values of the elements V_{tq} $(q = d, s, b)$ are determined from decays involving loops and by using the unitarity of the 3×3 CKM matrix. Hence one expects that due to the non-unitarity of the quark mixing matrix in the ZFCNC model, sizable departures from the SM predictions may be possible. In this paper, we explore the possibility of such deviations by performing a fit to current flavor physics data.

The addition of isosinglet down-type quark b' modifies the couplings of SM bottom quark with W, Z and Higgs boson. The deviations, if measured, can provide indirect evidence of vector quarks. In this work we study such possible deviations and provide an upper bound on them.

The quark mixing matrix in the SM, which is 3×3 unitary matrix, is parametrized by three angles, θ_{12}, θ_{13}, and θ_{23} and the CP-violating phase δ_{13}. The parametrization of 4×4 unitary quark-mixing matrix requires three additional angles θ_{14}, θ_{24}, and θ_{34} and two additional CP-violating phases δ_{14} and δ_{24}. In our analysis we use an exact parametrization of the CKM4 matrix [17–19]:

$$V_{CKM4} = \begin{pmatrix} c_{12}c_{13}c_{14} & c_{13}c_{14}s_{12} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \begin{array}{c} -c_{23}c_{24}s_{12} - c_{12}c_{24}s_{13}s_{23}e^{i\delta_{13}} \\ - c_{12}c_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})} \end{array} & \begin{array}{c} c_{12}c_{23}c_{24} - c_{24}s_{12}s_{13}s_{23}e^{i\delta_{13}} \\ - c_{13}s_{12}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})} \end{array} & \begin{array}{c} c_{13}c_{24}s_{23} \\ - s_{13}s_{14}s_{24}e^{-i(\delta_{13}+\delta_{24}-\delta_{14})} \end{array} & c_{14}s_{24}e^{-i\delta_{24}} \\ \begin{array}{c} -c_{12}c_{23}c_{34}s_{13}e^{i\delta_{13}} + c_{34}s_{12}s_{23} \\ - c_{12}c_{13}c_{24}s_{14}s_{34}e^{i\delta_{14}} \\ + c_{23}s_{12}s_{24}s_{34}e^{i\delta_{24}} \\ + c_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})} \end{array} & \begin{array}{c} -c_{12}c_{34}s_{23} - c_{23}c_{34}s_{12}s_{13}e^{i\delta_{13}} \\ - c_{12}c_{23}s_{24}s_{34}e^{i\delta_{24}} \\ - c_{13}c_{24}s_{12}s_{14}s_{34}e^{i\delta_{14}} \\ + s_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})} \end{array} & \begin{array}{c} c_{13}c_{23}c_{34} \\ - c_{13}s_{23}s_{24}s_{34}e^{i\delta_{24}} \\ - c_{24}s_{13}s_{14}s_{34}e^{i(\delta_{14}-\delta_{13})} \end{array} & c_{14}c_{24}s_{34} \\ \begin{array}{c} -c_{12}c_{13}c_{24}c_{34}s_{14}e^{i\delta_{14}} \\ + c_{12}c_{23}s_{13}s_{34}e^{i\delta_{13}} \\ + c_{23}c_{24}s_{12}s_{24}e^{i\delta_{24}} - s_{12}s_{23}s_{34} \\ + c_{12}c_{34}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})} \end{array} & \begin{array}{c} -c_{12}c_{23}c_{34}s_{24}e^{i\delta_{24}} + c_{12}s_{23}s_{34} \\ - c_{13}c_{24}c_{34}s_{12}s_{14}e^{i\delta_{14}} \\ + c_{23}s_{12}s_{13}s_{34}e^{i\delta_{13}} \\ + c_{34}s_{12}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})} \end{array} & \begin{array}{c} -c_{13}c_{23}s_{34} \\ - c_{13}c_{34}s_{23}s_{24}e^{i\delta_{24}} \\ - c_{24}c_{34}s_{13}s_{14}e^{i(\delta_{14}-\delta_{13})} \end{array} & c_{14}c_{24}c_{34} \end{pmatrix} \tag{1}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$. Thus all the elements of the measurable 3×4 sub-matrix of CKM4 are expressed in terms of the nine CKM4 parameters. All the flavor observables, in turn, can be written in terms of these measurable CKM4 elements.

In this work, we consider the following flavor observables:

1. The six directly measured magnitudes of the CKM matrix elements,
2. indirect and direct *CP* violation in $K_L \to \pi\pi$,
3. the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \mu^+\mu^-$,
4. various observables in $Z \to b\bar{b}$ decay,
5. B_s^0–$\bar{B}_s^0$ and B_d^0–$\bar{B}_d^0$ mixing,
6. the time-dependent indirect *CP* asymmetries in $B_d^0 \to J/\psi\, K_S$ and $B_s^0 \to J/\psi\, \phi$,
7. the measurement of the angle γ of the unitarity triangle from *tree-level decays*,
8. the branching ratio of the inclusive decay $B \to X_s l^+ l^-$ and of the exclusive decay $B \to K\mu^+\mu^-$,
9. many observables in $B \to K^*\mu^+\mu^-$,
10. the branching ratio of $B^+ \to \pi^+\mu^+\mu^-$,
11. the branching ratios of $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$ and $B^+ \to \tau^+\nu_\tau$,
12. the like-sign dimuon charge asymmetry A_{SL}^b,
13. the oblique parameters S, U and T, and
14. D–$\bar{D}$ mixing.

We compare the measured values of the above quantities to the theoretical expressions for them in the standard CKM and do a χ^2 fit to obtain the SM CKM parameters. Then we redo the fit, using the corresponding theoretical expressions in the isosinglet vector-like down-type quark model and obtain values for the SM CKM parameters as well as the new physics magnitudes θ_{14}, θ_{24} and θ_{34} and the new physics phases δ_{14} and δ_{24}.

We then turn on to predict observables that are expected to be affected by the b' quark, while still being consistent with the above measurements. We examine following observables: (i) the branching fraction of $K_L \to \pi^0\nu\bar{\nu}$, (ii) the branching fraction of $B \to X_s\nu\bar{\nu}$, (iii) direct *CP* asymmetry in $B \to (K, K^*)\,\mu^+\mu^-$, and (iv) deviations in the standard model Wtb couplings and bottom quark coupling to Higgs boson.

The paper is organized as follows. In Sec. 2, we define the model, list the input values of various quantities used in the fit and discuss the definitions of χ^2 for each individual observable. The results of the fit are presented in Sec. 3. Using the results of the fit, the predictions for several observables, which are to be measured, are given in Sec. 4. We conclude in Sec. 5 with a discussion of the results.

2. Flavor changing couplings of Z boson to down-type quarks

In SM the quark content is represented by:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R; \begin{pmatrix} c_L \\ s_L \end{pmatrix}, c_R, s_R; \begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R. \tag{2}$$

The left handed quarks are represented as doublets and the right handed quarks are represented as singlets under $SU(2)_L$. Here we extend the quark sector by adding an $SU(2)$ singlet vector-like quark of charge $(-1/3)$, labeled b'. The mixing of this quark with the SM quarks of charge $(-1/3)$ leads to a different structure for the CKM matrix. The 3×3 mixing matrix connecting the

Table 1

Experimental values of flavor-physics observables used as constraints. For V_{ub} we use the weighted average from the inclusive and exclusive semileptonic decays, $V_{ub}^{inc} = (44.1 \pm 3.1) \times 10^{-4}$ and $V_{ub}^{exc} = (32.3 \pm 3.1) \times 10^{-4}$. When not explicitly stated, the inputs are taken from the Particle Data Group [30]. The asymmetric experimental errors are symmetrized by taking the largest side error. Also, wherever there is more than one source of uncertainty, the total error is obtained by adding them in quadrature.

$\lvert V_{ud}\rvert = 0.97425 \pm 0.00022$	$\mathcal{B}(B \to X_s \ell^+\ell^-)_{\text{low}} = (1.60 \pm 0.48) \times 10^{-6}$ [22]
$\lvert V_{us}\rvert = 0.2252 \pm 0.0009$	$\mathcal{B}(B \to X_s \ell^+\ell^-)_{\text{high}} = (0.57 \pm 0.16) \times 10^{-6}$ [22]
$\lvert V_{cd}\rvert = 0.230 \pm 0.011$	$10^9\ \text{GeV}^2 \times \langle \frac{d\mathcal{B}}{dq^2} \rangle (B \to K\mu^+\mu^-)_{\text{low}} = 18.7 \pm 3.6$ [23]
$\lvert V_{cs}\rvert = 1.006 \pm 0.023$	$10^9\ \text{GeV}^2 \times \langle \frac{d\mathcal{B}}{dq^2} \rangle (B \to K\mu^+\mu^-)_{\text{high}} = 9.5 \pm 1.7$ [23]
$\lvert V_{ub}\rvert = 0.00382 \pm 0.00021$	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.60 \pm 0.61) \times 10^{-8}$ [24]
$\lvert V_{cb}\rvert = (40.9 \pm 1.0) \times 10^{-3}$	$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.7 \pm 1.1) \times 10^{-10}$
$\gamma = (68.0 \pm 11.0)^\circ$	$\mathcal{B}(K_L \to \mu^+\mu^-) \leq 2.5 \times 10^{-9}$ [25]
$\lvert\epsilon_K\rvert \times 10^3 = 2.228 \pm 0.011$	$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$ [26–28]
$\epsilon'/\epsilon = (16.6 \pm 2.3) \times 10^{-4}$	$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.9 \pm 1.6) \times 10^{-10}$ [26–28]
$\Delta M_d = (0.507 \pm 0.004)\ \text{ps}^{-1}$ [20]	$\mathcal{B}(B \to \tau\bar{\nu}) = (1.14 \pm 0.22) \times 10^{-4}$ [20]
$\Delta M_s = (17.72 \pm 0.04)\ \text{ps}^{-1}$ [20]	$A_{sl}^b = (-4.96 \pm 1.69) \times 10^{-3}$ [29]
$S_{J/\psi\,\phi} = 0.00 \pm 0.07$ [20]	$S = 0.05 \pm 0.10$
$S_{J/\psi\,K_S} = 0.68 \pm 0.02$ [20]	$U = -0.03 \pm 0.10$
$R_b = 0.21629 \pm 0.00066$ [21]	$T = 0.01 \pm 0.12$
$A_b^{FB} = 0.0992 \pm 0.0016$ [21]	
$A_b = 0.923 \pm 0.020$ [21]	
$R_c = 0.1721 \pm 0.003$ [21]	

charge (2/3) quarks to the charge $(-1/3)$ quarks of the SM is no longer unitary, but is a submatrix of a 4×4 unitary matrix. Without loss of generality, we can choose the interaction and mass eigenbases of charge (2/3) quarks to be the same. Hence the up-type mass matrix is diagonal and real. The mass matrix of the charge $(-1/3)$ quarks, in the interaction eigenbasis, is a general 4×4 complex matrix M, which is put in a diagonal form by a bi-unitary transformation of the form $M_{dia} = V_L^\dagger M V_R$. The unitary matrix V_L appears in the charged current interactions, when they are rewritten in the quark mass eigenbases. The first three rows of $V_L \equiv V$ are measurable in principle and the top 3×3 sub-block is no longer unitary. This leads the flavor changing couplings of the Z boson to the down-type quarks, which are given by

$$\mathcal{L}_{FCNC}^Z = -\frac{g}{2\cos\theta_W} U_{jk} \bar{d}_{jL} \gamma^\mu d_{kL} Z_\mu. \tag{3}$$

U_{jk} are defined in terms of the first three elements of the fourth row of V_L as $U_{ds} = -V_{4d}^* V_{4s}$, $U_{sb} = -V_{4s}^* V_{4b}$ and $U_{db} = -V_{4d}^* V_{4b}$.

The current experimental values for the 72 flavor physics observables enumerated in the introduction are listed in Tables 1 and 2. The theoretical expressions for these observables require additional inputs in the form of decay constants, bag parameters, QCD corrections and other parameters. These are listed in Table 3.

For the fit, we define the total χ^2 function as

$$\begin{aligned}\chi^2_{\text{total}} = {} & \chi^2_{\text{CKM}} + \chi^2_{|\epsilon_K|} + \chi^2_{\epsilon'/\epsilon} + \chi^2_{K\to\pi^+\nu\bar{\nu}} + \chi^2_{K_L\to\mu^+\mu^-} + \chi^2_{Z\to b\bar{b}} + \chi^2_{B_d^0} + \chi^2_{B_s^0} \\ & + \chi^2_{\sin 2\beta} + \chi^2_{\sin 2\beta_s} + \chi^2_\gamma + \chi^2_{B\to X_s\, l^+ l^-} + \chi^2_{B\to K\,\mu^+\mu^-} + \chi^2_{B\to K^*\,\mu^+\mu^-} \\ & + \chi^2_{B^+\to\pi^+\,\mu^+\mu^-} + \chi^2_{B_q\to\mu^+\mu^-} + \chi^2_{B\to\tau\,\nu} + \chi^2_{A^b_{SL}} + \chi^2_{\text{Oblique}} + \chi^2_D\,.\end{aligned} \tag{4}$$

Table 2
Experimental values of $B \to K^* \mu^+ \mu^-$ observables used as constraints. They are taken from Refs. [31,32]. Here the errors have been symmetrized by taking the largest side error. Also, wherever there is more than one source of uncertainty, the total error is obtained by adding them in quadrature.

$q^2 = 0.1$–2 GeV^2	$q^2 = 2$–4.3 GeV^2	$q^2 = 4.3$–8.68 GeV^2
$\langle \frac{d\mathcal{B}}{dq^2} \rangle = (0.60 \pm 0.10) \times 10^{-7}$	$\langle \frac{d\mathcal{B}}{dq^2} \rangle = (0.30 \pm 0.05) \times 10^{-7}$	$\langle \frac{d\mathcal{B}}{dq^2} \rangle = (0.49 \pm 0.08) \times 10^{-7}$
$\langle F_L \rangle = 0.37 \pm 0.11$	$\langle F_L \rangle = 0.74 \pm 0.10$	$\langle F_L \rangle = 0.57 \pm 0.08$
$\langle P_1 \rangle = -0.19 \pm 0.40$	$\langle P_1 \rangle = -0.29 \pm 0.65$	$\langle P_1 \rangle = 0.36 \pm 0.31$
$\langle P_2 \rangle = 0.03 \pm 0.15$	$\langle P_2 \rangle = 0.50 \pm 0.08$	$\langle P_2 \rangle = -0.25 \pm 0.08$
$\langle P_4' \rangle = 0.00 \pm 0.52$	$\langle P_4' \rangle = 0.74 \pm 0.60$	$\langle P_4' \rangle = 1.18 \pm 0.32$
$\langle P_5' \rangle = 0.45 \pm 0.24$	$\langle P_5' \rangle = 0.29 \pm 0.40$	$\langle P_5' \rangle = -0.19 \pm 0.16$
$\langle P_6' \rangle = 0.24 \pm 0.23$	$\langle P_6' \rangle = -0.15 \pm 0.38$	$\langle P_6' \rangle = 0.04 \pm 0.16$
$\langle P_8' \rangle = -0.12 \pm 0.56$	$\langle P_8' \rangle = -0.3 \pm 0.60$	$\langle P_8' \rangle = 0.58 \pm 0.38$

$q^2 = 14.18$–16 GeV^2	$q^2 = 16$–19 GeV^2
$\langle \frac{d\mathcal{B}}{dq^2} \rangle = (0.56 \pm 0.10) \times 10^{-7}$	$\langle \frac{d\mathcal{B}}{dq^2} \rangle = (0.41 \pm 0.07) \times 10^{-7}$
$\langle F_L \rangle = 0.33 \pm 0.09$	$\langle F_L \rangle = 0.38 \pm 0.09$
$\langle P_1 \rangle = 0.07 \pm 0.28$	$\langle P_1 \rangle = -0.71 \pm 0.36$
$\langle P_2 \rangle = -0.50 \pm 0.03$	$\langle P_2 \rangle = -0.32 \pm 0.08$
$\langle P_4' \rangle = -0.18 \pm 0.70$	$\langle P_4' \rangle = 0.70 \pm 0.52$
$\langle P_5' \rangle = -0.79 \pm 0.27$	$\langle P_5' \rangle = -0.60 \pm 0.21$
$\langle P_6' \rangle = 0.18 \pm 0.25$	$\langle P_6' \rangle = -0.31 \pm 0.39$
$\langle P_8' \rangle = -0.40 \pm 0.60$	$\langle P_8' \rangle = 0.12 \pm 0.54$

Table 3
Decay constants, bag parameters, QCD corrections and other parameters used in our analysis. When not explicitly stated, we take the inputs from the Particle Data Group [30].

$G_F = 1.16637 \times 10^{-5}$ GeV^{-2}	$\tau_{K_L} = (5.116 \pm 0.021) \times 10^{-8}$ s
$\sin^2\theta_W = 0.23116$	$\tau_{K^+} = (1.2380 \pm 0.0020) \times 10^{-8}$ s
$\alpha(M_Z) = \frac{1}{127.9}$	$\eta_c = 1.43 \pm 0.23$ [33]
$\alpha_s(M_Z) = 0.1184$	$\eta_{ct} = 0.496 \pm 0.047$ [34]
$m_t(m_t) = 163$ GeV	$\eta_t = 0.5765$ [35]
$m_c(m_c) = 1.275 \pm 0.025$ GeV	$f_K = 0.1561 \pm 0.0011$ [36]
$m_b(m_b) = 4.18 \pm 0.03$ GeV	$\hat{B}_K = 0.767 \pm 0.010$ [36]
$M_W = 80.385$ GeV	$\Delta M_K = (0.5292 \pm 0.0009) \times 10^{-2}$ ps^{-1}
$M_Z = 91.1876$ GeV	$f_D = (0.209 \pm 0.003)$ GeV [37]
$M_K = 0.497614$ GeV	$\hat{B}_D = 1.18 \pm 0.07$ [38]
$M_{K^*} = 0.89594$ GeV	$\kappa_\epsilon = 0.94 \pm 0.02$ [39,40]
$M_{B_d} = 5.27917$ GeV	$f_{bd} = (190.5 \pm 4.2)$ MeV [37]
$M_{B_s} = 5.36677$ GeV	$f_{bs} = (227.7 \pm 4.5)$ MeV [37]
$M_{B^\pm} = 5.27926$ GeV	$f_{B_d^0}\sqrt{B_{B_d^0}} = (0.216 \pm 0.015)$ GeV [37]
$M_D = 1.864$ GeV	$f_{B_s^0}\sqrt{B_{B_s^0}} = (0.266 \pm 0.018)$ GeV [37]
$m_\mu = 0.105$ GeV	$\mathcal{B}(B \to X_c \ell \nu) = (10.61 \pm 0.17) \times 10^{-2}$
$m_\tau = 1.77682$ GeV	$\mathcal{B}(K^+ \to \pi^0 e^+ \nu) = (5.07 \pm 0.04)\%$
$\tau_{B_d} = (1.519 \pm 0.007)$ ps	$\mathcal{B}(K^+ \to \mu^+ \nu) = (63.56 \pm 0.11)\%$
$\tau_{B_s} = (1.497 \pm 0.026)$ ps	$m_c/m_b = 0.29 \pm 0.02$
$\tau_{B^\pm} = (1.641 \pm 0.008)$ ps	$\eta_B^Z = 0.57$ [6]

In our analysis χ^2 of an observable A is defined as

$$\chi^2_A = \left(\frac{A - A^c_{\text{exp}}}{A^{\text{err}}_{\text{exp}}} \right)^2 , \tag{5}$$

where the measured value of A is $(A^c_{\text{exp}} \pm A^{\text{err}}_{\text{exp}})$. The individual components of the function χ^2_{total}, i.e. the χ^2 of different observables that we are using as inputs, are defined in the following subsections.

2.1. Direct measurements of the CKM elements

The contribution to the χ^2 from the direct measurements of the magnitudes of the CKM elements is given by

$$\begin{aligned} \chi^2_{\text{CKM}} = & \left(\frac{|V_{us}| - 0.2252}{0.0009} \right)^2 + \left(\frac{|V_{ud}| - 0.97425}{0.00022} \right)^2 + \left(\frac{|V_{cs}| - 1.006}{0.023} \right)^2 \\ & + \left(\frac{|V_{cd}| - 0.230}{0.011} \right)^2 + \left(\frac{|V_{ub}| - 0.00382}{0.00021} \right)^2 + \left(\frac{|V_{cb}| - 0.0409}{0.001} \right)^2 . \end{aligned} \tag{6}$$

2.2. Indirect CP violation ϵ_K in $K_L \to \pi\pi$

The mixing induced CP asymmetry in neutral K decays is described by the parameter $|\epsilon_K|$, which is proportional to $\text{Im}(M_K^{12})$. To calculate the contribution to χ^2 from $|\epsilon_K|$, we use the quantity

$$K_{\text{mix}} = \frac{12\sqrt{2}\pi^2 (\Delta M_K)_{\text{exp}} |\epsilon_K|}{G_F^2 M_W^2 f_K^2 m_K \hat{B}_K k_\epsilon} \tag{7}$$

With the theoretical and experimental inputs given in Tables 1 and 3, we find

$$K_{\text{mix, exp}} = (1.69 \pm 0.05) \times 10^{-7} . \tag{8}$$

The contribution to χ^2 from $|\epsilon_K|$ is then

$$\chi^2_{|\epsilon_K|} = \left(\frac{K_{\text{mix}} - 1.69 \times 10^{-7}}{0.05 \times 10^{-7}} \right)^2 + \chi^2_\eta , \tag{9}$$

where

$$\chi^2_\eta = \left(\frac{\eta_c - 1.43}{0.23} \right)^2 + \left(\frac{\eta_{ct} - 0.496}{0.047} \right)^2 . \tag{10}$$

Using the expression for $|\epsilon_K|$ given in [5], it is straightforward to find an expression for K_{mix}. In order to take into account the error in the QCD corrections η_c and η_{ct} which appear in the theoretical expression of $|\epsilon_K|$, we consider them to be parameters and have added a term, χ^2_η, in χ^2. We held the other QCD correction η_t fixed to its central value because its error is very small.

2.3. Direct CP violation ϵ'/ϵ in $K_L \to \pi\pi$

The ratio ϵ'/ϵ measures direct *CP* violation in $K_L \to \pi\pi$ and has been measured quite accurately by NA48 [41] and KTeV [42,43] collaborations. The current world average is $(16.6 \pm 2.3) \times 10^{-4}$. However, the SM prediction is subject to large uncertainties. Within the SM there is destructive interference between the QCD penguins and the electroweak penguins contributions. This one hand makes the theoretical predictions challenging but on the other hand makes this observable sensitive to new physics which, in general, is expected to contribute to Z penguins rather than the QCD penguins. Therefore in spite of large theoretical uncertainties, ϵ'/ϵ is expected to provide useful constraints on new physics parameters [44,45]. This ratio is sensitive to $\mathrm{Im}(U_{sd})$ [4,6] and hence is included in our analysis.

The dominant sources of uncertainties in the theoretical prediction of ϵ'/ϵ is due to two non-perturbative parameters $B_6^{1/2}$ and $B_8^{3/2}$ that parametrize the matrix elements of the dominant operators Q_6 and Q_8, respectively. These parameters are calculated within the framework of lattice QCD or the large N-approach [46,47]. Using the recent results by the RBC–UKQCD lattice collaboration [48,49], $(\epsilon'/\epsilon)_{\mathrm{SM}}$ is predicted to be $(1.9 \pm 4.5) \times 10^{-4}$ [50] which is substantially more precise than the previous estimates of $(\epsilon'/\epsilon)_{\mathrm{SM}}$ and differs from the experimental measurement at the level of 3σ.

The contribution to χ^2 from ϵ'/ϵ is given by

$$\chi^2_{\epsilon'/\epsilon} = \left(\frac{\epsilon'/\epsilon - 16.6 \times 10^{-4}}{2.3 \times 10^{-4}}\right)^2 + \chi^2_{th}\,, \tag{11}$$

where

$$\chi^2_{th} = \left(\frac{B_6^{1/2} - 0.57}{0.19}\right)^2 + \left(\frac{B_8^{3/2} - 0.76}{0.05}\right)^2 + \left(\frac{\hat{\Omega}_{\mathrm{eff}} - 14.8 \times 10^{-2}}{8 \times 10^{-2}}\right)^2 + \left(\frac{a_0^{1/2} - (-2.92)}{0.12}\right)^2 . \tag{12}$$

In order to include the error in quantities $B_6^{1/2}$, $B_8^{3/2}$, $\hat{\Omega}_{\mathrm{eff}}$ and $a_0^{1/2}$ which appear in the theoretical expression of ϵ'/ϵ, the term χ^2_{th} is added to $\chi^2_{\epsilon'/\epsilon}$. The theoretical expression for ϵ'/ϵ in ZFCNC model is taken from Refs. [4,6] whereas the numerical values of the theoretical inputs are taken from [50].

2.4. Branching fraction of the decay $K^+ \to \pi^+\nu\bar{\nu}$

Unlike other K decays, $K^+ \to \pi^+\nu\bar{\nu}$ is dominated by the short-distance (SD) interactions. The LD contribution to $K^+ \to \pi^+\nu\bar{\nu}$ is about 3 orders of magnitude smaller than that of the SD [51,52].

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

$$\chi^2_{K^+\to\pi^+\nu\bar{\nu}} = \left(\frac{K_{\mathrm{slep}} - 7.37 \times 10^{-5}}{4.77 \times 10^{-5}}\right)^2 + \chi^2_X\,, \tag{13}$$

where

$$\chi^2_X = \left(\frac{X_e^{nl} - 10.6 \times 10^{-4}}{1.5 \times 10^{-4}}\right)^2 + \left(\frac{X_\tau^{nl} - 7.1 \times 10^{-4}}{1.4 \times 10^{-4}}\right)^2 . \tag{14}$$

Using Tables 1 and 3, we obtain

$$K_{\rm slep} = \frac{2\pi^2 \sin^4\theta_W \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}{\alpha^2 r_K \mathcal{B}(K^+ \to \pi^0 e^+\nu)} = (7.37 \pm 4.77) \times 10^{-5}. \tag{15}$$

Here we have used $r_{K^+} = 0.901 \pm 0.027$ which epitomizes the isospin-breaking corrections in relating the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ to that of the well-measured leading decay $K^+ \to \pi^0 e^+\nu$. Using the expression for $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ given in [5], it is straightforward to find an expression for $K_{\rm slep}$. In order to include the error in quantities X_e^{nl} and X_τ^{nl} which appear in the theoretical expression of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, we consider them to be parameters and have added a term, χ^2_X, in χ^2.

2.5. Branching fraction of the decay $K_L \to \mu^+\mu^-$

Unlike $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \mu^+\mu^-$ is not dominated by clean SD effects. The LD and SD contributions are comparable in size. In order to extract bounds on the SD contribution to the branching ratio of $K_L \to \mu^+\mu^-$, it is extremely important to have a theoretical control on the $K_L \to \gamma\gamma$ form factors with off-shell photons. A conservative bound of 2.5×10^{-9} on $\mathcal{B}(K_L \to \mu^+\mu^-)$ from SD was obtained in Ref. [25]. We use this bound to constrain the ZFCNC parameters. In order to include $\mathcal{B}(K_L \to \mu^+\mu^-)$, we define

$$\chi^2_{K_L\to\mu^+\mu^-} = \left(\frac{K_{\rm lep} - 3.39 \times 10^{-6}}{3.78 \times 10^{-6}}\right)^2 + \chi^2_{Y_{NL}}\,, \tag{16}$$

where

$$\chi^2_{Y_{NL}} = \left(\frac{Y_{NL} - 2.94 \times 10^{-4}}{0.28 \times 10^{-4}}\right)^2. \tag{17}$$

Using the input Table 1, we obtain

$$K_{\rm lep} = \frac{\pi^2 \sin^4\theta_W \mathcal{B}(K_L \to \mu^+\mu^-)\tau_{K^+}}{\alpha^2 \mathcal{B}(K^+ \to \mu^+\nu)\tau_{K_L}} = (3.39 \pm 3.78) \times 10^{-6}. \tag{18}$$

Using the expression for $\mathcal{B}(K_L \to \mu^+\mu^-)$ given in [5], the theoretical expression for $K_{\rm lep}$ can be easily obtained. The quantity Y_{NL} appears in the theoretical expression for $\mathcal{B}(K_L \to \mu^+\mu^-)$. In order to include error in Y_{NL}, we consider it to be a parameter and have added a term, $\chi^2_{Y_{NL}}$, in χ^2.

2.6. $Z \to b\bar{b}$ decay

The b–b' mixing in ZFCNC model modifies the $Zb\bar{b}$ coupling at the tree level. This affects observables such as R_b, A^b_{FB}, A_b and R_c. The theoretical expressions of these observables in the ZFCNC model are given by [12]

$$\begin{aligned}
R_b &= R_b^{SM}\left(1 - 1.820\,|V_{4b}|^2\right),\\
A^b_{FB} &= A^{b,SM}_{FB}\left(1 - 0.164\,|V_{4b}|^2\right),\\
A_b &= A_b^{SM}\left(1 - 0.164\,|V_{4b}|^2\right),\\
R_c &= R_c^{SM}\left(1 - 0.500\,|V_{4b}|^2\right),
\end{aligned} \tag{19}$$

where the SM predictions are obtained from a fit in Ref. [30]. The χ^2 contribution is then given by

$$\chi^2_{Zb\bar{b}} = \Big(\frac{R_b - 0.21629}{0.00066}\Big)^2 + \Big(\frac{A^b_{FB} - 0.0992}{0.0016}\Big)^2 + \Big(\frac{A_b - 0.923}{0.020}\Big)^2 + \Big(\frac{R_c - 0.1721}{0.003}\Big)^2 . \tag{20}$$

2.7. B^0_q–$\bar{B}^0_q$ mixing ($q = d, s$)

The theoretical expressions for M^q_{12} ($q = d, s$) in the ZFCNC model is given by [2]

$$M^q_{12} = \frac{G_F^2 M_W^2 M_{B_q} f^2_{bq} \hat{B}_{bq}}{12\pi^2} \left[\left(V^*_{tq} V_{tb}\right)^2 - a \left(V^*_{tq} V_{tb}\right) U_{qb} + b\, U^2_{qb} \right] , \tag{21}$$

where

$$a = 8\frac{Y(x_t)}{S(x_t)}, \qquad b = \frac{2\sqrt{2}\pi^2}{G_F M_W^2 S(x_t)} \frac{\eta^Z_B}{\eta_B} . \tag{22}$$

Here $S(x_t)$ and $Y(x_t)$ are the Inami–Lim functions [53], while η_B and η^Z_B are the QCD correction factors. To calculate $\chi^2_{B_q}$ for B_q–$\bar{B}_q$ mixing, we use the quantity

$$B^q_{\rm mix} = \frac{6\pi^2 \Delta M_q}{G_F^2 M_W^2 M_{B_q} \hat{B}_{bq} f^2_{B_q} \eta_B S(x_t)} . \tag{23}$$

With the inputs given in Table 1, we get

$$B^d_{\rm mix,exp} = (6.56 \pm 0.77) \times 10^{-5}, \tag{24}$$

$$B^s_{\rm mix,exp} = (1.48 \pm 0.14) \times 10^{-3}. \tag{25}$$

Then one gets

$$\chi^2_{B^0_d} = \Big(\frac{B^d_{\rm mix} - 6.56 \times 10^{-5}}{0.77 \times 10^{-5}}\Big)^2, \tag{26}$$

$$\chi^2_{B^0_s} = \Big(\frac{B^s_{\rm mix} - 1.48 \times 10^{-3}}{0.14 \times 10^{-3}}\Big)^2. \tag{27}$$

2.8. Indirect CP violation in $B^0_d \to J/\psi\, K_S$ and $B^0_s \to J/\psi\, \phi$

In the SM, indirect CP violation in $B^0_d \to J/\psi\, K_S$ and $B^0_s \to J/\psi\, \phi$ probes $\sin 2\beta$ and $\sin 2\beta_s$, respectively. With NP, we have

$$S_{J/\psi\, K_S} = \frac{{\rm Im}(M^d_{12})}{|M^d_{12}|}, \qquad S_{J/\psi\, \phi} = -\frac{{\rm Im}(M^s_{12})}{|M^s_{12}|} . \tag{28}$$

The theoretical expressions for M^q_{12} ($q = d, s$) in the ZFCNC model are given in the previous subsection. Using the experimentally-measured values of $S_{J/\psi\, K_S}$ and $S_{J/\psi\, \phi}$ given in Table 1, we get

$$\chi^2_{\sin 2\beta} = \Big(\frac{S_{J/\psi\, K_S} - 0.68}{0.02}\Big)^2, \qquad \chi^2_{\sin 2\beta_s} = \Big(\frac{S_{J/\psi\, \phi} - 0.00}{0.07}\Big)^2 . \tag{29}$$

2.9. CKM angle γ

In the Wolfenstein parametrization, the CKM angle $\gamma = \tan^{-1}(\eta/\rho)$, which is the argument of V_{ub}. Therefore the χ^2 of γ is given by

$$\chi^2_\gamma = \left(\frac{\delta_{13} - 68\ (\pi/180)}{11\ (\pi/180)}\right)^2 . \tag{30}$$

2.10. Branching ratio of $B \to X_s\, l^+ l^-$

The effective Hamiltonian for the quark-level transition $b \to s\, l^+ l^-$ in the SM can be written as

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)\,, \tag{31}$$

where the form of the operators O_i and the expressions for calculating the coefficients C_i are given in Ref. [54]. The $Z\bar{b}s$ coupling generated in the ZFCNC model changes the values of the Wilson coefficients $C_{9,10}$. The Wilson coefficients $C_{9,10}^{\rm tot}$ in the ZFCNC model can be written as [11]

$$\begin{aligned} C_9^{\rm tot} &= C_9^{\rm eff} - \frac{\pi}{\alpha}\frac{U_{sb}}{V_{ts}^* V_{tb}}(4\sin^2\theta_W - 1) \\ C_{10}^{\rm tot} &= C_{10} - \frac{\pi}{\alpha}\frac{U_{sb}}{V_{ts}^* V_{tb}}\,. \end{aligned} \tag{32}$$

The theoretical prediction for the branching fraction of $B \to X_s \mu^+\mu^-$ in the intermediate q^2 region (7 GeV$^2 \le q^2 \le 12$ GeV^2) is rather uncertain due to the nearby charmed resonances. The predictions are relatively cleaner in the low-q^2 (1 GeV$^2 \le q^2 \le 6$ GeV^2) and the high-q^2 (14.2 GeV$^2 \le q^2 \le m_b^2$) regions. We therefore consider both low-q^2 and high-q^2 regions in the fit. The latest Belle measurement uses only 25% of its final data set [55]. The BaBar Collaboration has recently updated the measurement of $\mathcal{B}(B \to X_s\, l^+ l^-)$ using the full data set, which corresponds to 471×10^6 $B\bar{B}$ events [22].

The theoretical predictions for $\mathcal{B}(B \to X_s\, l^+ l^-)$ are computed using the program **SuperIso** [56,57], in which the higher-order and power corrections are taken from Refs. [58,59], while the electromagnetic logarithmically-enhanced corrections and Bremsstrahlung contributions are implemented following Refs. [60] and [61], respectively.

The contribution to $\chi^2_{\rm total}$ is

$$\begin{aligned} \chi^2_{B\to X_s l^+ l^-} = &\left(\frac{\mathcal{B}(B \to X_s\, l^+ l^-)_{\rm low} - 1.6 \times 10^{-6}}{0.49 \times 10^{-6}}\right)^2 \\ &+ \left(\frac{\mathcal{B}(B \to X_s\, l^+ l^-)_{\rm high} - 0.57 \times 10^{-6}}{0.23 \times 10^{-6}}\right)^2 , \end{aligned} \tag{33}$$

where we have added a theoretical error of 7% to $\mathcal{B}(B \to X_s\, l^+ l^-)_{\rm low}$, which includes corrections due to the renormalization scale and quark masses, and a theoretical error of 30% to $\mathcal{B}(B \to X_s\, l^+ l^-)_{\rm high}$, which includes the non-perturbative QCD corrections.

2.11. Branching ratio of $B \to K \mu^+ \mu^-$

The predictions for the branching ratio of $B \to K \mu^+ \mu^-$ are relatively cleaner in the low-q^2 ($1.1\ \mathrm{GeV}^2 \le q^2 \le 6\ \mathrm{GeV}^2$) and the high-$q^2$ ($15\ \mathrm{GeV}^2 \le q^2 \le 22\ \mathrm{GeV}^2$) regions. We include both regions in the fit. We use the recent LHCb measurements of $\langle d\mathcal{B}/dq^2\rangle(B \to K \mu^+ \mu^-)$ [23]. The theoretical expression for $\langle d\mathcal{B}/dq^2\rangle(B \to K \mu^+ \mu^-)$ in the SM are taken from Refs. [62,63] modulo the modified Wilson coefficients given in Eq. (32).

We include factorizable and non-factorizable corrections of $O(\alpha_s)$ in our numerical analysis following Refs. [62,64] in the low-q^2 region. In the high-q^2 region, we make use of the improved Isgur–Wise relation between the form factors [63]. The contribution to χ^2_{total} from $B \to K \mu^+ \mu^-$ is

$$\chi^2_{B\to K \mu^+ \mu^-} = \Big(\frac{\langle \frac{d\mathcal{B}}{dq^2}\rangle(B \to K \mu^+ \mu^-)_{\mathrm{low}} - 18.7\times 10^{-9}}{6.67\times 10^{-9}}\Big)^2 + \Big(\frac{\langle \frac{d\mathcal{B}}{dq^2}\rangle(B \to K \mu^+ \mu^-)_{\mathrm{high}} - 9.5\times 10^{-9}}{3.32\times 10^{-9}}\Big)^2 , \tag{34}$$

where we have included a theoretical error of 30% in both low- and high-q^2 bins. This is mainly due to uncertainties in the $B \to K$ form factors.

2.12. Constraints from $B \to K^* \mu^+ \mu^-$

A possible indicator of new physics in $b \to s$ sector could be the measurement of new angular observables in $B \to K^* \mu^+ \mu^-$ at the LHCb [32,65]. Here, we include all measured observables in $B \to K^* \mu^+ \mu^-$ in the low- and high-q^2 regions. The experimental results for $B \to K^* \mu^+ \mu^-$ decay are given in Table 2.

The complete angular distribution for the decay $B \to K^* \mu^+ \mu^-$ is described by four independent kinematic variables: the lepton-pair invariant mass squared q^2, two polar angles θ_μ and θ_K, and the angle between the planes of the dimuon and $K\pi$ decays, ϕ. The differential decay distribution of $B \to K^* \mu^+ \mu^-$ can be written as

$$\frac{d^4\Gamma[B \to K^*(\to K\pi)\mu^+\mu^-]}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi) , \tag{35}$$

where the angular-dependent term can be written as

$$\begin{aligned} J(q^2, \theta_l, \theta_K, \phi) &= J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l \\ &+ J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi \\ &+ J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l \\ &+ J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi . \end{aligned} \tag{36}$$

The J_i's depend on the six complex K^* spin amplitudes $A_\parallel^{L,R}$, $A_\perp^{L,R}$, $A_0^{L,R}$ and A_t. For example,

$$J_{1s} = \frac{(2+\beta_l^2)}{4}[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2] + \frac{4m_l^2}{q^2} Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}) . \tag{37}$$

We can also define the optimized observables like P_1, P_2, P_4', P_5', P_6', P_8' [66]. These observables are form factor independent observables and having reduced hadronic uncertainties at leading order in corresponding effective-theory expansions. These form factor independent observables integrated in q^2 bins can be defined as, for example:

$$< P_1 >_{bin} = \frac{1}{2} \frac{\int_{bin} dq^2 [J_3 + \bar{J}_3]}{\int_{bin} dq^2 [J_{2s} + \bar{J_{2s}}]}$$

where $\bar{J}_i$'s can be obtained from J_i's by all weak phases conjugated.

For $B \to K^* \mu^+ \mu^-$, we use the observables $\langle d\mathcal{B}/dq^2 \rangle$, P_1, P_2, P_4', P_5', P_6', P_8' and F_L in the low-q^2 bins 0.1–2 GeV^2, 2.0–4.3 GeV^2, 4.3–8.68 GeV^2, and the high-q^2 bins 14.18–16 GeV^2 and 16–19 GeV^2. The observables A_{FB}, F_L and P_2 are related as $A_{FB} = -\frac{3}{2}(1 - F_L)P_2$. These observables are highly correlated in most of the bins [67]. This is the reason why we use F_L, instead of A_{FB}, in the fit as it does not show a strong correlation with P_2. The SM theoretical expressions for all observables in $B \to K^* \mu^+ \mu^-$ are given in [66] and could be adapted to the ZFCNC model by modification of the Wilson coefficients values, Eq. (32). These predictions have errors associated with them. Excluding uncertainties due to CKM matrix elements, the main sources of uncertainties in the low-q^2 region are the form factors, unknown $1/m_b$ subleading corrections, quark masses, and the renormalization scale μ_b. Also, in the high-q^2 region, there is an additional subleading correction of $O(1/m_b)$ to the improved Isgur–Wise form factor relations. The theoretical error for each $B \to K^* \mu^+ \mu^-$ observable O_j, is incorporated in the fit by multiplying the theoretical result by $(1 \pm X_j)$, where X_j is the total theoretical error corresponding to the jth observable. This can be easily estimated using Table II of Ref. [68]. The theoretical predictions for all $B \to K^* \mu^+ \mu^-$ observables are computed using the program **SuperIso** [56,57].

For each bin, we compute the flavor observables. The χ^2, which includes the experimental correlations, is defined as

$$\chi^2_{B \to K^* \mu^+ \mu^-} = \sum_{\text{bins}} \left[\sum_{j,k \in (B \to K^* \mu^+ \mu^- \text{ obs.})} \left(O_j^{\text{exp}} - O_j^{\text{th}} \right) \left(\sigma^{bin} \right)^{-1}_{jk} \left(O_k^{\text{exp}} - O_k^{\text{th}} \right) \right], \quad (38)$$

where $\left(\sigma^{bin}\right)^{-1}_{jk}$ are the inverse of the covariance matrices for each bin which are computed using the correlation matrices given in Ref. [67].

2.13. Branching ratio of $B^+ \to \pi^+ \mu^+ \mu^-$

The decay $B^+ \to \pi^+ \mu^+ \mu^-$ is the first measurement of any decay channel induced by $b \to d\,\mu^+ \mu^-$. The measured branching ratio of $B^+ \to \pi^+ \mu^+ \mu^-$ is $(2.3 \pm 0.6 \pm 0.1) \times 10^{-8}$ [24]. The effective Hamiltonian for the quark level transition $b \to d\,\mu^+ \mu^-$ along with the modified Wilson coefficients in the ZFCNC model can be respectively obtained from Eqs. (31) and (32) by replacing s by d. The theoretical expression for $\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)$ in the ZFCNC model is obtained using the expressions given in Ref. [69]. The contribution to χ^2_{total} is

$$\chi^2_{B^+ \to \pi^+ \mu^+ \mu^-} = \left(\frac{\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) - 2.3 \times 10^{-8}}{0.66 \times 10^{-8}} \right)^2, \quad (39)$$

where we have included a theoretical error of 10% in $\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)$ which is mainly is due to uncertainties in the $B^+ \to \pi^+$ form factors [70].

2.14. *Branching ratio of $B_q \to \mu^+\mu^-$ $(q = s, d)$*

The branching ratio of $B_q \to \mu^+\mu^-$ in the ZFCNC model is given by

$$\mathcal{B}(B_q \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2 M_{B_q} m_\mu^2 f_{bq}^2 \tau_{B_q}}{16\pi^3} |V_{tq}^* V_{tb}|^2 \sqrt{1 - 4(m_\mu^2/M_{B_q}^2)} |C_{10}^{\mathrm{tot,q}}|^2 , \tag{40}$$

where $C_{10}^{\mathrm{tot,s}}$ is defined in Eq. (32), and $C_{10}^{\mathrm{tot,d}}$ is given by

$$C_{10}^{\mathrm{tot,d}} = C_{10} - \frac{\pi}{\alpha} \frac{U_{db}}{V_{td}^* V_{tb}} . \tag{41}$$

In order to include $\mathcal{B}(B_q \to \mu^+\mu^-)$ $(q = s, d)$ in the fit, we define

$$B_{\mathrm{lepq}} = \frac{16\pi^3 \mathcal{B}(B_q \to \mu^+\mu^-)}{G_F^2 \alpha^2 M_{B_q} m_\mu^2 f_{bq}^2 \tau_{B_q} \sqrt{1 - 4(m_\mu^2/M_{B_q}^2)}} . \tag{42}$$

Using the inputs given in Tables 1 and 3, we obtain $B_{\mathrm{leps,exp}} = 0.025 \pm 0.006$ and $B_{\mathrm{lepd,exp}} = 0.0048 \pm 0.0020$. The contribution to χ^2_{total} from $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B_d^0 \to \mu^+\mu^-)$ is then given by

$$\chi^2_{B_q \to \mu^+\mu^-} = \left(\frac{B_{\mathrm{leps}} - 0.025}{0.006}\right)^2 + \left(\frac{B_{\mathrm{lepd}} - 0.0048}{0.0020}\right)^2 . \tag{43}$$

2.15. *Branching ratio of $B \to \tau\bar{\nu}$*

The branching ratio of $B \to \tau\bar{\nu}$ is given by

$$\mathcal{B}(B \to \tau\bar{\nu}) = \frac{G_F^2 M_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{M_B^2}\right)^2 f_{bd}^2 |V_{ub}|^2 \tau_{B^\pm} . \tag{44}$$

In order to include $\mathcal{B}(B \to \tau\bar{\nu})$ in the fit, we define

$$B_{\mathrm{Btau\text{-}nu}} = \frac{8\pi \mathcal{B}(B \to \tau\bar{\nu})}{G_F^2 M_B m_\tau^2 f_{bd}^2 \tau_B (1 - m_\tau^2/M_B^2)^2} . \tag{45}$$

Using the inputs given in Tables 1 and 3, we obtain $B_{\mathrm{Btau\text{-}nu,exp}} = (1.779 \pm 0.352) \times 10^{-5}$. The contribution to χ^2_{total} from $\mathcal{B}(B \to \tau\bar{\nu})$ is then given by

$$\chi^2_{B \to \tau\nu} = \left(\frac{B_{\mathrm{Btau\text{-}nu}} - 1.779 \times 10^{-5}}{0.352 \times 10^{-5}}\right)^2 . \tag{46}$$

2.16. *Like-sign dimuon charge asymmetry A_{SL}^b*

The CP-violating like-sign dimuon charge asymmetry in the B system is defined as

$$A_{SL}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} , \tag{47}$$

where $N_b^{\pm\pm}$ is the number of events of $b\bar{b} \to \mu^\pm\mu^\pm X$. This asymmetry can be written as a linear combination of the asymmetry in B_d and B_s sector:

$$A^b_{SL} = c^d_{SL} A^d_{SL} + c^s_{SL} A^s_{SL}\,, \tag{48}$$

where $A^q_{SL} = \mathrm{Im}\left(\Gamma^{(q)}_{12}/M^{(q)}_{12}\right)$ $(q = s, d)$, with $c^d_{SL} = 0.594 \pm 0.022$ and $c^s_{SL} = 0.406 \pm 0.022$. A^b_{sl} has been measured by the DØ Collaboration. The measured value is $(-4.96 \pm 1.53 \pm 0.72) \times 10^{-3}$ [29] which deviates by 2.7σ from the SM prediction of A^b_{SL} which is $(-2.44 \pm 0.42) \times 10^{-4}$.

The theoretical expression for A^q_{SL} is given in Ref. [71]. The contribution to χ^2 from A^b_{SL} is given by

$$\chi^2_{A^b_{SL}} = \left(\frac{A^b_{SL} - (-4.96 \times 10^{-3})}{1.69 \times 10^{-3}}\right)^2 + \chi^2_c, \tag{49}$$

where

$$\chi^2_c = \left(\frac{c^d_{SL} - 0.594}{0.022}\right)^2 + \left(\frac{c^s_{SL} - 0.406}{0.022}\right)^2 + \left(\frac{a - 10.5}{1.8}\right)^2 + \left(\frac{b - 0.2}{0.1}\right)^2 + \left(\frac{c - (-53.3)}{12}\right)^2 . \tag{50}$$

The term χ^2_c is added to include errors in c^d_{SL} and c^s_{SL} as well as in quantities a, b and c which appear in the theoretical expressions for A^q_{SL} [71].

2.17. The oblique parameters S, U and T

The contribution to χ^2 from oblique parameters is given by

$$\chi^2_{\text{Oblique}} = \left(\frac{S - 0.05}{0.10}\right)^2 + \left(\frac{U - (-0.03)}{0.10}\right)^2 + \left(\frac{T - 0.01}{0.12}\right)^2. \tag{51}$$

The theoretical expressions for S, U and T given in Ref. [72].

2.18. D–$\bar{D}$ mixing

The fit is expected to have very weak dependence on b' mass as the theoretical expressions for all the observables discussed in the above subsections, except the oblique parameters, are independent of the mass of b' quark. In order to include the dependence of b' mass in the fit, one should include constraints from D–$\bar{D}$ mixing [73], despite the fact the we do not have a reliable estimate of the SM contribution to D–$\bar{D}$ mixing [74–83]. The new physics contribution to M^D_{12} in ZFCNC model, which is due to box diagram involving heavy b', can be reliably estimated [84,73].

In order to include constraints from D–$\bar{D}$ mixing, we follow [38] and use a model independent bound on the new physics mixing amplitude, $M^{D,NP}_{12}$, obtained in [85]. The contribution to χ^2 from D–$\bar{D}$ mixing is given by

$$\chi^2_D = \left(\frac{D_{\text{mix}} - 2.68 \times 10^{-6}}{3.35 \times 10^{-6}}\right)^2, \tag{52}$$

where

$$D_{\text{mix}} = \frac{12\pi^2 |M^{D,NP}_{12}|}{G_F^2 f_D^2 \hat{B}_D M_D M_W^2} = (2.76 \pm 3.43) \times 10^{-6}. \tag{53}$$

Table 4
The results of the fit to the parameters of CKM and ZFCNC.

Parameter	SM	$m_{b'} = 800$ GeV	$m_{b'} = 1200$ GeV
θ_{12}	0.2273 ± 0.0007	0.2271 ± 0.0008	0.2270 ± 0.0008
θ_{13}	0.0035 ± 0.0001	0.0038 ± 0.0001	0.0038 ± 0.0001
θ_{23}	0.0397 ± 0.0007	0.0391 ± 0.0007	0.0391 ± 0.0007
δ_{13}	1.10 ± 0.10	1.04 ± 0.08	1.04 ± 0.08
θ_{14}	–	0.0151 ± 0.0154	0.0147 ± 0.0149
θ_{24}	–	0.0031 ± 0.0039	0.0029 ± 0.0036
θ_{34}	–	0.0133 ± 0.0130	0.0123 ± 0.0122
δ_{14}	–	0.11 ± 0.22	0.11 ± 0.23
δ_{24}	–	3.23 ± 0.24	3.23 ± 0.27
$\chi^2/d.o.f.$	82.42/60	70.99/63	70.96/63

Table 5
Magnitudes of the 3×4 CKM elements obtained from the fit.

Quantity	SM	$m_{b'} = 800$ GeV	$m_{b'} = 1200$ GeV
$\lvert V_{ud}\rvert$	0.9743 ± 0.0002	0.9742 ± 0.0003	0.9742 ± 0.0003
$\lvert V_{us}\rvert$	0.225 ± 0.001	0.225 ± 0.001	0.225 ± 0.001
$\lvert V_{ub}\rvert$	$(3.50 \pm 0.10) \times 10^{-3}$	$(3.80 \pm 0.10) \times 10^{-3}$	$(3.80 \pm 0.10) \times 10^{-3}$
$\lvert V_{ub'}\rvert$	–	0.0151 ± 0.0154	0.0147 ± 0.0149
$\lvert V_{cd}\rvert$	0.225 ± 0.001	0.225 ± 0.001	0.2249 ± 0.0008
$\lvert V_{cs}\rvert$	0.9735 ± 0.0002	0.9736 ± 0.0002	0.9736 ± 0.0002
$\lvert V_{cb}\rvert$	0.040 ± 0.001	0.0391 ± 0.0007	0.0391 ± 0.0007
$\lvert V_{cb'}\rvert$	–	0.0031 ± 0.0039	0.0029 ± 0.0036
$\lvert V_{td}\rvert$	0.0080 ± 0.0004	0.0074 ± 0.0004	0.0075 ± 0.0004
$\lvert V_{ts}\rvert$	0.039 ± 0.001	0.0385 ± 0.0007	0.0385 ± 0.0007
$\lvert V_{tb}\rvert$	1	0.9991 ± 0.0002	0.9991 ± 0.0002
$\lvert V_{tb'}\rvert$	–	0.0133 ± 0.0130	0.0123 ± 0.0122

3. Results of the fit

The results of these fits are presented in Table 4. The results of the fit for the SM are consistent with those obtained in Ref. [30]. The results for ZFCNC model correspond to a b' mass of 800 GeV and 1200 GeV. The best fit values of the parameters of the upper 3×3 sub-block of CKM4 matrix are not affected much by the addition of a vector-like isosinglet down-type quark b' and are essentially the same as the SM CKM fit parameters. On the other hand, the new real parameters θ_{14}, θ_{24}, θ_{34} are consistent with zero. This also is consistent with the observation that no meaningful constraints are obtained on the new phases δ_{14} and δ_{24}: since vanishing θ_{14}, θ_{24} imply vanishing $V_{ub'}$, $V_{cb'}$, respectively, the phases of these two elements have no significance. Therefore we see that even if we invoke violation of unitarity by adding a vector isosinglet down-type quark b' to the SM particle spectrum, the constraints coming from the flavor physics sector does not allow any sizable deviations from the unitarity of 3×3 CKM matrix.

The magnitude of elements of the 3×4 quark mixing matrix, obtained by using the fit values presented in Table 4, are given in Table 5. Clearly all new elements of the quark mixing matrix are consistent with zero. Furthermore, the 3σ upper bound on the new CKM elements $V_{ub'}$, $V_{cb'}$ and $V_{tb'}$ are 0.07, 0.02 and 0.06, respectively indicating that the mixing of the b' quark to the other three is very small.

Table 6
Magnitude of ZFCNC couplings.

Quantity	$m_{b'} = 800$ GeV	$m_{b'} = 1200$ GeV
$\|U_{ds}\|$	$(0.27 \pm 5.89) \times 10^{-5}$	$(0.15 \pm 1.91) \times 10^{-5}$
$\|U_{db}\|$	$(2.05 \pm 2.84) \times 10^{-4}$	$(1.84 \pm 2.56) \times 10^{-4}$
$\|U_{sb}\|$	$(0.23 \pm 5.17) \times 10^{-5}$	$(0.12 \pm 1.51) \times 10^{-5}$

It is obvious from Table 5 that the values of CKM elements V_{td} and V_{ts} in ZFCNC model remains almost the same as compared to their SM predictions. However, the allowed range of V_{ub} gets slightly inflated. Because of this, the measured and predicted values of branching ratio of $B \to \tau\bar{\nu}$ are in better agreement with each other in ZFCNC model in comparison to SM. This can be seen by comparing the $\chi^2_{B\to\tau\nu}$ contribution to the total $\chi^2_{\rm min}$ in ZFCNC model with that of SM. In SM, $\chi^2_{B\to\tau\nu} = 2.47$ which reduces to 0.91 in the ZFCNC model indicating an improvement over the SM value.

The $s \to d$, $b \to d$, and $b \to s$ transitions, which are the relevant ones for K and B decays, get contributions from terms involving the SM bilinears $\lambda^i_{jk} \equiv V^*_{ij} V_{ik}$ $(i \in \{u, c, t\}$ and $j, k \in \{d, s, b\})$ and the new physics couplings U_{jk} which are expressed in terms of λ^4_{jk} $(U_{jk} = -V^*_{4j} V_{4k} = -\lambda^4_{jk})$. The values of the SM bilinears do not get much affected by the addition of the b' quark. This is due to the fact that the SM CKM parameters remains almost unaffected. The allowed values of ZFCNC couplings U_{sd}, U_{db} and U_{sb} are given in Table 6. It can be seen that there are large errors on them. For example, the new physics coupling relevant for rare K decays, U_{ds}, is obtained to be $(0.27 \pm 5.89) \times 10^{-5}$. Although the best fit value is 2.7×10^{-6} indicating tight constraint, due to large errors the 1σ upper limit gets inflated upto 6.16×10^{-5}. This is because these couplings are determined using the complicated functions of the nine CKM4 parameters with highly-correlated errors (by adding all errors in quadrature).

The fit indicates that $|U_{sb}| << |V^*_{ts} V_{tb}|$. Therefore new physics contribution in $b \to s$ sector is expected to be small in ZFCNC model. This can be seen, for example, from the study of observable P'_5 in bin [4.3–8.68] GeV^2. The discrepancy between the experimental measurement and the SM prediction of P'_5 in this bin is around the 4σ level. In the SM fit, $\chi^2_{P'_5}$ contribution to the total $\chi^2_{\rm min}$ is 16.94 indicating the disagreement between the experimental measurement and SM prediction. In ZFCNC fit, we find $\chi^2_{P'_5} = 17.00$, which is almost the same as in the SM.

The like-sign dimuon charge asymmetry in the B system, A^b_{SL}, receives contribution from both $b \to s$ and $b \to d$ sector. The experimental measurement of A^b_{SL} is 3σ away from the SM prediction. In the SM fit, $\chi^2_{A^b_{SL}}$ contribution to the total $\chi^2_{\rm min}$ is 7.73 indicating this discrepancy. In ZFCNC fit, we find $\chi^2_{A^b_{SL}} = 6.68$, indicating only a slight improvement over the SM value.

4. Predictions for other observables

We now turn on to predict some of the observables which are expected to deviate from their SM predictions due to addition of a b' quark. In ZFCNC model, the flavor changing neutral current transitions occur at tree level in the down sector whereas in the up sector, they occur at loop level. Hence the flavor signatures of ZFCNC model are expected to be coming from observables in the K and B sector. Given the tight constraints on new physics couplings obtained here, it will be interesting to see whether large deviations from SM is still allowed for some of the observables.

4.1. Branching fraction of $K_L \to \pi^0 \nu\bar{\nu}$

The branching fraction of $K_L \to \pi^0 \nu\bar{\nu}$, which is governed by CP violation, in ZFCNC model is [6]

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = r_{K_L} \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\alpha^2 \mathcal{B}(K^+ \to \pi^0 e^+ \bar{\nu})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \times \sum_{\text{l}=\text{e},\mu,\tau} \Big[X^l_{NL} \,\text{Im}(\lambda^c_{ds}) + \eta^X_t X_0(x_t) \text{Im}(\lambda^t_{ds}) - \frac{\pi^2 \text{Im}(U_{ds})}{\sqrt{2} G_F {M_W}^2} \Big]^2, \tag{54}$$

where r_{K_L} is the isospin breaking correction in relating $K_L \to \pi^0 \nu\bar{\nu}$ to $K^+ \to \pi^0 e^+ \bar{\nu}$. η_X is the NLO QCD correction, its value is estimated to be 0.994 [86]. The function $X_0(x_t)$ ($x_t = m_t^2/M_W^2$) is given by

$$X_0(x_t) = \frac{x_t}{8}\Big[-\frac{2+x_t}{1-x_t} + \frac{3x_t - 6}{(1-x_t)^2} ln\, x_t\Big].$$

The SM prediction for the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ is given by [87,88]

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (2.27 \pm 0.28) \times 10^{-11}. \tag{55}$$

The present experimental upper bound on its branching ratio is 2.6×10^{-8} at 90% C.L. [89], which is about three orders of magnitude above its SM prediction.

Using Table 4, we get $\text{Im}(U_{ds}) = (1.83 \pm 16.40) \times 10^{-6}$, for $m_{b'} = 800$ GeV, which gives $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (0.03 \pm 4.29) \times 10^{-11}$. At 2σ, $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \le 8.61 \times 10^{-11}$, indicating that large enhancement in $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ above its SM value is not possible in the ZFCNC model.

4.2. Branching fraction of $B \to X_s \nu\bar{\nu}$

In the SM, the decay $B \to X_s \nu\bar{\nu}$ is dominated by the Z^0 penguin and box diagrams involving top-quark exchange, and is theoretically clean. The branching fraction for $B \to X_s \nu\bar{\nu}$ in ZFCNC model is given by

$$\mathcal{B}(B \to X_s \nu\bar{\nu}) = \frac{\alpha^2}{2\pi^4 \sin^4\theta_W} \mathcal{B}(B \to X_c e\bar{\nu}) \frac{\bar{\eta} |V^*_{ts} V_{tb} X'_0(x_t)|^2}{|V_{cb}|^2 f(\hat{m}_c) \kappa(\hat{m}_c)} \tag{56}$$

where $X'_0(x_t)$ is the structure function in ZFCNC model given by [11]

$$X'_0(x_t) = X_0(x_t) + \Big(\frac{\pi \sin^2\theta_W}{\alpha V^*_{ts} V_{tb}} U_{sb}\Big).$$

The factor $\bar{\eta} \approx 0.83$ represents the QCD correction to the matrix element of the $b \to s\nu\bar{\nu}$ transition due to virtual and bremsstrahlung contributions, $f(\hat{m}_c)$ is the phase-space factor in $\mathcal{B}(B \to X_c e\bar{\nu})$, and $\kappa(\hat{m}_c)$ is the 1-loop QCD correction factor. The SM prediction for $\mathcal{B}(B \to X_s \nu\bar{\nu})$ is $(2.28 \pm 0.19) \times 10^{-5}$, while in the ZFCNC model, this branching ratio is predicted to be $(2.27 \pm 0.55) \times 10^{-5}$ for $m_{b'} = 800$ GeV. Therefore a large enhancement in the branching fraction of $B \to X_s \nu\bar{\nu}$ is not allowed.

4.3. Direct CP asymmetry in $B \to (K,\ K^*)\,\mu^+\,\mu^-$

In the SM, the direct *CP* asymmetry in the $b \to s\,\mu^+\,\mu^-$ modes is expected to be very small. Indeed, in SM the Wilson coefficients C_7 and C_{10} are real, while the Wilson coefficient $C_9^{\rm eff}$ becomes only slightly complex due to the on-shell parts of the $u\bar{u}$ and $c\bar{c}$ loops, which are proportional to $V_{ub}^* V_{us}$ and $V_{cb}^* V_{cs}$, respectively. This complex nature of $C_9^{\rm eff}$ is the only source of *CP* asymmetry in the SM.

Here we consider direct *CP* asymmetry in the branching ratio of $B \to (K,\ K^*)\,\mu^+\,\mu^-$ which is defined as

$$A_{\rm CP} = \frac{B\left(\bar{B} \to (\bar{K},\ \bar{K^*})\,\mu^+\,\mu^-\right) - B\left(B \to (K,\ K^*)\,\mu^+\,\mu^-\right)}{B\left(\bar{B} \to (\bar{K},\ \bar{K^*})\,\mu^+\,\mu^-\right) + B\left(B \to (K,\ K^*)\,\mu^+\,\mu^-\right)}\,, \tag{57}$$

where B represents the branching ratios of the given mode. Within the SM $A_{\rm CP} \sim \mathcal{O}(10^{-3})$ [90]. The interference between the $C_9^{\rm eff}$ term and the new physics coupling terms can enhance $A_{\rm CP}$ up to ± 0.15 [91]. Due to large errors, the present measurements for these modes are consistent with the SM prediction of small *CP* asymmetry [92].

Due to the extended quark mixing matrix, there are additional *CP* violating phases in the ZFCNC model. Therefore one expects to have large enhancement in the *CP* asymmetry. However due to tight constraints on the new physics couplings, the enhancement can only be up to 3–4 times that of the SM which could be too small to be observed at the LHC with current precision.

4.4. Deviations in Wtb coupling

Due to the non-unitarity of the quark mixing matrix, one can expect deviation of $|V_{tb}|$ from unity in this model. In the SM, $|V_{tb}|$ is determined using the unitarity condition. The direct determination of $|V_{tb}|$ without assuming unitarity is possible from the single top-quark-production cross section. The CDF and D0 measurement gives $|V_{tb}| = 1.03 \pm 0.06$ [93] whereas the LHC measurements gives $|V_{tb}| = 1.03 \pm 0.05$ [94]. Although the present measurements have large errors, they do not rule out large deviations of $|V_{tb}|$ from unity. We find $|V_{tb}| = 0.9991 \pm 0.0002$. Thus, at 3σ, we have $|V_{tb}| \geq 0.99$. Therefore this model cannot account for any large deviation of $|V_{tb}|$ from unity. The possible deviation in the Wtb coupling, i.e., $|V_{tb}| - 1$ is 0.0009 ± 0.0002. Thus at 3σ, deviations in bottom coupling to W can be only be up to 0.2% which is too small to be observed in the single top production at the LHC [94].

4.5. Deviations of the bottom couplings to Higgs boson

The Lagrangian of the SM bottom quark modified by the mixing with vector-singlet b' quark is given by [12]

$$\mathcal{L}_H = -\frac{g\,m_b}{2M_W} X_{bb}\,\bar{t}t\,H, \tag{58}$$

where $X_{bb} = 1 - |V_{4b}|^2$. Hence within the SM, $X_{bb} = 1$. Therefore, possible deviations of the bottom quark couplings to the Higgs boson is given by

$$\Delta X_{bb} = X_{bb} - (X_{bb})^{SM} = X_{bb} - 1 = -|V_{4b}|^2. \tag{59}$$

Using our fit results, we get

$$\Delta X_{bb} = -(0.17 \pm 0.34) \times 10^{-3}. \tag{60}$$

Thus at 3σ, the possible deviation in the Higgs Yukawa coupling is $<0.2\%$ which is again too small to be observed at LHC with the current precision.

5. Conclusions

In this paper we consider the minimal extension of SM by addition of an isosinglet, vector like down-type quark b'. Using input from many flavor-physics processes, we perform a χ^2 fit to constrain the elements of the 3×4 quark-mixing matrix and the ZFCNC couplings. The fit takes into account both experimental errors and theoretical uncertainties.

We conclude the following:

- The best-fit values of all three new real parameters of the CKM4 matrix are consistent with zero.
- The values of V_{ts} and V_{td} in this model are close to their SM predictions.
- The mixing of the b' quark with the other three is constrained to be $|V_{ub'}| < 0.07$, $|V_{cb'}| < 0.02$, and $|V_{tb'}| < 0.06$ at 3σ.
- The tree level ZFCNC couplings are constrained to be small. At 3σ, $U_{ds} \leq 1.8 \times 10^{-4}$, $U_{db} \leq 1.1 \times 10^{-3}$ and $U_{sb} \leq 1.6 \times 10^{-4}$.
- Large enhancement in the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ and $B \to X_s \nu\bar{\nu}$ is not allowed.
- Large enhancement in direct CP asymmetry in $B \to (K, K^*)\, \mu^+ \mu^-$ is not allowed.
- The deviations in Wtb coupling as well as SM bottom quark coupling to Higgs is too small to be measured at the LHC with current precision.

Therefore we observe that the current flavor physics data puts tight constraints on ZFCNC model. The possibility of detectable new physics signals in most of the flavor physics observables is ruled out for this model.

Acknowledgements

The work of AKA and SB is supported by CSIR, Government of India, grant No. 03(1255)/12/EMR-II.

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