When Flavor Changing Interactions Meet Hadron Colliders

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We have witnessed some flavor anomalies appeared in the past years, and explanations based on extended gauge sectors are among the most popular solutions. These beyond the Standard Model (SM) theories often assume flavor changing interactions mediated by new vector bosons, but at the same time they could yield deviations from the SM in the $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$, $B^0_d - \bar{B}^0$, and $B^0_s - \bar{B}^0_s$ meson systems. Using up-to-date data on the mass difference of these meson systems, we derive lower mass bounds on vector mediators for two different parametrizations of the quark mixing matrices. Focusing on a well-motivated model, based on the fundamental representation of the weak SU(3) gauge group, we put our findings into perspective with current and future hadron colliders to conclude that meson mass systems can give rise to bounds much more stringent than those from high-energy colliders and that recent new physics interpretations of the $b \to s$ and $R(D^*)$ anomalies are disfavored.

I. INTRODUCTION

Since flavor-changing neutral current (FCNC) processes are forbidden at tree-level in the Standard Model (SM), they are very sensitive to new physics. For this reason, meson-antimeson mixing that belong to the class of flavor-changing neutral current (FCNC) processes are great laboratories for flavor changing interactions. Mesons systems are key to our understanding of the fundamental interactions, and continuously give rise to important results such as the recent measurement of mixing and CP violation in neutral charm mesons collected by the LHCb experiment [1]. FCNCs have historically been important to the development of SM. From the considerations of FCNC, the charm quark was predicted to accommodate the data that ruled out larger FCNC effects [2].

Analyzing the neutral kaon meson system, the value of charm mass was estimated [3]. Charged Kaon decays revealed that Parity and Charge operators are not conserved by weak interactions. Moreover, the $K^+\pi$ decay into pions has shown that CP is not preserved [4]. The SM with two fermion generations was not able to reproduce this decay because CP-violating interactions of quarks necessarily involve complex couplings. Those complex couplings, if introduced in a 2 x 2 mixing matrix are eliminated after rotation, leaving in the end a real 2 x 2 Cabibbo matrix. Kobayashi and Maskawa have concluded in 1973 that such complex terms would survive in the quark mixing matrix, if there are at least three generations. This fact was ignored for quite some time, until the discovery of the bottom quark in 1977 by Ledermann [5], which later hinted the existence of the top quark [6, 7]. Therefore, it is clear that

Figure 1. An illustration of how flavor eingestates of mesons lead to mass eigenstates of mesons with different masses. The mass difference in such systems of mixed mesons is at the core of our study.

mesons have played a crucial role in our understanding of the fundamental interactions. As they are made up of one quark and one antimatter quark. The antimatter state of a given meson is also comprised of a quark and one antimatter quark. For
instance, the $D_0$ meson consists of a charm quark and an up antiquark, whereas its antiparticle, the $\bar{D}_0$, is made of a charm antiquark and an up quark. In the quantum physics world, the meson $D_0$ particle can be itself and its antiparticle at once, leading to a quantum superposition of states, say $D_1$ and $D_2$, each with their own mass and their decay width $\Gamma_1$ and $\Gamma_2$ (See Fig 1). This superposition allows a continuous oscillation between the $D_0$ particle and its antiparticle. The mass difference, $m_{D_1} - m_{D_2}$, determines the frequency of oscillations, which is measured [8–10], and reported in terms of the dimensionless parameter $x = (m_{D_1} - m_{D_2})/\Gamma$, where $\Gamma$ is the average width, $(\Gamma_1 + \Gamma_2)/2$. Such an oscillation pattern is present in four well-known meson systems, namely $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$, $B^0_d - B^0_d$, and $B^0_s - B^0_s$. In the SM FCNC occurs at one-loop level via a $W$ boson exchange in a box-diagram, involving the Cabibbo–Kobayashi–Maskawa (CKM) matrix, and precisely for that reason, any new physics inducing flavor changing interactions are tightly constrained by the mesons systems aforementioned. The relevant quantity for our reasoning is the mass difference between these mesons where an excellent agreement between theory and measurements are found. In other words, one can use precise measurements on the mass difference of these mesons to constrain any new physics contribution to the mass differences. These mesons are comprised of different quark flavors, and consequently are sensitive to different entries of the CKM matrix. Therefore, the new physics reach for meson mixing systems relies on the parametrization used for the quark mixing matrices. In summary, a robust assessment of the new physics potential of flavor probes requires a control over the systematic errors [11–13]. In our work, we focus on the FCNC effects stemming from neutral vector bosons. A wealth of Abelian and non-Abelian extended gauge symmetries predict the existence of extra neutral gauge bosons [14]. One can parametrize these new physics contributions in terms of gauge couplings and the mediator mass [15], but we will concentrate our phenomenology on vector bosons arising from $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ gauge group, shortly referred to as 3-3-1 models [16–20], because models based on this gauge symmetry have been considered as a plausible explanation to the $b \rightarrow s$ and $R(D^*)$ anomalies [21–26].

**II. THE MODEL**

Our FCNC investigation is dedicated to models which are based on the $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ symmetry which promotes the SM $SU(2)_L$ gauge group to a $SU(3)_L$ one. There are several ways to arrange fermions in a $SU(3)_L$ triplet, and these multiple possibilities give rise to different 3-3-1 models [18, 33, 34, 67–71]. In this work, we will focus on two of the most popular models based on the 3-3-1 symmetry, namely the 3-3-1 model with right-handed neutrinos and the 3-3-1 model with heavy neutral fermion. These two particular models based on the 3-3-1 symmetry can accommodate dark matter and neutrino masses, which are the most convincing evidence for physics beyond the SM. That said, the lepton sector is arranged in the following representations under the $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ gauge group:

\[
f^a_L = \begin{pmatrix} \nu^a_L \\ e^a_L \\ (\nu^a_R)^{\alpha} \end{pmatrix} \sim (1, 3, -1/3), \quad e_R^a \sim (1, 1, -1),
\]

where $a = 1, 2, 3$.

Regarding the hadronic sector, gauge anomaly cancellation requires that the quark generations transform differently under $SU(3)_L$ group. The most simple way to accomplish that without invoking several exotic new fermions is by assuming that the first generation transforms as triplets under $SU(3)_L$, whereas the second and third ones as anti-triplets as follows,

\[
Q_{1L} = \begin{pmatrix} u_1 \\ d_1 \\ u_1^T \end{pmatrix}_L \sim (3, 3, 1/3),
\]

\[
u_{1R} \sim (3, 1, 2/3), \quad d_{1R} \sim (3, 1, -1/3), \quad u_{1R} \sim (3, 1, 2/3),
\]

\[
Q_{iL} = \begin{pmatrix} u_i \\ d_i \\ u_i^T \end{pmatrix}_L \sim (3, 3, 0),
\]

\[
u_{iR} \sim (3, 1, 2/3), \quad d_{iR} \sim (3, 1, -1/3), \quad d_{iR}' \sim (3, 1, -1/3),
\]

where $i = 2, 3$, with $q'$ being heavy exotic quarks with electric charges $Q(u_1') = 2/3$ and $Q(d_{2,3}') = -1/3$.

\[\text{(i)}\] We take into account the four relevant meson systems including updated measurements;

\[\text{(ii)}\] We consider two different parametrizations to assess the impact of systematic errors;

\[\text{(iii)}\] As the SM prediction agrees well with the data we enforce the new physics contribution to be within the reported experimental error bar;

\[\text{(iv)}\] We put our results into perspective with future hadron colliders;

\[\text{(v)}\] We investigate whether recent proposals based on the 3-3-1 symmetry, are consistent with meson mixings and collider bounds.

Our goal is to find lower mass bounds on the vector mediator, a $Z'$, which mediates flavor changing interactions. Consequently, our findings are relevant to 3-3-1 constructions that feature a similar neutral current with SM quarks [50–66].

Our work is structured as follows: in section II we revise the key ingredients of the 3-3-1 model under study; in section III we derive the 3-3-1 contribution to the mass difference of these mesons; in section IV we discuss the current and future hadron collider bounds; in section V we draw our conclusions.

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Fermion masses are generated through the spontaneous symmetry breaking mechanism governed by three scalar triplets. From a top-down approach, the scalar triplet \( \chi \) acquires a vacuum expectation value (vev) in the scale of the TeVs with,

\[
\langle \chi \rangle = \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix},
\]

breaking \( SU(3)_c \otimes U(1)_X \) down to \( SU(2)_L \otimes U(1)_Y \), thus generating masses for the additional gauge bosons and new fermions, namely the exotic quarks via the Yukawa Lagrangian,

\[
\mathcal{L}_{\text{yuk}}^X = \lambda_{1a} \bar{Q}_1 u_L^{aR} \chi + \lambda_{2i} \bar{Q}_i d_L^i \chi^* + H.c.,
\]

where \( \chi \sim (1, 3, -1/3) \).

Then the \( SU(2)_c \otimes U(1)_Y \) breaks into electromagnetism when two scalar triplets \( \rho, \eta \) get a vev as follows,

\[
\langle \rho \rangle = \begin{pmatrix} 0 \\ v_\rho \\ 0 \end{pmatrix}, \quad \langle \eta \rangle = \begin{pmatrix} v_\eta \\ 0 \\ 0 \end{pmatrix},
\]

yielding masses for the SM quarks and charged lepton masses through,

\[
\mathcal{L}_{\text{yuk}} = \lambda_{1a} \bar{Q}_1 u_L^{aR} \rho + \lambda_{2i} \bar{Q}_i d_L^i \rho^* + G_{ab} \bar{f}^b_i (f^a_i)^* \rho^* + G'_{ab} \bar{f}^b_i (f^a_i)^* \rho^* + \lambda_{4ia} \bar{Q}_1 d_L^i \eta^* + H.c.,
\]

Notice that the scalar triplets transform as \( \rho \sim (1, 3, 2/3) \) and \( \eta \sim (1, 3, -1/3) \). Furthermore, the third term in Eq. (6) gives rise to two mass degenerate neutrinos and a massless one. It is well-known that this neutrino mass pattern cannot reproduce the three mass differences observed in the neutrino oscillation data [72–74]. However, one can nicely solve this problem by adding a scalar sextet and realizing a type II seesaw mechanism, or adding three right-handed Majorana neutrinos to incorporate an inverse or linear seesaw [75, 76]. We emphasize that either way neutrino masses are generated, our reasoning concerning FCNC is left unchanged.

Besides the usual bilinear and quartic terms in the scalar potential, these scalars give rise to the term \(-\frac{f^2}{2} e^{3f} h_{ij} \rho_i \rho_j \chi_k\), where \( f \) is in principle a free parameter which has energy dimension. The main energy scale in our work is the energy scale at which the 3-3-1 symmetry is broken down to the SM one. Hence, it is natural to assume that \( f \sim v_\chi \). If this is the case, the scalars in the model are very heavy, much heavier than the \( Z' \) boson, and for this reason are not relevant to FCNC. One could, however, assume different values for \( f \) allowing the scalars lighter than the \( Z' \) as has been explored in [49]. We will not contemplate this possibility here.

Now we have reviewed the key aspects of the model for our reasoning, we will concentrate on the main source of flavor neutral current, namely the \( Z' \) gauge boson.

### III. FCNC IN THE 3-3-1

Flavor changing neutral current is a common feature in 3-3-1 models because gauge anomaly cancellation requires one of the fermion generations to transform differently than the others. This requirement naturally induces flavor changing neutral current once one rotates the quark flavors and introduces the CKM matrix. In other words, the \( Z' \) does not have universal couplings to quarks, and thus flavor changing interactions arise. This is key because the \( Z \) boson does not change flavor in the SM, conversely to the charged current mediated by the W boson. Flavor changing interactions in the SM model occur through the charged current. Thus flavor changing interactions induced by a \( W' \) would be swamped by numerous W boson interactions. Therefore, it is wise to investigate flavor changing interactions mediated by a neutral gauge boson, as they are not masked by a large SM effect.

As we have explained earlier, mesons mass systems are great laboratories to probe such flavor changing interactions. \( Z' \) gauge bosons, even heavy ones, can induce sizeable flavor transitions and thus impact the mass difference of meson systems [77–79], see Fig.2.

We point out the FCNC yielded by scalar fields are suppressed compared to those generated by \( Z' \) bosons because these scalars are much heavier than the \( Z' \) field, see [35, 51] and references therein. It has been shown in [35] that two neutral scalars can induce sizeable FCNC, but their masses go as \( m \sim v_\chi \), rendering them too heavy. Besides, their contribution to FCNC adds an extra systematic effect to the 3-3-1 prediction, which is the choice for the Yukawa couplings in the Yukawa lagrangian, and the choice for the parameters in the scalar potential involving the scalar fields. Therefore, there is no predictivity regarding neutral scalar contributions to FCNC. Anyway, this aspect has been explored in [49]. Lastly, as these fields are very heavy and with no clean collider signature, there is no interplay with collider physics.

Even if one evokes small couplings in the scalar potential, the scalar that mediates FCNC is naturally much heavier than the \( Z' \). Albeit, in principle, one can certainly fine-tune the couplings in the scalar potential and generate a charged scalar lighter than the \( Z' \) boson making the reasoning in [49] valid, but thus far, this has not been explicitly proven. Therefore, our phenomenology will be driven by the \( Z' \) field.

Anyway, after developing the covariant derivative, we find the following currents,

\[
\mathcal{L}_{u'}^{Z'} = \frac{g}{2C_W} \left( \frac{3 - 4S_W^2}{3 \sqrt{3} - 4S_W^2} \right) [ \bar{u}_{aL} \gamma_{\mu} u_{aL} ] Z'_{\mu},
\]

\[
\mathcal{L}_{d'}^{Z'} = \frac{g}{2C_W} \left( \frac{3 - 4S_W^2}{3 \sqrt{3} - 4S_W^2} \right) [ \bar{d}_{aL} \gamma_{\mu} d_{aL} ] Z'_{\mu},
\]

\[
\mathcal{L}_{u'}^{Z'} = -\frac{g}{2C_W} \left( \frac{3 - 4S_W^2}{3 \sqrt{3} - 4S_W^2} \right) [ \bar{u}_{aL} \gamma_{\mu} u_{aL} ] Z'_{\mu},
\]

\[
\mathcal{L}_{d'}^{Z'} = -\frac{g}{2C_W} \left( \frac{3 - 4S_W^2}{3 \sqrt{3} - 4S_W^2} \right) [ \bar{d}_{aL} \gamma_{\mu} d_{aL} ] Z'_{\mu}.
\]
with \( a = 1, 2, 3 \), i.e., running through the three fermion generations. Note that Eqs. (7) and (8) are in the mass eigenstate basis, and once we rotate to the flavor basis FCNC arise. The mass eigenstate and flavor bases are connected as follows,

\[
\begin{pmatrix}
  u \\
  c \\
  t
\end{pmatrix}_{L,R} = V^U_{L,R} \begin{pmatrix}
  u' \\
  c' \\
  t'
\end{pmatrix}_{L,R}, \quad \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}_{L,R} = V^D_{L,R} \begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}_{L,R},
\]

where \( V^U_{L,R} \) and \( V^D_{L,R} \) are \( 3 \times 3 \) unitary matrices, which determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix \( V_{CKM} = V^U_L V^D_L \), known to be [80]

\[
V_{CKM} = \begin{pmatrix}
  0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\
  0.22486 \pm 0.00067 & 0.97349 \pm 0.0016 & 0.04182 \pm 0.00074 \\
  0.00857 \pm 0.00020 & 0.04110 \pm 0.00083 & 0.999118 \pm 0.000036
\end{pmatrix}
\]

Anyway, after rotation, we get the tree level \( Z' \) mediated neutral current interactions,

\[
\mathcal{L}_{Z'}^{K_0 - \bar{K}_0} = \mathcal{L}_{Z'}^{D_0 - \bar{D}_0} = \mathcal{L}_{Z'}^{B_0 - \bar{B}_0} = \mathcal{L}_{Z'}^{B_s - \bar{B}_s} = \Lambda \frac{M^2_{Z'}}{M^2_{Z'}} \left( |(V^D_{L})_{31}^* (V^D_{L})_{32}|^2 d^c_{1L} \gamma_\mu d^c_{2L} |^2, \right.
\]

and consequently [81–83],

\[
\begin{align*}
(\Delta m_K)_{Z'} &= \Lambda \frac{M^2_{Z'}}{M^2_{Z'}} \left( |(V^D_{L})_{31}^* (V^D_{L})_{32}|^2 f^2_K B_K \eta_K m_K, \right. \\
(\Delta m_D)_{Z'} &= \Lambda \frac{M^2_{Z'}}{M^2_{Z'}} \left( |(V^U_{L})_{31}^* (V^U_{L})_{32}|^2 f^2_D B_D \eta_D m_D, \right. \\
(\Delta m_{B_s})_{Z'} &= \Lambda \frac{M^2_{Z'}}{M^2_{Z'}} \left( |(V^D_{L})_{31}^* (V^D_{L})_{33}|^2 f^2_{B_s} B_{B_s} \eta_{B_s} m_{B_s}, \right. \\
(\Delta m_{B_d})_{Z'} &= \Lambda \frac{M^2_{Z'}}{M^2_{Z'}} \left( |(V^D_{L})_{32}^* (V^D_{L})_{33}|^2 f^2_{B_d} B_{B_d} \eta_{B_d} m_{B_d}. \right.
\end{align*}
\]

where \( \Lambda = \frac{4\sqrt{2}G_F}{3-4\alpha_W} \), with \( G_F \) being the Fermi constant, \( B_K, B_D, B_B \) the bag parameters, \( f_K, f_D, f_B \) the decay constants, and \( \eta_K, \eta_D, \eta_B \) the QCD leading order correction obtained in [25, 77–79, 84–86], and \( m_K, m_D, m_B, m_{B_s}, m_{B_d} \) the masses of the \( \tau \) in Table I we summarize the values of these parameters.

Our reasoning to constrain new physics contributions to the mass mixing systems goes as follows:

- (i) The experimental mass difference of the \( K_0 - \bar{K}_0 \) system is given by \( (\Delta m_K)_{exp} \).
- (ii) The SM prediction \( (\Delta m_K)_{SM} \) has a good agreement with the experimental, but errors are not included in the SM prediction. We find different values for the SM contribution in the literature;
- (iii) Therefore, instead of imposing \( (\Delta m_K)_{SM} + (\Delta m_K)_{Z'} < (\Delta m_K)_{exp} \) as done in previous works [38, 77–79], we enforce the \( Z' \) contribution to be smaller than the statistical error bar Table I. In this way, our conclusions are less sensitive to theoretical uncertainties and are driven by experimental measurements.
- (iv) We follow the same strategy for all four meson systems.
- (v) In summary, we impose,

\[
\begin{align*}
(\Delta m_K)_{Z'} &< 0.006 \times 10^{-12} \text{MeV} \\
(\Delta m_D)_{Z'} &< 2.69 \times 10^{-12} \text{MeV} \\
(\Delta m_{B_d})_{Z'} &< 0.013 \times 10^{-10} \text{MeV} \\
(\Delta m_{B_s})_{Z'} &< 0.0013 \times 10^{-8} \text{MeV}
\end{align*}
\]

We remind the reader that that \( Z' \) boson mediates FCNC at tree-level through Eq. (10) and for this reason, we will be able to severely constrain the mass of this particle. An advantage of working in the scope of a 3-3-1 model is the fact that \( Z' \) boson couples to SM fields proportional to the \( SU(2)_L \) gauge coupling. The only unknown quantities are the mixing matrices and the \( Z' \) mass.

We will assume two different parametrizations of the mixing matrices that yield significant changes in the new physics contribution to the mass difference systems. In this way, we can assess the impact that such parametrizations. We adopt parametrization I,

\[
V^D_L = V^D_R = \begin{pmatrix}
  0.972 & 0.5 & 0.46 \\
  0.45 & 1.00 & 0.88 \\
  0.1 & 0.1 & 1.01
\end{pmatrix}
\]
\[ (\Delta m_K)_{\text{exp}} = (3.483 \pm 0.013) \times 10^{-12} \text{ MeV} \]

\[ (\Delta m_K)_{\text{SM}} = 3.483 \times 10^{-12} \text{ MeV} \]

\[ m_K = 497.611 \pm 0.013 \text{ MeV} \]

\[ \sqrt{B_{K^0}f_K} = 131 \text{ MeV} \]

\[ \eta_K = 0.57 \]

\[ (\Delta m_D)_{\text{exp}} = (6.25316 \pm 0.2968) \times 10^{-12} \text{ MeV} \]

\[ (\Delta m_D)_{\text{SM}} = 10^{-14} \text{ MeV} \]

\[ m_D = 1865 \pm 0.005 \text{ MeV} \]

\[ \sqrt{B_{D^0}f_D} = 187 \text{ MeV} \]

\[ \eta_D = 0.57 \]

\[ (\Delta m_{B_s})_{\text{exp}} = (3.334 \pm 0.013) \times 10^{-10} \text{ MeV} \]

\[ (\Delta m_{B_s})_{\text{SM}} = (3.653 \pm 0.037 \pm 0.019) \times 10^{-10} \text{ MeV} \]

\[ m_{B_s} = (5279.65 \pm 0.12) \text{ MeV} \]

\[ \sqrt{B_{B_s}f_{B_s}} = 210.6 \text{ MeV} \]

\[ \eta_{B_s} = 0.55 \]

\[ (\Delta m_{B_d})_{\text{exp}} = (1.1683 \pm 0.0013) \times 10^{-8} \text{ MeV} \]

\[ (\Delta m_{B_d})_{\text{SM}} = (1.1577 \pm 0.022 \pm 0.051) \times 10^{-8} \text{ MeV} \]

\[ m_{B_d} = (5366.9 \pm 0.12) \text{ MeV} \]

\[ \sqrt{B_{B_d}f_{B_d}} = 256.1 \text{ MeV} \]

\[ \eta_{B_d} = 0.55 \]

Table I. Meson masses [10, 90–95] and of the bag parameters [80, 95].

and,

\[ V_L^U = V_R^U = \begin{pmatrix} 1.15614106 & -0.21661919 & -0.0893685 \\ -0.34952808 & 1.16542879 & -0.03937631 \\ -0.04500318 & -0.89069325 & 1.08186895 \end{pmatrix} \]

and parametrization 2,

\[ V_L^D = V_R^D = \begin{pmatrix} 0.972 & 0.5 & 0.46 \\ 0.45 & 1.00 & 0.88 \\ 0.01 & 0.1 & 1.01 \end{pmatrix} \]

and,

\[ V_L^U = V_R^U = \begin{pmatrix} 1.15671629 & -0.19797143 & -0.1108533 \\ -0.35262286 & 1.06510228 & 0.07621364 \\ -0.04263796 & -0.81401749 & 0.99352792 \end{pmatrix} \]

Knowing the entries of the up-quark and down-quark mixing matrices \( V_L^U \) and \( V_L^D \), we determine the \( Z' \) contribution to the mass difference of the meson systems and consequently place a lower mass bound. We adopt these parametrizations because they yield the strongest and weakest 3-3-1 contributions to FCNC processes respectively while keeping the CKM matrix in agreement with the data. With this information at hand we use Eq.(10) combined with Eq.(11) to plot our findings in Figs.(3)-(6).

Before discussing our results, it is important to put them into context with current and future collider bounds. To do so, we address those limits below.

### IV. DILEPTON RESONANCE SEARCHES AT THE LHC

\( Z' \) gauge bosons are often targets of experimental searches going from low to the multi-TeV mass range [96–99]. In the TeV range, which is the focus of our study, \( Z' \) gauge bosons that feature sizeable couplings to fermions can leave a clear signature at the LHC in the form of dijet and dilepton events. In the 3-3-1 model, the \( Z' \) has similar couplings to quarks and leptons. As dilepton events have relatively good signal efficiencies and acceptance and a well-controlled background originating primarily from Drell-Yann processes [98, 100, 101], tighter constraints on the \( Z' \) mass are found compared to dijet events. There have been experimental searches for \( Z' \) gauge bosons belonging to the 3-3-1 symmetry in the past [102, 103]. The most recent analysis taking advantage of the full dataset from LHC was carried out in [104]. We consider the most conservative bounds, which is the third benchmark scenario presented in Table IV of [104]. The LHC bound was based on an integrated luminosity of \( \mathcal{L} = 319 fb^{-1} \) with \( \sqrt{s} = 13 \text{ TeV} \), whereas for the High-Luminosity LHC setup \( \mathcal{L} = 3000 fb^{-1} \) with \( \sqrt{s} = 14 \text{ TeV} \). For the High-Energy LHC the latter luminosity was adopted, but using \( \sqrt{s} = 27 \text{ TeV} \).

- \( M_{Z'} \geq 4 \text{ TeV} \), LHC 13TeV
- \( M_{Z'} \geq 5.6 \text{ TeV} \), HL-LHC 14TeV
- \( M_{Z'} \geq 9.6 \text{ TeV} \), HE-LHC 27TeV

These limits are exhibited in Figs.(3)-(6). We have gathered enough information to discuss our results.

As for the \( K^0 - \bar{K}^0 \) system, the results are summarized in Fig.(3). The gray region corresponds to the region in which the \( Z' \) contribution exceeds the experimental error (see Eq.(11)). One can see that the parametrizations one and two give rise to distinct bounds on the \( Z' \) mass. Adopting parametrization 1 we find \( m_{Z'} > 113 \text{ TeV} \), whereas using

![Figure 3](image-url)
parametrization 2 we get \( m_{Z'} > 108 \text{ GeV} \). We superimposed the LHC 13\text{ TeV} bound as well as projections for the HL-LHC, HE-LHC.

Regarding \( D^0 - \bar{D}^0 \) system, we get \( m_{Z'} > 59 \text{ TeV} \) for parametrization 1, and parametrization 2 we get \( m_{Z'} > 51 \text{ TeV} \). We superimposed the LHC 13\text{ TeV} bound as well as projections for the HL-LHC, HE-LHC.

As for the \( B^0_s - \bar{B}^0_s \) system, we obtain \( m_{Z'} > 154 \text{ TeV} \) for parametrization 1, and parametrization 2 we get \( m_{Z'} > 127 \text{ GeV} \).

Lastly, for the \( B^0_d - \bar{B}^0_d \) system, we find \( m_{Z'} > 400 \text{ TeV} \) for both parametrizations.

VI. FLAVOR ANOMALIES

A. \( b \to s \) transitions

The \( b \to s \) transitions not consistent with the SM predictions have been observed in the LHCb data [106–110], which has triggered a multitude of new physics studies in the context of \( Z' \) models. Some of them which are of interest to us reside on the \( SU(3)_C \times SU(3)_L \times U(1)_N \) gauge group. It is true that there are several ways to arrange the fermion content under this gauge symmetry, and these arrangements have an impact on the precise neutral current mediated by \( Z' \) boson. How-
ever, the impact is minimum as far as collider physics goes. If there are new exotic fermions that couple to the $Z'$ boson and are sufficiently light, the collider limits based on dilepton searches will be weakened due to the presence of a new and significant decay mode. Besides collider physics, the mass difference of the four meson systems investigate also place a bound on the $Z'$ mass. That said, we will assess whether these interpretations to explain the $b \rightarrow s$ anomaly are indeed viable.

In [23] the authors considered a model similar to ours but with five lepton generations. The SM quarks possess the same quantum numbers as ours. If the exotic leptons in [23] are sufficiently have to not contribute to the $Z'$ decay width, the collider limits aforementioned are also applicable. In order to fit the $b \rightarrow sll$ anomaly, according to the recent global fits one needs $C^u_{10} = -C^d_{10} \simeq -0.6$. In [23] however, two quantities are important $r_{B_0}$ and $C^u_9$, with the former controlling the bound from the $B_s$ mixing and the latter the $b \rightarrow sll$ anomaly. The 3-3-1 model could explain the LHCb anomaly without being excluded by $B_s$ mixing if $C^u_{10} = -C^d_{10} \simeq -0.6$ and $r_{B_0} \simeq 0.1$. However, $r_{B_0}$ = $347 \times 10^3 (m_W/m_Z)^2 d^2$, and $C^u_9 = 11.3 \times 10^3 (m_W/m_Z)^2 d$, where $d = -0.005$ is a parameter that depends on the entries of the quark mixing matrices relevant for $B_s$ mixing. This value was assigned to obey the current bound. Given the current LHC bound on the $Z'$ mass, $\sim 4$ TeV, one cannot explain the LHCb anomaly. We emphasize that this 4 TeV bound relies on the assumption that there are no extra decay modes besides the usual 3-3-1 field content. Hence, a way to circumvent our conclusion is allowing the extra leptons added in [23] to be sufficiently light to decrease the $Z'$ branching ratio into charged leptons and consequently weaken the LHC bound. This is a non-trivial task knowing that these leptons are chiral leptons, thus can be produced via SM gauge bosons at colliders, and consequently are subject to strong collider bounds [111–118].

In [26] the authors investigated a similar 3-3-1 model, and advocated that existing collider bounds on the $Z'$ gauge boson belonging to 3-3-1 model could be significantly lowered if all $Z'$ decay channels modes are included. The possible 3-3-1 decay channels have already been included in [104]. Once more, a weakening of the LHC bound would require the chiral leptons introduced in [26] to be sufficiently light. Our reason to disfavor this possibility was mentioned above.

### B. $R(D^*)$ Anomaly

In [24] the authors considered an exotic field content based on the 3-3-1 symmetry, and focused on the charged higgs contribution to the semileptonic B-meson decay, particularly on $R(D^*)$ the anomaly reported by BABAR, Belle and LHCb. However, the authors argue that they can take the charged higgs mass below $1$ TeV, while keeping the gauge boson masses at sufficiently high scales. It has been shown that despite being a scalar, its mass it naturally predicted to be around the energy scale at which the 3-3-1 symmetry is spontaneously broken, unless very ones invokes a fine-tuning in the scalar parameters [49]. In other words, the mass of the charged scalar is around $\chi$. Therefore, given the collider bounds, and the FCNC bounds we derived, the proposed 3-3-1 explanation to the $R(D^*)$ anomaly is disfavored.

### VII. CONCLUSIONS

We have studied FCNC in a 3-3-1 model using the four meson systems, namely $K^0 - K^0$, $D^0 - \bar{D}^0$, $B^0_d - \bar{B}^0_d$, and $B^0_s - \bar{B}^0_s$. We derived lower mass bounds that range from 280 GeV up to 276 TeV using different parametrizations of the quark mixing matrices to solidly show that constraints stemming from FCNC are subject to large systematic uncertainties. We have shown that a robust assessment of FCNC should consider the four mesons systems, because specific parametrizations of the quark mixing matrices can suppress new physics effects at one of the mesons systems. However, as the CKM matrix should be preserved, these parametrizations tend to enhance FCNC effects on the other mesons. We carried out study based on the $Z'$ contributions to FCNC, as the scalars are typically much heavier than the $Z'$ field, their corrections to FCNC are subdominant. Considering only gauge interactions the systematics effects already drive the new physics sensitivity, let alone the scalar fields whose contributions depend on arbitrary choices of the Yukawa couplings and scalar potential parameters. In summary, a broader view of FCNC is needed before drawing conclusions. Lastly, we argued that recent anomalies in $b \rightarrow s$ and $R(D^*)$ transitions are disfavored in light of recent collider bounds.

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