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

Farinaldo S. Queiroz[1], Clarissa Siqueira[2], and José W. F. Valle[3*]
[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/Catedratico José Beltran, 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 $3.2\,\mathrm{fb}^{-1}$ 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 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 is 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. 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 [1] [1] 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 $B^0_d - \bar{B}^0_d$, 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 amongst observables, such as FCNC and resonance searches at the LHC. Simplified models have become powerful tools in this endeavor, since they capture the main features of UV–complete models [5–8]. 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 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 asympotic freedom [9–13]. Moreover, the model furnishes a suitable environment for neutrino masses through see-saw mechanisms [14–27], dark matter [28–44], explanation of the strong CP problem in the quark sector [45, 46], first-order phase transitions [47–49], lepton number violation processes [50–56], and several others [9, 57]. 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 [58].

That said, 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 [59], which are linked to the Z' boson. Due to the paucity of relevant parameters dictating the results of both observables, 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 reasoning; In Sec III, we obtain LHC bounds in the model using dilepton ATLAS 13 TeV data. In Sec. IV, we obtained FCNC stemming from the 3-3-1 model with right-

* queiroz@mpi-hd.mpg.de
[1] The concept of minimal flavor violation has guided us at how to suppress new physics interactions [2–4].

handed neutrinos and outline the region which a FCNC signal can be seen in agreement with LHC data.

II. THE MODEL

The $SU(3)_c \otimes SU(3)_L \otimes U(1)_N$ gauge symmetry means that the fermions can be placed in the fundamental representation of $SU(3)_L$, i.e triplets. In order to reproduce the SM spectrum the SM doublet should be enclosed. The third component in the model is arbitrary and can vary from neutrinos, heavy neutrino fermions and even exotic charged leptons, depending on the quantum number assignments. There are two ways to incorporate right-handed neutrinos in the model. One can either add three singlet right-handed neutrinos, or change the quantum numbers of the fermions in such way that right-handed neutrinos are embedded in the $SU(3)_L$ triplet. The latter scenario leads to an interesting and minimal model, which is the model we concentrate on, firstly presented in [60–62]. Thus the lepton sector is,

$$f^a_L = \begin{pmatrix} \nu^a_l \\ e^a_l \\ (\nu^c_R)^a \end{pmatrix} \sim (1,3,-1/3), e^a_R \sim (1,1,-1), \quad (1)$$

where a=1,2,3.

As for the hadronic sector, anomaly gauge cancellation demands that the first generation transform as triplets under $SU(3)_L$, whereas the second and third one as anti-triplet as follows,

$$\begin{aligned} &Q_{1L} = \begin{pmatrix} u_1 \\ d_1 \\ J_1 \end{pmatrix}_L \sim (3,3,2/3), \\ &u_{1R} \sim (3,1,2/3),\ d_{1R} \sim (3,1,-1/3),\ J_{1R} \sim (3,1,5/3), \\ &Q_{iL} = \begin{pmatrix} d_i \\ u_i \\ J_i \end{pmatrix}_L \sim (3,\bar{3},-1/3), \\ &u_{iR} \sim (3,1,2/3),\ d_{iR} \sim (3,1,-1/3), J_{iR} \sim (3,1,-4/3), \end{aligned} \quad (2)$$

where $i = 2,3$, with J_a being heavy exotic quarks with electric charges $Q(J_{1,2}) = 2/3$ and $Q(J_3) = -1/3$.

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 χ with,

$$\langle\chi\rangle = \begin{pmatrix} 0 \\ 0 \\ w \end{pmatrix}, \quad (3)$$

where w is the vacuum expectation value of the neutral scalar responsible for breaking $SU(3)_L \otimes U(1)_N$ into $SU(2)_L \otimes U(1)_Y$, give rises to the exotic quark masses via the Yukawa Lagrangian,

$$\mathcal{L}^{\chi}_{yuk} = \lambda_1 \bar{Q}_{1L} u^{'}_{1R} \chi + \lambda_{2ij} \bar{Q}_{iL} d^{'}_{jR} \chi^* + H.c., \quad (4)$$

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

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

$$\langle\rho\rangle = \begin{pmatrix} 0 \\ v_\rho \\ 0 \end{pmatrix},\ \langle\eta\rangle = \begin{pmatrix} v_\eta \\ 0 \\ 0 \end{pmatrix}, \quad (5)$$

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

$$\begin{aligned} \mathcal{L}_{Yuk} = &\lambda_{1a} \bar{Q}_{1L} d_{aR} \rho + \lambda_{2ia} \bar{Q}_{iL} u_{aR} \rho^* + G_{ab} \bar{f}^a_L (f^b_L)^c \rho^* \\ &+ G^{'}_{ab} \bar{f}^a_L e^b_R \rho + \lambda_{3a} \bar{Q}_{1L} u_{aR} \eta + \lambda_{4ia} \bar{Q}_{iL} d_{aR} \eta^* + H.c. \end{aligned} \quad (6)$$

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.6 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 [63–65]. There are ways to generate neutrino masses in agreement with data through effect effective operators [66, 67], or by adding extra scalar to incorporate an inverse seesaw mechanism [68, 69] with no prejudice to our reasoning which is concentrated in gauge interactions.

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

$$\begin{aligned} &M^2_{W^\pm} = \frac{1}{4} g^2 v^2\,,\ M^2_Z = M^2_{W^\pm}/C^2_W, \\ &M^2_{Z'} = \frac{g^2}{4(3-4S^2_W)} \left[4C^2_W v^2_{\chi'} + \frac{v^2}{C^2_W} + \frac{v^2(1-2S^2_W)^2}{C^2_W} \right], \\ &M^2_{V^\pm} = \frac{1}{4} g^2 (v^2_{\chi'} + v^2)\,,\ M^2_{U^0} = \frac{1}{4} g^2 (v^2_{\chi'} + v^2), \end{aligned} \quad (7)$$

where Z',$V^\pm$ and U^0, $U^{0\dagger}$ are new gauge bosons predicted by the model, with $v^2 = v^2_\rho + v^2_\eta$. We have now highlighted the key features of the model relevant, 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 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 [70–72] [2]. Using 8 TeV center-of-energy and $20fb^{-1}$ of integrated luminosity ATLAS collaboration has placed restrictive limits on the mass of gauge bosons arising in some new physics models [74], but an assessment particularly devoted to 3-3-1 models was performed in [75] 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} [59], 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 [59]. The signal $pp \to Z' \to l^+l^-$, where $l = e, \mu$, was simulated using MadGraph5 [76, 77] with the CTEQ6L parton distribution function [78] using efficiencies/acceptances described in [74].

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

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

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.

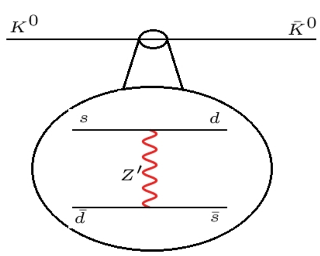

FIG. 1. Diagram contributing to $K^0 - \bar{K}^0$ mass difference in the 3-3-1 model with right-handed neutrinos.

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

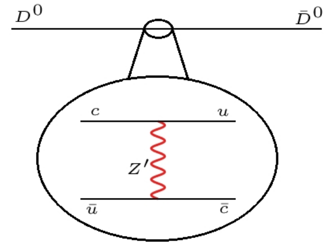

FIG. 2. Diagram contributing to $D^0 - \bar{D}^0$ mass difference in the 3-3-1 model with right-handed neutrinos.

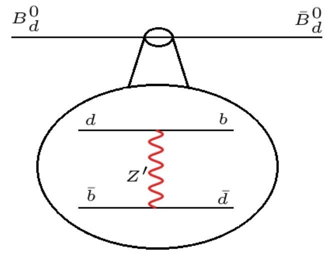

FIG. 3. Diagram contributing to $B_d^0 - \bar{B}_d^0$ mass difference in the 3-3-1 model with right-handed neutrinos.

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.1). 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. K_L has CP -1, thus decaying into three pions, whereas K_S CP $+1$, which decays 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 explicity example of the importance of the CP symmetry in weak interactions. Currently the mass difference of these mesons is measured to be $(\Delta m_K) = 3.483 \times 10^{-12}$ MeV. In a similar vein, the mesons D^0 made of $c\bar{u}$ and B_d^0 composed of $d\bar{b}$ have mass difference $(\Delta m_D) = 4.607 \times 10^{-11}$ MeV, $m_D = 1865$ MeV and $(\Delta m_{B_d}) = 3.33 \times 10^{-10}$ MeV [79–81]. Hence, FCNC processes can be constrained using the mass differences above [3]. In order to do so, 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,

$$\mathcal{L}_u^{Z'} = -\frac{g}{2C_W}\{\bar{u}_{3L}\gamma^\mu[\frac{(3-2S_W^2)}{3\sqrt{3-4S_W^2}}]u_{3L}\}Z'_\mu$$

[2] See [73] for an excellent review about LEP-II limits

[3] See [82–84] for relevant reviews.

$$+\frac{g}{2C_\omega}\{\bar{u}_{iL}\gamma^\mu[\frac{(3-4S_W^2)}{3\sqrt{3-4S_W^2}}]u_{iL}\}Z'_\mu, \qquad (8)$$

$$\mathcal{L}_d^{Z'} = -\frac{g}{2C_W}\{\bar{d}_{3L}\gamma^\mu[\frac{(3-2S_W^2)}{3\sqrt{3-4S_W^2}}]d_{3L}\}Z'_\mu$$
$$+\frac{g}{2C_W}\{\bar{d}_{iL}\gamma^\mu[\frac{(3-4S_W^2)}{3\sqrt{3-4S_W^2}}]d_{iL}\}Z'_\mu, \qquad (9)$$

with $i = 1, 2$, which results into,

$$\mathcal{L}_{Z'\,eff}^{K_0-\bar{K}_0} = \frac{4\sqrt{2}G_F C_W^4}{3-4s_W^2}\frac{M_Z^2}{M_{Z'}^2}|(V_L^d)^*_{31}(V_L^d)_{32}|^2|\bar{d}'_{1L}\gamma_\mu d'_{2L}|^2,$$
$$\mathcal{L}_{Z'\,eff}^{D_0-\bar{D}_0} = \frac{4\sqrt{2}G_F C_W^4}{3-44s_W^2}\frac{M_Z^2}{M_{Z'}^2}|(V_L^u)^*_{31}(V_L^u)_{32}|^2|\bar{u}'_{1L}\gamma_\mu u'_{2L}|^2,$$
$$\mathcal{L}_{Z'\,eff}^{B_d^0-\bar{B}_d^0} = \frac{4\sqrt{2}G_F C_W^4}{3-4s_W^2}\frac{M_Z^2}{M_{Z'}^2}|(V_L^d)^*_{31}(V_L^d)_{33}|^2|\bar{d}'_{1L}\gamma_\mu d'_{3L}|^2,$$
$$(10)$$

and consequently,

$$(\Delta m_K)_{Z'} = \frac{4\sqrt{2}G_F C_W^4}{(3-4s_W^2)}\frac{M_Z^2}{M_{Z'}^2}|(V_L^d)^*_{31}(V_L^d)_{32}|^2 f_K^2 B_K \eta_K m_K,$$
$$(\Delta m_D)_{Z'} = \frac{4\sqrt{2}G_F C_W^4}{3-44s_W^2}\frac{M_Z^2}{M_{Z'}^2}|(V_L^u)^*_{31}(V_L^u)_{32}|^2 f_D^2 B_D \eta_D m_D,$$
$$(\Delta m_B)_{Z'} = \frac{4\sqrt{2}G_F C_W^4}{3-4s_W^2}\frac{M_Z^2}{M_{Z'}^2}|(V_L^d)^*_{31}(V_L^d)_{33}|^2 f_B^2 B_B \eta_B m_B.$$
$$(11)$$

We emphasize that the Z' does mediate FCNC in the 3-3-1 model because the hadronic generations do not transform identically under $SU(3)_L$. In Eq.9-11 $u_i = u, d, t$ and $d_i = d, s, b$ for $i = 1, 2, 3$ respectively, and q' representing the flavor eigenstate of a given quark.

In order to compute the theoretical prediction from the 3-3-1 model based on Eq.11 we need to know the bag parameter (B), the decay constant (f), and η the QCD leading order correction. These parameter were obtained in [82–84]. In table I we summarize some of ingredients needed to obtain the new physics contribution to the mass difference systems under study as a function of the Z' mass. In addition to these parameters related to the QCD computations, one has to know the CKM entries of Eq.11. They are bound by the CKM matrix which is reasonably well measured, but the constraints on the individual entries of the matrices that diagionalize the quarks masses V_L^u and V_L^d are still not very tight. That said, we work in two regimes which we name as *parametrization 1* and *parametrization 2*, which yield as we shall see the strongest and weakest limits keeping the CKM matrix intact respectively. In the *parametrization 1*, we found,

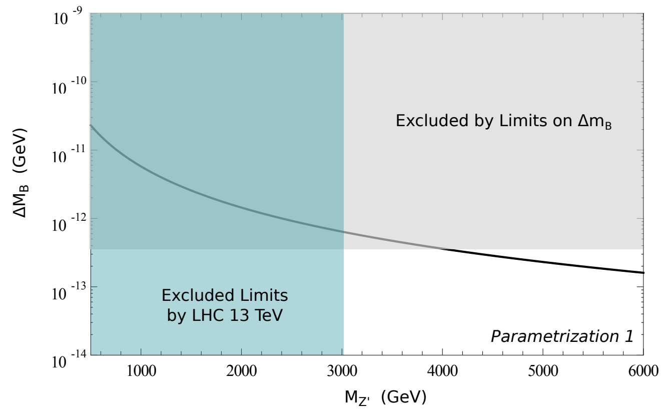

FIG. 4. $\Delta m_B \times Z'$ mass. The light gray region is excluded by constraints on Δm_b and the the shaded light-blue region indicate the exclusion limits on Z' mass.

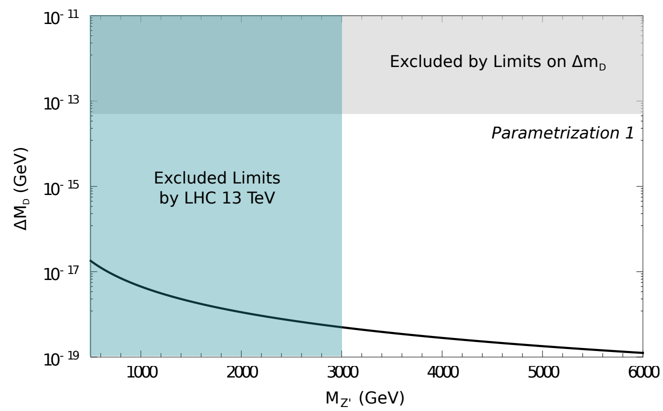

FIG. 5. $\Delta m_D \times Z'$ mass. The light gray region is excluded by constraints on Δm_D and the the shaded light-blue region indicate the exclusion limits on Z' mass.

$\Delta m_K = 3.483 \times 10^{-12}$ MeV
$m_K = 497.614$ MeV
$\sqrt{B_K} f_K = 135$ MeV
$\eta_K = 0.57$

$\Delta m_D = 4.607 \times 10^{-11}$ MeV
$m_D = 1865$ MeV
$\sqrt{B_D} f_D = 187$ MeV
$\eta_D = 0.57$

$\Delta m_{B_d} = 3.33 \times 10^{-10}$ MeV
$m_B = 5279.5$ MeV
$\sqrt{B_B} f_B = 208$ MeV
$\eta_K = 0.55$

$$V_{Ld} = V_{Rd} = \begin{pmatrix} 0.97 & 0.23 & 0.0265598 \\ 0.23 & 0.97 & 0.096 \\ 0.043 & 0.089 & 0.995 \end{pmatrix}$$

and,

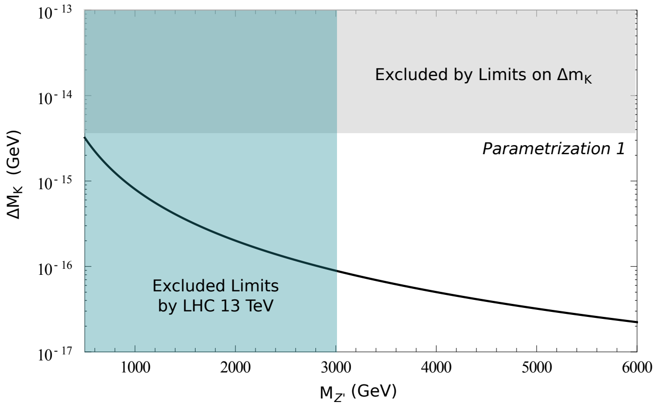

FIG. 6. $\Delta m_K \times Z'$ mass. The light gray region is excluded by constraints on Δm_K and the shaded light-blue region indicate the exclusion limits on Z' mass.

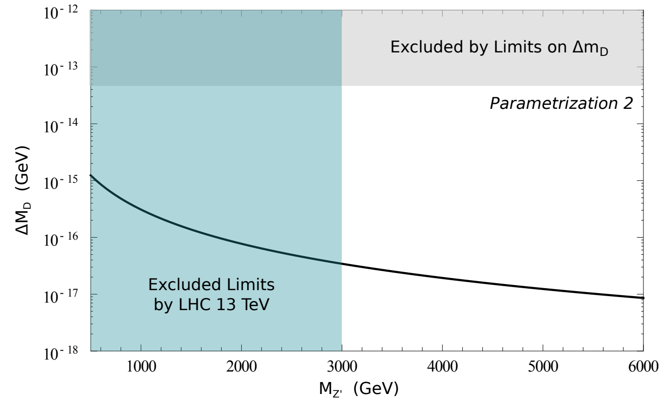

FIG. 8. $\Delta m_D \times Z'$ mass. The light gray region is excluded by constraints on Δm_D and the the shaded light-blue region indicate the exclusion limits on Z' mass.

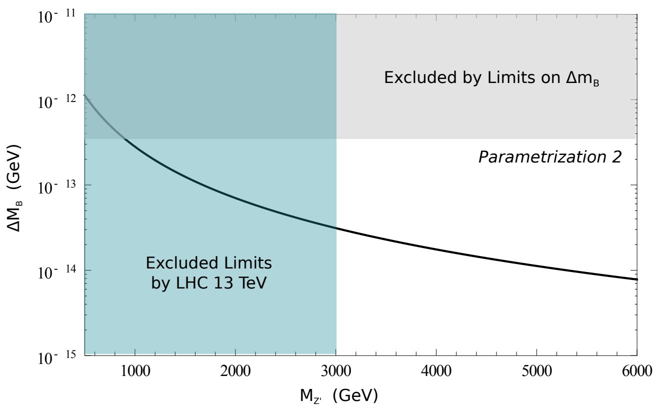

FIG. 7. $\Delta m_B \times Z'$ mass. The light gray region is excluded by constraints on Δm_b and the the shaded light-blue region indicate the exclusion limits on Z' mass.

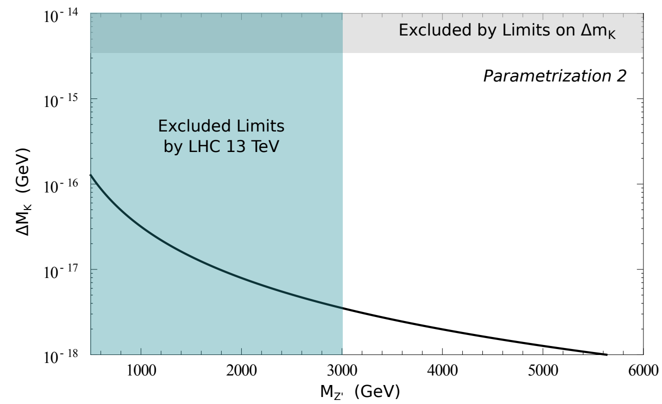

FIG. 9. $\Delta m_K \times Z'$ mass. The light gray region is excluded by constraints on Δm_K and the the shaded light-blue region indicate the exclusion limits on Z' mass.

$$V_{Lu} = V_{Ru} = \begin{pmatrix} 0.89 & -0.45 & 0.00046 \\ -0.45 & -0.89 & 0.06 \\ 0.0267 & 0.054 & 0.998 \end{pmatrix}.$$

whereas for the *parametrization 2* we found,

$$V_{Ld} = V_{Rd} = \begin{pmatrix} 0.965666 & -0.268135 & 0.0265598 \\ -0.268135 & -0.968733 & 0.054013 \\ 0.0003757 & 0.0521882 & 0.99845 \end{pmatrix}$$

and,

$$V_{Lu} = V_{Ru} = \begin{pmatrix} 0.877099 & -0.4759 & 0.00270598 \\ -0.4739 & -0.8723 & 0.0106513 \\ 0.011237 & 0.020358 & 0.99999 \end{pmatrix}.$$

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'. In Fig.4 using *parametrization 1* we show the 3-3-1 contribution to Δm_B as a function of the Z' mass and we overlay in gray and green the existing limits on the Z' mass coming from dilepton resonance searches and the observed limit on the B_d mass difference. Using this parametrization 1 is visible that the meson physics gives rise to a limit stronger than LHC 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. However, in Figs.5-6 we see that the 3-3-1 corrections to the mass difference of the K^0 and D^0 mesons is rather small clearly showing the LHC offers the best probe and a possible signal in any of these two systems would be excluded by the LHC data.

As an attempt to quantify the uncertainties in which such constrained are subject to, we now exhibit in Fig.7-9 the 3-3-1 contribution to the mass difference for all three meson systems using *parametrization 2*, which still reproduces the correct quark masses and CKM matrix. Notice that this time, the 3-3-1 correction is small to the point which 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. Thus, dilepton data 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 is advocated as it occurs in the *parametrization 1*.

V. CONCLUSION

We have investigated the degree of complementarity between FCNC in the neutral mesons systems $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$ and $B^0_d - \bar{B}^0_d$ 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 coming 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 1* the 3-3-1 contribution to the latter, we concluded that bounds on the Z' stemming from dilepton resonance searches impose much stronger limits, unless the parametrization 1 is used. In order words, if a signal 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 does not offer a feasible solution.

ACKNOWLEDGMENTS

This work is supported by the Spanish grants FPA2014-58183-P, Multidark CSD2009-00064, SEV-2014-0398 (MINECO) and PROMETEOII/2014/084 (GVA). CS acknowledges support from CNPq, Brazil. JV thanks Carlos Pires for hospitality at the Departamento de Física, Universidade Federal da Paraíba in João Pessoa, Brazil. FSQ thanks UFABC and the particle physics group for the hospitality during final stages of this project. FSQ is also specially grateful to Alex Dias and Vanidia Dias for their hospitality.

[1] S. L. Glashow, J. Iliopoulos, and L. Maiani, *Meeting of the Italian School of Physics and Weak Interactions Bologna, Italy, April 26-28, 1984*, Phys. Rev. **D2**, 1285 (1970).
[2] A. J. Buras, P. Gambino, M. Gorbahn, S. Jager, and L. Silvestrini, Phys. Lett. **B500**, 161 (2001), arXiv:hep-ph/0007085 [hep-ph].
[3] A. J. Buras, *Theoretical physics. Proceedings, 43rd Cracow School, Zakopane, Poland, May 30-June 8, 2003*, Acta Phys. Polon. **B34**, 5615 (2003), arXiv:hep-ph/0310208 [hep-ph].
[4] G. D'Ambrosio, G. F. Giudice, G. Isidori, and A. Strumia, Nucl. Phys. **B645**, 155 (2002), arXiv:hep-ph/0207036 [hep-ph].
[5] B. Allanach, F. S. Queiroz, A. Strumia, and S. Sun, (2015), arXiv:1511.07447 [hep-ph].
[6] A. Celis, W.-Z. Feng, and D. Lst, JHEP **02**, 007 (2016), arXiv:1512.02218 [hep-ph].
[7] G. Blanger and C. Delaunay, (2016), arXiv:1603.03333 [hep-ph].
[8] W. Altmannshofer, C.-Y. Chen, P. S. B. Dev, and A. Soni, (2016), arXiv:1607.06832 [hep-ph].
[9] M. Singer, J. W. F. Valle, and J. Schechter, Phys. Rev. **D22**, 738 (1980).
[10] F. Pisano and V. Pleitez, Phys. Rev. **D46**, 410 (1992), arXiv:hep-ph/9206242 [hep-ph].
[11] R. Foot, O. F. Hernandez, F. Pisano, and V. Pleitez, Phys. Rev. **D47**, 4158 (1993), arXiv:hep-ph/9207264 [hep-ph].
[12] J. C. Montero, F. Pisano, and V. Pleitez, Phys. Rev. **D47**, 2918 (1993), arXiv:hep-ph/9212271 [hep-ph].
[13] A. G. Dias and V. Pleitez, Phys. Rev. **D80**, 056007 (2009), arXiv:0908.2472 [hep-ph].
[14] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).
[15] P. Minkowski, Phys. Lett. **B67**, 421 (1977).
[16] J. Schechter and J. W. F. Valle, Phys. Rev. **D22**, 2227 (1980).
[17] R. N. Mohapatra and G. Senjanovic, Phys. Rev. **D23**, 165 (1981).
[18] G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. **B181**, 287 (1981).
[19] J. Schechter and J. W. F. Valle, Phys. Rev. **D25**, 774 (1982).
[20] W.-Y. Keung and G. Senjanovic, Phys. Rev. Lett. **50**, 1427 (1983).
[21] G. Senjanovic, Int. J. Mod. Phys. **A26**, 1469 (2011), arXiv:1012.4104 [hep-ph].
[22] D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle, JHEP **09**, 142 (2011), arXiv:1107.6009 [hep-ph].
[23] L. Dorame, S. Morisi, E. Peinado, J. W. F. Valle, and A. D. Rojas, Phys. Rev. **D86**, 056001 (2012), arXiv:1203.0155 [hep-ph].
[24] C.-Y. Chen, P. S. B. Dev, and R. N. Mohapatra, Phys. Rev. **D88**, 033014 (2013), arXiv:1306.2342 [hep-ph].
[25] S. M. Boucenna, S. Morisi, Q. Shafi, and J. W. F. Valle, Phys. Rev. **D90**, 055023 (2014), arXiv:1404.3198 [hep-ph].
[26] C. Bonilla, R. M. Fonseca, and J. W. F. Valle, Phys. Rev. **D92**, 075028 (2015), arXiv:1508.02323 [hep-ph].
[27] J. W. F. Valle and C. A. Vaquera-Araujo, Phys. Lett. **B755**, 363 (2016), arXiv:1601.05237 [hep-ph].
[28] C. A. de S. Pires and P. S. Rodrigues da Silva, JCAP **0712**, 012 (2007), arXiv:0710.2104 [hep-ph].
[29] J. K. Mizukoshi, C. A. de S. Pires, F. S. Queiroz, and P. S. Rodrigues da Silva, Phys. Rev. **D83**, 065024 (2011),

arXiv:1010.4097 [hep-ph].
[30] J. D. Ruiz-Alvarez, C. A. de S. Pires, F. S. Queiroz, D. Restrepo, and P. S. Rodrigues da Silva, Phys. Rev. **D86**, 075011 (2012), arXiv:1206.5779 [hep-ph].
[31] F. S. Queiroz, *Proceedings, Workshop on Dark Matter, Neutrino Physics and Astrophysics CETUP* 2013: 7th International Conference on Interconnection between Particle Physics and Cosmology (PPC 2013): Lead/Deadwood, South Dakota, USA, July, 8-13, 2013*, AIP Conf. Proc. **1604**, 83 (2014), arXiv:1310.3026 [astro-ph.CO].
[32] C. Kelso, C. A. de S. Pires, S. Profumo, F. S. Queiroz, and P. S. Rodrigues da Silva, Eur. Phys. J. **C74**, 2797 (2014), arXiv:1308.6630 [hep-ph].
[33] S. Profumo and F. S. Queiroz, Eur. Phys. J. **C74**, 2960 (2014), arXiv:1307.7802 [hep-ph].
[34] C. Kelso, H. N. Long, R. Martinez, and F. S. Queiroz, Phys. Rev. **D90**, 113011 (2014), arXiv:1408.6203 [hep-ph].
[35] P. V. Dong, N. T. K. Ngan, and D. V. Soa, Phys. Rev. **D90**, 075019 (2014), arXiv:1407.3839 [hep-ph].
[36] P. V. Dong, D. T. Huong, F. S. Queiroz, and N. T. Thuy, Phys. Rev. **D90**, 075021 (2014), arXiv:1405.2591 [hep-ph].
[37] D. Cogollo, A. X. Gonzalez-Morales, F. S. Queiroz, and P. R. Teles, JCAP **1411**, 002 (2014), arXiv:1402.3271 [hep-ph].
[38] R. Martnez, J. Nisperuza, F. Ochoa, and J. P. Rubio, Phys. Rev. **D90**, 095004 (2014), arXiv:1408.5153 [hep-ph].
[39] R. Martinez, J. Nisperuza, F. Ochoa, J. P. Rubio, and C. F. Sierra, Phys. Rev. **D92**, 035016 (2015), arXiv:1411.1641 [hep-ph].
[40] P. S. Rodrigues da Silva, (2014), arXiv:1412.8633 [hep-ph].
[41] P. V. Dong, C. S. Kim, D. V. Soa, and N. T. Thuy, Phys. Rev. **D91**, 115019 (2015), arXiv:1501.04385 [hep-ph].
[42] R. Martinez and F. Ochoa, JHEP **05**, 113 (2016), arXiv:1512.04128 [hep-ph].
[43] D. T. Huong and P. V. Dong, (2016), arXiv:1605.01216 [hep-ph].
[44] C. A. de S. Pires, P. S. Rodrigues da Silva, A. C. O. Santos, and C. Siqueira, (2016), arXiv:1606.01853 [hep-ph].
[45] A. G. Dias, V. Pleitez, and M. D. Tonasse, Phys. Rev. **D67**, 095008 (2003), arXiv:hep-ph/0211107 [hep-ph].
[46] A. G. Dias and V. Pleitez, Phys. Rev. **D69**, 077702 (2004), arXiv:hep-ph/0308037 [hep-ph].
[47] V. Q. Phong, H. N. Long, V. T. Van, and N. C. Thanh, Phys. Rev. **D90**, 085019 (2014), arXiv:1408.5657 [hep-ph].
[48] V. Q. Phong, H. N. Long, V. T. Van, and L. H. Minh, Eur. Phys. J. **C75**, 342 (2015), arXiv:1409.0750 [hep-ph].
[49] H. N. Long, (2015), 10.3844/pisp.2016.1.14, arXiv:1501.01852 [hep-ph].
[50] A. Palcu, Mod. Phys. Lett. **A22**, 939 (2007), arXiv:hep-ph/0701066 [hep-ph].
[51] P. V. Dong and H. N. Long, Phys. Rev. **D77**, 057302 (2008), arXiv:0801.4196 [hep-ph].
[52] P. T. Giang, L. T. Hue, D. T. Huong, and H. N. Long, Nucl. Phys. **B864**, 85 (2012), arXiv:1204.2902 [hep-ph].
[53] L. T. Hue, D. T. Huong, and H. N. Long, Nucl. Phys. **B873**, 207 (2013), arXiv:1301.4652 [hep-ph].
[54] L. T. Hue, H. N. Long, T. T. Thuc, and T. Phong Nguyen, Nucl. Phys. **B907**, 37 (2016), arXiv:1512.03266 [hep-ph].
[55] V. Van Vien, Braz. J. Phys. **45**, 467 (2015), [Erratum: Braz. J. Phys.45,no.6,807(2015)], arXiv:1506.07388 [hep-ph].
[56] A. C. B. Machado, J. Montao, and V. Pleitez, (2016), arXiv:1604.08539 [hep-ph].
[57] J. Schechter and J. W. F. Valle, Phys. Rev. **D25**, 2951 (1982).
[58] D. Cogollo, A. V. de Andrade, F. S. Queiroz, and P. Rebello Teles, Eur. Phys. J. **C72**, 2029 (2012), arXiv:1201.1268 [hep-ph].
[59] G. Aad *et al.* (ATLAS), ATLAS-CONF-2015-70 (2015).
[60] R. Foot, H. N. Long, and T. A. Tran, Phys. Rev. **D50**, R34 (1994), arXiv:hep-ph/9402243 [hep-ph].
[61] H. N. Long, Phys. Rev. **D54**, 4691 (1996), arXiv:hep-ph/9607439 [hep-ph].
[62] H. N. Long, Phys. Rev. **D53**, 437 (1996), arXiv:hep-ph/9504274 [hep-ph].
[63] J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, JHEP **05**, 050 (2013), arXiv:1303.3011 [hep-ph].
[64] M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, Nucl. Phys. **B908**, 199 (2016), arXiv:1512.06856 [hep-ph].
[65] J. Bergstrom, M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, JHEP **09**, 200 (2015), arXiv:1507.04366 [hep-ph].
[66] F. Queiroz, C. A. de S. Pires, and P. S. R. da Silva, Phys. Rev. **D82**, 065018 (2010), arXiv:1003.1270 [hep-ph].
[67] C. A. d. S. Pires, (2014), 10.3844/pisp.2015.33.41, arXiv:1412.1002 [hep-ph].
[68] A. G. Dias, C. A. de S. Pires, P. S. Rodrigues da Silva, and A. Sampieri, Phys. Rev. **D86**, 035007 (2012), arXiv:1206.2590.
[69] S. M. Boucenna, J. W. F. Valle, and A. Vicente, Phys. Rev. **D92**, 053001 (2015), arXiv:1502.07546 [hep-ph].
[70] T. Jezo, M. Klasen, D. R. Lamprea, F. Lyonnet, and I. Schienbein, JHEP **12**, 092 (2014), arXiv:1410.4692 [hep-ph].
[71] T. Jeo, M. Klasen, D. R. Lamprea, F. Lyonnet, and I. Schienbein (2015) arXiv:1508.03539 [hep-ph].
[72] M. Klasen, F. Lyonnet, and F. S. Queiroz, (2016), arXiv:1607.06468 [hep-ph].
[73] F. del Aguila, J. de Blas, and M. Perez-Victoria, JHEP **09**, 033 (2010), arXiv:1005.3998 [hep-ph].
[74] G. Aad *et al.* (ATLAS), Phys. Rev. **D90**, 052005 (2014), arXiv:1405.4123 [hep-ex].
[75] C. Salazar, R. H. Benavides, W. A. Ponce, and E. Rojas, JHEP **07**, 096 (2015), arXiv:1503.03519 [hep-ph].
[76] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, JHEP **07**, 079 (2014), arXiv:1405.0301 [hep-ph].
[77] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, JHEP **06**, 128 (2011), arXiv:1106.0522 [hep-ph].
[78] H.-L. Lai, J. Huston, S. Mrenna, P. Nadolsky, D. Stump, W.-K. Tung, and C. P. Yuan, JHEP **04**, 035 (2010), arXiv:0910.4183 [hep-ph].
[79] N. Garron, in *CKM unitarity triangle. Proceedings, 6th International Workshop, CKM 2010, Warwick, UK, September 6-10, 2010* (2011) arXiv:1102.1671 [hep-lat].

[80] S. Durr *et al.*, Phys. Lett. **B705**, 477 (2011), arXiv:1106.3230 [hep-lat].
[81] J. Beringer *et al.* (Particle Data Group), Phys. Rev. **D86**, 010001 (2012).
[82] M. Misiak, S. Pokorski, and J. Rosiek, Adv. Ser. Direct. High Energy Phys. **15**, 795 (1998), arXiv:hep-ph/9703442 [hep-ph].
[83] G. Barenboim, F. J. Botella, and O. Vives, Phys. Rev. **D64**, 015007 (2001), arXiv:hep-ph/0012197 [hep-ph].
[84] A. Datta, Phys. Rev. **D78**, 095004 (2008), arXiv:0807.0795 [hep-ph].