Study of new physics effects in lepton flavour violating $B \rightarrow K_2^*(1430) l_1 l_2$ decays

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Abstract

Lepton flavour violation (LFV) is one of the most trending topics to probe new physics (NP). The powerful accelerators have enhanced their intensities to observe the LFV decays very precisely. In this situation, the theorists are also interested to study these decays in various NP models and in model independent way to get precise results. Motivated by these results we have studied $B \rightarrow K_2^*(1430)l_1l_2$ decays in non-universal Z' model. Here, we have structured the two-fold angular distribution of the decays in terms of transversity amplitudes and the transversity amplitudes are formed with NP Wilson coefficients. The variation of the branching ratios and forward backward asymmetries show the sensitivity of NP. The observables calculated in this work are very interesting and might provide a new way towards NP.

Keywords: Lepton flavour violating decays, Flavour-changing neutral currents, Semileptonic decays, Models beyond the standard model

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I. Introduction:

The discovery of Higgs boson completed the family picture of the standard model (SM) of particle physics. The SM has successfully described most of the phenomena of nature at the energies near to electroweak scale. But now it is accepted that the SM needs to be modified to explain the new physics (NP) phenomenologies such as origin of dark matter, neutrino oscillations, the well-known flavour puzzle, etc. The experimental status of B anomalies is recorded by the B factories as well as the LHCb. Nowadays, the lepton flavour universality test is done by measuring R_{D,D^*} . The observable R_{D^*} is measured at Belle [1, 2], BaBar [3] and LHCb [4]. The recent measurements of Belle [5] are: $R_D = 0.307 \pm 0.37 \pm 0.016$ and $R_{D^*} =$ $0.283 \pm 0.018 \pm 0.14$. These results are greater than the SM predictions calculated in ref. [6] and ref. [7] by 2.3σ and 3.4σ deviations respectively. The LHCb [4] reported their preliminary result of R_D and R_{D^*} as $R_D^{LHCb2022} = 0.441 \pm 0.060 \pm 0.066$ and $R_{D^*}^{LHCb2022} = 0.281 \pm 0.02000$ 0.018 ± 0.024 . The world averages of the $R_{D^{(*)}}$ measurements are [8]: $R_D = 0.358 \pm 0.025 \pm$ 0.012 and $R_{D^*} = 0.285 \pm 0.010 \pm 0.008$. Though the latest measurements of R_K and R_{K^*} are found to be in agreement with the SM value in the bin range $0.045 \le q^2 \le 1.1$ and $1.1 \le q^2 \le 1.1$ 6.0 [9-12] (where q^2 is the momentum transfer term), there are lots of footprints for the existence of NP.

Another recent topic to test the SM is the lepton flavour violation (LFV). Study on LFV decays was started with the discovery of muon particle as a separate one at early 1940's. The evidence of quark flavour violation is very prompt in the colliders whereas the lepton flavour violation is noticeable but is not established experimentally. The neutrino oscillation process indicates the fact of neutrino flavour violation. As all the fermions other than leptons in the SM of particle physics show flavour violation, we can expect that the charged leptons could mix. It is already known that if the neutrinos have masses and get mixed then the mixing can be transferred to charged leptons via $v_l - e - W$ coupling. The experiments have proclaimed that the neutrinos are massive and they mix, so it is obvious to exist mixings among the charged leptons. The SM predicts neutrinos to be massless which contradicts the accelerators. To include massive neutrinos into the theory we need to extend the SM. The neutrino mass is very tiny, approximately smaller than 1eV and this propels the neutrino Yukawa coupling to be of 10⁻¹². The LFV decays such as $B^0 \to \tau^{\pm} \mu^{\mp}$ and $B_s^0 \to \tau^{\pm} \mu^{\mp}$ are extremely suppressed in the SM with expected branching ratios of the order of 10^{-54} [13] whereas the LHCb [14] has reported the upper limits for the branching ratios at 90% confidence level as $\mathcal{B}(B^0 \to \tau^{\pm} \mu^{\mp}) <$ 1.4×10^{-5} and $\mathcal{B}(B_s^0 \to \tau^{\pm} \mu^{\mp}) < 4.2 \times 10^{-5}$. Recently, the Belle Collaboration [15] has set upper limit on branching ratio at 90% confidence level as $\mathcal{B}(B_s^0 \to \mu^{\mp} \tau^{\pm}) < 7.3 \times 10^{-4}$.

Here, we have chosen the $B \to K_2^*$ channel because the colliders have provided better understanding of the radiative decays in inclusive level with the $B \to K_2^* \gamma$ decay. On the other hand, the SM branching ratio value for $B \to K_2^*(1430)ll$ shows that this decay channel can provide an independent test of the SM [16, 17]. Therefore, we have selected this channel in LFV mode to probe the NP. We hope the precise measurement of $B \to K_2^*(1430)l_1l_2$ decays would be possible with the increasing of the sensitivity of the current experiments in future.

There are several theoretical attempts to demonstrate the experimental tensions which are discussed above. Though there are only experimental bounds exist on the LFV decays, various NP models have explained them. These decays are studied with the effect of FCNC mediated Z boson [18, 19], in non-universal Z' model [20-22], in leptoquark model [23-26], in MSSM [27-29] and other NP models [30] and also in model independent way [31]. Previously, Biswas et al. have studied the LFV Λ_b decays [32], $B \to K^* l_1 l_2$ and $B_s \to \varphi l_1 l_2$ decays [33] in non-universal Z' model where l_1 and l_2 are charged leptons of different flavours. Here, our work is based on the same NP model mentioned previously. In this paper, we have studied $B \rightarrow$ $K_2^*(1430)l_1l_2$ decays in non-universal Z' model. Structuring the two-fold decay distribution of the decays we have investigated the sensitivity of NP on various observables with the contribution of vector, axial-vector NP operators. The non-universal Z' model explains the NP contribution at tree level through Z'-mediated flavour changing $b \rightarrow s$ transitions. The Z' boson associates to the quark sector as well as to the leptonic sector. The Z' boson is not observed at the colliders till now but its mass is constrained differently in different in grand unified theories (GUTs). Various experiments and detectors have also restricted the upper and lower bounds of the mass of Z' boson. The model-dependent lower bound for Z' mass is set at 500 GeV by different accelerators [34-36]. Sahoo et al. have predicted the range of Z' mass as 1352 - 1665 GeV from $B_q - \overline{B_q}$ mixing [37]. Several other studies have also set the mass limits which are discussed in the refs. [38-41]. The ATLAS collaboration has constrained the

lower bound of Z' mass for Z'_{ψ} and Z'_{SSM} as 4.5 TeV and 5.1 TeV respectively at 95% C. L. [42]. Recently [43], the mass difference of B_s meson is studied in extended standard model and the upper limit of Z' mass is constrained as 9 TeV. In this paper, we have taken the Z' mass in TeV range.

This paper is arranged as follows: The effective Hamiltonian for LFV decays is discussed in Sec. II. The details of the decay and the description of the observables are illustrated in Sec. III. In Sec. IV, the contribution of non-universal Z' model is incorporated in the decays by modifying the Wilson coefficients. We have presented the numerical analysis in Sec. V. And finally, we have concluded the findings in Sec. VI.

II. Effective Hamiltonian:

In this section, we structure the effective Hamiltonian for the lepton flavour violating $b \rightarrow sl_1l_2$ transition. The leptons l_1 and l_2 are considered of the same flavour l in the SM but in BSM physics the NP particle Z' will couple differently with leptons of different families. The structured Hamiltonian is represented as follows [21, 27, 30]

$$\mathcal{H}^{eff} = -\frac{G_F \alpha}{2\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{r=9,10} C_r^{NP} O_r + h.c.,$$
(1)

where G_F represents the Fermi coupling constant, α represents the electromagnetic coupling constant. The C_r^{NP} parts are the Wilson Coefficients containing NP contributions. The CKM matrix elements $V_{tb}V_{ts}^*$ are introduced in the Hamiltonian due to the virtual effects induced by $t\bar{t}$ loops. It is to be noted that the LFV decays occur at tree level in this Z' model; therefore, the NP should contribute in the fashion where $t\bar{t}$ loops get cancelled. Moreover, there is an electromagnetic operator O_7 in the SM for $b \rightarrow sll$ transition. Non-universal Z' model is basically sensitive to the semileptonic current operators O_9 and O_{10} involving NP contributions in C_9^{NP} and C_{10}^{NP} [21, 26, 44]. Here,

$$O_{9} = [\bar{s}\gamma_{\mu}(1-\gamma_{5})b][\bar{l}_{1}\gamma^{\mu}l_{2}],$$

$$O_{10} = [\bar{s}\gamma_{\mu}(1-\gamma_{5})b][\bar{l}_{1}\gamma^{\mu}\gamma_{5}l_{2}].$$
(2)

III. The $B \rightarrow K_2^*(1430) l_1 l_2$ decays

The $B \to K_2^*(1430)l_1l_2$ decay can be structured in terms of following kinematic variables: (i) θ_l , the angle made by l_1 lepton with z axis in the dilepton rest frame, (ii) $q^2 (= (p - k)^2)$, the four momentum of dilepton pair (where p and k are the four momentum of B and K_2^* mesons respectively). The two fold decay differential branching ratio can be described as [32, 45, 46]

$$\frac{d^2\mathcal{B}}{dq^2d\cos\theta_l} = A(q^2) + B(q^2)\cos\theta_l + C(q^2)\cos^2\theta_l \,. \tag{3}$$

Here, the terms $A(q^2)$, $B(q^2)$ and $C(q^2)$ can be written as follows

$$A(q^{2}) = \frac{3}{4} \left\{ \frac{1}{4} \left[\left(1 + \frac{m_{+}^{2}}{q^{2}} \right) \beta_{-}^{2} + \left(1 + \frac{m_{-}^{2}}{q^{2}} \right) \beta_{+}^{2} \right] \left(\left| A_{L}^{\parallel} \right|^{2} + \left| A_{L}^{\perp} \right|^{2} + (L \leftrightarrow R) \right) \right. \\ \left. + \frac{1}{2} (\beta_{+}^{2} + \beta_{-}^{2}) (\left| A_{L}^{0} \right|^{2} + \left| A_{R}^{0} \right|^{2}) \right. \\ \left. + \frac{4m_{1}m_{2}}{q^{2}} Re \left[A_{R}^{0} A_{L}^{0*} + A_{R}^{\parallel} A_{L}^{\parallel*} + A_{R}^{\perp} A_{L}^{\perp*} - A_{L}^{t} A_{R}^{t*} \right] \right. \\ \left. + \frac{1}{2} (\beta_{+}^{2} + \beta_{-}^{2} - 2\beta_{-}^{2} \beta_{+}^{2}) (\left| A_{L}^{t} \right|^{2} + \left| A_{R}^{t} \right|^{2}) \right\},$$

$$(4)$$

$$B(q^{2}) = \frac{3}{2}\beta_{-}\beta_{+} \left\{ Re\left[A_{L}^{\perp*}A_{L}^{\parallel} - (L \leftrightarrow R)\right] + \frac{m_{+}m_{-}}{q^{2}}Re\left[A_{L}^{0*}A_{L}^{t} + (L \leftrightarrow R)\right] \right\},$$
(5)

$$C(q^{2}) = \frac{3}{8}\beta_{+}^{2}\beta_{-}^{2}\left\{\left(\left|A_{L}^{\parallel}\right|^{2} + |A_{L}^{\perp}|^{2} - 2|A_{L}^{0}|^{2}\right) + (L \leftrightarrow R)\right\},\tag{6}$$

where $m_{\pm} = (m_1 \pm m_2)$, $\beta_{\pm} = \sqrt{1 - \frac{(m_1 \pm m_2)^2}{q^2}}$ and m_1 , m_2 are the masses of leptons l_1 and l_2 respectively. The angular coefficients of the differential branching fraction of eq. (3) are expressed in terms of the transversity amplitudes which are described in the Appendix A. The transversity amplitudes are structured in terms of the Wilson coefficients and the form factors. Basically, the short distance physics are incorporated at the NP Wilson coefficients and the long distance physics are inserted via $B \rightarrow K_2^*$ hadronic elements.

The hadronic matrix elements for $B \to K_2^*$ transition are parameterized in terms of four form factors $V(q^2)$ and $A_{0,1,2}(q^2)$. The matrix elements for vector and axial vector currents are structured as follows

$$\langle K_2^*(k,\epsilon^*)|\bar{s}\gamma^{\mu}b|\bar{B}(p)\rangle = -\frac{2V(q^2)}{m_B + m_{K_2^*}}\epsilon^{\mu\nu\rho\sigma}\epsilon^*_{T\nu}p_{\rho}k_{\sigma},\tag{7}$$

$$\langle K_{2}^{*}(k,\epsilon^{*})|\bar{s}\gamma^{\mu}\gamma_{5}b|\bar{B}(p)\rangle$$

$$= 2im_{K_{2}^{*}}A_{0}(q^{2})\frac{\epsilon_{T}^{*}\cdot q}{q^{2}}q^{\mu} + i\left(m_{B} + m_{K_{2}^{*}}\right)A_{1}(q^{2})\left[\epsilon_{T}^{*\mu} - \frac{\epsilon_{T}^{*}\cdot q}{q^{2}}q^{\mu}\right]$$

$$- iA_{2}(q^{2})\frac{\epsilon_{T}^{*}\cdot q}{\left(m_{B} + m_{K_{2}^{*}}\right)}\left[(p+k)^{\mu} - \frac{\left(m_{B}^{2} - m_{K_{2}^{*}}^{2}\right)}{q^{2}}q^{\mu}\right].$$

$$(8)$$

The form factors used in this calculation are derived using the light cone QCD sum rule. We have used the updated values of the form factors from the reference [47]. The numerical values of the form factors are collected in the Appendix B. The K_2^* meson is the higher excited state of K^* meson having spin-2. The details of the polarization vector of K_2^* is discussed in the Appendix C. In our analysis, we have structured the leptonic helicity amplitudes which are discussed briefly in the Appendix D.

With all these structures, we have calculated the differential decay rate by integrating over the angle θ_l as

$$\frac{d\mathcal{B}}{dq^2} = 2\left[A(q^2) + \frac{\mathcal{C}(q^2)}{3}\right].$$
(9)

To probe NP in LFV decays we have structured another powerful tool, the forward-backward asymmetry. It is defined as

$$A_{FB}(q^2) = \frac{\int_0^1 \frac{d^2 \mathcal{B}}{dq^2 d\cos\theta_l} d\cos\theta_l - \int_{-1}^0 \frac{d^2 \mathcal{B}}{dq^2 d\cos\theta_l} d\cos\theta_l}{\int_0^1 \frac{d^2 \mathcal{B}}{dq^2 d\cos\theta_l} d\cos\theta_l + \int_{-1}^0 \frac{d^2 \mathcal{B}}{dq^2 d\cos\theta_l} d\cos\theta_l} d\cos\theta_l}.$$
 (10)

The observable can be expressed as

$$A_{FB}(q^2) = \frac{B(q^2)}{2\left[A(q^2) + \frac{C(q^2)}{3}\right]}$$
(11)

IV. The contribution of Z' boson in $B \rightarrow K_2^*(1430) l_1 l_2$ decays

The presence of Z' boson can reform the effective Hamiltonian of $b \rightarrow s$ transitions to provide an appreciable deviation from the SM values and to explain the collider results. An extra U(1)'gauge group is introduced with the SM gauge group [48, 49] and the Z' boson is evolved through spontaneous symmetry breaking process. This new massive boson couples to quarks as well as the lepton pair and can explain the FCNC transitions at the tree level. According to refs. [50-52] Z' boson associates with the third generation of quark differently from the other two generations and show similar behaviour for the lepton families also. In this paper, we have taken different family non-universal Z' couplings for different lepton families in the model. These couplings are diagonal and non-universal in nature.

The current can be represented in NP as

$$J_{\mu} = \sum_{i,j} \bar{\psi}_{j} \gamma_{\mu} \left[\epsilon_{\psi_{L_{ij}}} P_{L} + \epsilon_{\psi_{R_{ij}}} P_{R} \right] \psi_{i}.$$
(12)

Here, this sum is applied for all fermions $\psi_{i,j}$ and $\epsilon_{\psi_{R,L_{ij}}}$ are the chiral couplings of the new gauge boson. The FCNCs are explained in both left-handed and right-handed sectors at the tree level in Z' model. Therefore, we can represent $B_{ij}^{\psi_L} \equiv \left(V_L^{\psi} \epsilon_{\psi_L} V_L^{\psi^{\dagger}}\right)_{ij}$ and $B_{ij}^{\psi_R} \equiv \left(V_R^{\psi} \epsilon_{\psi_R} V_R^{\psi^{\dagger}}\right)_{ij}$. The NP coupling is introduced as

$$\mathcal{L}_{FCNC}^{Z'} = -g' \left(B_{sb}^L \bar{s}_L \gamma_\mu b_L + B_{sb}^R \bar{s}_R \gamma_\mu b_R \right) Z'^\mu + h. c., \tag{13}$$

where g' is the new gauge coupling linked with the extra U(1)' group and the effective Hamiltonian becomes,

$$H_{eff}^{Z'} = \frac{8G_F}{\sqrt{2}} \left(\rho_{sb}^L \bar{s}_L \gamma_\mu b_L + \rho_{sb}^R \bar{s}_R \gamma_\mu b_R \right) \left(\rho_{l_i l_j}^L \bar{l}_j \gamma_\mu l_{i_L} + \rho_{l_i l_j}^R \bar{l}_j \gamma_\mu l_{i_R} \right), \tag{14}$$

where $\rho_{l_i l_j}^{L,R} \equiv \frac{g' M_Z}{g M_{Z'}} B_{l_i l_j}^{L,R}$, g and g' are the gauge couplings of Z and Z' bosons (here, $g = \frac{e}{\sin \theta_W \cos \theta_W}$) respectively.

In this work, we have incorporated some simplifications regarding this NP model which are:

(i) we have ignored kinetic mixing because it represents the redefinition of unknown couplings,

(ii) we have also neglected the mixing of Z - Z' [48, 53-56] for its very small value. The upper bound of mixing angle is found 10^{-3} by Bandyopadhyay et al. [40] and 10^{-4} by Bobovnikov et al. [57],

(iii) we have considered that there are no significant contributions of renormalization group (RG) evolution between M_W and $M_{Z'}$ scales,

(iv) we accept the considerable contribution of the flavour-off-diagonal left-handed quark couplings in the flavour changing quark transition [58-62] in our investigation. The detail of this assumption is discussed in our previous work [32],

(v) here, the value of the term $\left|\frac{g'}{g}\right|$ is not fixed yet. As both U(1) gauge groups, included in

this Z' model, are generated from the same origin of some GUT, we have taken $\left|\frac{g'}{a}\right| \sim 1$,

(vi) we have taken
$$\left|\frac{M_Z}{M_{Z'}}\right| \sim 0.1$$
 for Z' of TeV-scale.

The LEP experiments have also recommended the Z' existence with the identical couplings as the SM Z boson. We can say that if $|\rho_{sb}^L| \sim |V_{tb}V_{ts}^*|$, then B_{sb}^L will be $\mathcal{O}(10^{-3})$. Considering all above discussions, we can structure the effective Hamiltonian for the LFV $b \rightarrow sl_1l_2$ transition as

$$H_{eff}^{Z'} = -\frac{2G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[\frac{B_{sb}^L B_{l_1 l_2}^L}{V_{tb} V_{ts}^*} (\bar{s}b)_{V-A} (\bar{l}_1 l_2)_{V-A} + \frac{B_{sb}^L B_{l_1 l_2}^R}{V_{tb} V_{ts}^*} (\bar{s}b)_{V-A} (\bar{l}_1 l_2)_{V+A} \right] + h.c,(15)$$

where B_{sb}^{L} is the left-handed coupling of Z' boson with quarks, $B_{l_1l_2}^{L}$ and $B_{l_1l_2}^{R}$ are the lefthanded and right-handed couplings with the leptons respectively. The NP quark coupling consists of a NP weak phase term, which is related as $B_{sb}^{L} = |B_{sb}^{L}|e^{-i\varphi_{s}^{L}}$. The Wilson coefficients can be structured including the NP terms as

$$C_{9}^{NP} = \frac{4\pi B_{sb}^{L}}{\alpha V_{tb} V_{ts}^{*}} \left(B_{l_{1}l_{2}}^{L} + B_{l_{1}l_{2}}^{R} \right),$$

$$C_{10}^{NP} = \frac{4\pi B_{sb}^{L}}{\alpha V_{tb} V_{ts}^{*}} \left(B_{l_{1}l_{2}}^{L} - B_{l_{1}l_{2}}^{R} \right).$$
(16)

Including the NP parts through the modified Wilson coefficients, we have studied the observables defined in eqs. (9) and (11) in the non-universal Z' model.

V. Numerical Analysis

In this work, we have studied differential branching ratios and forward backward asymmetries for the LFV decays $B \to K_2^*(1430)\mu\tau$ and $B \to K_2^*(1430)e\mu$ in the framework of nonuniversal Z' model. We have mainly modified the terms C_9^{NP} and C_{10}^{NP} with the NP coupling terms which are constrained from $B_s - \bar{B}_s$ mixing data of UTfit Collaboration [63-69] and various inclusive and exclusive decays. The numerical values of the b - s - Z' couplings and the NP weak phases φ_s^l are tabulated below in Table-1. The first two scenarios are taken from refs. [44, 70]. The third scenario is constrained from the recent values of the mass differences updated in ref. [43]. Using the recent updated values of mass differences, we have constrained NP terms at our previous work [71]. Other input parameters are recorded in Appendix E [72].

Scenarios	$ B_{sb} \times 10^{-3}$	φ_s^l (in degree)
<i>S</i> ₁	(1.09 ± 0.22)	(-72 ± 7)°
<i>S</i> ₂	(2.20 ± 0.15)	$(-82 \pm 4)^{\circ}$
<i>S</i> ₃	$0 \le B_{sb}^L \le 1.539 \times 10^{-3}$	For $0^\circ \le \varphi_s^L \le 180^\circ$

Table-1: Numerical values of coupling parameters

To increase as well as to examine the sensitivity of NP in our investigation we have posed the maximum values of the NP couplings in the observables. With the help of Table-1 we have selected three sets of Z' couplings as below.

For scenario 1 (S₁): $|B_{sb}| = (1.31 \times 10^{-3})$ and $\varphi_s^l = -65^\circ$.

For scenario 2 (S₂): $|B_{sb}| = (2.35 \times 10^{-3})$ and $\varphi_s^l = -78^\circ$.

For scenario 3 (S₃): $|B_{sb}| = (1.539 \times 10^{-3})$ and $\varphi_s^l = 180^\circ$.

Here, in our work we have composed the leptonic couplings as $S_{l_1l_2} = (B_{l_1l_2}^L + B_{l_1l_2}^R)$, and $D_{l_1l_2} = (B_{l_1l_2}^L - B_{l_1l_2}^R)$. The maximally allowed region for leptonic couplings are found in the ref. [32] and these values are: $S_{\mu e} = 0.0079$, $D_{\mu e} = -0.0079$ and $S_{\tau \mu} = 0.11$, $D_{\tau \mu} =$ -0.11. Another consideration we have adopted in this work is $C_9^{NP} = -C_{10}^{NP}$ because the $C_9^{NP} = C_{10}^{NP}$ scenario is very weak to produce effective results (which can be confirmed with the results of the refs. [73, 74]). On the other hand, the $C_9^{NP} = -C_{10}^{NP}$ scenario provides lots of fruitful results under the philosophy of both model and model-independent strategies. Some of these best results are presented in the refs. [26, 73-78].

With all these numerical data and theoretical considerations, we have varied the differential branching ratio within allowed kinematic region of q^2 in Fig. 1a and Fig. 1b for $B \rightarrow K_2^* \mu \tau$ and $B \rightarrow K_2^* e \mu$ channels respectively. Here, all the plots are drawn using the central values of the form factors and other input parameters. In the Fig. 1, the magenta line represents the 1st scenario, the red line represents the 2nd scenario and the blue line represents the 3rd scenario. We observe that the branching ratio has greater value on mid q^2 region for $B \rightarrow K_2^* \mu \tau$ transition and on low q^2 region for $B \rightarrow K_2^* e \mu$ transition. There is a difference between the natures of these differential branching ratios due to the lighter mass of electron. But both the decay channels have more branching value for higher contribution of NP which confirms the

responsiveness of the non-universal Z' model. Another conclusion which can be drawn here is that the maximum attained value of the observable for 2^{nd} scenario is large in comparison to the other scenarios. Integrating over the whole q^2 phase space we have estimated the average values of branching ratios for these decays which are shown in Table-2. Here, we have presented the maximum allowed values of the branching ratios considering the maximum contribution of NP couplings.

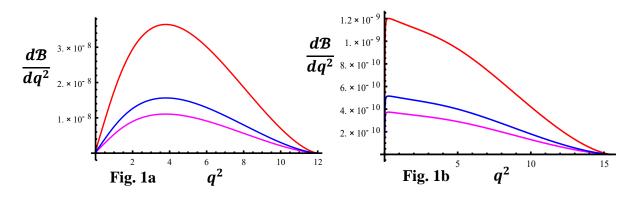


Fig. 1: Variation of differential branching ratio within allowed kinematic region of q^2 using the bound of NP couplings for (a) $B \to K_2^* \mu \tau$, (b) $B \to K_2^* e \mu$.

Kinematic	Differential branching ratio value		
region (q^2)	For $B \to K_2^* \mu \tau$ mode		
$(in \text{ GeV}^2)$	1^{st} Scenario (S_1)	2^{nd} Scenario (S_2)	$3^{\rm rd}$ Scenario (S_3)
In $q^2 = 2$	$(9.20 \pm 0.24) \times 10^{-9}$	$(3.28 \pm 0.32) \times 10^{-8}$	$(1.47 \pm 0.20) \times 10^{-8}$
$\ln q^2 = 6$	$(9.35 \pm 1.52) \times 10^{-9}$	$(3.46 \pm 1.63) \times 10^{-8}$	$(1.51 \pm 0.58) \times 10^{-8}$
In $q^2 = 10$	$(2.34 \pm 1.21) \times 10^{-9}$	$(7.59 \pm 3.25) \times 10^{-9}$	$(3.24 \pm 2.93) \times 10^{-9}$
	For $B \to K_2^* e \mu$ mode		
	1^{st} Scenario (S_1)	2^{nd} Scenario (S_2)	$3^{\rm rd}$ Scenario (S_3)
In $q^2 = 2$	$(3.76 \pm 0.02) \times 10^{-10}$	$(1.36 \pm 0.13) \times 10^{-9}$	$(5.13 \pm 0.21) \times 10^{-10}$
In $q^2 = 6$	$(2.90 \pm 1.20) \times 10^{-10}$	$(8.69 \pm 2.85) \times 10^{-10}$	$(3.88 \pm 1.35) \times 10^{-10}$
In $q^2 = 10$	$(1.54 \pm 1.21) \times 10^{-10}$	$(4.47 \pm 2.25) \times 10^{-10}$	$(2.14 \pm 1.80) \times 10^{-10}$

Table-2: Predicted values of differential branching ratios for LFV $B \rightarrow K_2^* \mu \tau$ and $B \rightarrow K_2^* e \mu$ decays in 1st, 2nd and 3rd scenarios

To probe the Z' contribution in the decay modes we have investigated the variation of forward backward asymmetries with respect to whole kinematic region. We have previously studied the observable in NP for LFV bottom baryonic and mesonic decays [32, 33]. We have studied the variation of forward-backward asymmetries in the Z' model in the allowed q^2 region in Fig. 2a and Fig. 2b for $B \to K_2^* \mu \tau$ and $B \to K_2^* e \mu$ channels respectively. The colour

description of the figures is similar to the previous ones. The change in the zero crossing positions interpret the sensitivity of Z' boson on these LFV decays. According to the Figs. 2, the zero crossing point of $B \rightarrow K_2^* \mu \tau$ decay channel is at $q^2 = 7.585 \text{ GeV}^2$ for 1st scenario, at $q^2 = 4.148 \text{ GeV}^2$ for 2nd scenario and at $q^2 = 5.614 \text{ GeV}^2$ for 3rd scenario. The observable is negative for low q^2 region and attained the maximum value at high q^2 region. Here, we observe that the zero crossings gradually shift towards the origin with the increment of NP contributions. Similar to differential branching ratios the forward backward asymmetries also have different nature for $B \rightarrow K_2^* e\mu$ decay channel. Here, the observable has very small negative value at low q^2 region and the variation is mainly positive throughout the kinematic region. The zero crossing point of $B \rightarrow K_2^* e\mu$ decay channel is at $q^2 = 0.748 \text{ GeV}^2$ for 1st scenario, at $q^2 = 0.502 \text{ GeV}^2$ for 2nd scenario and at $q^2 = 0.592 \text{ GeV}^2$ for 3rd scenario. The zero crossing series value with more Z' contributions in this $B \rightarrow K_2^* e\mu$ channel. The zero crossing are located clearly in Fig. 3a and Fig. 3b for $B \rightarrow K_2^* \mu \tau$ and $B \rightarrow K_2^* e\mu$ channels respectively. The values of the forward-backward asymmetries are calculated and represented in Table-3.

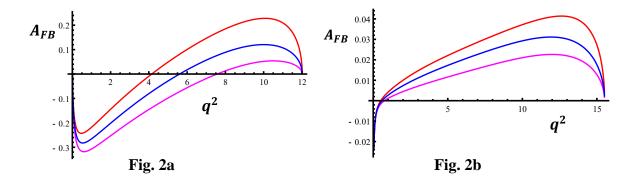


Fig. 2: Variation of forward backward asymmetries within allowed kinematic region of q^2 using the bound of NP couplings for (a) $B \to K_2^* \mu \tau$, (b) $B \to K_2^* e \mu$.

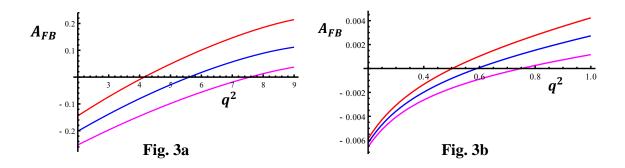


Fig. 3: Variation of forward backward asymmetries within allowed kinematic region of q^2 using the bound of NP couplings for (a) $B \to K_2^* \mu \tau$, (b) $B \to K_2^* e \mu$ to locate zero crossing points.

decays in 1 st , 2 nd and 3 rd scenarios				
Kinematic	Forward backward asymmetry value			
region (q^2)	For $B \to K_2^* \mu \tau$ mode			
$(in \text{ GeV}^2)$	1^{st} Scenario (S_1)	2^{nd} Scenario (S_2)	$3^{\rm rd}$ Scenario (S_3)	
$\ln q^2 = 2$	-0.250 ± 0.030	-0.142 ± 0.002	-0.200 ± 0.021	
$\ln q^2 = 6$	-0.056 ± 0.009	0.105 ± 0.010	0.019 ± 0.007	
$\ln q^2 = 10$	0.054 ± 1.206	0.229 ± 0.221	0.125 ± 0.111	
	For $B \to K_2^* e\mu$ mode			
	1^{st} Scenario (S_1)	2^{nd} Scenario (S_2)	3^{rd} Scenario (S_3)	
$\ln q^2 = 2$	0.005 ± 0.001	0.011 ± 0.002	0.008 ± 0.002	
$\ln q^2 = 6$	0.014 ± 0.010	0.026 ± 0.010	0.021 ± 0.010	
$\ln q^2 = 10$	0.022 ± 0.019	0.038 ± 0.028	0.031 ± 0.029	

Table-3: Predicted values of forward asymmetries for LFV $B \rightarrow K_2^* \mu \tau$ and $B \rightarrow K_2^* e \mu$ decays in 1st, 2nd and 3rd scenarios

VI. Conclusion:

The lepton flavour non-universality in $b \rightarrow s l^+ l^-$ transitions has been the tantalizing sector to probe NP over the years. Recently the accelerators have studied the LFV $h \rightarrow \mu \tau$ decays which becomes a clear cut hint for BSM physics to explore. If we have a look on PDG, we can see several updated measurements on LFV decays which enthuse the theoretical community to study the lepton flavour violation in various NP models as well as in model independent way. Previously we have found the NP LFV couplings [32] and studied the $b \rightarrow sl_1^-l_2^+$ decays in the refs. [32, 33]. In this work, we have chosen the excited state of K^* meson with spin two. The lepton flavour conserving and violating decays of this K_2^* meson are previously studied with effect of vector leptoquark [45, 79]. We have studied the LFV $B \to K_2^* \mu \tau$ and $B \to K_2^* e \mu$ channels in the non-universal Z' model. Here, we have calculated the branching ratio values and forward backward asymmetries for these decays. The NP couplings which are constrained in the ref. [32] have provided fruitful results and have shown the sensitivity of the Z' boson in the channel. The variation of the observables over the whole kinematic region shows that the 2nd scenario provides the maximum values of the observables which infers the clear cut signature of the NP. Here, the change in zero crossing positions with respect to three scenarios conveys the responsivity of NP in the decays. From the Fig. 3a and Fig. 3b, we see that the zero crossings approach the origin with the increment of contribution of non-universal Z'boson. Therefore, it can be stated that the contribution of Z' boson flips the value of A_{FB} faster and it attains the maximum value at high q^2 regime. Another thing we observe from the Fig. 1, 2, 3 that the nature of the observables for $B \to K_2^* \mu \tau$ decay channel is quite different from $B \rightarrow K_2^* e \mu$ decay channel due to the difference in leptonic masses. This variance of character probes the NP on the LFV decays.

The authors in ref. [45] have studied the $B \to K_2^* \mu \tau$ decay channel and calculated the maximum value of branching ratio over whole kinematic region as 1.64×10^{-7} in vector leptoquark model whereas the average values of the branching ratios are calculated as (0.63×10^{-8}) for 1st scenario, (2.09×10^{-8}) for 2nd scenario and (0.89×10^{-8}) for 3rd scenario in non-universal Z' model. The maximum value of forward backward asymmetry for $B \to K_2^* \mu \tau$ decay is calculated as (-0.347) with the contribution of vector leptoquark. On the other hand, the average values of A_{FB} are constrained in non-universal Z' model as (-0.086) for 1st scenario, 0.053 for 2nd scenario and (-0.025) for 3rd scenario. These decays are not studied so far at experiments. The study of these LFV decays in various NP models establishes BSM physics. It can be expected that the new run of LHCb and Belle II experiments will inspect the lepton flavour violation more accurately and will be able to observe the contribution of the NP particles. We hope that the results obtained in Table-2, 3 and 4 will be very useful to the investigation in near future.

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Appendix A

Expressions of transversity amplitudes:

The transversity amplitudes can be represented as

$$A_{L,R}^{0} = N \frac{\sqrt{\lambda}}{2\sqrt{6}m_{B}m_{K_{2}^{*}}^{2}\sqrt{q^{2}}} \bigg[(C_{9}^{NP} \mp C_{10}^{NP}) \bigg\{ (m_{B}^{2} - m_{K_{2}^{*}}^{2} - q^{2})(m_{B} + m_{K_{2}^{*}})A_{1} \\ - \frac{\lambda}{(m_{B} + m_{K^{*}})}A_{2} \bigg\} \bigg], \qquad (A1)$$

$$A_{L,R}^{\perp} = -\sqrt{2}N \frac{\sqrt{\lambda}}{\sqrt{8}m_B m_{K_2^*}} \left[(C_9^{NP} \mp C_{10}^{NP}) \frac{\sqrt{\lambda}V}{(m_B + m_{K_2^*})} \right], \tag{A2}$$

$$A_{L,R}^{\parallel} = \sqrt{2}N \frac{\sqrt{\lambda}}{\sqrt{8}m_B m_{K_2^*}} \left[(C_9^{NP} \mp C_{10}^{NP}) (m_B + m_{K_2^*}) A_1 \right], \tag{A3}$$

$$A_L^t = N \frac{\lambda}{\sqrt{6}m_B m_{K_2^*} \sqrt{q^2}} \left[(C_9^{NP} \mp C_{10}^{NP}) A_0 \right], \tag{A4}$$

where the normalization constant is defined as

$$N = \sqrt{\frac{G_F^2 \alpha_e^2 |V_{tb} V_{ts}^*|^2 q^2}{3 \times 2^{10} m_B^3 \pi^5}} \beta_+ \beta_- \sqrt{\lambda} \mathcal{B}(K_2^* \to K\pi) .$$

The Kallen function can be expressed as $\lambda(m_B^2, m_{K_2^*}^2, q^2) = m_B^4 + m_{K_2^*}^4 + q^4 - 2(m_B^2 m_{K_2^*}^2 + m_B^2 q^2 + m_{K_2^*}^2 q^2).$

Appendix B

The q^2 dependent form factors are parameterized by the light cone QCD sum rule as

$$F^{B_q T}(q^2) = \frac{\sum_{n=0}^{1} \alpha_n^F \{ z(q^2) - z(0) \}^n}{1 - \left(\frac{q^2}{m_{R,F}^2}\right)} .$$
(B1)

Where $z(q^2) = \frac{\sqrt{t_+ - s} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - s} + \sqrt{t_+ - t_0}}$, $t_{\pm} = (m_B + m_{K_2^*})^2$ and $t_0 = t_+(1 - \sqrt{1 - t_-/t_+})$. Here, the term $m_{R,F}$ is known as the resonance mass associated with the corresponding quantum number of the form factor. The fitted values of α_n^F are tabulated below.

α_n^F	$lpha_0$	α1
V	$0.22^{+0.11}_{-0.08}$	$-0.90\substack{+0.37\\-0.50}$
A ₀	$0.30\substack{+0.06\\-0.05}$	$-1.23^{+0.23}_{-0.23}$
<i>A</i> ₁	$0.19^{+0.09}_{-0.07}$	$-0.46^{+0.19}_{-0.25}$
<i>A</i> ₂	$0.11^{+0.05}_{-0.06}$	$-0.40^{+0.23}_{-0.16}$

The uncertainties which arise in the form factors are a result of variation of the input parameters associated with the light cone sum rule (LCSR) calculation. Among the various input parameters, the non-perturbative parameters along with the continuum threshold chiefly contribute to these uncertainties [47].

Appendix C

The polarization state of K_2^* meson $\epsilon^{\mu\nu}(n)$ can be written as

$$\epsilon_{\mu\nu}(\pm 2) = \epsilon_{\mu}(\pm 1)\epsilon_{\nu}(\pm 1),$$

$$\epsilon_{\mu\nu}(\pm 1) = \frac{1}{\sqrt{2}} [\epsilon_{\nu}(\pm)\epsilon_{\nu}(0) + \epsilon_{\nu}(\pm)\epsilon_{\mu}(0)],$$

$$\epsilon_{\mu\nu}(0) = \frac{1}{\sqrt{6}} [\epsilon_{\mu}(\pm)\epsilon_{\nu}(-) + \epsilon_{\nu}(\pm)\epsilon_{\mu}(-)] + \sqrt{\frac{2}{3}}\epsilon_{\mu}(0)\epsilon_{\nu}(0),$$
 (C1)

where the spin-1 polarization vectors are represented as

$$\epsilon_{\mu}(0) = \frac{1}{m_{K_{2}^{*}}} (\vec{k}_{z}, 0, 0, k_{0}), \qquad \epsilon_{\mu}(\pm) = \frac{1}{\sqrt{2}} (0, 1, \pm i, 0).$$
(C2)

Here, in this work the helicity states of K_2^* meson $n = \pm 2$ is not realized and a polarization vector is newly introduced as

$$\epsilon_{T_{\mu}}(h) = \frac{\epsilon_{\mu\nu}p^{\nu}}{m_B}$$

The expressions of polarization vectors are explicitly structured as

$$\epsilon_{T_{\mu}}(\pm 1) = \frac{1}{m_{B}} \frac{1}{\sqrt{2}} \epsilon(0) \cdot p \epsilon_{\mu}(\pm) = \frac{\sqrt{\lambda}}{\sqrt{8}m_{B}m_{K_{2}^{*}}} \epsilon_{\mu}(\pm),$$

$$\epsilon_{T_{\mu}}(0) = \frac{1}{m_{B}} \sqrt{\frac{2}{3}} \epsilon(0) \cdot p \epsilon_{\mu}(0) = \frac{\sqrt{\lambda}}{\sqrt{6}m_{B}m_{K_{2}^{*}}} \epsilon_{\mu}(0).$$
(C3)

The term $\lambda(m_B^2, m_{K_2^*}^2, q^2)$ is already defined.

The virtual gauge boson also has three types of polarization states which are longitudinal, transverse and time-like. The components are defined below as

$$\epsilon_V^{\mu}(0) = \frac{1}{\sqrt{q^2}} (-|\vec{q}_z|, 0, 0, -q_0), \epsilon_V^{\mu}(\pm) = \frac{1}{\sqrt{2}} (0, 1, \pm i, 0), \epsilon_V^{\mu}(t) = \frac{1}{\sqrt{q^2}} (q_0, 0, 0, q_z), \quad (C4)$$

where $q^{\mu} = (q_0, 0, 0, q_z)$ is four momentum of gauge boson.

Appendix D

To study the decay distribution, we need the leptonic matrix elements along with the hadronic matrix elements. Here, we have used the strategy of the ref. [46, 80]. We can define the leptonic matrix elements as follows

$$\left\langle l_1(\lambda_1)\bar{l}_2(\lambda_2)\big|\bar{l}\Gamma^X l\big|0\right\rangle = \bar{u}(\lambda_1)\Gamma^X v(\lambda_2) = L(\lambda_1,\lambda_2).$$
(D1)

Here, the term Γ^X is the leptonic parts of the NP operators. The spinors are defined as

$$u_{\frac{1}{2}} = \begin{pmatrix} \sqrt{E_1 + m_1} \\ 0 \\ \sqrt{E_1 - m_1} \end{pmatrix}, u_{-\frac{1}{2}} = \begin{pmatrix} 0 \\ \sqrt{E_1 + m_1} \\ 0 \\ -\sqrt{E_1 - m_1} \end{pmatrix}, v_{-\frac{1}{2}} = \begin{pmatrix} 0 \\ \sqrt{E_2 - m_2} \\ 0 \\ -\sqrt{E_2 - m_2} \\ 0 \end{pmatrix}, v_{-\frac{1}{2}} = \begin{pmatrix} 0 \\ \sqrt{E_2 - m_2} \\ 0 \\ \sqrt{E_2 - m_2} \\ 0 \\ \sqrt{E_2 + m_2} \end{pmatrix}.$$
(D2)

We can define the leptonic energy terms as

 $E_{1,2} = \sqrt{m_{1,2}^2 + \lambda(m_1^2, m_2^2, q^2)/4q^2}$ and $E_1 + E_2 = \sqrt{q^2}$. The normalized spinors are:

$$\bar{u}(\lambda_1)u(\lambda_2) = \delta_{\lambda_1\lambda_2} 2m_1, \qquad \bar{v}(\lambda_1)v(\lambda_2) = -\delta_{\lambda_1\lambda_2} 2m_2$$

Along with all the expressions we have structured the leptonic helicity amplitudes as below.

$$L^{L,R}(1/2, 1/2, 0) = (m_{-}\beta_{+} \pm m_{+}\beta_{-})/2,$$

$$L^{L,R}(-1/2, -1/2, 0) = (m_{-}\beta_{+} \mp m_{+}\beta_{-})/2,$$

$$L^{L,R}(1/2, 1/2, 1) = (m_{+}\beta_{-} \pm m_{-}\beta_{+})/2,$$

$$L^{L,R}(-1/2, -1/2, 1) = (m_{+}\beta_{-} \mp m_{-}\beta_{+})/2,$$

$$L^{L,R}(-1/2, 1/2, 1) = -\sqrt{q^{2}}(\beta_{-} \pm \beta_{+})/\sqrt{2},$$

$$L^{L,R}(1/2, -1/2, 1) = -\sqrt{q^{2}}(\beta_{+} \pm \beta_{-})/\sqrt{2}.$$
(D3)

Here, $\beta_{\pm} = \sqrt{1 - \frac{(m_1 \pm m_2)^2}{q^2}}$ and $m_{\pm} = (m_1 \pm m_2)$. Other than these above written helicity amplitudes are zero.

Appendix E:

Table-8: values of other input parameters [72]		
Parameter	Values	
m_{μ}	(105.66 ± 0.0000024) MeV	
m_e	(0.51 ± 0.000000031) MeV	
$m_{ au}$	(1776.86 ± 0.12) MeV	
$m_{K_2^*}$	(1427.3 ± 1.5) MeV	
m_B	(5279.55 ± 0.26) MeV	
G_F	$(1.166 \pm 0.0000006) \times 10^{-5} \text{GeV}^{-2}$	
$ V_{tb} $	(1.019 ± 0.025)	
$ V_{ts} $	$(39.4 \pm 2.3) \times 10^{-3}$	

Table-8: Values of other input parameters [72]

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