FCNC in the minimal 3-3-1 model revisited

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Abstract

We show that in the minimal 3-3-1 model the flavor changing neutral currents (FCNCs) do not impose necessarily strong constraints on the mass of the $Z'$ of the model if we also consider the neutral scalar contributions to such processes, like the neutral meson mass differences and their rare semileptonic decays. We first obtain numerical values for all the mixing matrices of the model i.e., the unitary matrices that rotate the left- and right-handed quarks in each charge sector and give the correct mass of all the quarks and the CKM mixing matrix. Then, we find that there is a range of parameters in which the neutral scalar contributions to these processes may interfere with those of the $Z'$, implying that this vector boson may be lighter than it has been thought.

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I. INTRODUCTION

The so called 3-3-1 models, with gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ are interesting extensions of the standard model (SM). The main feature of these models is that, by choosing appropriately the representation content, the triangle anomalies cancel out only if there are three families [1–3]. In particular, the so called minimal 3-3-1 model (m3-3-1 for short) [1] has other interesting predictions: it explains why $\sin^2 \theta_W < 1/4$ is observed and at the same time it implies the existence of a Landau-like pole at energies of the order of TeVs [4]; the existence of this Landau-like pole also stabilize the electroweak scale avoiding the hierarchy problem [5]; the model allows the quantization of electric charge [6, 7]; it has also an almost automatic Peccei-Quinn symmetry, if the trilinear term in the scalar potential becomes a dynamical degree of freedom [8]; and there are also new sources of CP violation which allow to obtain $\epsilon$ and $\epsilon'/\epsilon$ even without the CKM phase i.e., if we put $\delta = 0$ [9]. And, probably it could explain CP violation in the $B\bar{B}$ mesons as well. One important feature that distinguishes the model from any other is the prediction of extra charged and doubly charged gauge bosons [10] and also exotic charged quarks while the lepton sector is the same of the SM plus, if necessary, right-handed neutrinos. These exotic charged particles may have effect in the two photon decay of the SM-like Higgs scalar [11].

A common feature of all 3-3-1 models is that two of the quark triplets transform differently from the third one, and this implies flavor changing neutral currents (FCNC) at tree level, mediated by the extra neutral vector boson, $Z'$, [12–14] and by neutral scalars and pseudoscalars. However, in these models it is not straightforward to put constraints on the $Z'$ boson mass from the analysis of the FCNC processes because the relevant observables of these processes depend on the mixing matrix elements, that are unknown, and that are needed to diagonalize the quark mass matrices. These unitary matrices, $V_{L,R}^{U,D}$, survive in some parts of the Lagrangian, besides the combination of these matrices appearing in the CKM matrix, here defined as $V_{CKM} = V_L^U V_L^{D\dagger}$.

A possibility, as in [15], is not to attempt to place lower bounds on the $Z'$ mass, but rather set its mass at several fixed values and try to obtain some information about the structure of the $V_{L,R}^{U,D}$ matrices. Moreover, usually it is considered that the dominant contribution, by far, to FCNC is that mediated by the $Z'$ since the contributions of the (pseudo)scalars are assumed to be negligible. Notwithstanding, we show here that this is not the most general
case and there is a range of the parameters that allows negative interference between the $Z'$ and, at least, one neutral scalar which we assume as being the SM-like Higgs with a mass around 125 GeV. Other contributions involving a light neutral pseudoscalar are not considered. Hence, we are not in the most general case but given just an example of how more intricate is the analysis of FCNC in 3-3-1 models than it has been thought until now.

Our analysis implies that there is a new range of the parameters of 3-3-1 models that have not been taken into account yet [15–17]. Another difference of our analysis from those in the literature is that we first calculate the quark masses and all the mixing matrices appearing in the model. Then, we calculate the $Z'$ and neutral scalar contributions to FCNC processes. Here we will not consider CP violation.

The outline of the paper is the following. In the Sec. II we consider the quark masses and mixing in the models of Refs. [1, 2]. In Sec. III we show the FCNC processes that arise at tree level in the m3-3-1 model. Those related to the $Z'$ in Subsec. III A and those related to neutral scalars in Subsec. III B. Neutral processes with $\Delta F = 2$ are considered in Sec. IV in Subsec. IV A we consider the $\Delta M_K$ and in Subsec. IV B the $\Delta M_B$ mass differences. Then, in Sec. V we show in what conditions the neutral scalar with mass of 125 GeV has the same coupling to the top quark as in the SM implying that the production mechanism is, for all practical purposes, the same in both models. $\Delta F = 1$ processes are considered in VI. The last section is devoted to our conclusions.

II. QUARK MASSES AND MIXING MATRICES IN THE MINIMAL 3-3-1 MODEL

In the m3-3-1 model the left-handed quark fields are chosen to form two anti-triplets $Q_{mL} = (d_m, -u_m, j_m)^T_L \sim (3^*, -1/3); m = 1, 2$; and a triplet $Q_{3L} = (u_3, d_3, J)^T_L \sim (3, 2/3)$. The right-handed ones are in singlets: $u_{\alpha R} \sim (1, 2/3), d_{\alpha R} \sim (1, -1/3), \alpha = 1, 2, 3, j_{mR} \sim (1, -4/3)$, and $J_R \sim (1, 5/3)$. The scalar sector, that couples to quarks, is composed by three triplets: $\eta = (\eta^0, \eta^+_1, \eta^+_2)^T \sim (3, 0), \rho = (\rho^+, \rho^0, \rho^{++})^T \sim (3, 1)$ and $\chi = (\chi^-, \chi^{--}, \chi^0)^T \sim (3, -1)$. Above, the numbers between parenthesis means the transformation properties under $SU(3)_L$ and $U(1)_X$, respectively.

The model also needs a scalar sextet to give mass to the charged leptons and neutrinos. However, it is also possible to obtain these masses considering only the three triplets above.
and non-renormalizable interactions, for details see Ref. [18].

With the fields above, the Yukawa interactions using the quark symmetry eigenstates $U'_{L,R}, D'_{L,R}$ are

$$- \mathcal{L}_Y = \bar{Q} m_L [G_{\alpha a} U'_{\alpha R} \rho^* + \tilde{G}_{\alpha a} D'_{\alpha R} \eta^*] + \bar{Q}_3 L [F_{3\alpha} U'_{\alpha R} \eta + \tilde{F}_{3\alpha} D'_{\alpha R} \rho] + \text{H.c.}$$  

(1)

From Eq. (1) we obtain the following mass matrices in the basis $U'_{L(R)} = (-u_1, -u_2, u_3)_{L(R)}$ and $D'_{L(R)} = (d_1, d_2, d_3)_{L(R)}$,

$$M^U = \begin{pmatrix}
  r G_{11} & r G_{12} & r G_{13} \\
  r G_{21} & r G_{22} & r G_{23} \\
  F_{31} & F_{32} & F_{33}
\end{pmatrix} |\eta|, \quad M^D = \begin{pmatrix}
  r^{-1} \tilde{G}_{11} & r^{-1} \tilde{G}_{12} & r^{-1} \tilde{G}_{13} \\
  r^{-1} \tilde{G}_{21} & r^{-1} \tilde{G}_{22} & r^{-1} \tilde{G}_{23} \\
  \tilde{F}_{31} & \tilde{F}_{32} & \tilde{F}_{33}
\end{pmatrix} |\rho|.$$  

(2)

By choosing $|\rho| = 54 \text{ GeV}$ and $|\eta| = 240 \text{ GeV}$, $r = |\rho|/|\eta| = 0.225$, the mixing between $Z$ and $Z'$ vanishes independently of the value of $|\chi|$ (see the next section and Ref. [19] for details). For simplicity we will consider all VEVs and Yukawa couplings as being real numbers.

The symmetry eigenstates $U'_{L,R}, D'_{L,R}$ and the mass eigenstates $U_{L,R}, D_{L,R}$ are related by $U'_{L,R} = (V^U_{L,R})^\dagger U_{L,R}$ and $D'_{L,R} = (V^D_{L,R})^\dagger D_{L,R}$. $V^U_{L,R}$ are unitary matrices such that $V^U_{L} M^U V^U_{R\dagger} = \hat{M}^U$ and $V^D_{L} M^D V^D_{R\dagger} = \hat{M}^D$, where $\hat{M}^U = \text{diag}(m_u, m_c, m_t)$ and $\hat{M}^D = \text{diag}(m_d, m_s, m_b)$. In order to obtain the mass eigenvalues we have to solve the matrix equations:

$$V^D_{L} M^D V^D_{R\dagger} V^D_{R\dagger} = V^D_{R} M^D V^D_{R\dagger}, \quad (\hat{M}^D)^2,$$

$$V^U_{L} M^U V^U_{R\dagger} V^U_{R\dagger} = V^U_{R} M^U V^U_{R\dagger}, \quad (\hat{M}^U)^2.$$  

(3)

The notation in these matrices is, for instance,

$$V^D_{L} = \begin{pmatrix}
  (V^D_{L})_{dd} & (V^D_{L})_{ds} & (V^D_{L})_{db} \\
  (V^D_{L})_{sd} & (V^D_{L})_{ss} & (V^D_{L})_{sb} \\
  (V^D_{L})_{bd} & (V^D_{L})_{bs} & (V^D_{L})_{bb}
\end{pmatrix},$$  

(4)

and similarly for $V^D_{R}$ and $V^U_{L,R}$.

Solving numerically Eqs. (3) we find the matrices $V^U_{L,R}$, which give the correct quark mass square values and, at the same time, the Cabibbo–Kobayashi–Maskawa quark mixing.
matrix. We get:

\[
V^U_L = \begin{pmatrix}
-0.00032 & 0.07163 & -0.99743 \\
0.00433 & -0.99742 & -0.07163 \\
0.99999 & 0.00434 & -0.00001
\end{pmatrix},
\]

\[
V^D_L = \begin{pmatrix}
0.00273 \to 0.00562 & (0.03 \to 0.03682) & -(0.99952 \to 0.99953) \\
-(0.19700 \to 0.22293) & -(0.97436 \to 0.97993) & -0.03052 \\
0.97483 \to 0.98039 & -(0.19708 \to 0.22291) & -(0.00415 \to 0.00418)
\end{pmatrix},
\] (5)

and the CKM matrix \((V_{CKM} = V^U_L V^D_L)\)

\[
|V_{CKM}| = \begin{pmatrix}
0.97385 \to 0.97952 & 0.20134 \to 0.22714 & 0.00021 \to 0.00399 \\
0.20116 \to 0.22679 & 0.97307 \to 0.97869 & 0.04116 \to 0.04118 \\
0.00849 \to 0.01324 & 0.03919 \to 0.04028 & 0.99914 \to 0.99915
\end{pmatrix},
\] (6)

which is in agreement with the data [21]. In the same way we obtain the \(V^U_R, V^D_R\) matrices:

\[
V^U_R = \begin{pmatrix}
-0.45440 & 0.82278 & -0.34139 \\
0.13857 & -0.31329 & -0.93949 \\
0.87996 & 0.47421 & -0.02834
\end{pmatrix},
\]

\[
V^D_R = \begin{pmatrix}
-(0.000178 \to 0.000185) & (0.005968 \to 0.005984) & -0.999982 \\
-(0.32512 \to 0.32559) & -(0.94549 \to 0.94566) & -(0.00558 \to 0.00560) \\
0.94551 \to 0.94567 & -(0.32511 \to 0.32558) & -(0.00211 \to 0.00212)
\end{pmatrix},
\] (7)

The values for the coupling constants in Eq. (2) which give the numerical values for the matrix entries above are: \(G_{11} = 1.08, G_{12} = 2.97, G_{13} = 0.09, G_{21} = 0.0681, G_{22} = 0.2169, G_{23} = 0.1 \times 10^{-2}, F_{31} = 9 \times 10^{-6}, F_{32} = 6 \times 10^{-6}, F_{33} = 1.2 \times 10^{-5}, G_{11} = 0.0119, G_{12} = 6 \times 10^{-5}, G_{13} = 2.3 \times 10^{-5}, G_{21} = 3.2 \times 10^{-4}, G_{22} = 2.13 \times 10^{-4}, G_{23} = 7 \times 10^{-5}, F_{31} = (02-2.2) \times 10^{-4}, F_{32} = (1.645 - 1.95) \times 10^{-4}, F_{33} = 1.312 \times 10^{-4}\). With the values above we obtain from Eq. (3) the masses at the Z pole (in GeV): \(m_u = 0.00175, m_c = 0.6194, m_t = 171.163, m_d = (33.6 - 39.3) \times 10^{-4}, m_s = (0.0543765 - 0.0546863), m_b = (2.8537 - 2.8574)\) which are in agreement with the values given in Ref. [22]. For the sake of simplicity, we are only allowing the \(d\)-type quark masses to vary within the 3σ experimental error range. These results are valid for the models in Refs. [12] but other 3-3-1 models can be similarly studied along this line.
III. NEUTRAL CURRENT INTERACTIONS

It is usually considered that 3-3-1 models reduce to the SM only at high energies. If $v_\chi$ is the VEV that breaks the 3-3-1 symmetry down to the 3-2-1 one, then $v_\chi \gg v_{SM} = (1/\sqrt{2}G_F)^{1/2} \approx 246$ GeV. In this limit the lightest neutral vector boson, $Z_1$, whose mass is $M_{Z_1}$, for all practical purposes, the same couplings with fermions of the SM $Z$, since in this case the mixing among $Z$ and $Z'$ is less than $10^{-3}$ [14]. In Ref. [19], it was put forward that this mixing is small due to the existence of an approximate $SU(2)_{L+R}$ custodial global symmetry. However, another solution which also reproduces the SM model couplings of the $Z_1$, without imposing $v_\chi \gg v_{SM}$, may be obtained. This is a non trivial solution that implies that $Z$ and $Z'$ do not mix, at the tree level, independently of the value of $v_\chi$ as it was shown in Ref. [20]. There, it is defined the $\rho_1$-parameter as $\rho_1 = c_W^2 M_{Z_1}^2 / M_W^2$, where $M_{Z_1}$ has a complicate dependence on all the VEVs and $\sin \theta_W$. In general $\rho_1 \leq 1$ since $M_{Z_1} \leq M_Z$. In the SM context it is defined $\rho_0 = c_W^2 M_Z^2 / M_W^2$ (notice that in Refs. [19, 20] it was used, for the sake of making easier the calculations, the inverse of the SM $\rho_0$). We define the SM limit of the 3-3-1 model, at the tree level, imposing the condition $\rho_1 = \rho_0 = 1$. We find that this condition is satisfied in two cases: first, the usual one when $v_\chi \to \infty$. A second non trivial solution for satisfying this condition can be found by solving for $v_\rho = \sqrt{2} \langle \rho^0 \rangle$, given the solution $\bar{v}_\rho^2 = [(1 - 4s_W^2)/2c_W^2] \bar{v}_{SM}^2$, where $\bar{v}_\rho = v_\rho/v_\chi$, and $\bar{v}_{SM} = v_{SM}/v_\chi$. As $v_\rho$ and $v_\eta$ ($v_\eta = \sqrt{2} \langle \eta^0 \rangle$) are constrained by $v_{SM}$ as $v_\rho^2 + v_\eta^2 = v_{SM}^2$, in order to give the correct mass to $M_W$, we find $\bar{v}_\eta^2 = [(1 + 2s_W^2)/2c_W^2] \bar{v}_{SM}^2$, where $\bar{v}_\eta = v_\eta/v_\chi$. It implies that the VEVs of the triplets $\eta$ and $\rho$ must have the values considered above ($|v_\rho| = 54$ GeV and $|v_\eta| = 240$ GeV), while leaving $v_\chi$ completely free, and it may be even of the order of the electroweak scale.

The nontrivial solution above is in fact the SM limit of the 3-3-1 model since when the expressions of $\bar{v}_\rho$ and $\bar{v}_\eta$ are used it results that $M_{Z_1} = M_Z$, and also all the couplings of $Z_1$ with the known fermions, which in this model are also complicated functions of all VEVs and $\sin \theta_W$, are exactly the same as the respective couplings of the SM $Z$. Moreover, this SM limit is obtained regardless the $v_\chi$ scale, since it factorizes in both sides of the relations. In any case the $Z'$, which mass depends mainly on $v_\chi$, may be lighter than it was thought before if $v_\chi \gtrsim v_{SM}$. From this SM limit it results that $M_{Z_1} \equiv M_Z$, $Z_1 \equiv Z$, and $Z_2 \equiv Z'$, and there is no mixing at all between $Z$ and $Z'$ at the tree level.
Light $Z'$ is then a theoretical possibility. However, the phenomenology of FCNC may impose strong lower bounds on $M_{Z'}$ and it is necessary to verify which values for $M_{Z'}$ are indeed allowed. Here we will consider FCNC processes induced by both, $Z'$ and neutral scalars. We will show that there is destructive or constructive interference between both contributions depending on a given range of the parameters. This sort of interference happens when at least one the neutral scalars, with mass of the order of the 125 GeV is considered. The scalars have to be included since their interactions with quarks are not proportional to the quark masses. In the next subsections we make explicit the quark neutral current interactions which induce FCNC, for both the $Z'$ and scalar fields.

A. Neutral currents mediated by the $Z'$

The neutral vector boson $Z'$ induces FCNC at tree level. In fact, its interactions with quarks are given by the Lagrangian

$$\mathcal{L}_{Z'} = -\frac{g}{2\cos\theta_W}[\bar{U}_L\gamma^\mu K^U_{LL}U_L + \bar{U}_R\gamma^\mu K^U_{RR}U_R + \bar{D}_L\gamma^\mu K^D_{LL}D_L + \bar{D}_R\gamma^\mu K^D_{RR}D_R]Z'_\mu, \quad (8)$$

where we have defined

$$K^U_{LL} = V^U_{LL}Y^U_{LL}V^U_{LL\dagger}, \quad K^U_{RR} = V^U_{RR}Y^U_{RR}V^U_{RR\dagger}, \quad K^D_{LL} = V^D_{LL}Y^D_{LL}V^D_{LL\dagger}, \quad K^D_{RR} = V^D_{RR}Y^D_{RR}V^D_{RR\dagger}; \quad (9)$$

with $V^U_{L,R}$ given in Eqs. (5) and (7) and

$$Y^U = Y^D_L = -\frac{1}{2\sqrt{3}h(x)}\begin{pmatrix} -2(1-2x) & 0 & 0 \\ 0 & -2(1-2x) & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (10)$$

and

$$Y^U_R = -\frac{4x}{\sqrt{3}h(x)}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y^D_R = \frac{2x}{\sqrt{3}h(x)}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (11)$$

and $h(x) \equiv (1-4x)^{1/2}, \quad x = \sin^2\theta_W$. See Ref. [23].
Using the matrices in Eqs. (5), (10) and (11) we obtain for the matrices defined in Eqs. (9)

\[
K^U_L \approx \begin{pmatrix}
-1.04793 & -0.08905 & -0.00004 \\
-0.08905 & 1.12718 & -10^{-6} \\
-0.00004 & -10^{-6} & 1.13088
\end{pmatrix},
\]

\[
K^D_L \approx \begin{pmatrix}
-1.05154 & -0.00140 & -0.00826 \\
-0.00140 & 1.13082 & -5 \cdot 10^{-6} \\
-0.00826 & -5 \cdot 10^{-6} & 1.13078
\end{pmatrix}.
\] (12)

Since \( Y^{U,D}_R \) are proportional to the identity matrix, there are no FCNC in the right-handed quark sector coupled with the \( Z' \), and using the matrices in Eqs. (7) we obtain \( K^U_R \approx -1.94465 \mathbf{1}_{3 \times 3} \) and \( K^D_R \approx 0.97232 \mathbf{1}_{3 \times 3} \).

B. Neutral currents mediated by scalars

As we said before, there are also FCNCs at the tree level in the scalar sector. From Eq. (1) we obtain the following neutral scalar-quark interactions

\[
- \mathcal{L}_{qqh} = \overline{U}_L \mathcal{K}^U U_R + \overline{D}_L \mathcal{K}^D D_R + \text{mass terms} + H.c.,
\] (13)

where \( \mathcal{K}^U = V^U_L \mathcal{Z}^U V^U_R \) and \( \mathcal{K}^D = V^D_L \mathcal{Z}^D V^D_R \) and we have arranged, for simplicity, the interactions in matrix form:

\[
\mathcal{Z}^U = \begin{pmatrix}
G_{11} \eta^0 & G_{12} \rho^0 & G_{13} \rho^0 \\
G_{21} \rho^0 & G_{22} \rho^0 & G_{23} \rho^0 \\
F_{31} \eta^0 & F_{32} \eta^0 & F_{33} \eta^0
\end{pmatrix},
\]

\[
\mathcal{Z}^D = \begin{pmatrix}
\tilde{G}_{11} \eta^0 & \tilde{G}_{12} \eta^0 & \tilde{G}_{13} \eta^0 \\
\tilde{G}_{21} \eta^0 & \tilde{G}_{22} \eta^0 & \tilde{G}_{23} \eta^0 \\
\tilde{F}_{31} \rho^0 & \tilde{F}_{32} \rho^0 & \tilde{F}_{33} \rho^0
\end{pmatrix},
\] (14)

where \( \eta^0 \) and \( \rho^0 \) are symmetry eigenstates. The notation used is \( \sqrt{2}x^0 = \text{Re} x^0 + i \text{Im} x^0 \), with \( x^0 = \eta^0, \rho^0 \), and \( \text{Re} \eta^0 = \sum_i U_{\eta h_i} h_i^0 \), \( \text{Re} \rho^0 = \sum_i U_{\rho h_i} h_i^0 \) with \( h_i^0 \) being mass eigenstates with mass \( m_i \), and similarly for the imaginary part. Notice that the matrices \( V^U,D_{L,R} \) survive in these interactions.

Using the values of \( G, F, \tilde{G}, \tilde{F} \), written below Eq. (7), in Eq. (14) and the matrices \( V^D_L \) and \( V^D_R \), given in Eqs. (5) and (7), respectively, the matrix \( \mathcal{K}^D \) in Eq. (13) is given by

\[
\mathcal{K}^D \approx \begin{pmatrix}
10^{-4} \rho^0 - 10^{-6} \eta^0 & 10^{-4} \rho^0 - 10^{-5} \eta^0 & -10^{-4} \rho^0 + 10^{-5} \eta^0 \\
10^{-6} \rho^0 + 10^{-4} \eta^0 & 10^{-5} \rho^0 + 10^{-3} \eta^0 & -10^{-6} \rho^0 + 10^{-2} \eta^0 \\
10^{-6} \rho^0 - 10^{-5} \eta^0 & 10^{-6} \rho^0 - 10^{-3} \eta^0 & -10^{-6} \rho^0 + 10^{-2} \eta^0
\end{pmatrix}.
\] (15)
where we have shown only the order of magnitude of each entry. This shows that all the neutral scalars are fermiophobic, mainly with the $d$ and $s$ quarks. These sort of scalars have been excluded in the mass ranges 110.0-118.0 GeV and 119.5-121.0 GeV [24]. The present model corresponds to a two-Higgs doublet and a Higgs singlet model. We will consider one of the Higgs scalars with a mass consistent with the recent results from LHC, $m_1 = 125$ GeV [25]. We stress that in (15), $\eta^0$ and $\rho^0$ are symmetry eigenstates.

IV. $\Delta F = 2$ PROCESSES

In 3-3-1 models $\Delta F = 2$ transitions ($F = S, B, C$) at tree and loop level arise. Here we will consider only the strange and beauty cases. Since the main contributions to these processes are those at tree level and they are mediated by $Z'$ and neutral (pseudo-)scalars, we will be concerned here only with these ones.

A. $\Delta M_K$

In the context of the SM, the $\Delta M_K$ mass difference in the neutral kaon system is given by $\Delta M_K^{SM} = \zeta_{sd} \langle \bar{K}^0 |(\bar{s}d)^2_{V-A}|K^0 \rangle$ where, using only the $c$-quark contribution, we have

$$\zeta_{sd} = \frac{G_F^2 m_c^2}{16\pi^2} \left[ (V_{CKM})^{*}_{cd}(V_{CKM})_{cs} \right]^2 \approx 10^{-14} \text{GeV}^{-2},$$

and we have neglected QCD corrections and in the vacuum insertion approximation we have $\langle \bar{K}^0 |(\bar{s}d)^2_{V-A}|K^0 \rangle = 2M_K f_K^2/3$, see Ref. [26].

Let us consider first the contribution of the extra neutral vector boson. From Eq. (8) the effective $Z'$ interaction Hamiltonian inducing the $\bar{K}^0 \rightarrow K^0$ transition, at tree level, is given by

$$\mathcal{H}_{\Delta S=2}^{\text{eff}}|_{Z'} = \frac{g^2}{4e^2_W M_{Z'}^2} [\bar{s}_L (K^0_D)_{sd} \gamma^\mu d_L]^2,$$

and we obtain the following extra contribution to $\Delta M_K$

$$\Delta M_K|_{Z'} = 2\text{Re} \langle \bar{K}^0 |\mathcal{H}_{\Delta S=2}^{\text{eff}}|_{Z'} |K^0 \rangle = \text{Re} \zeta_{sd}^2 \frac{2}{3} M_K f_K^2,$$

where

$$\text{Re} \zeta_{sd} = \text{Re} \frac{G_F}{2\sqrt{2}c_W^2} \frac{M_W^2}{M_{Z'}^2} \left[ (K^0_D)_{ds} \right]^2 = \frac{M_W^2}{M_{Z'}^2} 10^{-11} \text{GeV}^{-2},$$

9
since, from Eq. (12) we have Re \((K^D_L)_{sd} = -1.4 \times 10^{-3}\). If this were the only contribution to \(\Delta M_K\), and imposing \(\zeta_{sd}' < \zeta_{sd}^{SM}\), we must have that \(M_{Z'} > 2.5\) TeV, which implies \(|v_{\chi}| = 1.8\) TeV. See Eq. (46) below.

Let us now consider the scalar contributions to \(\Delta M_K\). From Eq. (13), the scalar interactions between the \(d\) and \(s\) quarks mediated by \(h_i^0\) (for simplicity we take only the real scalar contributions) are given by

\[
-\mathcal{L}_{dsh} = \frac{1}{\sqrt{2}} \sum_i \left[ (I_{K}^i)_{ds} \bar{s}_L d_R h_i^0 + (I_{K}^{i*})_{sd} \bar{d}_L s_R h_i^0 + H.c. \right] = \frac{1}{2\sqrt{2}} \sum_i \left[ (I_{K}^{i+})_{ds} (\bar{d} s) + (I_{K}^{-i})_{ds} (\bar{d} \gamma_5 s) \right] h_i^0 + H.c., \tag{20}
\]

where, \(I_K^i = K^D U_{ai}\) with \(\alpha = \eta, \rho\), and \(i\) run over the neutral scalar mass eigenstates and the matrix \(K_D\) is defined in (15). Then, we have

\[
(I_{K}^i)_{sd} \approx 10^{-4} U_{\rho i} - 10^{-5} U_{\eta i}, \quad (I_{K}^i)_{ds} \approx 10^{-6} U_{\rho i} + 10^{-4} U_{\eta i}. \tag{21}
\]

In the right hand side of (20) we have defined \((I_{K}^{i\pm})_{ds} = (I_{K}^i)_{ds} \pm (I_{K}^{i*})_{sd}\).

The effective Hamiltonian induced by Eq. (20), contributing to the \(K^0 \leftrightarrow \bar{K}^0\) transition is:

\[
\mathcal{H}_{\Delta S=2}^{eff}\big|_h = \sum_i \frac{1}{8m_i^2} \left[ (I_{K}^{i+})_{ds} (\bar{s} d)^2 + (I_{K}^{-i})_{ds} (\bar{s} \gamma_5 d)^2 \right]. \tag{22}
\]

Defining as usual

\[
\Delta M_K|_h = 2 \text{Re} \zeta_{sd}^h \langle \bar{K}^0 |(\bar{s} d)^2 |-K^0\rangle, \tag{23}
\]

and using the matrix elements (26)

\[
\langle \bar{K}^0 |(\bar{s} d)(\bar{s} d)| K^0\rangle = -\frac{1}{8} \left[ 1 - \frac{M_K^2}{(m_s + m_d)^2} \right] \langle \bar{K}^0 |(\bar{s} d)^2 |K^0\rangle, \tag{24a}
\]

\[
\langle \bar{K}^0 |(\bar{s} \gamma_5 d)(\bar{s} \gamma_5 d)| K^0\rangle = \frac{1}{8} \left[ 1 - \frac{M_K^2}{(m_s + m_d)^2} \right] \langle \bar{K}^0 |(\bar{s} d)^2 |K^0\rangle, \tag{24b}
\]

we find

\[
\text{Re} \zeta_{sd}^h = \text{Re} \sum_i \frac{1}{64 m_i^2} \left[ -(I_{K}^{i+})_{ds} \left[ 1 - \frac{M_K^2}{(m_s + m_d)^2} \right] + (I_{K}^{-i})_{ds} \left[ 1 + \frac{11M_K^2}{(m_s + m_d)^2} \right] \right] \text{GeV}^{-2}, \tag{25}
\]

and

\[
(I_{K}^{i\pm})_{ds} \approx [(10U_{\rho i} - 2U_{\eta i})U_{\rho i}^* \pm (10U_{\rho i} - U_{\eta i})U_{\eta i} + 10(U_{\eta i})^2] \times 10^{-9}, \tag{26}
\]
then

\[ \text{Re} e_{sd}^h = \text{Re} \sum_i \frac{1}{64 m_i^2} [24((10U_{\rho i}^* - 2U_{\eta i}^*)U_{\rho i}^* + (10U_{\rho i}^* - U_{\eta i}^*)U_{\eta i} + 10(U_{\eta i})^2]
- 272[(10U_{\rho i}^* - 2U_{\eta i}^*)U_{\rho i}^* - (10U_{\rho i}^* - U_{\eta i}^*)U_{\eta i} + 10(U_{\eta i})^2] \times 10^{-9} \text{GeV}^{-2}. \]  
(27)

Thus, the \( \Delta M_K \) in the present model includes both \( Z' \) and neutral scalar contributions,

\[ \Delta M_K |_{331} \approx \Delta M_K^{SM} + \Delta M_K^{Z'} + \Delta M_K^h, \]  
(28)

with \( \zeta_{331} = \zeta_{sd}^{SM} + \zeta_{sd}^{Z'} + \zeta_{sd}^h \), and we impose that \( \zeta_{sd}^{Z'} + \zeta_{sd}^h < \zeta_{sd}^{SM} \), hence

\[ \text{Re} (\zeta_{sd}^{Z'} + \zeta_{sd}^h) < 10^{-14} \text{GeV}^{-2}. \]  
(29)

Using Eqs. (19) and (27) in Eq. (29) and assuming that only one of the SM-like neutral Higgs scalar contribute, say \( h_1^0 \) (the others are considered too heavy and their contributions can be neglected), Eq. (29) becomes

\[ 1 \times 10^{-2} \frac{M_W^2}{M_{Z'}^2} + \text{Re} \frac{1}{64 m_1^2} \left\{ 24((10U_{\rho 1}^* - 2U_{\eta 1}^*)U_{\rho 1}^* + (10U_{\rho 1}^* - U_{\eta 1}^*)U_{\eta 1} + 10(U_{\eta 1})^2]
- 272[(10U_{\rho 1}^* - 2U_{\eta 1}^*)U_{\rho 1}^* - (10U_{\rho 1}^* - U_{\eta 1}^*)U_{\eta 1} + 10(U_{\eta 1})^2] \right\} < 10^{-5} \text{GeV}^{-2}. \]  
(30)

Once we are considering a SM-like neutral scalar its mass \( m_1 \) is fixed in 125 GeV. Hence, in Eq. (30) the only free parameters are the \( Z' \) mass, and the matrix elements \( U_{\eta 1} \) and \( U_{\rho 1} \).

Assuming that \( U_{\eta 1} \) and \( U_{\rho 1} \) are real, and keeping one of them constant and varying the other one, we obtain the corresponding \( Z' \) mass which satisfies Eq. (30) that runs from GeVs to few TeVs. See the curves in Fig. 1.

In the next subsection we will consider FCNC processes as in the previous one but now involving the \( b \) quark.

\section*{B. \( \Delta M_B \)}

We can also consider the \( B_d^0 - \bar{B}_d^0 \) mass difference, \( \Delta M_B^{SM} = \zeta_{bd}^{SM} \langle \bar{B}_d^0 | (\bar{s}d)^2 | B_d^0 \rangle \) where \( \langle B_0 | (\bar{b}d)^2 | B^0 \rangle = 2M_B f_B^2 / 3 \) [27], and, as before, we factorized the model independent factors

\[ \zeta_{bd}^{SM} = G_F M_W^2 \frac{12 \pi^2}{S_0(x_t)} [(V_{CKM})_{td}(V_{CKM})_{tb}]^2 \approx 2.8 \times 10^{-8} \text{GeV}^{-2}, \]  
(31)

where \( x_t = m_t^2 / M_W^2 \) and we have used \( S_0(x) \approx 0.784 x_0^{0.76} \) [28].
From Eqs. (8)-(11) the effective Hamiltonian contributing to $B^0_d \leftrightarrow \bar{B}^0_d$ transition is given by

$$H_{\Delta B}^{\Delta B = 2}|_{Z'} = \frac{g^2}{4c_W^2 M_{Z'}^2} [\bar{b}_L (K_D^D)_{bd} \gamma^\mu d_L]^2,$$  \hfill (32)

and we obtain the following extra contributions to $\Delta M_B$

$$\Delta M_B|_{Z'} = 2 \text{Re} \langle \bar{B}^0| H_{\Delta B}^{\Delta B = 2}|_{Z'} | B^0 \rangle = \text{Re} \zeta_{bd}^2 \frac{2}{3} M_B f_{B_d}^2,$$  \hfill (33)

where, as in the case of the standard model we have not considered the QCD corrections and the bag parameter $B_B = 1$. We obtain

$$\text{Re} \zeta_{bd}^2 = \frac{G_F}{2 \sqrt{2} c_W} \frac{M_{Z'}^2}{M_W^2} ((K_D^D)_{bd})^2 = 10^{-9} \frac{M_{Z'}^2}{M_W^2} \text{GeV}^{-2},$$  \hfill (34)

where we have used \(12\), i.e., $\text{Re} (K_D^D)_{bd} = -8.3 \times 10^{-3}$. Notice that for all reasonable values of $M_{Z'}$, which are consistent with $\Delta M_B$ the contribution of $Z'$ is always smaller than the SM one in (31).

Similarly we have the scalar contributions in the $B^0_q - \bar{B}^0_q$ system ($q = d, s$). From Eqs. (13) and (15) the scalar interactions between the $b, d$ quarks mediated by the scalars $h_0^i$ (again, for simplicity we take only the real scalar contributions) are give by

$$- \mathcal{L}_{bqh} = \frac{1}{\sqrt{2}} \sum_i [(I_{ib})_{bd} \bar{b}_L d_R + (I_{ib}^*)_{ed} \bar{d}_L b_R] h_i^0 + H.c.$$  \hfill (35)

where we have defined $(I_{ib}^+)^*_{bd} = (I_{ib}^+)^*_{bd} \pm (I_{ib}^+)^*_{dq}$. For the case when $q = d$ we obtain from Eq. (15)

$$(I_{ib}^+)^*_{bd} \approx 10^{-6} U_{\rho i} - 10^{-5} U_{\eta i}, \quad (I_{ib}^i)^*_{db} \approx -10^{-4} U_{\rho i} + 10^{-5} U_{\eta i}.$$  \hfill (36)

The effective Hamiltonian induced by (35), contributing to the $B^0_d \leftrightarrow \bar{B}^0_d$ transitions is:

$$H_{\Delta B = 2}^{\Delta B = 2}|_h = \sum_i \frac{1}{8 m_i^2} [(I_{ib}^+)^2 (\bar{b} q)^2 + (I_{ib}^-)^2 (\bar{b} \gamma^5 q)^2].$$  \hfill (37)

and, as usual we define

$$\Delta M_B|_h = \text{Re} \langle \bar{B}^0| H_{\Delta B = 2}^{\Delta B = 2}|_h | B^0 \rangle = 2 \text{Re} \zeta_{bd}^S M_B f_{B_d}^2,$$  \hfill (38)
where

\[
\text{Re} \zeta_{bd} = \text{Re} \sum_i \frac{1}{64m_i^2} \left[ 0.6(I_B^{i+})_{bd}^2 - 16.5(I_B^{i-})_{bd}^2 \right] \text{GeV}^{-2}, \tag{39}
\]

and

\[
(I_B^{\pm})_{bd} = [(U_{\rho i} - 0.2U_{\eta i}^{*})U_{\rho i} \pm 0.2U_{\eta i}U_{\rho i}] \times 10^{-8}; \tag{40}
\]

then

\[
\text{Re} \zeta_{bd} = \text{Re} \sum_i \frac{1}{64m_i^2} \left\{ 0.6((U_{\rho i} - 0.2U_{\eta i}^{*})U_{\rho i} + 0.2U_{\eta i}U_{\rho i}) \right. \\
\left. -16.5((U_{\rho i} - 0.2U_{\eta i}^{*})U_{\rho i} - 0.2U_{\eta i}U_{\rho i}) \right\}. \tag{41}
\]

Assuming that only one of the scalars contribute in (25), we obtain a constraint on the contributions of \(Z'\) and \(h_1^0\) to \(\Delta M_B\) like that in Eq. (29):

\[
10^{-1} \frac{M_{Z'}}{M_{Z'}} + \frac{1}{64m_i^2} \left\{ 0.6[(U_{\rho 1} - 0.2U_{\eta 1}^{*})U_{\rho 1} + 0.2U_{\eta 1}U_{\rho 1}] \\
-16.5[(U_{\rho 1} - 0.2U_{\eta 1}^{*})U_{\rho 1} - 0.2U_{\eta 1}U_{\rho 1}] \right\} < 2.8 \text{ GeV}^{-2}. \tag{42}
\]

Once we find that the constraint equation in (30) is satisfied, Eq. (42) is also satisfied. No new constraint on the \(Z'\) arises from the \(B_0^q - \bar{B}_0^q\) system.

V. WHAT HIGGS BOSON IS THIS?

We have assumed that the mass of the lighter scalar is equal to that of the resonance found at LHC [25]. In this situation we see from Fig. [1] that the values of the \(M_{Z'}\) allowed by \(\Delta F = 2\) processes depend on both \(U_{\rho 1}\) and \(U_{\eta 1}\) matrix elements in the neutral scalar sector. Assuming that the production processes are the same of the SM (new sources should be suppressed by the masses of the extra particles in the model), the neutral scalar, besides the mass around 125 GeV, must couple to fermions, at least to the top quark, with a similar strength to those in the SM in order to have the compatible Higgs production rate.

The latter point is important since the new resonance discovery at LHC [25] seems more and more like the SM Higgs [29]. From Eqs. (13) and (14), the \(u\)-type quark-neutral-scalar-\(h_1^0\) couplings are

\[
\mathcal{K}^U \approx \begin{pmatrix}
0.00991\rho^0 & -0.00067\eta^0 & 0.00398\rho^0 - 10^{-5}\eta^0 & 0.0109\rho^0 - 10^{-5}\eta^0 \\
-0.13846\rho^0 + 10^{-7}\eta^0 & 0.05556\rho^0 + 10^{-6}\eta^0 & -0.15212\rho^0 - 10^{-6}\eta^0 \\
1.9228\rho^0 - 10^{-11}\eta^0 & 0.8656\rho^0 - 10^{-10}\eta^0 & 2.35689\rho^0 - 10^{-10}\eta^0
\end{pmatrix}. \tag{43}
\]
We note from Eq. (43) that the larger coupling of \( h_1^0 \) is with the top quark and it is equal to the coupling in the SM if \( U_{\rho 1} = 0.38 \) regardless the value of \( U_{\eta 1} \).

For \( U_{\rho 1} = 0.38 \) we show in Fig. 2 \( M_{Z'} \) as a function of \( U_{\eta 1} \) solving Eqs. (30) and (42). We see from this figure that these \( \Delta F = 2 \) processes allow a rather light \( Z' \). From (43) we see that the coupling of \( c \)-quark is dominated by the neutral scalar \( \rho_0 \), and it is larger than the SM respective value. On the other hand, the coupling with \( b \)-quarks, from Eq. (15), is smaller than the respective SM value. Moreover, as we have seen before, the neutral scalars in this model have flavour changing couplings that are not negligible.

Notwithstanding, we will show in the next section that the \( \Delta F = 1 \) forbidden processes are more restrictive than the previous ones.

VI. \( \Delta F = 1 \) PROCESSES

Concerning the \( \Delta S = 1 \) processes, we consider as an illustration the leptonic decay of a neutral meson \( M^0 \), i.e., \( M^0 \rightarrow l^+ l'^- \), with \( l, l' = e, \mu \) and \( M^0 \) an strange or a beauty meson. We recall that these processes involve only one vertex in the quark sector and the \( Z' \) has natural flavor conservation in the lepton sector. The other vertex involves the interactions of the charged leptons with the neutral scalars which, in general, do not conserve flavor.

In the m3-3-1 model the partial width decay of the meson \( M^0(q_1 \bar{q}_2) \rightarrow l^+ l'^- \) has contributions at tree level which, are given by

\[
B_{M \rightarrow l^+ l'^-}^{331} = \left\{ \frac{G_SM_W^2}{16\sqrt{2}M_W^2} |(K_L^D)_{q_1 q_2}|^2 \frac{2f_{K^*}^2 M_L^2 m_i^2}{M_{Z'}^4} + \frac{M_W^6 f_M^2}{2(m_{q_1} + m_{q_2})^2 m_{h_1}^4} |(I_K)_{q_1 q_2} U_{l^+}^*| \right\} \left( \frac{1 - 4m_l^2}{M_M^2} \right)^2 \frac{1}{16\pi M_M}, (44)
\]

where we have used the meson matrix elements

\[
\langle 0|\bar{q}_f \gamma_\mu \gamma_5 q_i |M\rangle = i f_M p_{M\mu}, \quad \langle 0|\bar{q}_f \gamma_5 q_i |M\rangle = -i f_M \frac{M_M^2}{m_{q_f} + m_{q_i}}, (45)
\]

and \( p_M = p_1 + p_2 \).

The m3-3-1 model may have FCNC in the scalar-charged lepton interactions if the triplet \( \eta \) and the sextet \( S \) couple to leptons. In this case we denoted \( U_{l^+} \), the unknown mixing matrix in this sector, which may have, or not, a hierarchy structure i.e., to be almost diagonal.
A. $K_L \to l^+ l^-$

The experimental data are $B_{K_L \to e^+ e^-} < 10^{-12}$ and $B_{K_L \to \mu^+ \mu^-} = (6.84 \pm 0.11) \times 10^{-9}$ [21]. Using $q_1 = s$ and $q_2 = d$, $M_M = M_K$, $f_M = f_K$, we obtain from Eq. [44] that the decay into electrons impose a strong bond on the values of $U_{\eta 1}$, as show in Fig. 3. We have an additional free parameter $U_{ee}$ that weakens this bonds. See Fig. 4. On the other hand, the bound from the two muon decay on the $Z'$ mass, it is less restrictive than $K_L \to e^+ e^-$. See Fig. 5.

B. $B_s \to \mu^+ \mu^-$

Next we consider $\Delta B = 1$ processes. Recently, it has been observed the branching ratio $B_{B_s \to \mu^+ \mu^-} = 3.2 \times 10^{-9}$ [30]. In this case there is not constraint in $U_{\mu \mu}$ and $U_{\eta 1}$ and the constraint on $M_{Z'}$ is weaker than those coming from the other processes. In fact, these processes allow a rather light $Z'$ as is shown in Fig. 6. In the latter figure we show also the constraint coming from the $K_L$ decays and $\Delta M_K$.

VII. RESULTS

In Fig. 1 we show the values of $M_{Z'}$, as a function of $U_{\rho 1}$ ($U_{\eta 1}$) for fixed $U_{\eta 1}$ ($U_{\rho 1}$), which are allowed by solving simultaneously Eqs. [30] and [42]. Both $U_{\rho 1}$ and $U_{\eta 1}$ are allowed to vary in the interval $[-1, 1]$. We see from Fig. 1 that a large range for the $Z'$ mass values is allowed. However, by demanding $\rho^0$ to be the equivalent to the SM Higgs implies, from Eq. [43], that its coupling to the top quark is equal to the SM Higgs if $U_{\rho 1} = 0.38$. In this case, the only variable is $U_{\eta 1}$, and the $Z'$ mass can still be of the order of the electroweak scale or even lower. See Fig. 2.

We would like to stress that these light values for the $Z'$ mass are allowed only if there is negative interference, however, the option of a heavy $Z'$ is still allowed. In the latter case the scalar contributions in Eq. [30] would be suppressed mainly by the mass of $h^0_1$ and also by the matrix elements $U_{\eta 1}$ ($= -0.210259$). On the other hand, Eq. [42] would be already enough suppressed mainly by the $h^0_1$ mass.

The Fig. 3 shows the allowed values for $M_{Z'}$ and $U_{\eta 1}$, for fixed $U_{ee} = 0.1$ by the $K_L \to ee$ decay. We use Eq. [44] with $l = l' = e$ and $M^0 = K$. The red (dashed) vertical line is
the contribution of $Z'$ only and the allowed range is to the right of the curve, the minimal value being around 445 GeV. The blue (dashed) horizontal lines are the contributions of the scalar only and the allowed range for $U_{\eta 1}$, i.e., $-0.2 < U_{\eta 1} < 0.2$ for any value of $M_{Z'}$. The total contribution is given by the green (continuous) curve and the allowed region is inside that curve, and the minimal value for $M_{Z'}$ has moved to 500 GeV. Fig. 4 shows the total contribution (the green curve in Fig. 3) for several values of $U_{ee}$.

For the decay $K_L \rightarrow \mu\mu$ we use Eq. (44) with $l = l' = \mu$ and $M = K$. In Fig. 5, as in Fig. 3, the red (solid) vertical line is the contribution of the $Z'$ only and the lower bound on the $Z'$ mass is around 705 GeV. The scalar contribution does not constrain $U_{\eta 1}$. The total contribution is given by the blue (dashed) curved line and $M_{Z'} > 740$ GeV. The decay $B_s \rightarrow \mu\mu$ does not constrain these parameters anymore. Finally, in Fig. 6 we summarize all our results and Fig. 7 is a blow up of Fig. 6.

Notice that the scalar contribution not always implies in lowering the bound on $M_{Z'}$. This in fact happens in the $K^0 - \bar{K}^0$ system, but the effect is the opposite in $\Delta F = 1$ processes.

When the nontrivial SM limit discussed in Sec. III is satisfied, $Z$ and $Z'$ decouple i.e., the mixing angle $\theta$ is zero at the tree level, the masses of the neutral vector bosons are

$$M_1^2 = \frac{g_1^2}{4c_W^2}v_W^2 \equiv M_Z^2, \quad M_2^2 = \frac{g_2^2}{2c_W^2} \left( \frac{1 - 2s_W^2}{4} \right) \left( \frac{4 + \bar{v}_W^2}{1 - 4s_W^2} \right) v_\chi \equiv M_{Z'}^2,$$

where $v_W^2 = v_\eta^2 + v_\rho^2 + 2v_S^2$, $\bar{v}_W = v_W/v_\chi$, and $v_S$ is the VEV of the sextet that we can neglect here. A lower limit of 740 GeV for $M_{Z'}$ implies $v_\chi > 510$ GeV, from Eq. (46). On the other hand, since the mass of the charged vector bosons, $W^\pm, V^\pm, U^\pm$, are given by

$$M_W^2 = \frac{g_2^2}{4}v_W^2, \quad M_V^2 = \frac{g_2^2}{4}(v_\eta^2 + 2v_S^2 + v_\chi^2), \quad M_U^2 = \frac{g_2^2}{4}(v_\rho^2 + 2v_S^2 + v_\chi^2),$$

with $v_\chi > 510$ GeV we have $M_V > 183$ GeV and $M_U > 167$ GeV, using $g_2^2 = 4\pi\alpha(Z)$. These values satisfy the upper bound [19]

$$\frac{\sqrt{M_V^2 - M_U^2}}{M_W} \leq \sqrt{3}\tan\theta_W,$$

and not $M_V = M_U$, as is the case when we assume $v_\chi \gg v_\eta, v_\rho$ from the very start. Notice that the exotic charged quarks, which masses are of the form $m_j = g_j v_\chi/\sqrt{2}$, may have masses of the order of 200-300 GeV for reasonable values of the dimensionless Yukawa couplings $g_j$. 

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VIII. CONCLUSIONS

Here we have considered constraints coming from FCNC processes, $\Delta M_{K,B}, K_L \rightarrow ll$ and $B_s \rightarrow \mu\mu$, on the mass of the $Z'$ neutral vector boson in the $m3$-3-1 model. We calculated all its couplings but the matrix elements in the scalar sector $U_{\eta 1}, U_{\rho 1}$, and take into account, besides the $Z'$, the contribution to those processes of the lightest scalar field, $h'^0_1$, which we assume having a mass of 125 GeV. This scalar induces FCNC processes but its coupling to the top quark is numerically equal to the coupling of the Higgs and the top quark in the SM. Since the couplings of $h'^0_1$ to $W$ and $Z$ are also numerically equal to those of the SM, the production mechanism is for all practical purposes the same of the Higgs of the SM. However, the amplitude of at least one of the neutral scalars interfere some times destructively, as in $\Delta M_K$, and some times constructively, as in $K_L \rightarrow ll$ decay. If only $Z'$ is considered, the strongest lower bound on $M_{Z'}$ comes from $\Delta M_K$ which implies $M_{Z'} > 2.5$ TeV. When the neutral scalar is considered as well, the constraint is weaker allowing a rather light $Z'$. However, the leptonic kaon decay into two electrons rises up the lower bound to 740 GeV. This is the strongest constraint on the $Z'$ mass if the contribution of a neutral scalar with mass 125 GeV, with $U_{\rho 1} = 0.38$ and $-0.2 < U_{\eta 1} < 0.2$, is considered.

In the present model there are contributions to the magnetic dipole transitions $b \rightarrow s + \gamma$ or $b \rightarrow d + \gamma$ which have branching ratios of the order of $10^{-4}$ and are in agreement with the SM predictions [31]. For a recent analysis see Ref. [32]. As in the SM, in the present model this sort of decays and CP violation arise at the 1-loop order through penguin and box diagrams. However, in the present case there are contributions of the single and double charged scalars, exotic quarks, and single and double charged vector bosons present in the model.

The search for a $Z'$-like resonance has been done at the LHC. However, as in previous searches, the results are usually obtained in the context of a given model. For instance, in a topcolor assisted spontaneous symmetry breaking scenario this sort of (leptophobic) resonance has been excluded for $M_{Z'} < 1.3$ TeV, if $\Gamma_{Z'} = 0.012 M_{Z'}$, and $M_{Z'} < 1.9$ TeV, if $\Gamma_{Z'} = 0.10 M_{Z'}$. [33]. Notwithstanding, the application of these bounds to the model considered here is not straightforward and has to be done in separate study.

The main goal of our paper is to point out that there is a range of $M_{Z'}$ values that has not been considered before, if the interference effects with at least one neutral scalar is
considered. This effect may be at work in $Z'$-searches at the LHC as well. The solutions we have found here do not exhaust all the possibilities. More solutions are expected to be found if more than one scalar is assumed to contribute to the FCNC processes. There are also solutions with heavy $Z'$ when there is no destructive interference in the $\Delta M_K$ amplitude. Moreover, more detailed calculations and other FCNC processes and $CP$ violation have to be considered and will be shown elsewhere.

Last but not the least, we would like to say that the solution presented here can be falsifiable when all the couplings of the 125 GeV Higgs boson with all the fermions are measured and they are found to be SM ones.

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FIG. 1: $Z'$ mass values satisfying Eq. (30) and Eq. (42), simultaneously, for a fixed value of the element $U_{\rho 1}$ ($U_{\eta 1}$), and the other $U_{\eta 1}$ ($U_{\rho 1}$) running in the range $[-1,1]$. 
FIG. 2: Same as Fig. 1 but now with $U_{\rho_1} = 0.38$ (the value that ensures that the coupling of $h_1^0$ with the top quark is equal to the SM), and $U_{\eta_1}$ running in the interval $[-1, 1]$. 
FIG. 3: Allowed region for $M_{Z'}$ and $U_{\eta 1}$, for fixed $U_{ee} = 0.1$ by the $K_L \rightarrow e e$ decay (using the Eq. (44) with $l = l' = e$ and $M = K$). The red (dashed) vertical line is the contribution of $Z'$ only, and the allowed range is to the right of the curve. The region within the blue (dashed) horizontal lines is the allowed region for the scalar contribution only. The total contribution is given by the green (continuous) curve and the allowed region is the area within this curve.
FIG. 4: Same as Fig. 3 with $U_{ee} = 0.1$ red (continuous line), $U_{ee} = 0.5$ black (thin dashed) line and $U_{ee} = 1$ green (thick green) line. The allowed region is always to the right and bounded by the curves.
FIG. 5: Allowed region, to the right of the curves, for $M_{Z'}$ and $U_{\eta 1}$, for fixed $U_{\mu\mu} = 0.1$ from the $K_L \to \mu\mu$ decay. (using the Eq. (44) with $l = l' = \mu$ and $M = K$). The red (solid) vertical line is the contributions of the $Z'$ only. The blue (dashed) curved line is the total contribution to the decay.
FIG. 6: The allowed region for the $Z'$ mass and $U_{\eta 1}$ that simultaneously satisfy the Eqs. (30) and (42), for $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$ mass differences and the kaon and $B_s$ decays assuming $U_{ee} = 0.5$. However, as is shown in Fig. (4) $U_{ee}$ in the full interval $[-1, 1]$ are allowed. Note that the allowed region is always to the right and bounded by the curves.
FIG. 7: Blow up of the Fig. 6.