Constraining Flavor Changing Interactions from LHC Run-2
dilepton Bounds with Vector Mediators

Farinaldo S. Queiroz, Clarissa Siqueira, and José W. F. Valle

1 Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
2 Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58051-970, João Pessoa - PB, Brazil
AHEP Group, Instituto de Física Corpuscular C.S.I.C./Universitat de Valencia Edificio de Institutos de Paterna, C/Catedrático José Beltrán, 2 E-46980 Paterna (Valencia) - SPAIN

Within the context of vector mediators, is a new signal observed in flavor changing interactions, particularly in the neutral mesons systems \(K^0 - \bar{K}^0\), \(D^0 - \bar{D}^0\) and \(B^0 - \bar{B}^0\), consistent with dilepton resonance searches at the LHC? In the attempt to address this very simple question, we discuss the complementarity between flavor changing neutral current (FCNC) and dilepton resonance searches at the LHC run 2 at 13 TeV with 3.2 fb\(^{-1}\) of integrated luminosity, in the context of vector mediators at tree level. Vector mediators, are often studied in the flavor changing framework, specially in the light of the recent LHCb anomaly observed at the rare B decay. However, the existence of stringent dilepton bound severely constrains flavor changing interactions, due to restrictive limits on the \(Z'\) mass. We discuss this interplay explicitly in the well motivated framework of a 3-3-1 scheme, where fermions and scalars are arranged in the fundamental representation of the weak SU(3) gauge group. Due to the paucity of relevant parameters, we conclude that dilepton data leave little room for a possible new physics signal stemming from these systems, unless a very peculiar texture parametrization is used in the diagonalization of the CKM matrix. In other words, if a signal is observed in such flavor changing interactions, it unlikely comes from a 3-3-1 model.

I. INTRODUCTION

The Standard Model (SM) has passed all precision tests thus far, and it is the best description of nature. Although, we need physics beyond the standard model so as to account for neutrino masses and dark matter. Many models that address these puzzles are plagued by flavor changing neutral current (FCNC) processes, which are, however, absent in the SM at tree-level, thanks to the GIM mechanism. Therefore, precise measurement of flavor transition processes, such as those from neutral meson oscillations, \(K^0 - \bar{K}^0\), \(D^0 - \bar{D}^0\) and \(B^0 - \bar{B}^0\), which are forbidden in the SM at tree level, provide an excellent laboratory to test new physics models, due to lack of standard model background. Conversely, flavor changing charged currents, are overwhelmed by numerous W boson processes.

That said, flavor changing neutral currents are often examined in the context of neutral vector gauge boson, \(Z'\). A multitude of Abelian and non-Abelian models predict the existence of extra neutral gauge bosons. Generally speaking they provide a straightforward cross-correlation among observables, such as FCNC and \(Z'\) at the LHC. Simplified models have become powerful tools in this endeavor, since they capture the main features of UV-complete models. However, at the end of the day one needs a full theory to draw conclusive statements. In this attempt, we will address the complementarity between flavor changing neutral currents and dilepton resonance searches at the LHC, which refers to those with charged lepton pairs in the final state, in the context of electroweak extensions of the SM, based on the \(SU(3)_c \otimes SU(3)_L \otimes U(1)_N\) gauge group, shortly referred as 3-3-1 models.

3-3-1 models are self-consistent if there exists only three generations due to the combined effect of triangle gauge anomalies cancellations and QCD asymptotic freedom. Moreover, the model furnishes a suitable environment for neutrino masses through see-saw mechanisms, explaining the strong CP problem in the quark sector, first-order phase transitions, lepton number violation processes, and several others. 3-3-1 models are burden with FCNC interactions and they naturally arise at tree level in 331 model because one of the generations has to transform differently from the other two, breaking the universality and leading to flavor changing interactions involving the new neutral gauge boson \(Z'\).

In principle, there are also other sources of FCNC in the model involving the CP-even and -odd neutral scalar, but those are suppressed.

In summary, in this work, we will investigate the degree of complementarity among flavor changing interactions and dilepton resonance searches at the LHC at 13 TeV with 3.2 fb\(^{-1}\) of integrated luminosity using ATLAS analysis, which are linked to the \(Z'\) boson. Due to the paucity of relevant parameters dictating the results of both observables, and the fact that other 3-3-1 models feature mild changes in the \(Z'\) interactions with SM quarks, we are able to draw general conclusions which are applicable to many 3-3-1 models.

The paper is structured as follows: In Sec. II we briefly discuss the key aspects of the model relevant for our rea-
where the spontaneous symmetry breaking mechanism three triplet bers. In order to generate the fermion masses through the demands that the first generation transforms as triplets as follows, where \( a = 1, 2, 3 \).

As for the hadronic sector, anomaly gauge cancellation demands that the first generation transforms as triplets under \( SU(3)_L \), whereas the second and third one as antitriplet as follows,

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

\[
u_1 \sim (3, 1, 2/3), \quad d_{1R} \sim (3, 1, 1/3), \quad v_1' \sim (3, 1, 2/3),
\]

\[
Q_{1L} = \begin{pmatrix} d_i \\ u_i \end{pmatrix} \sim (3, 3, 0),
\]

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

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

One can straightforwardly check that all gauge anomalies cancel with the above choice of gauge quantum numbers. In order to generate the fermion masses through the spontaneous symmetry breaking mechanism three triplet scalars are needed. From a top-down approach, the scalar triplet \( \chi \) with,

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

where \( v_\chi \) is the vacuum expectation value of the neutral scalar responsible for breaking \( SU(3)_c \otimes U(1)_X \) into \( SU(2)_L \otimes U(1)_Y \), gives rise to the exotic quark masses via the Yukawa Lagrangian,

\[
\mathcal{L}_{\text{yuk}}^\chi = \lambda_1 Q_{1L} u_1' R \chi + \lambda_{2ij} Q_{1L} d_{jR} \chi^* + H.c.,
\]

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

Then the \( SU(2) \otimes U(1)_Y \) breaks into electromagnetism when two triplets \( \rho, \eta \) acquire a vev with,

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

giving rise to quark and charged lepton masses through the Yukawa lagrangian,

\[
\mathcal{L}_{\text{yuk}} = \lambda_{1a} Q_{1L} d_{aR} \rho + \lambda_{3ia} Q_{1L} u_{aR} \rho^* + G_{ab} f_L^a (f_L^b)^* \rho^* \\
+ G_{ac} f_L^a c_{R}^* \eta + \lambda_{3ia} Q_{1L} u_{aR} \eta + \lambda_{4ia} Q_{1L} d_{aR} \eta^* + H.c.,
\]

with the scalar triplets transforming as \( \rho \sim (1, 3, 2/3) \) and \( \eta \sim (1, 3, -1/3) \). Moreover, the third term in Eq. \[8\] generates two degenerate masses to the neutrinos leaving one massless. This is problematic because one cannot explain the three mass differences observed in the neutrino oscillation data \[85\,87\]. There are ways to generate neutrino masses in agreement with data through effect effective operators \[88\,89\], or by adding extra scalar to incorporate an inverse seesaw mechanism \[90\,91\] with no prejudice to our reasoning which is concentrated on gauge interactions.

In this symmetry breaking pattern the 125 GeV higgs mass is easily achieved and the SM gauge boson masses correctly obtained with,

\[
M_{W^\pm}^2 = \frac{1}{4} g^2 v^2, \quad M_{Z^\pm}^2 = M_{W^\mp}/C_W^2, \\
M_{Z}^2 = \frac{g^2}{4(3 - 4S_W^2)} \left[ 4C_W^2 v_\chi^2 + \frac{v^2}{C_W^2} + \frac{1}{2} S_W^2 \right],
\]

\[
M_{Z}^2 = \frac{1}{4} g^2 (v_\chi^2 + v^2), \quad M_{U_{10}}^2 = \frac{1}{4} g^2 (v_\chi^2 + v^2),
\]

where \( Z^*, Y^\pm \) and \( U^{0}, U^{0\dagger} \) are new gauge bosons predicted by the model, with \( v^2 = v_\chi^2 + v_\eta^2 \). We have now highlighted the key features of the model relevant to our reasoning, thus it is a good timing to discuss the collider phenomenology.

III. DILEPTON RESONANCE SEARCHES AT THE LHC

Heavy dilepton resonance searches at the LHC (see Fig[1]) have proven to be an effective channel to probe
new physics models due to relatively good efficiencies/acceptance and well controlled background which comes mostly from Drell-Yann processes [92,94]. Using 8 TeV center-of-energy and 20 fb$^{-1}$ of integrated luminosity ATLAS collaboration has placed restrictive limits on the mass of gauge bosons arising in some new physics models [96], but an assessment particularly devoted to 3-3-1 models was performed in [97] ruling out $Z'$ masses below 2.65 TeV in the 3-3-1 model with right-handed neutrinos.

Here we take the dilepton results from LHC run II data at 13 TeV with $\mathcal{L} = 3.2$ fb$^{-1}$ [9], which has given rise to stringent limits on the $Z'$ mass of several models including the sequential standard model reading 3.4 TeV. For this type of analysis we have taken the background events using the results in [9]. The signal $pp \to Z' \to l^+l^-$, where $l = e,\mu$, was simulated using MadGraph5 [98,99] with the CTEQ6L parton distribution function [100] using efficiencies/acceptances described in [96].

Similarly to previous analysis we selected the signal events using the cuts,

- $E_T(e_1) > 30$ GeV, $E_T(e_2) > 30$ GeV, $|\eta_e| < 2.5$,
- $p_T(\mu_1) > 30$ GeV, $p_T(\mu_2) > 30$ GeV, $|\eta_\mu| < 2.5$,
- $500$ GeV $< M_{ll} < 6000$ GeV,

with $M_{ll}$ being the dilepton invariant mass.

These signals are peaked at the $Z'$ mass, thus one can use cuts the dilepton invariant mass to discriminate signal from background. In summary, since no excess of events has been observed we can re-interpret ATLAS results to derive a limit on the $Z'$ mass. Re-analyzing the ATLAS dilepton results we found $M_{Z'} > 3$ TeV. It is important to stress that this limit is robust due to the paucity of relevant parameter in the analysis, namely the gauge couplings, which are fixed by the gauge symmetry of the model. With this limit in mind we now obtain the 3-3-1 contribution to FCNC processes in what follows.

IV. FCNC IN THE 3-3-1

All mesons are unstable, with the longest-lived lasting for only a few hundredths of a microsecond. Although

no meson is stable, those of lower mass are nonetheless more stable than the most massive mesons, and are easier to observe in colliders. In particular the $K^0$ meson is a bound state composed of $d\bar{s}$, implying that kaons cannot be their own antiparticles. There must be then two different neutral kaons, differing by two units of strangeness, i.e. $K^0$ and $\bar{K}^0$ (see Fig. 2). The eigenstates which are obtained after mass diagonalization are known as Kaon long ($K_L$) and Kaon short ($K_S$) which yield opposite CP value, with $K_L$ decaying into three pions, and $K_S$ into two pions. Since $K_L$ is slightly heavier than three pion masses, its lifetime is much longer than the $K_S$. The physics of Kaon mixing is a explicit example of the importance of the CP symmetry in weak interactions. The mass difference of these mesons is precisely measured to be $(\Delta m_K) = 3.83 	imes 10^{-12}$ MeV. In a similar vein, the mesons $D^0$ made of $c\bar{u}$ and $\bar{B}_d^0$ composed of $d\bar{b}$ have mass difference $(\Delta m_D) = 4.607 \times 10^{-11}$ MeV, $m_{D_s} = 1865$ MeV and $(\Delta m_{B_s}) = 3.33 \times 10^{-10}$ MeV [101,102] (see Figs 3,4 and Table I). Hence, new physics FCNC processes which might yield sizeable contributions to the mass differences

\[\text{FIG. 1. Feynman diagram relevant for dilepton production at the LHC.}\]

\[\text{FIG. 2. Diagram contributing to } K^0 - \bar{K}^0 \text{ mass difference in the 3-3-1 model with right-handed neutrinos.}\]

\[\text{FIG. 3. Diagram contributing to } D^0 - \bar{D}^0 \text{ mass difference in the 3-3-1 model with right-handed neutrinos.}\]

\[\text{FIG. 4. Diagram contributing to } B_d^0 - \bar{B}_d^0 \text{ mass difference in the 3-3-1 model with right-handed neutrinos.}\]
above can be probed using these meson systems\footnote{See \cite{104,105} for relevant reviews.}. In the 3-3-1 model these FCNC processes that contribute to the mass difference of these meson systems surface through the neutral current mediated by $Z'$ gauge boson (scalar contributions are dwindled). That said, in order to derive the 3-3-1 corrections to these mass differences in a pedagogic way, we need first to derive the neutral current in the 3-3-1 model. As in the SM the $Z$ bosons does not mediated FCNC, only the $Z'$ does through,

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

$$
- \frac{g}{2C_W} \left( \frac{(3 - 4S_W^2)}{3\sqrt{3 - 4S_W^2}} \right) \left[ d_{aL} \gamma_{\mu} d_{aL} \right] Z_{\mu}^{d'}, \tag{8}
$$

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

$$
- \frac{g}{2C_W} \left( \frac{(3 - 4S_W^2)}{3\sqrt{3 - 4S_W^2}} \right) \left[ u_{aL} \gamma_{\mu} u_{aL} \right] Z_{\mu}^{u'}, \tag{9}
$$

with $a = 1, 2, 3$, i.e. running through the three generations. Notice that Eqs. (8) and (9) are in the mass-eigenstate basis, but we need to move to the flavor basis in order to connect to meson observables using the transformations,

$$
\begin{pmatrix} u \\ c \\ t \end{pmatrix}_{L,R} = U_{L,R} \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_{L,R}, \quad \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{L,R} = V_{L,R} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix},
$$

where the matrices $U_{L,R}$ and $V_{L,R}$ are $3 \times 3$ unitary and determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix with $V_{CKM} = (U_{L})^{\dagger}(V_{L})$. Using this transformations one can find\footnote{See \cite{104,105} for relevant reviews.} \cite{107,109}.\footnote{See \cite{104,105} for relevant reviews.}

$$
\mathcal{L}_{K_0-Z' eff}^{K_0-\bar{K}_0} = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \frac{M_Z^2}{M_{Z'}^2} \left| (V_L)_{31}^* (V_L)_{32} \right|^2 \left| d_{1L} \gamma_{\mu} d_{2L} \right|^2,
$$

$$
\mathcal{L}_{K_0-Z' eff}^{B_0-\bar{B}_0} = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \frac{M_Z^2}{M_{Z'}^2} \left| (U_L)_{31}^* (U_L)_{32} \right|^2 \left| u_{1L} \gamma_{\mu} u_{2L} \right|^2,
$$

$$
\mathcal{L}_{Z' eff}^{B_0-\bar{B}_0} = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \frac{M_Z^2}{M_{Z'}^2} \left| (V_L)_{31}^* (V_L)_{33} \right|^2 \left| d_{1L} \gamma_{\mu} d_{3L} \right|^2,
$$

and consequently,

$$
\Delta m_K = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \left| (V_L)_{31}^* (V_L)_{32} \right|^2 \left| f_K B_K \eta_K m_K \right|,
$$

$$
\Delta m_D = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \left| (U_L)_{31}^* (U_L)_{32} \right|^2 \left| f_D B_D \eta_D m_D \right|,
$$

$$
\Delta m_{B_0} = \frac{4\sqrt{2}G_FC_W^3}{3 - 4S_W^2} \left| (V_L)_{31}^* (V_L)_{33} \right|^2 \left| f_B B_B \eta_B m_B \right|,
$$

with $G_F$ being the Fermi constant, $S_W(C_W)$ the sine (cossine) of the Weinberg angle, and $B_K, B_D, B_B$ 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\footnote{See \cite{104,105} for relevant reviews.} \cite{104,105}. In Eqs. (8)-(12) $u_a = u, d, t$ and $d_a = d, s, b$ for $a = 1, 2, 3$ respectively, and $q'$ representing the flavor eigenstate of a given quark.

\textbf{Input parameters}

\begin{align*}
\Delta m_K &= 3.483 \times 10^{-12} \text{ MeV} \\
m_K &= 497.614 \text{ MeV} \\
\sqrt{\langle B_K f_K \rangle} &= 135 \text{ MeV} \\
\eta_K &= 0.57 \\
\Delta m_D &= 4.607 \times 10^{-12} \text{ MeV} \\
m_D &= 1865 \text{ MeV} \\
\sqrt{\langle B_D f_D \rangle} &= 187 \text{ MeV} \\
\eta_D &= 0.57 \\
\Delta m_{B_0} &= 3.33 \times 10^{-10} \text{ MeV} \\
m_{B_0} &= 5279.5 \text{ MeV} \\
\sqrt{\langle B_B f_B \rangle} &= 208 \text{ MeV} \\
\eta_B &= 0.55
\end{align*}

\textbf{TABLE I.} Limits on meson masses and numerical values for the bag parameters.

$$
V_{CKM} =
\begin{pmatrix}
0.97427_{\pm0.00014} & 0.22536_{\pm0.00061} & 0.00355_{\pm0.00015} \\
0.22522_{\pm0.00061} & 0.97343_{\pm0.00015} & 0.0414_{\pm0.0012} \\
0.00886_{\pm0.00033} & 0.0405_{\pm0.0011} & 0.99914_{\pm0.00005}
\end{pmatrix}
$$

Now to compute the theoretical prediction from the 3-3-1 model to the mass difference systems under study as a function of the $Z'$ mass, we simply need to plug into Eq.[12] the parameters summarized in Table[1] knowing the entries of the quark mixing matrices $V_L^u$ and $V_L^d$. These entries are bound by the CKM matrix (see Eq. [13]), which is reasonably well measured but the constraints on the individual entries of the matrices ($V_L^u$ and $V_L^d$) are loose\footnote{See \cite{104,105} for relevant reviews.}. Therefore, one can work on two possible regimes which we name as parametrization 1 and parametrization 2, which yield the strongest and weakest 3-3-1 contributions to FCNC processes respectively, while
keeping the CKM matrix intact. In the *parametrization 1*, we found,

\[
V_L = V_R = \begin{pmatrix}
0.97 & 0.23 & 0.0265598 \\
0.23 & 0.97 & 0.096 \\
0.043 & 0.089 & 0.995
\end{pmatrix}
\]

and,

\[
U_L = U_R = \begin{pmatrix}
0.89 & -0.45 & 0.00046 \\
-0.45 & -0.89 & 0.06 \\
0.0267 & 0.054 & 0.998
\end{pmatrix},
\]

whereas for the *parametrization 2* we found,

\[
V_L = V_R = \begin{pmatrix}
0.965666 & -0.268135 & 0.0265598 \\
-0.268135 & -0.968733 & 0.054013 \\
0.0003757 & 0.0521882 & 0.99845
\end{pmatrix}
\]

and,

\[
U_L = U_R = \begin{pmatrix}
0.877099 & -0.4759 & 0.0027058 \\
-0.4739 & -0.8723 & 0.0106513 \\
0.011237 & 0.020358 & 0.99999
\end{pmatrix}.
\]

In Fig. 5 we show the $\Delta m_{B_d} \times Z'$ mass for two different parametrizations of the quark mixing matrices. The pink region is excluded by constraints on $\Delta m_{B_d}$, whereas the shaded blue region indicates the exclusion limit on the $Z'$ mass coming from dilepton resonance searches at the LHC.

We have now collected all information needed to present the degree of complementarity between FCNC and dilepton searches at the LHC in the context of the vector mediator, $Z'$ taking into account the uncertainties in which such constraints are subject to.

In Fig. 6 we show the 3-3-1 contribution to $\Delta m_{B_d}$ for *parametrizations 1-2* as a function of the $Z'$ mass and we overlay in pink and blue the existing limits on the on the $B_d$ mass difference, and on the $Z'$ mass coming from dilepton resonance searches at the LHC. Only using *parametrization 1* meson physics gives rise to a limit stronger than LHC one on the $Z'$ mass. In other words, if in the near future a signal is observed in the $B_d$ system below the current limit, that would be consistent with LHC searches for a neutral vector boson. The 3-3-1 contribution to FCNC processes using *parametrization 2* is rather small, with LHC bound driving the limit on the $Z'$ mass.

Moreover, in Figs. 6 and 7 we see that the 3-3-1 corrections to the mass difference of the $K^0$ and $D^0$ mesons is quite dwindled. Thus LHC rules out any possibility for a possible signal in the foreseeable future coming from the 3-3-1 model, since the LHC limits on the $Z'$ mass is very stringent and robust, which reads $M_{Z'} > 3$ TeV. In other words, dilepton data from the LHC leaves basically no window for a possible FCNC signal in these systems to come from a 3-3-1 model unless a parametrization which...
enhances the 3-3-1 corrections to FCNC processes is advocated as it occurs in the parametrization 1 for the $B_d$ meson system.

V. CONCLUSION

We have investigated the degree of complementarity between FCNC in the neutral mesons systems $K^0 - K^0$, $D^0 - D^0$ and $B^0_d - B^0_d$ in the context of vector mediators, using the 3-3-1 model with right-handed neutrinos as framework. Our goal was to assess the possibility of explaining a possible FCNC signal in these systems having in mind the stringent limits stemming from dilepton resonance searches at the LHC. After briefly presenting the model we derived the 13 TeV LHC 3.2 fb$^{-1}$ limit on the $Z'$ mass which reads 3 TeV. Then we proceeded to the 3-3-1 corrections to the mass differences of the three mesons above. We found that the 3-3-1 contributes appreciably only the $B^0_d$ mass difference. Using two different parametrizations, one that enhances, parametrization 1 and other that suppresses parametrization 2 the 3-3-1 contribution to the latter, we concluded that bounds on the $Z'$ rising from dilepton resonance searches generally impose much stronger limits than FCNC ones. Conversely, a small window for a signal in the $B_d$ system exists if parametrization 1 is used. Therefore, if a FCNC signal is seen in these mesons systems in the foreseeable future, unless a parametrization very similar to parametrization 1 is advocated, the 3-3-1 model cannot offer a feasible solution.

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