Diagnosing New Physics with LUV and LFV B Decays.

Alakabha Datta

Department of Physics and Astronomy, University of Mississippi, 108 Lewis Hall, Oxford, MS 38677, USA

An important prediction of the standard model is the universality of the gauge interactions of the three generation of charged leptons. Violation of this universality would be a clean evidence of new physics (NP) beyond the standard model. In recent times anomalies in measurements of certain $B$ decays indicate violation of lepton universality (LUV). I will discuss how one may probe this LUV new physics via related decays and distributions. I will point out that LUV new physics can often lead to lepton flavor violation (LFV) and I will discuss some promising decays to look for LFV new physics.

PRESENTED AT

Thirteenth Conference on the Intersections of Particle and Nuclear Physics, CIPANP2018
Palm Springs, CA, USA.

\[^{1}\text{This research was supported by the U.S. NSF under Grant No. PHY-1414345.}\]
1 Introduction

At present, there are several measurements of $B$ decays that may indicate the presence of physics beyond the standard model (SM). In particular these measurements indicate lepton universality violation (LUV). In the SM the gauge bosons couple equally to all members of the quark and the lepton families. Hence measurement of LUV is evidence of physics beyond the SM.

The LUV are observed in two groups— in charged current (CC) processes and in the neutral current (NC) processes. We will discuss them separately first and then consider how the CC and NC LUV might have a common origin.

1.1 CC LUV

The charged-current decays $B \to D^{(*)} \tau \nu_{\tau}$ have been measured by the BaBar [1], Belle [2] and LHCb [3] Collaborations. It is found that the values of the ratios $R(D^{(*)}) \equiv B(\bar{B} \to D^{(*)} \tau^{-} \nu_{\tau})/B(\bar{B} \to D^{(*)} \ell^{-} \nu_{\ell})$ ($\ell = e, \mu$) considerably exceed their SM predictions. These ratios of branching fractions have certain advantages over the absolute branching fraction measurements as they are relatively less sensitive to form factor variations and several systematic uncertainties such as those on the experimental efficiency as well as the dependence on the value of $|V_{cb}|$ cancel in the ratios. There are lattice determination of the ratio $R(D^{(*)})_{SM}$ [4, 5] that are in general agreement with one another.

\begin{align}
R(D)_{SM} &= 0.299 \pm 0.011, \quad \text{FNAL/MILC} [4] \\
R(D)_{SM} &= 0.300 \pm 0.008, \quad \text{HPQCD} [5] \\
R(D^{*})_{SM} &= 0.252 \pm 0.003.
\end{align}

(1)

Calculation of $R(D^{*})_{SM}$ is not available from lattice and so one has to use SM phenomenological prediction [6, 7, 8] where the form factors are obtained from fits to the angular distributions in $\bar{B} \to D^{(*)} \ell^{-} \nu_{\ell}$.

By averaging the most recent measurements, the HFAG Collaboration has found [9]

\begin{align}
R(D) &= 0.407 \pm 0.039 \pm 0.024, \\
R(D^{*}) &= 0.304 \pm 0.013 \pm 0.007.
\end{align}

(2)

where the first uncertainty is statistical and the second is systematic. $R(D^{*})$ and $R(D)$ exceed the SM predictions by 3.4$\sigma$ and 2.3 $\sigma$, respectively. The combined analysis of $R(D^{*})$ and $R(D)$, taking into account measurement correlations, leads to a deviation is 4.1$\sigma$ from the SM prediction [9].

In general there have been many analyses of the $R(D^{(*)})$ puzzles both in model independent framework as well as in specific models (see, for example, Refs. [10, 11, 12, 13, 14, 15]).
1.1.1 Distributions and CP violation

The new physics proposed for the \( R(D^*) \) puzzled can be probed in distributions [10, 16, 17]. Some of the observables in the distributions have been measured. In the coming years more of these will be measured. These measurements will discover or constrain new physics and provide important clues to the nature of new physics. An important observable is CP violation in the distribution [16, 18] as this is free of hadronic uncertainties. Measurement of non zero value of CP violation will be a clear sign of new physics. The complete three-angle distribution for the decay

\[
B \to D^*(\to D\pi) l^- \nu_l \text{ decay.}
\]

Figure 1: The description of the angles \( \theta_l, \theta^* \) and \( \chi \) in the angular distribution of \( B \to D^*(\to D\pi) l^- \nu_l \) decay.

\[
B \to D^*(\to D\pi) l^- \nu_l \text{ in the presence of NP can be expressed in terms of four kinematic variables, } q^2 \text{ (the momentum transfer squared), two polar angles } \theta_l, \theta^{D^*}, \text{ and the azimuthal angle } \chi. \text{ The angle } \theta_l \text{ is the polar angle between the charged lepton and the direction opposite to the } D^* \text{ meson in the } (l\nu_l) \text{ rest frame. The angle } \theta^{D^*} \text{ is the polar angle between the } D \text{ meson and the direction of the } D^* \text{ meson in the } (D\pi) \text{ rest frame. The angle } \chi \text{ is the azimuthal angle between the two decay planes spanned by the 3-momenta of the } (D\pi) \text{ and } (l\nu_l) \text{ systems. These angles are described in Fig. 1.}
\]

The three-angle distribution can be obtained by using the helicity formalism. We can write the angular distribution for \( B \to D^*(\to D\pi) l^- \nu_l \) as [10, 19, 20, 21, 22]

\[
\frac{d^4 \Gamma}{dq^2 \cos \theta_l \cos \theta^{D^*} d\chi} = \frac{9}{32\pi} NF \left( \sum_{i=1}^{8} I_i + \frac{m_l^2}{q^2} \sum_{j=1}^{8} J_i \right),
\]

(3)

where the \( I_i \) and \( J_i \) are functions of the helicity amplitudes and the helicity angles [16].
The complex NP couplings lead to CP violation which is sensitive to the angular terms \( \sin \chi \) and \( \sin 2\chi \) in the distribution. The coefficients of these terms are triple products (TP) and have the structure \( \sim \text{Im}[A_i A_j^*] \sim \sin(\phi_i - \phi_j) \), where \( A_{i,j} = |A_{i,j}|e^{i\phi_{i,j}} \). In the SM these terms vanish, as there is only one dominant contribution to the decay and so all amplitudes have the same weak phase. Hence any non-zero measurements of TPs are clear signs of NP without any hadronic uncertainties. For the charged conjugate modes, the weak phases change sign and \( A_{i,j} = |A_{i,j}|e^{-i\phi_{i,j}} \) and the TPs change sign. Even though we focus on \( \tau \) final states, we should point out that this distribution is applicable also for \( e \) and \( \mu \) in the final state. Since experiments have already studied the distributions for \( e \), \( \mu \) final states it might be worth checking the \( \sin \chi \) and \( \sin 2\chi \) terms in the distributions for these decays for signals of non-SM physics.

1.1.2 Other \( b \) decays: \( \Lambda_b \to \Lambda_c \tau \nu_\tau \)

There are other \( b \) decays that can be used to constrain the models discussed to explain the \( R(D^{(*)}) \) measurements. It was pointed out that the underlying quark level transition \( b \to c \tau^- \nu_\tau \) in the \( R(D^{(*)}) \) puzzles can be probed in both \( B \) and \( \Lambda_b \) decays. The \( \Lambda_b \to \Lambda_c \tau \nu_\tau \) decays could be useful to confirm possible new physics in the \( R(D^{(*)}) \) puzzles and to point to the correct model of new physics. Recently, in Ref. [23] this decay was discussed in the standard model and with new physics in Ref. [24, 25, 26]. In Ref. [25] the following quantities were calculated within the SM and with various new physics operators.

\[
R_{\Lambda_c} = \frac{BR[\Lambda_b \to \Lambda_c \tau \nu_\tau]}{BR[\Lambda_b \to \Lambda_c \ell \nu_\ell]},
\]

\[
B_{\Lambda_c}(q^2) = \frac{\frac{d\Gamma[\Lambda_b \to \Lambda_c \tau \nu_\tau]}{dq^2}}{\frac{d\Gamma[\Lambda_b \to \Lambda_c \ell \nu_\ell]}{dq^2}},
\]

where \( \ell \) represents \( \mu \) or \( e \). The value of \( R_{\Lambda_c} \) in the SM with lattice form factors can also be found in Ref. [27]. In a recent paper [28] the phenomenology of this decay was studied in details with the most general new physics operators and in specific models which have been considered for the \( R(D^{(*)}) \) measurements. Lattice form factors for the \( \Lambda_b \to \Lambda_c \) transitions were used for precise calculations of the above ratios. In particular it was found that future measurements of the above ratios can strongly constrain or rule out certain models of new physics.

1.1.3 NC LUV

The LHCb Collaboration has made measurements of \( B \to K^* \mu^+ \mu^- \) [29, 30] that deviate from the SM predictions [31]. The Belle Collaboration finds similar results [32].
The main discrepancy is in the angular observable $P'_5 \, [33]$ though the significance of the discrepancy depends on the assumptions about the theoretical hadronic uncertainties. The LHCb Collaboration has also measured the branching fraction and performed an angular analysis of $B^0_s \to \phi \mu^+ \mu^-$ [34, 35]. They find a 3.5σ disagreement with the predictions of the SM, which are based on lattice QCD [36, 37] and QCD sum rules [38].

To find clear evidence of new physics one should consider observables largely free of hadronic uncertainties. One such observable is $R_K \equiv B(B^+ \to K^+ \mu^+ \mu^-)/B(B^+ \to K^+ e^+ e^-)$ [39, 40], which has been measured by LHCb [41]:

$$R_{\text{expt}}^K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}, \quad 1 \leq q^2 \leq 6.0 \text{ GeV}^2.$$  \hspace{1cm} (6)

This differs from the SM prediction, $R_{\text{SM}}^K = 1 \pm 0.01$ [42] by 2.6σ. Note, the observable $R_K$ is a measure of lepton flavor universality and requires different new physics for the muons versus the electrons, while it is possible to explain the anomalies in the angular observables in $b \to s \mu^+ \mu^-$ in terms of lepton flavor universal new physics [43].

Recently, the LHCb Collaboration reported the measurement of the ratio $R_{K^*} \equiv B(B^0 \to K^{*0} \mu^+ \mu^-)/B(B^0 \to K^{*0} e^+ e^-)$ in two different ranges of the dilepton invariant mass-squared $q^2$ [44]:

$$R_{\text{expt}}^{K^*} = 0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)}, \quad 0.045 \leq q^2 \leq 1.1 \text{ GeV}^2, \quad \text{(low } q^2\text{)},$$

$$0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)}, \quad 1.1 \leq q^2 \leq 6.0 \text{ GeV}^2, \quad \text{(central } q^2\text{)}.$$  \hspace{1cm} (7)

These differ from the SM predictions by 2.2-2.4σ (low $q^2$) and 2.4-2.5σ (central $q^2$), which further strengthens the hint of lepton non-universality observed in $R_K$.

Fits to new physics with heavy mediators have been considered by several groups but it has generally been difficult to understand the low $q^2$ measurements with heavy mediators [45]. There are attempts to understand the low $q^2$ $R_{K^*}$ measurement in terms of light mediators [46, 47]. This scenario was found to have interesting signatures in coherent neutrino scattering [48].

1.1.4 Lepton Universality Violation and Lepton Flavor Violation

Any interesting question is whether the CC LUV and the NC LUV are related. In Ref. [49, 50], it was pointed out that, assuming the scale of NP is much larger than the weak scale, operators contributing to $R_K$ anomalies should be made invariant under the full $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group. There are two possibilities if only left handed particles are involved:

$$O_1^{NP} = \frac{G_1}{\Lambda_{NP}^2} (\overline{Q}_L \gamma_\mu Q'_L)(\overline{L}'_L \gamma^\mu L'_L),$$

$$O_2^{NP} = \frac{G_2}{\Lambda_{NP}^2} (\overline{Q}_L \gamma_\mu \sigma^I Q'_L)(\overline{L}'_L \gamma_\mu \sigma^I L'_L).$$
\[
\frac{G_2}{\Lambda_{NP}^2} \left[ 2(\overline{Q}'_L\gamma_\mu Q'_{L}) (\overline{L}'_\gamma^\mu L'_L) - (\overline{Q}'_L\gamma_\mu Q'_{L}) (\overline{L}'_L\gamma^\mu L'_L) \right], \tag{8}
\]

where \(G_1\) and \(G_2\) are both \(O(1)\), and the \(\sigma'\) are the Pauli matrices. Here \(Q' \equiv (t', b')^T\) and \(L' \equiv (\nu', \tau')^T\). The key point is that \(\mathcal{O}_{NP}^2\) contains both neutral-current (NC) and charged-current (CC) interactions. The NC and CC pieces can be used to respectively explain the \(R_K\) and \(R_{D(S)}\) puzzles. In this scenario new physics affects only the third generation but via mixing effect LUV and lepton flavor violation (LFV) effects involving lighter generations are generated \([51, 50]\).

In Ref. \([52]\) UV completions that can give rise to \(\mathcal{O}_{NP}^{1, 2}\) [Eq. (8)], were discussed. These include leptoquark models and vector boson (VB) models. Concrete VB models are discussed as in Ref. \([53, 54]\). Within specific models there are new LUV processes as well as lepton flavor violating (LFV) processes. A fairly exhaustive analysis of specific models was carried out in the recent publication \([55]\). Several decay modes were discussed which in the future could distinguish among the different models. In particular it was shown that the observation of \(\tau \to 3\mu\) would be a clear sign of the VB model while the observation of \(\Upsilon \to \mu\tau\) would point towards the leptoquark model.

**2 Conclusion**

In conclusion we discussed the LUV anomalies in charged current (CC) and neutral current (NC) \(B\) decays. We showed how related decays and angular distributions including CP violating observables can shed more light on the CC anomalies. We discussed framework for a joint explanation of the CC and NC anomalies. These scenarios also typically lead to lepton flavor violating decays and we identified the interesting modes \(\tau \to 3\mu\) and \(\Upsilon(3S) \to \mu\tau\). Observations of these modes will point to specific models of new physics.

**ACKNOWLEDGEMENTS**

I am grateful to the high energy physics group at the University of California, Irvine for hospitality where this work was completed.

**References**

[1] J. P. Lees et al. [BaBar Collaboration], Phys. Rev. Lett. 109, 101802 (2012) doi:10.1103/PhysRevLett.109.101802 [arXiv:1205.5442 [hep-ex]]; J. P. Lees et al. [BaBar Collaboration], “Measurement of an Excess of \(\bar{B} \to D^{(*)}\tau^-\nu_\tau\) Decays
and Implications for Charged Higgs Bosons,” Phys. Rev. D 88, no. 7, 072012 (2013) doi:10.1103/PhysRevD.88.072012 [arXiv:1303.0571 [hep-ex]].

[2] M. Huschle et al. [Belle Collaboration], “Measurement of the branching ratio of \( \mathcal{B} \rightarrow D^{(*)} \tau^- \overline{\nu}_\tau \) relative to \( \mathcal{B} \rightarrow D^{(*)} \ell^- \overline{\nu}_\ell \) decays with hadronic tagging at Belle,” Phys. Rev. D 92, no. 7, 072014 (2015) doi:10.1103/PhysRevD.92.072014 [arXiv:1507.03233 [hep-ex]]; A. Abdesselam et al. [Belle Collaboration], arXiv:1603.06711 [hep-ex]; S. Hirose et al. [Belle Collaboration], Phys. Rev. Lett. 118, no. 21, 211801 (2017) doi:10.1103/PhysRevLett.118.211801 [arXiv:1612.00529 [hep-ex]].

[3] R. Aaij et al. [LHCb Collaboration], “Measurement of the ratio of branching fractions \( \mathcal{B}(\mathcal{B}^0 \rightarrow D^{(*)+} \tau^- \overline{\nu}_\tau) / \mathcal{B}(\mathcal{B}^0 \rightarrow D^{(*)+} \mu^- \overline{\nu}_\mu) \),” Phys. Rev. Lett. 115, no. 11, 111803 (2015) doi:10.1103/PhysRevLett.115.159901 [arXiv:1506.08614 [hep-ex]]; FPCP conference, 2017.

[4] J. A. Bailey et al., Phys. Rev. Lett. 109, 071802 (2012) doi:10.1103/PhysRevLett.109.071802 [arXiv:1206.4992 [hep-ph]]; J. A. Bailey et al. [MILC Collaboration], Phys. Rev. D 92, no. 3, 034506 (2015) doi:10.1103/PhysRevD.92.034506 [arXiv:1503.07237 [hep-lat]].

[5] H. Na et al. [HPQCD Collaboration], Phys. Rev. D 92, no. 5, 054510 (2015) Erratum: [Phys. Rev. D 93, no. 11, 119906 (2016)] doi:10.1103/PhysRevD.93.119906, 10.1103/PhysRevD.92.054510 [arXiv:1505.03925 [hep-lat]].

[6] M. Tanaka and R. Watanabe, Phys. Rev. D 82, 034027 (2010) doi:10.1103/PhysRevD.82.034027 [arXiv:1005.4306 [hep-ph]].

[7] S. Fajfer, J. F. Kamenik and I. Nisandzic, Phys. Rev. D 85, 094025 (2012) doi:10.1103/PhysRevD.85.094025 [arXiv:1203.2654 [hep-ph]].

[8] F. U. Bernlochner, Z. Ligeti, M. Papucci and D. J. Robinson, Phys. Rev. D 95, no. 11, 115008 (2017) doi:10.1103/PhysRevD.95.115008 [arXiv:1703.05330 [hep-ph]].

[9] Y. Amhis et.al., Averages of b-hadron,c-hadron, and lepton properties as of winter 2016. HFLAV: Semileptonic B Decay Parameters.

[10] A. Datta, M. Duraisamy and D. Ghosh, Phys. Rev. D 86, 034027 (2012) doi:10.1103/PhysRevD.86.034027 [arXiv:1206.3760 [hep-ph]].

[11] A. Celis, M. Jung, X. Q. Li and A. Pich, JHEP 1301, 054 (2013) doi:10.1007/JHEP01(2013)054 [arXiv:1210.8443 [hep-ph]].
[12] A. Crivellin, A. Kokulu and C. Greub, Phys. Rev. D 87, no. 9, 094031 (2013) doi:10.1103/PhysRevD.87.094031 [arXiv:1303.5877 [hep-ph]].

[13] I. Dorner, S. Fajfer, N. Konik and I. Niandri, JHEP 1311, 084 (2013) doi:10.1007/JHEP11(2013)084 [arXiv:1306.6493 [hep-ph]].

[14] M. Freytsis, Z. Ligeti and J. T. Ruderman, Phys. Rev. D 92, no. 5, 054018 (2015) doi:10.1103/PhysRevD.92.054018 [arXiv:1506.08896 [hep-ph]].

[15] N. G. Deshpande and X. G. He, arXiv:1608.04817 [hep-ph].

[16] M. Duraisamy and A. Datta, JHEP 1309, 059 (2013) doi:10.1007/JHEP09(2013)059 [arXiv:1302.7031 [hep-ph]].

[17] M. Duraisamy, P. Sharma and A. Datta, Phys. Rev. D 90, no. 7, 074013 (2014) doi:10.1103/PhysRevD.90.074013 [arXiv:1405.3719 [hep-ph]].

[18] K. Hagiwara, M. M. Nojiri and Y. Sakaki, Phys. Rev. D 89, no. 9, 094009 (2014) doi:10.1103/PhysRevD.89.094009 [arXiv:1403.5892 [hep-ph]].

[19] W. Dungel et al. [Belle Collaboration], Phys. Rev. D 82, 112007 (2010) [arXiv:1010.5620 [hep-ex]].

[20] J. D. Richman and P. R. Burchat, Rev. Mod. Phys. 67, 893 (1995) [hep-ph/9508250].

[21] J. G. Korner and G. A. Schuler, Z. Phys. C 46, 93 (1990).

[22] J. G. Korner and G. A. Schuler, Phys. Lett. B 231 (1989) 306. J. G. Korner and G. A. Schuler,

[23] T. Gutsche, M. A. Ivanov, J. G. Korner, V. E. Lyubovitskij, P. Santorelli and N. Habyl, arXiv:1502.04864 [hep-ph].

[24] R. M. Woloshyn, PoS Hadron 2013, 203 (2013).

[25] S. Shivashankara, W. Wu and A. Datta, Phys. Rev. D 91, no. 11, 115003 (2015) doi:10.1103/PhysRevD.91.115003 [arXiv:1502.07230 [hep-ph]].

[26] R. Dutta, Phys. Rev. D 93, no. 5, 054003 (2016) doi:10.1103/PhysRevD.93.054003 [arXiv:1512.04034 [hep-ph]].

[27] W. Detmold, C. Lehner and S. Meinel, Phys. Rev. D 92, no. 3, 034503 (2015) doi:10.1103/PhysRevD.92.034503 [arXiv:1503.01421 [hep-lat]].

[28] A. Datta, S. Kamali, S. Meinel and A. Rashed, JHEP 1708, 131 (2017) doi:10.1007/JHEP08(2017)131 [arXiv:1702.02243 [hep-ph]].
[29] R. Aaij et al. [LHCb Collaboration], “Measurement of Form-Factor-Independent Observables in the Decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$,” Phys. Rev. Lett. 111, 191801 (2013) doi:10.1103/PhysRevLett.111.191801 [arXiv:1308.1707 [hep-ex]].

[30] R. Aaij et al. [LHCb Collaboration], “Angular analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay using 3 fb$^{-1}$ of integrated luminosity,” JHEP 1602, 104 (2016) doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[31] U. Egede, T. Hurth, J. Matias, M. Ramon and W. Reece, “New observables in the decay mode $\overline{B}_d \rightarrow K^{*0}\ell^+\ell^-$,” JHEP 0811, 032 (2008) doi:10.1088/1126-6708/2008/11/032 [arXiv:0807.2589 [hep-ph]].

[32] A. Abdesselam et al. [Belle Collaboration], “Angular analysis of $B^0 \rightarrow K^*(892)^0\ell^+\ell^-$,” arXiv:1604.04042 [hep-ex].

[33] S. Descotes-Genon, T. Hurth, J. Matias and J. Virto, “Optimizing the basis of $B \rightarrow K^*\ell\ell$ observables in the full kinematic range,” JHEP 1305, 137 (2013) doi:10.1007/JHEP05(2013)137 [arXiv:1303.5794 [hep-ph]].

[34] R. Aaij et al. [LHCb Collaboration], “Differential branching fraction and angular analysis of the decay $B^0_s \rightarrow \phi\mu^+\mu^-$,” JHEP 1307, 084 (2013) doi:10.1007/JHEP07(2013)084 [arXiv:1305.2168 [hep-ex]].

[35] R. Aaij et al. [LHCb Collaboration], “Angular analysis and differential branching fraction of the decay $B^0_s \rightarrow \phi\mu^+\mu^-$,” JHEP 1509, 179 (2015) doi:10.1007/JHEP09(2015)179 [arXiv:1506.08777 [hep-ph]].

[36] R. R. Horgan, Z. Liu, S. Meinel and M. Wingate, “Calculation of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0_s \rightarrow \phi\mu^+\mu^-$ observables using form factors from lattice QCD,” Phys. Rev. Lett. 112, 212003 (2014) doi:10.1103/PhysRevLett.112.212003 [arXiv:1310.3887 [hep-ph]].

[37] “Rare $B$ decays using lattice QCD form factors,” PoS LATTICE 2014, 372 (2015) [arXiv:1501.00367 [hep-lat]].

[38] A. Bharucha, D. M. Straub and R. Zwicky, “$B \rightarrow V\ell^+\ell^-$ in the Standard Model from Light-Cone Sum Rules,” arXiv:1503.05534 [hep-ph].

[39] G. Hiller and F. Kruger, “More model independent analysis of $b \rightarrow s$ processes,” Phys. Rev. D 69, 074020 (2004) [arXiv:hep-ph/0310219].

[40] C. Bobeth, G. Hiller and G. Piranishvili, “Angular distributions of $\overline{B}_d \rightarrow K\ell^+\ell^-$ decays,” JHEP 0712, 040 (2007) [arXiv:0709.4174 [hep-ph]].
[41] R. Aaij et al. [LHCb Collaboration], “Test of lepton universality using $B^+ \rightarrow K^+\ell^+\ell^-$ decays,” Phys. Rev. Lett. **113**, 151601 (2014) [arXiv:1406.6482 [hep-ex]].

[42] M. Bordone, G. Isidori and A. Pattori, Eur. Phys. J. C **76**, no. 8, 440 (2016) [arXiv:1605.07633 [hep-ph]].

[43] A. Datta, M. Duraisamy and D. Ghosh, Phys. Rev. D **89**, no. 7, 071501 (2014) doi:10.1103/PhysRevD.89.071501 [arXiv:1310.1937 [hep-ph]].

[44] R. Aaij et al. [LHCb Collaboration], arXiv:1705.05802 [hep-ex].

[45] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar and D. London, arXiv:1704.07397 [hep-ph].

[46] A. Datta, J. Liao and D. Marfatia, Phys. Lett. B **768**, 265 (2017) [arXiv:1702.01099 [hep-ph]].

[47] A. Datta, J. Kumar, J. Liao and D. Marfatia, Phys. Rev. D **97**, no. 11, 115038 (2018) doi:10.1103/PhysRevD.97.115038 [arXiv:1705.08423 [hep-ph]].

[48] A. Datta, B. Dutta, S. Liao, D. Marfatia and L. E. Strigari, arXiv:1808.02611 [hep-ph]. Submitted to JHEP.

[49] R. Alonso, B. Grinstein and J. M. Camalich, “Lepton universality violation and lepton flavor conservation in $B$-meson decays,” JHEP **1510**, 184 (2015) doi:10.1007/JHEP10(2015)184 [arXiv:1505.05164 [hep-ph]].

[50] B. Bhattacharya, A. Datta, D. London and S. Shivashankara, “Simultaneous Explanation of the $R_{K}$ and $R(D^{(*)})$ Puzzles,” Phys. Lett. B **742**, 370 (2015) doi:10.1016/j.physletb.2015.02.011 [arXiv:1412.7164 [hep-ph]].

[51] S. L. Glashow, D. Guadagnoli and K. Lane, “Lepton Flavor Violation in $B$ Decays?,” Phys. Rev. Lett. **114**, 091801 (2015) doi:10.1103/PhysRevLett.114.091801 [arXiv:1411.0565 [hep-ph]].

[52] L. Calibbi, A. Crivellin and T. Ota, “Effective Field Theory Approach to $b \rightarrow s \ell\ell(\ell^c)$, $B \rightarrow K^{(*)}\nu\bar{\nu}$ and $B \rightarrow D^{(*)}\tau\nu$ with Third Generation Couplings,” Phys. Rev. Lett. **115**, 181801 (2015) doi:10.1103/PhysRevLett.115.181801 [arXiv:1506.02661 [hep-ph]].

[53] A. Greljo, G. Isidori and D. Marzocca, “On the breaking of Lepton Flavor Universality in $B$ decays,” JHEP **1507**, 142 (2015) doi:10.1007/JHEP07(2015)142 [arXiv:1506.01705 [hep-ph]].
[54] S. M. Boucenna, A. Celis, J. Fuentes-Martin, A. Vicente and J. Virto, “Nonabelian gauge extensions for B-decay anomalies,” arXiv:1604.03088 [hep-ph].

[55] B. Bhattacharya, A. Datta, J. P. Guvin, D. London and R. Watanabe, “Simultaneous Explanation of the $R_K$ and $R_{D^{(*)}}$ Puzzles: a Model Analysis,” arXiv:1609.09078 [hep-ph].