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Cheng-Wei Chiang, Xiao-Gang He, and German Valencia

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A Z' Model for $b \to s\ell\bar{\ell}$ Flavour Anomalies

Cheng-Wei Chiang[1,2,3a], Xiao-Gang He[4,3,5b], German Valencia[6c]

[1] *Department of Physics and Center for Mathematics and Theoretical Physics, National Central University, Chungli, Taiwan 32001*

[2] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529*

[3] *Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan 30013*

[4] *INPAC,Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai*

[5] *Department of Physics, National Taiwan University, Taipei,*

[6] *School of Physics and Astronomy, Monash University, 3800 Melbourne Australia.*[d]

Abstract

We study the implications of flavour-changing neutral currents (FCNC's) in a model with the $SU(2)_l \times SU(2)_h \times U(1)_Y$ electroweak gauge symmetry for several anomalies appearing in $b \to s\ell\bar{\ell}$ induced B decays in LHCb data. In this model, $SU(2)_l$ and $SU(2)_h$ govern the left-handed fermions in the first two generations and the third generation, respectively. The physical Z and Z' generate the $b \to s$ transition at tree level, leading to additional contributions to the $b \to s$ semileptonic operators $\mathcal{O}_{9,10}$. We find that although B_s-$\bar{B}_s$ mixing constrains the parameters severely, the model can produce values of $\mathcal{C}_{9,10}^{\rm NP}$ in the range determined by Descotes-Genon *et. al.* in Ref. [1] for this scenario to improve the global fit of observables in decays induced by the $b \to s\mu\bar{\mu}$ transition. The Z' boson in this model also generates tree-level FCNC's for the leptonic interactions that can accommodate the experimental central value of $R_K = \mathcal{B}(B \to K\mu\bar{\mu})/\mathcal{B}(B \to Ke\bar{e}) = 0.75$. In this case, the model predicts sizeable branching ratios for $B \to Ke\bar{\tau}$, $B \to K\tau\bar{e}$, and an enhancement of $B \to K\tau\bar{\tau}$ with respect to its SM value.

[a] Electronic address: chengwei@ncu.edu.tw

[b] Electronic address: hexg@phys.ntu.edu.tw

[c] Electronic address: German.Valencia@monash.edu.au

[d] On leave from Department of Physics, Iowa State University, Ames, IA 50011.

I. INTRODUCTION

Experimental data have hinted at several anomalies in B decays induced by the flavour-changing neutral current (FCNC) process $b \to s\ell\bar{\ell}$. In 2013, LHCb measured four observables related to the angular distribution of $B \to K^*\mu^+\mu^-$ in six bins of dimuon invariant mass squared, q^2, and found a deviation at the 3.7σ level from the standard model (SM) in one of them [2]. LHCb also measured the rates for the $B \to K^{(*)}\mu^+\mu^-$ decay [3], finding values slightly below the SM expectations. Recently, with finer binning, LHCb confirmed their earlier anomaly in the angular distribution of $B \to K^*\mu^+\mu^-$ decay [4]. In addition, LHCb has studied other modes induced by the $b \to s\mu^+\mu^-$ transition as well, namely, the $B_s \to \phi\mu^+\mu^-$ decay [5] and also $b \to se^+e^-$ in the $B \to K^*e^+e^-$ decay [6] with results consistent with the SM.

A particularly interesting discrepancy between experiment and the SM is in the ratio R_K of the branching fraction of $B^+ \to K^+\mu^+\mu^-$ to that of $B^+ \to K^+e^+e^-$. Lepton-universality in the SM predicts R_K to be very close to 1. Yet LHCb found $R_K \equiv \mathcal{B}(B \to K\mu\bar{\mu})/\mathcal{B}(B \to Ke\bar{e}) = 0.745^{+0.090}_{-0.074} \pm 0.036$ [7] for the dilepton invariant mass squared range of $1 - 6$ GeV^2. This disagreement occurs only at the 2.6σ level, but would be extremely interesting if confirmed.

As expected, the anomalies in the $b \to s\ell\bar{\ell}$ measurements have received considerable attention in the literature [8] and several models have been put forward as possible new physics explanations [9]. It has also been argued that more careful treatment of long distance physics would eliminate most of these anomalies, as done most recently in Ref. [10]. Models have also been put forth attempting to explain the apparent lepton non-universality observed in R_K [11]. A recent analysis of these experimental results is that of Ref. [1], where global fits of the observables in terms of new physics parametrised by deviations from the SM values of certain Wilson coefficients are presented. This model-independent analysis and its results are the starting point of our discussions.

In this paper we will focus our discussion around the scenario in which new physics affects primarily the $\mathcal{C}_9$ and $\mathcal{C}_{10}$ Wilson coefficients, which has been found in Ref. [1] to significantly improve the agreement between the measurements and the theoretical predictions. We recall that these coefficients appear in the low-energy effective Hamiltonian responsible for $b \to s\ell\bar{\ell}$

transitions as follows:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\mathcal{C}_9^{\ell\ell} \mathcal{O}_9 + \mathcal{C}_{10}^{\ell\ell} \mathcal{O}_{10} \right) \ ,$$
$$\mathcal{O}_9 = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b \right) \left(\bar{\ell}\gamma^\mu \ell \right) \ , \quad \mathcal{O}_{10} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b \right) \left(\bar{\ell}\gamma^\mu \gamma_5 \ell \right) \ , \tag{1}$$

where $P_L = (1-\gamma_5)/2$ and, in the absence of flavour universality, $\mathcal{C}_{9,10}^{\ell\ell}$ can have different values for different lepton flavours.

Within the SM, $\mathcal{C}_{9,10}^{\ell\ell}$ are approximately the same for all leptons with $\mathcal{C}_9^{\text{SM}} \approx 4.1$, and $\mathcal{C}_{10}^{\text{SM}} \approx -4.1$. To reduce the tension in the global fit associated with the $b \to s\mu\bar{\mu}$ anomalies, the new physics contribution $\mathcal{C}_9^{\text{NP},\mu\mu}$ is required to be of order -1.0 and for scenarios where $\mathcal{C}_{10}^{\text{NP},\mu\mu}$ is also not zero, the best fit occurs for $\mathcal{C}_{10}^{\text{NP},\mu\mu} \sim 0.3$ [1]. To address the anomaly in the value of R_K, the absolute value of $\mathcal{C}_{9,10}^{\text{SM}} + \mathcal{C}_{9,10}^{\text{NP},ee}$ is required to be larger than that of $\mathcal{C}_{9,10}^{\text{SM}} + \mathcal{C}_{9,10}^{\text{NP},\mu\mu}$.

When going beyond the SM, additional operators with different chiral structures that contribute to $b \to s\ell\bar{\ell}$ can also be generated, such as $\mathcal{O}_9' = (e^2/16\pi^2) \left(\bar{s}\gamma_\mu P_R b \right) \left(\bar{\ell}\gamma^\mu \ell \right)$ and $\mathcal{O}_{10}' = (e^2/16\pi^2) \left(\bar{s}\gamma_\mu P_R b \right) \left(\bar{\ell}\gamma^\mu \gamma_5 \ell \right)$, where $P_R = (1+\gamma_5)/2$. For the remaining of this paper, we will neglect this possibility and concentrate on a scenario with modified $\mathcal{C}_{9,10}$ only, corresponding to a particular Z' interpretation of the anomalies. This particular interpretation is motivated by the possibility of lepton non-universality hinted at by R_K, and its occurrence in non-universal Z' models that single out the third generation.

A common extension of the SM that produces tree-level FCNC's is a Z' boson, particularly when it is non-universal in generations. This new interaction can have different types of chiral structures in both quark and lepton sectors. A model that singles out the third generation with an additional right-handed interaction [12] leads to tree-level FCNC's for $\mathcal{O}_{9,10}'$ which, according to the global fits of Ref. [1], do not help much in addressing the observed anomalies. At one-loop level, it is possible to produce the pattern $\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$ which is disfavoured by the data on $B_s \to \mu\mu$. In this context, a model that more naturally fits the $\mathcal{C}_{9,10}$ scenario is one where the $SU(2)_L$ gauge group in the SM is extended to be generation-dependent [13], an example of which has been dubbed 'top-flavour' before [14].

The model has the $SU(2)_l \times SU(2)_h \times U(1)_Y$ gauge symmetry, where $SU(2)_l$ governs the left-handed fermions in the first two light generations and $SU(2)_h$ governs those in the third heavy generation. This model has been studied before by two of us in Ref. [15]. It affects the $b \to s\ell\bar{\ell}$ process at tree level mostly through modifications to $\mathcal{C}_{9,10}$. The relevant parameters are severely constrained by B_s-$\bar{B}_s$ mixing. Nevertheless, the model can still produce values of $\mathcal{C}_{9,10}^{\rm NP}$ in the right ranges to improve the global fits as described in Ref. [1]. In addition, the model can break lepton universality and lepton number, accommodating R_K and predicting sizeable branching ratios for $B \to K e\bar{\tau}$, $B \to K\tau\bar{e}$ and an enhancement of $B \to K\tau\bar{\tau}$ with respect to its SM value.

This paper is organized as follows. In Section II, we review the tree-level FCNC's induced by the Z and Z' exchanges in the model, deriving the basis for the latter analyses. In Section III, we compute the corrections to the Wilson coefficients $\mathcal{C}_{9,10}^{NP}$ occurring in this model. In Section IV, we update the global fit to the electroweak precision data and the B_s-$\bar{B}_s$ mixing constraint, thereby obtaining preferred ranges of the theory parameters. The results are then used to evaluate $\mathcal{C}_{9,10}^{\rm NP}$ numerically and to check against the preferred values presented in Ref. [1]. Taking a step further, we make predictions for R_K and the decay branching ratios of $B \to K e\bar{\tau}$, $B \to K\tau\bar{e}$, and $B \to K\tau\bar{\tau}$. Section V summarizes our findings.

II. TREE-LEVEL FCNC'S DUE TO Z AND Z' IN THE MODEL

With the gauge group extended from $SU(3)_C \times SU(2)_L \times U(1)_Y$ to $SU(3)_C \times SU(2)_l \times SU(2)_h \times U(1)_Y$, there are additional gauge bosons: a pair of $W'^{\pm}_{\mu}$ bosons and a Z' boson. With an appropriate Higgs sector, the $SU(2)_l \times SU(2)_h$ symmetry is broken down to $SU(2)_L$ at the TeV scale, leaving the SM gauge group followed by the standard electroweak symmetry breakdown [15] . The Z and Z' FCNC's relevant to the $b \to s\ell\bar{\ell}$ transitions are caused by the neutral gauge boson interactions with fermions.

The left-handed quark doublets Q_L, the right-handed quark singlets U_R and D_R, the left-handed lepton doublets L_L, and the right-handed charged leptons E_R transform under the original gauge group as

$$\begin{aligned}
&Q_L^{1,2} : (3,2,1,1/3)\ ,\ \ Q_L^3 : (3,1,2,1/3)\ ,\ \ U_R^{1,2,3} : (3,1,1,4/3)\ ,\ \ D_R^{1,2,3} : (3,1,1,-2/3)\ ,\\
&L_L^{1,2} : (1,2,1,-1)\ ,\ \ L_L^3 : (1,1,2,-1)\ ,\ \ E_R^{1,2,3} : (1,1,1,-2)\ ,
\end{aligned} \tag{2}$$

where the numbers in each bracket are the quantum numbers of the corresponding field under $SU(3)_C$, $SU(2)_l$, $SU(2)_h$ and $U(1)_Y$, respectively. The superscript on each field labels the generation of the fermion.

The neutral gauge boson interactions with fermions are given by

$$\mathcal{L} = \bar{\psi}\gamma_\mu \left[eA^\mu Q + \frac{g}{c_W} Z_L^\mu \left(T_3^l + T_3^h - Q s_W^2\right) + g Z_H^\mu \left(\frac{s_E}{c_E} T_3^l - \frac{c_E}{s_E} T_3^h \right) \right] \psi \ , \tag{3}$$

where ψ represents a quark or lepton field, $T_3^{l,h}$ are the third components of the $SU(2)_{l,h}$ generators, the electric charge Q is given by $Q = T_3 + Y/2$ with $T_3 = T_3^l + T_3^h$, and s_E and c_E respectively are defined in terms of the gauge couplings $g_{1,2}$ of $SU(2)_{l,h}$ by

$$s_E^2 \equiv \sin^2\theta_E = \frac{g_1^2}{g_1^2 + g_2^2} \quad c_E^2 \equiv \cos^2\theta_E = \frac{g_2^2}{g_1^2 + g_2^2} \ . \tag{4}$$

The SM couplings g and e are then given in terms of $g_{1,2}$ and $U(1)_Y$ coupling g' by

$$g^2 = \frac{g_1^2 g_2^2}{g_1^2 + g_2^2} \ , \quad e^2 = \frac{g^2 g'^2}{g^2 + g'^2} \ . \tag{5}$$

The fields $A,\ Z_L,\ Z_H$ are defined in terms of the third components $W_{l,h}^3$ of the $SU(2)_{l,h}$ gauge fields and the $U(1)_Y$ gauge field B through the following transformation:

$$\begin{pmatrix} W_3^l \\ W_3^h \\ B \end{pmatrix} = \begin{pmatrix} s_E & c_E c_W & c_E s_W \\ -c_E & s_E c_W & s_E s_W \\ 0 & -s_W & c_W \end{pmatrix} \begin{pmatrix} Z_H \\ Z_L \\ A \end{pmatrix} \ , \tag{6}$$

where

$$s_W^2 = \frac{g'^2}{g^2 + g'^2} \quad c_W^2 = \frac{g^2}{g^2 + g'^2} \ . \tag{7}$$

In general $Z_{L,H}$ are not mass eigenstates. Writing them in terms of light and heavy mass eigenstates Z_l and Z_h, we have

$$Z_L = -\sin\xi Z_h + \cos\xi Z_l \ , \quad Z_H = \cos\xi Z_h + \sin\xi Z_l \ , \tag{8}$$

where a rotation angle ξ is introduced.

Assume that the breaking of $SU(2)_l \times SU(2)_h$ to $SU(2)_L$ is achieved by a bi-doublet η : $(1,2,2,0)$ with a non-zero vacuum expectation value (VEV), $u \sim \mathcal{O}(\text{TeV})$, and the subsequent symmetry breaking is achieved by two doublets $\Phi_1 : (1,2,1,1)$ and $\Phi_2 : (1,1,2,1)$ with respective VEV's v_1 and v_2 with $v_1^2 + v_2^2 = (174 \text{ GeV})^2$. We then have to the leading order in $\epsilon \equiv v/u$

$$\xi \approx \frac{s_E c_E}{c_W}(s_\beta^2 - s_E^2)\epsilon^2 \ , \quad \frac{m_{Z_l}^2}{m_{Z'_h}^2} \approx \epsilon^2 \frac{s_E^2 c_E^2}{c_W^2} \ , \tag{9}$$

where $s_\beta^2 \equiv v_1^2/(v_1^2+v_2^2)$. Because of the mass hierarchy between fermions belonging to the third generation and the first two generations, s_β^2 is expected to be small.

Now we can express the neutral gauge boson interactions with fermions in the small ϵ limit as

$$\mathcal{L} = \bar{f}\gamma_\mu \left\{ eQA_\mu + \frac{g}{c_W} Z_l^\mu \left[T_3 - Qs_W^2 - \epsilon^2 c_E^2 (s_E^2 T_3 - T_3^h) \right] \right. \\ \left. + g\frac{Z_h^\mu}{s_E c_E} \left[s_E^2 T_3 - T_3^h + \epsilon^2 \frac{s_E^2 c_E^4}{c_W^2} (T_3 - Qs_W^2) \right] \right\} f \ . \tag{10}$$

T_3^h acts only on the third generation and the terms proportional to it will induce FCNC's in the fermion mass eigenstate basis.

III. $b \to s\ell\bar{\ell}$ TRANSITIONS

Through the exchanges of Z and Z' at tree level, the following effective four-fermion interactions can be induced:

$$\mathcal{H}_{\text{eff}} = -\frac{g_Z^2}{8m_{Z_l}^2}\epsilon^2 c_E^2 \left(\bar{q}\tilde{\Delta}^q \gamma_\mu P_L q\right) \left(\bar{\ell}\gamma^\mu (4s_W^2 - 1 + \gamma_5)\ell\right) \\ -\frac{g^2}{8s_E^2 c_E^2 m_{Z_h}^2} \left(\bar{q}\tilde{\Delta}^q \gamma_\mu P_L q\right) \left(\bar{\ell}\gamma^\mu (s_E^2 I - \tilde{\Delta}^l)(1-\gamma_5)\ell\right) \ , \tag{11}$$

where $\tilde{\Delta}^f = T_f^\dagger \text{diag}(0,0,1) T_f$ with $\bar{f}_R M_f f_L = \bar{f}_R S_f \hat{M}_f T_f^\dagger f_L$, and S_f and $T_f = (T_{ij}^f)$ are unitary matrices for a bi-unitary transformation to obtain the diagonal eigenmass matrix $\hat{M}_f$. Here we have used the fact that the eigenvalue of T_3 for down quarks and charged leptons is $-1/2$. One can further re-write the above expression as

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\pi}{\alpha}\epsilon^2 c_E^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*}\delta_{ij} \left[(4s_W^2 - 1)\mathcal{O}_9^{ij} + \mathcal{O}_{10}^{ij}\right] \\ -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\pi}{\alpha}\epsilon^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*} (s_E^2 \delta_{ij} - \tilde{\Delta}_{ij}^\ell) \left(\mathcal{O}_9^{ij} - \mathcal{O}_{10}^{ij}\right) \ , \tag{12}$$

where $\tilde{\Delta}_{sb}^q = T_{bs}^{q*} T_{bb}^q$ and $\tilde{\Delta}_{ij}^\ell = T_{3i}^{\ell *} T_{3j}^\ell$, and

$$\mathcal{O}_9^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) \left(\bar{\ell}_i \gamma^\mu \ell_j\right) \ , \quad \mathcal{O}_{10}^{ij} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) \left(\bar{\ell}_i \gamma^\mu \gamma_5 \ell_j\right) \ . \tag{13}$$

From Eq. (12), we can read off the expressions for $\mathcal{C}_{9,10}^{ij}$ as

$$Z \ \text{contribution}: \ \mathcal{C}_9^{Z,ij} = \frac{\pi}{\alpha}\epsilon^2 c_E^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*} \left(4s_W^2 - 1\right)\delta_{ij} \ , \ \ \mathcal{C}_{10}^{Z,ij} = \frac{\pi}{\alpha}\epsilon^2 c_E^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*}\delta_{ij} \ , \\ Z' \ \text{contribution}: \ \mathcal{C}_9^{Z',ij} = -\mathcal{C}_{10}^{Z',ij} = \frac{\pi}{\alpha}\epsilon^2 \frac{\tilde{\Delta}_{sb}^q}{V_{tb}V_{ts}^*} \left(s_E^2 \delta_{ij} - \tilde{\Delta}_{ij}^\ell\right) \ . \tag{14}$$

The total new physics contributions to the Wilson coefficients are $\mathcal{C}_{9,10}^{\mathrm{NP},ij} = \mathcal{C}_{9,10}^{Z,ij} + \mathcal{C}_{9,10}^{Z',ij}$. This implies that within this model and $\tilde{\Delta}_{ij}^{\ell} = 0$ for $i \neq j$, we have the relation

$$\mathcal{C}_{10}^{\mathrm{NP}} = \frac{\mathcal{C}_{9}^{\mathrm{NP}}}{2s_W^2(\sec 2\theta_E + 1) - 1}. \tag{15}$$

IV. NUMERICAL ANALYSIS

We now explore the numerical ranges that can be obtained for $\mathcal{C}_{9,10}^{NP}$ and compare them with those of Ref. [1] that can reduce the tension between the predictions and measurements for the observables in $b \to s\ell\bar{\ell}$ induced B decays. For this purpose, we need to know the constraints for the new model parameters, ϵ, c_E, $\tilde{\Delta}_{sb}^{q}$ and $\tilde{\Delta}_{ij}^{\ell}$.

The model parameters ϵ and c_E were constrained by the electroweak precision data in Ref. [15]. We update this fit here using the latest data [16]. The χ^2 contours on the ϵ^2-c_E^2 plane are shown in Fig. 1. It is seen that the best fit values for ϵ^2 and c_E^2 are 0.0031 and 0.4629, respectively. The former indicates that both the VEV of η and the Z' mass are about 3 TeV. The 1σ and 2σ upper bounds on ϵ^2 are 0.0064 and 0.0085 as marked by the vertical dashed and dotted lines, respectively. c_E^2 can range from 0 to 1 at both 1σ and 2σ levels. In particular, Eq. (15) allows $\mathcal{C}_{10}^{NP}$ to be vanishing when $\theta_E = \pm\pi/4$.

The parameters $\tilde{\Delta}_{ij}^{\ell}$ involve only leptons and are not well constrained yet. On the other hand, $\tilde{\Delta}_{sb}^{q}$ is severely constrained by the B_s-$\bar{B}_s$ mixing. The contribution of Z' exchange to ΔM_{B_s} of the B_s mixing system is given by

$$\begin{aligned}
\Delta M_{B_s}^{Z'} &= \frac{G_F}{\sqrt{2}m_{B_s}}\epsilon^2(\tilde{\Delta}_{sb}^{q})^2\langle \bar{B}_s|\,(\bar{s}\gamma^\mu P_L b)\,(\bar{s}\gamma_\mu P_L b)\,|B_s\rangle\;\hat{\eta}_B \\
&= \frac{\sqrt{2}G_F}{3}\left(\epsilon\tilde{\Delta}_{sb}^{q}\right)^2 m_{B_s} f_{B_s}^2 B_{B_s}\hat{\eta}_B \\
&= \sqrt{2}G_F\frac{\alpha}{6\pi s_W^2}V_{tb}V_{ts}^* m_{B_s} f_{B_s}^2 B_{B_s}\hat{\eta}_B\tilde{\Delta}_{sb}^{q}\left[\mathcal{C}_9^{\mathrm{NP}} + \mathcal{C}_{10}^{\mathrm{NP}}(1-2s_W^2)\right]\;,
\end{aligned} \tag{16}$$

where the last expression has been written in terms of the Wilson coefficients $\mathcal{C}_{9,10}^{\mathrm{NP}}$ given in Eq. (14) to emphasize the correlation. Note that $\mathcal{C}_{9,10}^{\mathrm{NP}}$ are also linear in the flavour-changing coupling $\tilde{\Delta}_{sb}^{q}$.

Numerically, $f_{B_s}\sqrt{B_{B_s}} = (216\pm15)$ MeV [17]. We have also included the QCD correction factor $\hat{\eta}_B \approx 0.84$ [17] to account for the renormalization group running of the operator from the electroweak scale to the B_s scale and neglected a small correction from additional running

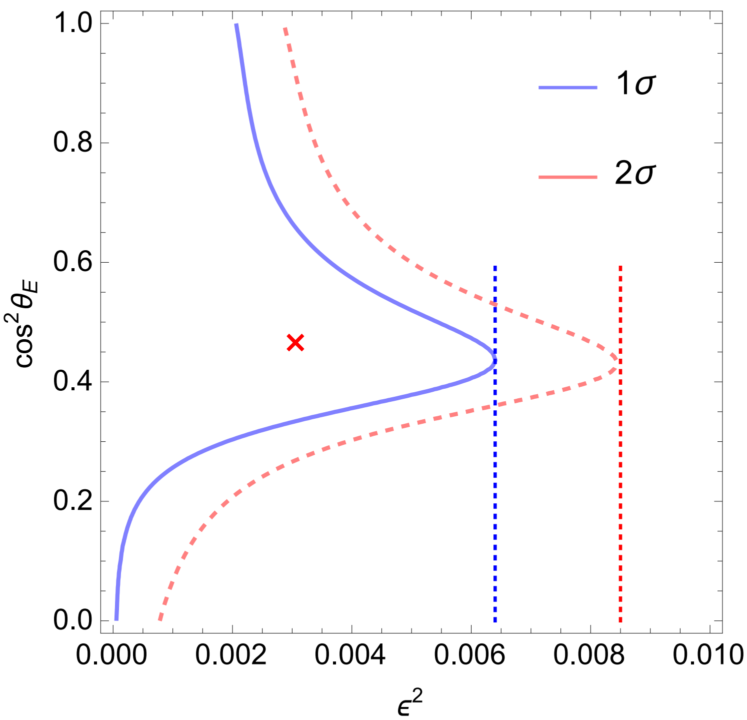

FIG. 1. χ^2 contours of fit to electroweak precision data. The best-fit point, 1σ contour and 2σ contour are marked by a red cross, a blue solid curve, and a red dashed curve, respectively. The vertical dotted lines mark the 1σ and 2σ upper bounds on ϵ^2.

of the operator between the electroweak scale and the Z' scale. For our numerical estimates, it is convenient to rewrite the non-perturbative factors in terms of the SM contribution:

$$\begin{aligned} \frac{\Delta M_{B_s}^{Z'}}{\Delta M_{B_s}^{\rm SM}} &= \frac{2\sqrt{2}\pi^2}{G_F M_W^2 S_0[x_t]} \left(\frac{\epsilon\tilde{\Delta}_{sb}^q}{|V_{tb}V_{ts}^*|}\right)^2 \\ &\approx 161.8 \left(\frac{\epsilon\tilde{\Delta}_{sb}^q}{|V_{tb}V_{ts}^*|}\right)^2 \left(\frac{2.29}{S_0[x_t]}\right). \end{aligned} \tag{17}$$

We thus remove the main uncertainties from non-perturbative QCD factors, and ignore all but parametric uncertainties in the short-distance part due to the Z' exchange.

Experiments have determined ΔM_{B_s} to high precision. The latest HFAG average [18] of the CDF [19] and LHCb [20] results is $\Delta M_{B_s}^{\rm exp} = (17.757 \pm 0.021)$ ps^{-1}. This value is consistent with the latest SM prediction, $\Delta M_{B_s}^{\rm SM} = (18.3 \pm 2.7)$ ps^{-1} [17], leaving little room for new physics, particularly if it interferes constructively with the SM as the term in Eq. (16) does. Combining these errors in quadrature, we restrict the new physics contribution to be $0 \leq \Delta M_{B_s}^{Z'} \leq 2.7$ (5.4) ps^{-1} at 1σ (2σ).

In Fig. 2, we show the 1σ (solid blue) and 2σ (dashed blue) contours in the $\mathcal{C}_{9,10}^{\rm NP}$ parameter space, as determined by the electroweak precision data in Fig. 1 and by $\Delta M_{B_s}^{\rm exp}$, for the particular value $\tilde{\Delta}_{sb}^{q} = 0.02$. This value is chosen so that it allows the 2σ contour to be in the vicinity of the best fit for the $b \to s\ell\bar{\ell}$ anomalies in the $\mathcal{C}_{9,10}^{\rm NP}$ scenario of Ref. [1], shown by the red $\times$. The 1σ (solid red) and 2σ (dashed red) contours from that global fit are also shown in the figure. Our results show that although it is not possible to reach the best-fit point within our model, there is a substantial overlap at the 2σ level between the values of $\mathcal{C}_{9,10}^{\rm NP}$ that can be obtained in this model and those that improve the $b \to s\ell\bar{\ell}$ global fit.

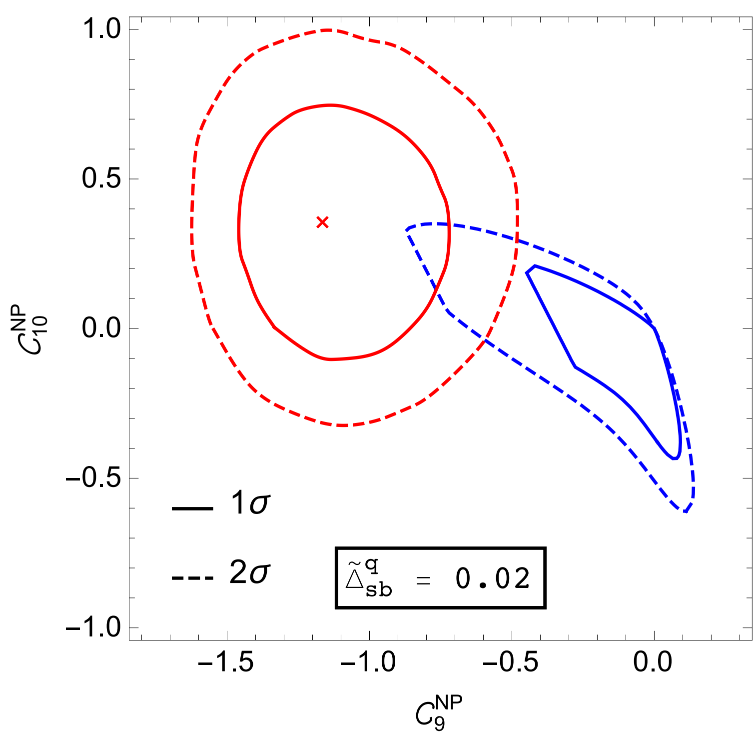

FIG. 2. The region allowed by the electroweak precision data fit and $\Delta M_{B_s}^{\rm exp}$ is shown in blue (the curves on the right). The region allowed by a global fit to $b \to s\ell\bar{\ell}$ observables in Ref. [1] is shown in red (the curves on the left) for comparison.

So far we have assumed $\tilde{\Delta}_{ij}^{\ell} = 0$ for $i \neq j$ in Eq. (14). Nevertheless, they can be non-vanishing and lead to the possibilities of lepton non-universality and of lepton-flavour violation within this model. To limit the parameter space, we start with a point within the

2σ contour of Fig. 2 that is closest to the best-fit point; namely,

$$\begin{aligned}
&\tilde{\Delta}^q_{sb} = 0.02 \ , \ \epsilon = 0.088 \ , \ \cos\theta_E = 0.63 \ , \\
&\Delta M^{Z'}_{B_s} = 5.4 \text{ ps}^{-1} \ , \ \mathcal{C}^{\rm NP}_9 = -0.87 \ , \ \mathcal{C}^{\rm NP}_{10} = 0.32 \ .
\end{aligned} \tag{18}$$

Since $\tilde{\Delta}^\ell_{ij} = T^{\ell *}_{3i} T^\ell_{3j}$, setting $\tilde{\Delta}^\ell_{22} = 0$ will maximize $\mathcal{C}^{\rm NP,\mu\mu}_9$. This implies that for real T^ℓ, it has the following form

$$T^\ell = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix} \ . \tag{19}$$

The non-zero entries for $\tilde{\Delta}^\ell_{ij}$ are then: $\tilde{\Delta}^\ell_{11} = \sin^2\theta$, $\tilde{\Delta}^\ell_{13} = \tilde{\Delta}^\ell_{31} = \sin\theta\cos\theta$ and $\tilde{\Delta}^\ell_{33} = \cos^2\theta$. Varying the value for $\sin\theta$ will change our predictions for $B \to K(e\bar{e}, \tau\bar{\tau}, e\bar{\tau}, \tau\bar{e})$, breaking both lepton universality and lepton flavour conservation.

In particular, the model can accommodate the value $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$. Neglecting the lepton masses, we have

$$\begin{aligned}
&\mathcal{B}(B \to K\ell_i\bar{\ell}_j) \propto \left(\mathcal{C}^{\rm SM}_9 + \mathcal{C}^{{\rm NP},ij}_9\right)^2 + \left(\mathcal{C}^{\rm SM}_{10} + \mathcal{C}^{{\rm NP},ij}_{10}\right)^2 \ , \\
&\mathcal{B}(B \to Ke\bar{e}) \propto \left(\mathcal{C}^{\rm SM}_9 + \mathcal{C}^{\rm NP,\mu\mu}_9 - \tilde{\Delta}^\ell_{11}\frac{\mathcal{C}^{\rm NP,\mu\mu}_{10}}{c_E^2}\right)^2 + \left[\mathcal{C}^{\rm SM}_{10} + \mathcal{C}^{\rm NP,\mu\mu}_{10}\left(1 + \frac{\tilde{\Delta}^\ell_{11}}{c_E^2}\right)\right]^2 \ , \\
&\mathcal{B}(B \to K\tau\bar{\tau}) \propto \left(\mathcal{C}^{\rm SM}_9 + \mathcal{C}^{\rm NP,\mu\mu}_9 - \tilde{\Delta}^\ell_{33}\frac{\mathcal{C}^{\rm NP,\mu\mu}_{10}}{c_E^2}\right)^2 + \left[\mathcal{C}^{\rm SM}_{10} + \mathcal{C}^{\rm NP,\mu\mu}_{10}\left(1 + \frac{\tilde{\Delta}^\ell_{33}}{c_E^2}\right)\right]^2 \ , \\
&\mathcal{B}(B \to Ke\bar{\tau}, \tau\bar{e}) \propto 2\left(\mathcal{C}^{\rm NP,\mu\mu}_{10}\right)^2 \left(\frac{\tilde{\Delta}^\ell_{13}}{1 - 2c_E^2}\right)^2 \ .
\end{aligned} \tag{20}$$

With the numbers given in Eq. (18), we then obtain

$$R_K = 0.745 \Rightarrow \sin^2\theta = 0.37 \ , \tag{21}$$

$$\frac{\mathcal{B}(B \to K\tau\bar{\tau})}{\mathcal{B}(B \to K\mu\bar{\mu})} = 1.36 \ , \tag{22}$$

$$\frac{\mathcal{B}(B \to K(e\bar{\tau}, \tau\bar{e}))}{\mathcal{B}(B \to K\mu\bar{\mu})} = 0.037 \ . \tag{23}$$

V. SUMMARY AND CONCLUSIONS

As one intriguing feature, the model with the $SU(2)_l \times SU(2)_h \times U(1)_Y$ electroweak gauge symmetry proposed earlier [15] has flavour-changing neutral currents (FCNC's) at tree level, mediated by both Z and Z' bosons. In this model, fermions of the first two generations and those of the third generations are charged respectively under the $SU(2)_l$ and $SU(2)_h$ groups. A scalar η in the bi-fundamental representation of $SU(2)_l \times SU(2)_h$ is introduced to break the symmetry to $SU(2)_L$ in the standard model (SM) with a vacuum expectation value (VEV) of u. The $SU(2)_L \times U(1)_Y$ is then broken by two Higgs doublets, Φ_1 and Φ_2, with respective VEV's v_1 and v_2 and $v^2 = v_1^2 + v_2^2 = (174 \text{ GeV})^2$.

In this work, we first extracted two important parameters ϵ and $\cos\theta_E$ of the model using the latest electroweak precision data, where ϵ^2 denotes the ratio $(v/u)^2$ and $\cos^2\theta_E$ denotes the ratio of the two $SU(2)$ gauge couplings, $g_2^2/(g_1^2 + g_2^2)$. Their best-fit values were found to be 0.0031 and 0.4629, respectively. The former indicates that the breaking scale of the $SU(2)_l \times SU(2)_h$ symmetry as well as the Z' mass are both around 3 TeV.

Based on the results of a global fit [1] to the $b \to s\ell\ell$ anomalies recently reported by LHCb, we discussed how the FCNC interactions in our model would affect the Wilson coefficients $\mathcal{C}_{9,10}^{\rm NP}$ associated with the $b \to s\ell\bar{\ell}$ operators $\mathcal{O}_{9,10}$ to get close to the values found by the global fit to address the anomalies. We noticed that a stringent constraint on $\mathcal{C}_{9,10}^{\rm NP}$ came from the B_s-$\bar{B}_s$ mixing data, and showed the correlation within the model. We found that at the 2σ level, the model could accommodate the best-fit values for $\mathcal{C}_{9,10}^{\rm NP}$ while satisfying the ΔM_{B_s} measurement.

Moreover, the Z' boson could have non-universal or even flavour-changing couplings to lepton pairs. By proposing a specific mixing pattern in the lepton sector, we extracted the mixing parameter $\sin^2\theta = 0.37$ by accommodating $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$. Using this information, we then made a prediction for the lepton non-universality in the $B \to K\tau\bar{\tau}$ and $K\mu\bar{\mu}$ decays as well as the lepton flavour violating decays $B \to K(e\bar{\tau}, \tau\bar{e})$.

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[1] S. Descotes-Genon, L. Hofer, J. Matias and J. Virto, arXiv:1510.04239 [hep-ph].

[2] **LHCb** Collaboration, PRL **111** (2013) 191801, arXiv:1308.1707 [hep-ex].

[3] **LHCb** Collaboration, JHEP **1406** (2014) 133, arXiv:1403.8044 [hep-ex].

[4] R. Aaij *et al.* [LHCb Collaboration], arXiv:1512.04442 [hep-ex].

[5] **LHCb** Collaboration, JHEP **1307** (2013) 084, arXiv:1305.2168 [hep-ex].

[6] **LHCb** Collaboration, JHEP **1504** (2015) 064, arXiv:1501.03038 [hep-ex].

[7] **LHCb** Collaboration, Phys. Rev. Lett. **113** (2014) 151601, arXiv:1406.6482 [hep-ex].

[8] See for example J. Matias, F. Mescia, M. Ramon and J. Virto, JHEP **1204** (2012) 104, arXiv:1202.4266 [hep-ph], and references therein.

[9] S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88**, 074002 (2013), arXiv:1307.5683 [hep-ph]; W. Altmannshofer and D. M. Straub, arXiv:1308.1501 [hep-ph]; T. Hurth and F. Mahmoudi, JHEP **1404** (2014) 097, arXiv:1312.5267 [hep-ph]; F. Mahmoudi, S. Neshatpour and J. Virto, Eur. Phys. J. C **74** (2014) 6, 2927, arXiv:1401.2145 [hep-ph]; T. Hurth, F. Mahmoudi and S. Neshatpour, JHEP **1412** (2014) 053, arXiv:1410.4545 [hep-ph]; S. Jäger and J. Martin Camalich, JHEP **1305** (2013) 043, arXiv:1212.2263 [hep-ph]; G. Hiller and M. Schmaltz, Phys. Rev. D **90** (2014) 054014, arXiv:1408.1627 [hep-ph]; A. J. Buras, F. De Fazio and J. Girrbach, JHEP **1402** (2014) 112, arXiv:1311.6729 [hep-ph]; A. J. Buras, F. De Fazio and J. Girrbach-Noe, JHEP **1408** (2014) 039, arXiv:1405.3850 [hep-ph]; R. Gauld, F. Goertz and U. Haisch, JHEP **1401** (2014) 069, arXiv:1310.1082 [hep-ph]; R. Gauld, F. Goertz and U. Haisch, Phys. Rev. D **89** (2014) 015005, arXiv:1308.1959 [hep-ph]; E. Lunghi and J. Matias, JHEP **0704** (2007) 058, hep-ph/0612166; W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub and M. Wick, JHEP **0901** (2009) 019, arXiv:0811.1214 [hep-ph]; D. Aristizabal Sierra, F. Staub and A. Vicente, Phys. Rev. D **92**, no. 1, 015001 (2015), arXiv:1503.06077 [hep-ph].

[10] M. Ciuchini, M. Fedele, E. Franco, S. Mishima, A. Paul, L. Silvestrini and M. Valli, arXiv:1512.07157 [hep-ph]; A. Khodjamirian, T. Mannel, A. A. Pivovarov and Y.-M. Wang,

JHEP **1009** (2010) 089, arXiv:1006.4945 [hep-ph].

[11] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski and J. Rosiek, Phys. Rev. D **92** (2015) 5, 054013, arXiv:1504.07928 [hep-ph]; W. Altmannshofer and I. Yavin, arXiv:1508.07009 [hep-ph]; D. Ghosh, M. Nardecchia and S. A. Renner, JHEP **1412** (2014) 131, arXiv:1408.4097 [hep-ph]; S. L. Glashow, D. Guadagnoli and K. Lane, Phys. Rev. Lett. **114** (2015) 091801, arXiv:1411.0565 [hep-ph]; B. Bhattacharya, A. Datta, D. London and S. Shivashankara, Phys. Lett. B **742**, 370 (2015), arXiv:1412.7164 [hep-ph]; A. Crivellin, G. D'Ambrosio and J. Heeck, Phys. Rev. Lett. **114**, 151801 (2015), arXiv:1501.00993 [hep-ph]; D. Bečirevič, S. Fajfer and N. Konik, Phys. Rev. D **92** (2015) 1, 014016, arXiv:1503.09024 [hep-ph]; A. Celis, J. Fuentes-Martin, M. Jung and H. Serodio, Phys. Rev. D **92**, no. 1, 015007 (2015), arXiv:1505.03079 [hep-ph]. C. J. Lee and J. Tandean, JHEP **1508**, 123 (2015), arXiv:1505.04692 [hep-ph]; A. Falkowski, M. Nardecchia and R. Ziegler, arXiv:1509.01249 [hep-ph].

[12] X. G. He and G. Valencia, Phys. Rev. D **66**, 013004 (2002) [Phys. Rev. D **66**, 079901 (2002)] doi:10.1103/PhysRevD.66.013004, 10.1103/PhysRevD.66.079901 [hep-ph/0203036]; X. G. He and G. Valencia, Phys. Rev. D **74**, 013011 (2006) doi:10.1103/PhysRevD.74.013011 [hep-ph/0605202].

[13] E. Ma and D. Ng, Phys. Rev. D **38**, 304 (1988). doi:10.1103/PhysRevD.38.304

[14] D. J. Muller and S. Nandi, Phys. Lett. B **383**, 345 (1996) doi:10.1016/0370-2693(96)00745-9 [hep-ph/9602390].

[15] C. W. Chiang, N. G. Deshpande, X. G. He and J. Jiang, Phys. Rev. D **81**, 015006 (2010) doi:10.1103/PhysRevD.81.015006 [arXiv:0911.1480 [hep-ph]].

[16] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014). doi:10.1088/1674-1137/38/9/090001

[17] M. Artuso, G. Borissov and A. Lenz, arXiv:1511.09466 [hep-ph].

[18] Y. Amhis *et al.* [Heavy flavour Averaging Group (HFAG) Collaboration], arXiv:1412.7515 [hep-ex].

[19] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006) doi:10.1103/PhysRevLett.97.242003 [hep-ex/0609040].

[20] R. Aaij *et al.* [LHCb Collaboration], New J. Phys. **15**, 053021 (2013) doi:10.1088/1367-2630/15/5/053021 [arXiv:1304.4741 [hep-ex]].