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# Are the B decay anomalies related to neutrino oscillations?

Sofiane M. Boucenna,[1, *] José W.F. Valle,[2, †] and Avelino Vicente[2, 3, ‡]
[1] *INFN, Laboratori Nazionali di Frascati, C.P. 13, 100044 Frascati, Italy.*
[2] *Instituto de Física Corpuscular (CSIC-Universitat de València), Apdo. 22085, E-46071 Valencia, Spain.*
[3] *IFPA, Dep. AGO, Université Liège, Bat B5, Sart-Tilman B-4000, Liège 1, Belgium*

Neutrino oscillations are solidly established, with a hint of CP violation just emerging. Similarly, there are hints of lepton universality violation in $b \to s$ transitions at the level of $2.6\sigma$. By assuming that the unitary transformation between weak and mass charged leptons equals the leptonic mixing matrix measured in neutrino oscillation experiments, we predict several lepton flavor violating (LFV) B meson decays. We are led to the tantalizing possibility that some LFV branching ratios for B decays correlate with the leptonic CP phase $\delta$ characterizing neutrino oscillations. Moreover, we also consider implications for $\ell_i \to \ell_j \ell_k \ell_k$ decays.

PACS numbers:

## Introduction

The historical discovery of the Higgs boson [1, 2] would have completed our picture of particle physics, were it not for the solid evidence we now have that neutrino flavors interconvert [3]. Apart from neutrino oscillations and cosmology, no other signs of new physics (NP) have been established. However, some indirect signs might have been found by the LHCb collaboration. In 2013, they have published the results of the measurement of a variety of observables in $b \to s$ transitions. In some cases, the experimental result was found to be in clear tension with the Standard Model (SM) prediction. These include angular observables [4–7] in $B \to K^* \mu^+ \mu^-$ [8], as well as a sizable suppression of several branching ratios [9, 10]. Recently, the LHCb announced new results based on the complete LHC Run I dataset [11]. The inclusion of new data has confirmed the anomalies, which are currently at the $\sim 4\sigma$ level. Furthermore, in 2014, the LHCb collaboration found an intriguing indication of lepton universality violation in the ratio [12]

$$R_K = \frac{\text{BR}(B \to K \mu^+ \mu^-)}{\text{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \, . \quad (1)$$

This experimental measurement, obtained in the low dilepton invariant mass regime, is $2.6\sigma$ away from the SM result $R_K^{SM} = 1.0003 \pm 0.0001$ [13]. Although the statistical significance of this discrepancy is not enough to claim a discovery, it is highly suggestive that several independent global fits [14–18] have shown that this hint can be explained by the same type of new physics contributions as the previous $b \to s$ anomalies.

The violation of lepton universality usually comes together with the violation of lepton flavor. Based on symmetry arguments, Glashow, Guadagnoli and Lane [19] recently argued that the observation of universality violation in the lepton flavor conserving (LFC) $B \to K \ell_i^+ \ell_i^-$ decays implies the existence of the lepton flavor violating (LFV) processes $B \to K \ell_i^+ \ell_j^-$ (with $i \neq j$). The idea of LFV in $B$ meson decays has been further explored in [20–24].

Here we take a step further in this direction. Since we lack a theory a flavor, we can not make definite predictions for the LFV rates using the LFC ones as input. Hence we make the simplest alternative assumption, namely, that the unitary transformation between weak and mass charged lepton states is given by the leptonic mixing matrix measured in neutrino oscillation experiments. Under this assumption we make numerical predictions for several LFV observables in the B system. We emphasize that this assumption is not completely *ad hoc*. It will actually be a prediction in models where the leptonic mixing arises from the charged lepton sector. We refer to [25] for a general discussion and an example model.

## General aspects of the $b \to s$ anomalies

The effective hamiltonian describing $b \to s$ transitions can be expressed as:

$$\mathcal{H}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left( C_i \mathcal{O}_i + C'_i \mathcal{O}'_i \right) + \text{h.c.} \quad (2)$$

Here $G_F$ is the Fermi constant, $e$ the electric charge and $V$ the CKM matrix. The Wilson coefficients $C_i$ and $C'_i$ encode the different (SM and NP) contributions to the effective operators $\mathcal{O}_i$ and $\mathcal{O}'_i$. The analysis of the available experimental data on $b \to s$ transitions reveals that the effective operators relevant for the resolution of the $b \to s$ anomalies are:

$$\mathcal{O}_9 \equiv \mathcal{O}_9^{\mu\mu} = (\bar{s} \gamma_\alpha P_L b) \, (\bar{\mu} \gamma^\alpha \mu) \, , \quad (3)$$
$$\mathcal{O}_{10} \equiv \mathcal{O}_{10}^{\mu\mu} = (\bar{s} \gamma_\alpha P_L b) \, (\bar{\mu} \gamma^\alpha \gamma_5 \mu) \, , \quad (4)$$

where $P_L = \frac{1}{2}(1 - \gamma_5)$ is the left-chirality projector. Several independent global fits [15–18] find a significant ten-

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[*] Electronic address: boucenna@lnf.infn.it
[†] Electronic address: valle@ific.uv.es
[‡] Electronic address: avelino.vicente@ulg.ac.be

sion between the SM results for the Wilson coefficients of these operators and the experimental data. This can be clearly alleviated in the presence of NP contributions. According to the global fit [18], the $C_9^{\mu\mu}$ coefficient is the key to improve the fits. More precisely, one finds a reasonable agreement with data when NP provides a negative contribution to $\mathcal{O}_9^{\mu\mu}$, with $C_9^{\mu\mu,\text{NP}} \sim -30\% \times C_9^{\mu\mu,\text{SM}}$. Similar improvements are found when NP enters in the $SU(2)_L$ invariant direction $C_9^{\mu\mu,\text{NP}} = -C_{10}^{\mu\mu,\text{NP}}$, with $C_9^{\mu\mu,\text{NP}} \sim -12\% \times C_9^{\mu\mu,\text{SM}}$.

## Predicting lepton flavor violation in $B$ meson decays

Here we raise the following question: can the leptonic mixing matrix provide the required lepton flavor structure in $\mathcal{O}_9$ and $\mathcal{O}_{10}$? And if so, what are the predictions for lepton flavor violation in the $B$ sector? As suggested by global fits, let us assume that the relevant NP operator contains a left-handed leptonic current. In this case, this operator can be generally written in the mass basis as:

$$\mathcal{O}^{ij} = \frac{1}{\Lambda^2} J_\alpha^d J_{\ell_{ij}}^\alpha \,, \tag{5}$$

where

$$\begin{aligned} J_\alpha^d &= C_{bs}^Q \, \bar{b}\gamma_\alpha P_L s \,, && (6) \\ J_{\ell_{ij}}^\alpha &= C_{ij}^L \, \bar{\ell}_i \gamma^\alpha P_L \ell_j \,, && (7) \end{aligned}$$

and $\Lambda$ is the energy scale of the NP inducing this operator. The $i,j$ indices denote the lepton flavor combination characterizing the operator in eq. (7). The $3\times3$ matrices $C^Q$ and $C^L$ completely determine the relations among the Wilson coefficients for different flavor choices. On the other hand, in the interaction (gauge) basis, $\mathcal{O}$ takes the same form, but the quark and lepton currents are written in terms of gauge eigenstates $d'$ and $\ell'$ as

$$\begin{aligned} J_\alpha^d &= \tilde{C}_{mn}^Q \, \bar{d}'_m \gamma_\alpha P_L d'_n \,, && (8) \\ J_{\ell_{ij}}^\alpha &= \tilde{C}_{ij}^L \, \bar{\ell}'_i \gamma^\alpha P_L \ell'_j \,. && (9) \end{aligned}$$

We now focus on the leptons. By combining eqs. (7) and (9) one finds the relation between $C^L$ and $\tilde{C}^L$,

$$C^L = U_\ell^\dagger \tilde{C}^L U_\ell \,, \tag{10}$$

where $U_\ell$ is the unitary matrix which relates the left-handed charged lepton gauge and mass eigenstates as $\ell' = U_\ell \ell$. Similarly, the left-handed neutrino gauge and mass eigenstates are connected by another matrix, $U_\nu$, as $\nu' = U_\nu \nu$. The product of these two matrices determines the leptonic charged current weak interaction,

$$\begin{aligned} \mathcal{L}_{\text{cc}} &= -\frac{g}{2\sqrt{2}} \left[ W_\mu^- \, \bar{\ell}' \gamma^\mu P_L \nu' + \text{h.c.} \right] \\ &= -\frac{g}{2\sqrt{2}} \left[ W_\mu^- \, \bar{\ell} \gamma^\mu K P_L \nu + \text{h.c.} \right] \,, \qquad (11) \end{aligned}$$

where $K = U_\ell^\dagger U_\nu$ is the leptonic mixing matrix measured in neutrino oscillation experiments. If $U_\nu = \mathbb{I}$, the left-handed neutrino gauge and mass eigenstates are the same and all the mixing is in the left-handed charged leptons. In this case $K = U_\ell^\dagger$ and eq. (10) leads to

$$C^L = K \tilde{C}^L K^\dagger \,. \tag{12}$$

We do not attempt to give any model prediction for $\tilde{C}^L$. Instead, we will assume that it is diagonal but with non-universal entries. In that case one can determine the required $\tilde{C}^L$ which, after using eq. (12), leads to a $C^L$ matrix compatible with the observations in $b \to s$ transitions. In particular, the resulting $C^L$ must have a strong hierarchy between the $ee$ and $\mu\mu$ entries, $C_{ee}^L \ll C_{\mu\mu}^L$, in order to induce a sizable correction to $B \to K^{(*)}\mu^+\mu^-$ and a negligible one to $B \to K^{(*)}e^+e^-$.

### *"Deriving" $C^L$ from neutrino oscillations*

Barring tuning of the parameters, we find two generic $\tilde{C}^L$ matrices in the gauge basis that lead to valid $C^L$ matrices in the mass basis. Their forms define our two scenarios:

- **Scenario A**: $\tilde{C}^L = \text{diag}(0, \epsilon, 1)$
- **Scenario B**: $\tilde{C}^L = \text{diag}(\epsilon, 0, 1)$

Here $\epsilon \ll 1$ is a small parameter (interestingly enough, note that Ref. [19] considered $\tilde{C}^L = \text{diag}(0,0,1)$, which corresponds to any of our scenarios in the limit $\epsilon = 0$) [1]. Using the standard parameterization for the leptonic mixing matrix $K$, one finds that in order to suppress the contributions to the $ee$ Wilson coefficients, $\epsilon$ must be close to

$$\epsilon_{\text{A}} = -\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}} \qquad \text{in scenario A} \,, \tag{13}$$

$$\epsilon_{\text{B}} = -\frac{\tan^2\theta_{13}}{\cos^2\theta_{12}} \qquad \text{in scenario B} \,. \tag{14}$$

Taking $3\sigma$ ranges for the mixing angles from the latest global fit to neutrino oscillation data [26], one finds the ranges $[-0.10, -0.05]$ for scenario A and $[-0.05, -0.03]$ for scenario B, irrespective of the neutrino mass spectrum; normal and inverted hierarchies giving basically the same results. Interestingly, $\theta_{13} \neq 0$ implies $\epsilon \neq 0$, indicating a suggestive connection between quarks and leptons.

We can now obtain $C^L$ for both scenarios. Let us first consider case A. Assuming $\epsilon = \epsilon_{\text{A}}$ and taking the best-fit values from [26], we find:

$$C^L = \begin{pmatrix} 0 & -0.023 + 0.117\, e^{i\delta} & 0.026 + 0.102\, e^{i\delta} \\ -0.023 + 0.117\, e^{-i\delta} & 0.005 \cos\delta + 0.532 & -0.001 \cos\delta + 0.005\, i\, \sin\delta + 0.509 \\ 0.026 + 0.102\, e^{-i\delta} & -0.001 \cos\delta - 0.005\, i\, \sin\delta + 0.509 & 0.394 - 0.005 \cos\delta \end{pmatrix}\,, \tag{15}$$

where $\delta$ is the Dirac leptonic CP violating phase. In the CP conserving case ($\delta = 0$) this matrix simplifies to

$$C^L = \begin{pmatrix} 0 & 0.094 & 0.128 \\ 0.094 & 0.537 & 0.508 \\ 0.128 & 0.508 & 0.389 \end{pmatrix}\,. \tag{16}$$

Regarding case B, assuming now $\epsilon = \epsilon_{\rm B}$ and taking the best-fit values for the mixing angles from [26], one finds

$$C^L = \begin{pmatrix} 0 & 0.011 + 0.117\, e^{i\delta} & -0.012 + 0.102\, e^{i\delta} \\ 0.011 + 0.117\, e^{-i\delta} & 0.548 - 0.003 \cos\delta & -0.003\, i\, \sin\delta + 0.489 \\ -0.012 + 0.102\, e^{-i\delta} & 0.003\, i\, \sin\delta + 0.489 & 0.003 \cos\delta + 0.416 \end{pmatrix}\,. \tag{17}$$

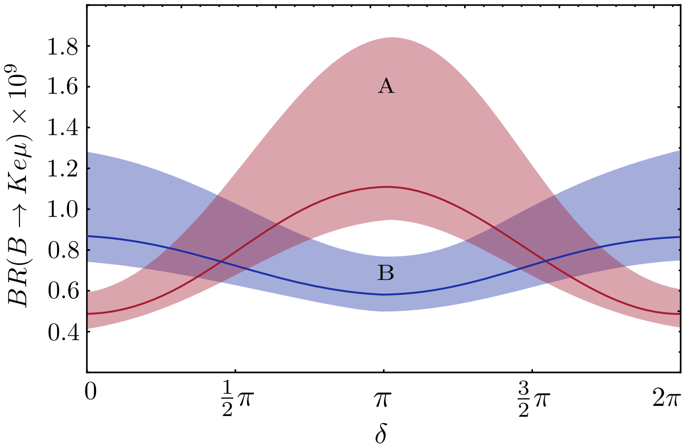

FIG. 1: The branching ratio of the decay $B \to Ke\mu$ versus the CP violating phase $\delta$ in scenarios A and B. The bands are obtained by taking the leptonic mixing angles within their $1\sigma$ range w.r.t. the best-fit value (solid line) [26].

In the CP conserving case ($\delta = 0$) this matrix simplifies to

$$C^L = \begin{pmatrix} 0 & 0.128 & 0.090 \\ 0.128 & 0.545 & 0.489 \\ 0.090 & 0.489 & 0.419 \end{pmatrix}\,. \tag{18}$$

Comparing the $C^L$ matrices for our two scenarios, we find that they are of the same of order of magnitude and the most significant difference lies in the terms involving $\delta$. This is what will allow us to relate $B$ decays to the leptonic CP phase.

## Lepton flavor violation in the B system

The matrix $C^L$ can be used to make definite predictions for ratios of branching ratios in $B \to K \ell_i^+ \ell_j^-$ decays,

$$\mathrm{BR}(B \to K \ell_i^\pm \ell_j^\mp) = 2\, \rho_{\rm NP}^2\, \Phi_{ij} \left| \frac{C^L_{ij}}{C^L_{\mu\mu}} \right|^2 \mathrm{BR}(B \to K \mu^+ \mu^-)\,. \tag{19}$$

Here $\mathrm{BR}(B \to K \ell_i^\pm \ell_j^\mp) = \mathrm{BR}(B \to K \ell_i^+ \ell_j^-) + \mathrm{BR}(B \to K \ell_i^- \ell_j^+)$ and $\mathrm{BR}(B \to K\mu^+\mu^-) = (4.29 \pm 0.22) \times 10^{-7}$ is the LHCb result [9], measured using the 3 $\mathrm{fb}^{-1}$ dataset after LHC Run I in the complete $q^2$ range, where $q^2 = M^2_{\mu\mu}$ is the dimuon invariant mass. The factor $\rho_{\rm NP}$ is the NP fraction of the $B \to K\mu^+\mu^-$ amplitude, $\rho_{\rm NP} = \mathcal{M}_{\rm NP}/\mathcal{M}_{\rm Total}$ [19]. Using the results of the global fit [18], which gives $C_9^{\mu\mu,{\rm NP}} \sim -12\% \times C_9^{\mu\mu,{\rm SM}}$, $\rho_{\rm NP}$ is found to be $\rho_{\rm NP} \sim -0.136$ [2]. Finally, the $\Phi_{ij}$ factor accounts for phase space and charged lepton mass effects. These introduce sizable corrections for final states including $\tau$ leptons. Using the results of Ref. [27], we find $\Phi_{\mu e} \simeq 1$ and $\Phi_{\tau e} = \Phi_{\tau\mu} \simeq 0.63$. Finally, we note that the parameterization in terms of $\rho_{\rm NP}$ is only exact in the limit of vanishing non-factorizable contributions. However, we have found that these corrections are negligible for the processes we are interested in.

For $\delta = 0$, we obtain the following predictions for the

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[2] The authors of [19] derive their value for $\rho_{\rm NP}$ from the LHCb $R_K$ measurement, obtaining $\rho_{\rm NP} \sim -0.159$.

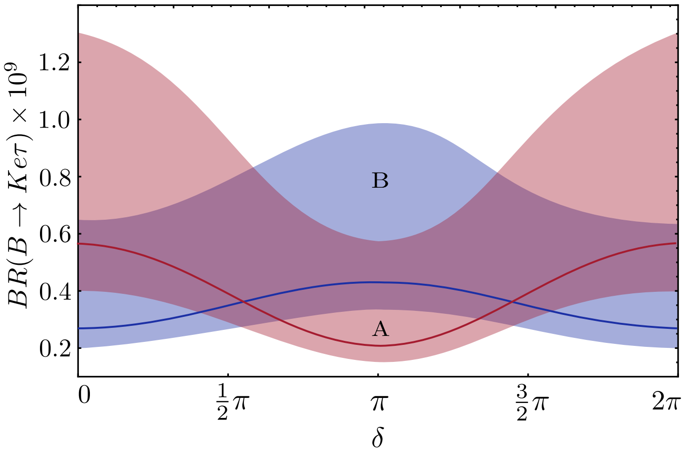

FIG. 2: Same as fig. (1) for the branching ratio of the decay $B \to Ke\tau$.

$B \to K$ LFV transitions in scenario A,

$$\mathrm{BR}(B \to K e^{\pm}\mu^{\mp}) \in [4.3, 6.2] \times 10^{-10}\,, \tag{20}$$
$$\mathrm{BR}(B \to K e^{\pm}\tau^{\mp}) \in [0.4, 1.3] \times 10^{-9}\,, \tag{21}$$
$$\mathrm{BR}(B \to K \mu^{\pm}\tau^{\mp}) \in [0.8, 1.6] \times 10^{-8}\,. \tag{22}$$

These have been derived using the LHCb central value and taking the leptonic mixing angles in the preferred $1\sigma$ ranges found by the fit [26]. The main generic prediction from our setup is thus

$$\mathrm{BR}(B \to K\mu^{\pm}\tau^{\mp}) \gg \mathrm{BR}(B \to Ke^{\pm}\mu^{\mp}), \mathrm{BR}(B \to Ke^{\pm}\tau^{\mp})\,. \tag{23}$$

However, experimentally the decay $B \to Ke^{\pm}\mu^{\mp}$ is the easiest to search for and reconstruct. Indeed, electron and tau final states are, $\mathcal{O}(20\%)$ and $\mathcal{O}(80\%)$ respectively, worse to reconstruct. Moreover future RUN II data will probe the region of $\mathcal{O}(10^{-10})$ for this channel providing a test of our scenario.

## Rare B decays and leptonic CP violation

One can now consider a scenario with a non-zero value of the CP violating phase $\delta$ characterizing neutrino oscillations. In this case, we are led to the fascinating possibility that the LFV branching ratios for B meson decays will depend upon $\delta$. Our results can be found in figs. (1) and (2) corresponding to the decay modes $B \to K\mu^{\pm}e^{\mp}$ and $B \to K\tau^{\pm}e^{\mp}$ respectively. This would suggest an alternative way of probing $\delta$ by using LFV $B$ meson decays.

## $\ell_i \to \ell_j \ell_k \ell_k$ decays

The same strategy can be extended to other LFV observables if induced mainly by vectorial operators, as in eqs. (3) and (4). Assuming the same leptonic currents, the analogous operators for the purely leptonic LFV processes $\ell_i \to \ell_j \ell_k \ell_k$ are:

$$\mathcal{O}_{4\ell} = \frac{1}{\Lambda^2}\left(C^L_{ij}\,\bar{\ell}_i\gamma_\alpha P_L \ell_j\right)\left(C^L_{mn}\,\bar{\ell}_m\gamma^\alpha P_L \ell_n\right)\,. \tag{24}$$

Here we assume that the scale of the NP responsible for the vectorial LFV operators is the same as the one relevant for $B$ meson decays, eq. (5), although in full generality these could be unrelated. The flavor structure of $\mathcal{O}_{4\ell} \equiv \mathcal{O}^{ijmn}_{4\ell}$ is given by the product $C^L_{ij}C^L_{mn}$ which, following the same prescription as for the $B$ meson decays, can be written as $C^L_{ij}C^L_{mn} = \left(K\tilde{C}^L K^\dagger\right)_{ij}\left(K\tilde{C}^L K^\dagger\right)_{mn}$.

The $\mathcal{O}_{4\ell}$ operator induces several $\ell_i \to \ell_j \ell_k \ell_k$ decay processes: (i) $\ell_i^- \to \ell_j^- \ell_k^- \ell_k^+$, and (ii) $\ell_i^- \to \ell_j^+ \ell_k^- \ell_k^-$ (with $k \neq j$). Their branching ratios can be written as [28]

$$\mathrm{BR}(\ell_i \to \ell_j \ell_k \ell_k) = \kappa\,\frac{m_{\ell_i}^5}{512\pi^3\Gamma_{\ell_i}}\,\frac{|M_{ijk}|^2}{\Lambda^4}\,, \tag{25}$$

where $\kappa = 2/3$ when there are two identical leptons in the final state, and $\kappa = 1/3$ otherwise, and $m_{\ell_i}$ and $\Gamma_{\ell_i}$ are the mass and decay width of the $\ell_i$ lepton, respectively. The coefficient $M_{ijk}$ takes the form $C^L_{ij}C^L_{kk}$ in case (i), $C^L_{ik}C^L_{jk}$ in case (ii).

One can now use the experimental limits on these LFV branching ratios to derive bounds on $\Lambda$. Processes involving $C^L_{ee}$ are strongly suppressed and thus they do not provide meaningful bounds. This is the case of $\mu^- \to e^- e^- e^+$, $\tau^- \to e^- e^- e^+$ and $\tau^- \to \mu^- e^- e^+$. In contrast, the combined LHCb+BaBar+Belle limit $\mathrm{BR}(\tau^- \to \mu^-\mu^-\mu^+) < 1.2 \times 10^{-8}$ [29] translates into $\Lambda \gtrsim 6.7$ TeV (in both scenarios, A and B). The other $\tau$ decay modes lead to slightly less stringent bounds. Future B factories are expected to improve on the search for $\tau^- \to \mu^-\mu^-\mu^+$, with sensitivies to branching ratios as low as $\sim 10^{-9}$ [30], allowing us to probe NP scales up to $\Lambda \sim 12$ TeV.

## Conclusions and discussion

In summary, we have suggested that the universality and flavor violating $b \to s$ anomalies may be related to the pattern of neutrino oscillations. By assuming that the unitary transformation between weak and mass charged lepton eigenstates is given by the leptonic mixing matrix measured in neutrino oscillations we predict several lepton flavor violating B meson decay rates. This way we are led to the thrilling possibility that some of the rare LFV B decay branching ratios correlate with the leptonic CP phase $\delta$ that characterizes neutrino oscillations. Other lepton flavor violating processes processes such as $\ell_i \to \ell_j \ell_k \ell_k$ have been considered in a similar manner. Improved measurements at Belle should probe new physics scale at the level $\Lambda \sim 12$ TeV. Relevant scenarios involve additional neutral currents, such as schemes containing an extra $Z'$ boson with lepton universality violation in

$B$ decays [31–34], or possibly some realizations of the electroweak symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ [35–40]. Such schemes should be taken seriously should the observed hints in the B sector persist. Finally, we note that in this paper we have focussed on the case where the violation of lepton universality is caused by NP in $B \to K\mu\mu$, with negligible contributions to $B \to Kee$. The alternative hypothesis is also plausible, though it has a lower constraining power since the electron channel is experimentally somewhat less constrained than the muonic one.

## Note added

A few days ago, an update of [18] was presented in [41]. While this would change slightly the value of $\rho_{NP}$ used in our analysis, our main point remains and the numerical results are also left essentially unchanged.

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[1] **ATLAS Collaboration** Collaboration, G. Aad *et al.*, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Phys.Lett.* **B716** (2012) 1–29, `arXiv:1207.7214 [hep-ex]`.

[2] **CMS Collaboration** Collaboration, S. Chatrchyan *et al.*, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," *Phys.Lett.* **B716** (2012) 30–61, `arXiv:1207.7235 [hep-ex]`.

[3] M. Maltoni, T. Schwetz, M. Tortola, and J. Valle, "Status of global fits to neutrino oscillations," *New J.Phys.* **6** (2004) 122, `arXiv:hep-ph/0405172 [hep-ph]`.

[4] J. Matias, F. Mescia, M. Ramon, and J. Virto, "Complete Anatomy of $\bar{B}_d \to \bar{K}^{*0}(K\pi)l^+l^-$ and its angular distribution," *JHEP* **1204** (2012) 104, `arXiv:1202.4266 [hep-ph]`.

[5] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, "Implications from clean observables for the binned to analysis of $BK*\mu^+\mu^-$ at large recoil," *JHEP* **1301** (2013) 048, `arXiv:1207.2753 [hep-ph]`.

[6] S. Descotes-Genon, T. Hurth, J. Matias, and J. Virto, "Optimizing the basis of $B \to K^*\ell^+\ell^-$ observables in the full kinematic range," *JHEP* **1305** (2013) 137, `arXiv:1303.5794 [hep-ph]`.

[7] S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88**, 074002 (2013) [arXiv:1307.5683 [hep-ph]].

[8] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$," *Phys.Rev.Lett.* **111** no. 19, (2013) 191801, `arXiv:1308.1707 [hep-ex]`.

[9] **LHCb** Collaboration, R. Aaij *et al.*, "Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays," *JHEP* **1406** (2014) 133, `arXiv:1403.8044 [hep-ex]`.

[10] **LHCb** Collaboration, R. Aaij *et al.*, "Differential branching fraction and angular analysis of the decay $B_s^0 \to \phi\mu^+\mu^-$," *JHEP* **1307** (2013) 084, `arXiv:1305.2168 [hep-ex]`.

[11] C. Langenbruch, "Latest results on rare decays from LHCb,". `https://indico.in2p3.fr/event/10819/session/10/contribution/84/material/slides/0.pdf`. Talk presented in the EW session of the 50th Rencontres de Moriond, 20th March, 2015.

[12] **LHCb** Collaboration, R. Aaij *et al.*, "Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays," *Phys.Rev.Lett.* **113** no. 15, (2014) 151601, `arXiv:1406.6482 [hep-ex]`.

[13] G. Hiller and F. Kruger, "More model independent analysis of $b \to s$ processes," *Phys.Rev.* **D69** (2004) 074020, `arXiv:hep-ph/0310219 [hep-ph]`.

[14] R. Alonso, B. Grinstein, and J. Martin Camalich, "$SU(2) \times U(1)$ gauge invariance and the shape of new physics in rare $B$ decays," *Phys.Rev.Lett.* **113** no. 24, (2014) 241802, `arXiv:1407.7044 [hep-ph]`.

[15] G. Hiller and M. Schmaltz, "$R_K$ and future $b \to s\ell\ell$ physics beyond the standard model opportunities," *Phys.Rev.* **D90** no. 5, (2014) 054014, `arXiv:1408.1627 [hep-ph]`.

[16] D. Ghosh, M. Nardecchia, and S. Renner, "Hint of Lepton Flavour Non-Universality in $B$ Meson Decays," *JHEP* **1412** (2014) 131, `arXiv:1408.4097 [hep-ph]`.

[17] T. Hurth, F. Mahmoudi, and S. Neshatpour, "Global fits to b $\to s\ell\ell$ data and signs for lepton non-universality," *JHEP* **1412** (2014) 053, `arXiv:1410.4545 [hep-ph]`.

[18] W. Altmannshofer and D. M. Straub, "State of new physics in $b \to s$ transitions," `arXiv:1411.3161 [hep-ph]`.

[19] S. L. Glashow, D. Guadagnoli, and K. Lane, "Lepton Flavor Violation in B Decays?," *Phys.Rev.Lett.* **114** no. 9, (2015) 091801, `arXiv:1411.0565 [hep-ph]`.

[20] B. Gripaios, M. Nardecchia, and S. Renner, "Composite leptoquarks and anomalies in $B$-meson decays," `arXiv:1412.1791 [hep-ph]`.

[21] B. Bhattacharya, A. Datta, D. London, and S. Shivashankara, "Simultaneous Explanation of the $R_K$

and $R(D^{(*)})$ Puzzles," *Phys.Lett.* **B742** (2015) 370–374, `arXiv:1412.7164 [hep-ph]`.

[22] S. Sahoo and R. Mohanta, "Scalar leptoquarks and the rare B meson decays," `arXiv:1501.05193 [hep-ph]`.

[23] I. d. M. Varzielas and G. Hiller, "Clues for flavor from rare lepton and quark decays," `arXiv:1503.01084 [hep-ph]`.

[24] R. Alonso, B. Grinstein and J. M. Camalich, "Lepton universality violation and lepton flavor conservation in $B$-meson decays," `arXiv:1505.05164 [hep-ph]`.

[25] G. Altarelli, F. Feruglio and I. Masina, "Can neutrino mixings arise from the charged lepton sector?," *Nucl. Phys. B* **689** (2004) 157, `arXiv:hep-ph/0402155 [hep-ph]`.

[26] D. Forero, M. Tortola, and J. Valle, "Neutrino oscillations refitted," *Phys.Rev.* **D90** no. 9, (2014) 093006, `arXiv:1405.7540 [hep-ph]`.

[27] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski and J. Rosiek, "Lepton-Flavour Violating $B$ Decays in Generic $Z'$ Models," `arXiv:1504.07928 [hep-ph]`.

[28] A. Abada, M. E. Krauss, W. Porod, F. Staub, A. Vicente, *et al.*, "Lepton flavor violation in low-scale seesaw models: SUSY and non-SUSY contributions," *JHEP* **1411** (2014) 048, `arXiv:1408.0138 [hep-ph]`.

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

[30] T. Aushev, W. Bartel, A. Bondar, J. Brodzicka, T. Browder, *et al.*, "Physics at Super B Factory," `arXiv:1002.5012 [hep-ex]`.

[31] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, "Quark flavor transitions in $L_\mu - L_\tau$ models," *Phys.Rev.* **D89** no. 9, (2014) 095033, `arXiv:1403.1269 [hep-ph]`.

[32] A. Crivellin, G. D'Ambrosio, and J. Heeck, "Explaining $h \to \mu^\pm \tau^\mp$, $B \to K^* \mu^+ \mu^-$ and $B \to K \mu^+ \mu^- / B \to K e^+ e^-$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$," `arXiv:1501.00993 [hep-ph]`.

[33] A. Crivellin, G. D'Ambrosio, and J. Heeck, "Addressing the LHC flavour anomalies with horizontal gauge symmetries," `arXiv:1503.03477 [hep-ph]`.

[34] D. A. Sierra, F. Staub, and A. Vicente, "Shedding light on the $b \to s$ anomalies with a dark sector," `arXiv:1503.06077 [hep-ph]`.

[35] M. Singer, J. Valle, and J. Schechter, "Canonical Neutral Current Predictions From the Weak Electromagnetic Gauge Group SU(3) X $u(1)$," *Phys.Rev.* **D22** (1980) 738.

[36] A. J. Buras, F. De Fazio, J. Girrbach, and M. V. Carlucci, "The Anatomy of Quark Flavour Observables in 331 Models in the Flavour Precision Era," *JHEP* **1302** (2013) 023, `arXiv:1211.1237 [hep-ph]`.

[37] S. M. Boucenna, S. Morisi, and J. W. F. Valle, "Radiative neutrino mass in 331 scheme," *Phys.Rev.* **D90** (2014) 013005, `arXiv:1405.2332 [hep-ph]`.

[38] S. M. Boucenna, R. M. Fonseca, F. Gonzalez-Canales, and J. W. F. Valle, "Small neutrino masses and gauge coupling unification," `arXiv:1411.0566 [hep-ph]`.

[39] A. J. Buras, F. De Fazio, and J. Girrbach-Noe, "Z-Z' mixing and Z-mediated FCNCs in SU(3)$_C$ x SU(3)$_L$ x U(1)$_X$ models," *JHEP* **1408** (2014) 039, `arXiv:1405.3850 [hep-ph]`.

[40] S. M. Boucenna, J. W. F. Valle, and A. Vicente, "Predicting charged lepton flavor violation from gauge symmetry," `arXiv:1502.07546 [hep-ph]`.

[41] W. Altmannshofer and D. M. Straub, "Implications of $b \to s$ measurements," `arXiv:1503.06199 [hep-ph]`.