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Lepton flavor non-universality in TAU sector

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Recently, the LHCb experiment has observed lepton flavor non-universality parameters R_K and R_{K^*} for exclusive $B \to (K, K^*)l^+l^-$ decay modes, respectively. These R_K and R_{K^*} are the ratios of branching fraction of μ-channel to e-channel for the corresponding decay modes and are found to have ~3 σ deviation from their standard model (SM) values. Here, we are interested to study the exclusive decay mode $B \to K\tau^+\tau^-$ and predict the branching ratio in the SM and also in one new physics model, i.e., the non-universal Z' model. We also look towards the ratios of branching fractions of τ-channel to μ- and e-channels, i.e., $R_K^{\tau\mu}$ and $R_K^{\tau e}$ respectively, to find out whether any lepton flavor non-universality is present in τ sector. As the decay channels like $B \to K, K^*$ having τ leptons in their final states are still out of the experimental reach, so we hope our predictions could give a new approach for the search of τ-channels as well as the existence of lepton flavor non-universality.

Keywords: Exclusive B decays, Non-universal $\boldsymbol{Z'}$ model, Lepton flavor non-universality, New physics

1 Introduction

The rare semileptonic decays of B meson such as $B \to Ml^+l^-$ $(M = K, K^*, \phi, K_1, X_{s,d}, \text{etc.})$ induced by $b \to s$ quark transition are allowed at loop level in the standard model (SM) through GIM mechanism. These decays are relatively clean compared to the pure hadronic transitions and also expected to be promising probe of new physics (NP). In this work, we have considered one of the exclusive modes, i.e., $B \to Kl^+l^-$ (where, $l = e, \mu, \tau$) as this channel is found to be quite fascinating in recent times. The experimental values provided by the LHCb[1] and the SM values[2] for branching ratio of the decay channel $B \to Kl^+l^- (l = e, \mu)$ are given as:

$\mathcal{B}(B \to Kl^+l^-)_{SM} = (0.35 \pm 0.12) \times 10^{-6}$,

$\mathcal{B}(B \to K\mu^+\mu^-)_{Exp} = (3.39 \pm 0.34) \times 10^{-7}$ and

$\mathcal{B}(B \to Ke^+e^-)_{Exp} = (1.6^{+1.0}_{-0.8}) \times 10^{-7}$

On the other hand detail study of $B \to K\tau^+\tau^-$ mode is still out of the theoretical attention and is also far away from the experimental confirmation. There is only an experimental upper limit given by BaBar collaboration[3] which is $\mathcal{B}(B \to K\tau^+\tau^-) \le 2.25 \times 10^{-3}$.

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The experimental value[4] of the ratio of branching fraction of μ- to e- channel for $B \to Kl^+l^-$ decay mode (R_K) is found to have a noticeable deviation of ~2.6 σ from its SM value. This anomaly in R_K provides significant hint to lepton flavor universality violation (LFUV).

Here, we are interested to study the $B \to K\tau^+\tau^-$ decay mode. Another light dileptonic channels are well measured, the τ leptons are expected to be the keyhole of explanation of various anomalies and a possible way to probe NP. In this work, we have predicted the branching ratio for the above stated decay channel in the SM by considering dispersion quark model. After that we have implemented a new model, i.e., family non-universal Z' model to find out the branching ratio and compared the value with that of the SM. In analogous with the ratio R_K we have defined another two ratios $R_K^{\tau e}$ and $R_K^{\tau\mu}$ which are also expected to be sensitive to (LFUV).

2 Theoretical Formulation

In the SM, neglecting the doubly cabibo - supressed contributions, the effective Hamiltonian[5] describing the $b \to sl^+l^-$ transitions can be written as:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu), \qquad \text{... (1)}$$

For particular to our study the effective Hamiltonian leads to the following form:

$$\mathcal{H}_{eff}(b \to sl^+l^-) = \frac{G_F}{\sqrt{2}}\frac{\alpha_{em}}{2\pi}V_{tb}V_{ts}^*[-2\frac{C_{7\gamma}(m_b)}{q^2}((m_b+m_s)(\bar{s}i\sigma_{\mu\nu}q^\nu b) + (m_b-m_s)(\bar{s}i\sigma_{\mu\nu}q^\nu\gamma_5 b))(\bar{l}\gamma^\mu l) + C_{9V}^{eff}(m_b,q^2)(\bar{s}\gamma_\mu(1-\gamma_5)b)(\bar{l}\gamma^\mu l) + C_{10A}(m_b)(\bar{s}\gamma_\mu(1-\gamma_5)b)(\bar{l}\gamma^\mu\gamma_5 l)]. \quad \ldots (2)$$

Now from the matrix elements of $B \to Kl^+l^-$ we calculate the double differential decay width[6] which is given as:

$$\frac{d^2\Gamma(\mathrm{B}\to\mathrm{K}l^+l^-)}{d\hat{s}d\hat{t}} = \frac{G_F^2M_B^5|V_{ts}^*V_{tb}|^2\alpha_{em}^2}{265\pi^5}[-\widehat{\Pi}\beta_P + 2\widehat{m}\delta_P], \quad \ldots (3)$$

Where,

$$\beta_P = |C_{9V}^{eff}(m_b,q^2)f_+(q^2) + 2(m_b+m_s)C_{7\gamma}(m_b)s(q^2)|^2 + |C_{10A}(m_b)f_+(q^2)|^2 \quad \ldots (4)$$

$$\widehat{\Pi} = (\hat{t}-1)(\hat{t}-\hat{r}) + \hat{s}\hat{t} + \widehat{m}(1+\hat{r}+\widehat{m}-\hat{s}-2\hat{t}) \quad \ldots (5)$$

$$\delta_P = |C_{10A}|^2\left\{\left(1+\hat{r}-\frac{\hat{s}}{2}\right)|f_+(q^2)|^2 + (1-\hat{r})Re[f_+(q^2)f_-^*(q^2)] + \frac{\hat{s}}{2}|f_-(q^2)|^2\right\} \quad \ldots (6)$$

With, $\hat{r} \equiv (M_K/M_B)^2$, $\widehat{m} \equiv (m_l/M_B)^2$ and $\hat{s} = q^2/M_B^2$ (q^2 is the dilepton mass squared). After integrating over the variable $\hat{t}$ we have got the differential decay rate:

$$\frac{d\Gamma(B\to Kl^+l^-)}{d\hat{s}} = \frac{G_F^2M_B^5|V_{ts}^*V_{tb}|^2\alpha_{em}^2}{1536\pi^5}\left[\sqrt{1-\frac{4\widehat{m}}{\hat{s}}}\lambda^{\frac{1}{2}}(1,\hat{s},\hat{r})\beta_P + 12\widehat{m}\delta_P\right] \quad \ldots (7)$$

Here,

$$\lambda(1,\hat{s},\hat{r}) = 1+\hat{r}^2+\hat{s}^2-2\hat{r}-2\hat{s}-2\hat{r}\hat{s}$$

The form factors $f_+(q^2), f_-(q^2)$ and $s(q^2)$are taken from GI-OGE model fit[6].

In the presence of non-universal Z', Hamiltonian for FCNC transitions could be written as:

$$\mathcal{H}_{eff}^{Z'} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left[\Lambda_{sb}C_9^{Z'}O_9 + \Lambda_{sb}C_{10}^{Z'}O_{10}\right] \ldots (8)$$

Where, $\Lambda_{sb} = \frac{4\pi e^{-i\phi_{sb}}}{\alpha_{em}V_{tb}V_{ts}^*}$, $C_9^{Z'} = |B_{sb}|S_{ll}^{LR}$, $C_{10}^{Z'} = |B_{sb}|D_{ll}^{LR}$ with, $S_{ll}^{LR} = B_{ll}^L + B_{ll}^R$, $D_{ll}^{LR} = B_{ll}^L - B_{ll}^R$

Here, B_{sb} corresponds to off diagonal left-handed coupling of Z' with quarks, B_{ll}^L and B_{ll}^R are left- and right-handed couplings for Z' with leptons, ϕ_{sb} is the new weak phase angle. The most useful feature of Z' model is that the operator basis remains same as in the SM; only the modifications are done for C_9 and C_{10} while $C_{7\gamma}$ remains unchanged. The new Wilson coefficients C_9 and C_{10} with the total contributions of SM and Z' model are written as:

$$\left.\begin{aligned} C_9^{Total} &= C_9^{eff} + C_9^{NP} \\ C_{10}^{Total} &= C_{10} + C_{10}^{NP} \end{aligned}\right\} \quad \cdots (9)$$

Where, $C_9^{NP} = \Lambda_{sb}C_9^{Z'}$ and $C_{10}^{NP} = \Lambda_{sb}C_{10}^{Z'}$

The numerical values of the Z' couplings suffer from several constraints which arise due to different exclusive and inclusive B decays. We have used three scenarios in our calculation, corresponding to three different fitting values of $B_s - \bar{B}_s$ mixing data which present the couplings as well as the weak phase angle. The numerical values of input parameters are set by UTfit collaborations[8] and recollected in Table 1.

3 Results and Discussion

We have predicted the branching ratio for $B \to K\tau^+\tau^-$ channel in the SM by integrating the Eq. (7) over the range $14 < q^2 < q_{max}^2$ and then multiplying it with the lifetime of B meson. Next we have implicated the Z' model by considering the relations given in Eq. (9) and calculated the branching ratio in the Z' model also. The results are summarized in Table 2.

Figure 1 depicts the variation of branching ratio of $B \to K\tau^+\tau^-$channel with $\hat{s}$ which shows a clean peak around $\hat{s} = m_{\psi'}^2/M_B^2 \sim 0.49$. This peak is due to the uncertainty coming from charm loop contribution.

As described in section 1, we define the lepton flavor non-universality parameter as:

Table 1 — Input values of Z' parameters.

	$\|B_{sb}\| \times 10^{-3}$	ϕ_{sb} (Deg.)	$S_{LL} \times 10^{-2}$	$D_{LL} \times 10^{-2}$
$\mathcal{S}_1$	1.09 ± 0.22	-72 ± 7	-2.8 ± 3.9	-6.7 ± 2.6
$\mathcal{S}_2$	2.20 ± 0.15	-82 ± 4	1.2 ± 1.4	-2.5 ± 0.9
$\mathcal{S}_3$	4.0 ± 1.5	150 ± 10 (or -150 ± 10)	0.8	-2.6

Table 2 — Branching ratio × 10^{-7} for the decay channel $B \to K\tau^+\tau^-$.

SM result	Z' model			Expt. result
	$\mathcal{S}_1$	$\mathcal{S}_2$	$\mathcal{S}_3$	
1.132	2.197-2.289	1.786-1.939	0.565-0.881	[3]

$$R_K^{\tau l} = \frac{\mathcal{B}(B \to K\tau^+\tau^-)}{\mathcal{B}(B \to Kl^+l^-)} (l = e \text{ or } \mu).$$

While, measuring this parameter it is observed that $R_K^{\tau l} > 1$ which shows a certain violation of $\tau - \mu$ as well as $\tau - e$ universality. Authors of literature[9] have predicted these ratios in the SM as:

$$R_K^{\tau\mu} = 1.158(39), R_K^{\tau e} = 1.161(40),$$
$$R_K^{\tau l} = 1.159(40)$$

Within the range $14.18\,\text{GeV}^2$ to q^2_{max}. We have predicted these two parameters in the SM as well as in Z' model and presented the results in Table 3.

From the results of Table 3, we can see that when we consider the Z' contribution only in τ-sector the ratios is enhanced for first two scenarios. In third scenario, the branching ratio for $B \to K\tau^+\tau^-$ is reduced (Table 2) and thus the ratio is also decreased. Whereas, considering the NP contribution to all three lepton sectors, the results indicate that ditau channel has larger NP effect than other two dileptonic channels for second scenario of the Z' model with maximum parametric values (Table 1). Therefore, the measurements of $R_K^{\tau\mu}$ and $R_K^{\tau e}$ in future will help to either confirm or discard our model as a viable description of the LFUV.

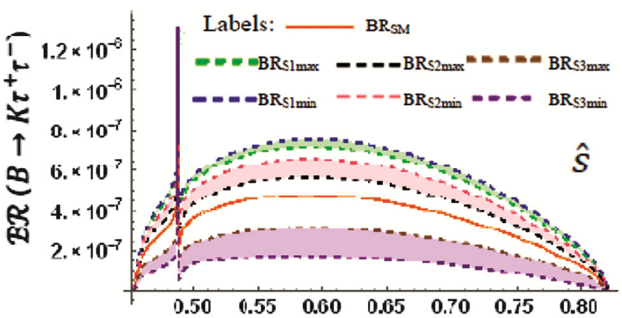

Fig. 1 — Variation of branching ration with ŝ.

Table 3 — Numerical results of $R_K^{\tau\mu}$, $R_K^{\tau e}$

		$R_K^{\tau\mu}$	$R_K^{\tau e}$
SM result		1.318	1.323
Z' effect only in τ-sector	S_{1max}	1.941	1.949
	S_{1min}	2.022	2.03
	S_{2max}	1.578	1.584
	S_{2min}	1.713	1.719
	S_{3max}	0.778	0.781
	S_{3min}	0.499	0.501
Z' effect in all three lepton (e, μ, τ) sector	S_{1max}	1.293	1.298
	S_{1min}	1.269	1.273
	S_{2max}	1.351	1.356
	S_{2min}	1.275	1.279
	S_{3max}	1.286	1.291
	S_{3min}	1.395	1.4

4 Conclusions

From the above study we can conclude that the decay channels which include tau leptons in its final state are very difficult to examine as τ leptons decay very quickly. So experimentalists need a high precision machine to discover these decay modes. In our work, we have predicted the branching ratio of $B \to K\tau^+\tau^-$ channel in the SM as well as in the Z' model. We have taken the kinematical region above 14 GeV^2 as the uncertainty could be reduced at high q^2 region for both ditau and other light dileptonic channels. In this low recoil regime, the branching ratio is enhanced for first two scenarios of Z' model and reduced in third case. So, we are in favour of neglecting the third scenario. We have also predicted two lepton flavor non-universality parameters $R_K^{\tau\mu}$ and $R_K^{\tau e}$ and found that there is a significant hint for LFUV. We have also noted that the NP effect might be slightly larger for tau leptons than electron or muon. After gathering all the points on a single note we can say that the search of tau leptons could enlighten many new facts about the physics beyond the SM. We hope that the Z' searches at LHC could provide some new information about the processes which are still away from experimental reach due to lack of precise measurements.

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References

1 Tanabashi M, et al, (Particle Data Group), *Phys Rev D,* 98 (2018) 030001.
2 Ali A, Lunghi E, Greub C & Hiller G, *Phys Rev D*, 66 (2002) 034002.
3 Lees J P, et al, (BaBar Collaboration), *Phys Rev Lett*, 118 (2017) 031802.
4 Aaij R et al, (LHCb Collaboration), *Phys Rev Lett*, 113 (2014) 151601.
5 Grinstein B, Savage M J & Wise M B, *Nucl Phys B*, 319 (1989) 271.
6 Melikhov D, Nikitin N & Simula S, *Phys Rev D*, 57 (1998) 6814.
7 Ahmed I & Rehman A, *Chin Phys C*, 42 (2018) 063103.
8 Bona M, et al, (UTfit collaborations), *PMC Phys A*, 3 (2009) 6.
9 Bouchard C, Lepage G P, Monahan C, Na H & Shigemitsu J (HPQCD Collaboration), *Phys Rev Lett*, 111 (2013) 162002.