6
Correlation between Br($B_s^* \to \tau^+\tau^-$) and $R_{D,D^*,J/\psi}$ anomaly

6.1 Introduction

In chapters 4 and 5, we have been focusing on new physics in $b \to sl^+l^-$ sector. As pointed out in chapter 2, there are a number of anomalous measurements in the charged current $b \to c\tau\bar{\nu}$ sector as well:

1. The current world average of the ratio $R_D = \mathcal{B}(B \to D\,\tau\,\bar{\nu})/\mathcal{B}(B \to D\{e/\mu\}\,\bar{\nu})$, measured by BaBar and Belle, deviates 2.3σ from the SM prediction [189]

2. There is a series of measurements of the ratio $R_{D^*} = \mathcal{B}(B \to D^*\,\tau\,\bar{\nu})/\mathcal{B}(B \to D^*\{e/\mu\}\,\bar{\nu})$ by BaBar, Belle and LHCb experiments. Recent world average of R_{D^*} shows a discrepancy with respect to the SM prediction at a level of 3.4σ. Including the measurement correlation between R_D and R_{D^*}, the current experimental world averages of $R_{D^{(*)}}$ show a $\sim 4\sigma$ deviation from the SM predictions [189]

3. The measured value of $R_{J/\psi} = \mathcal{B}(B \to J/\psi\,\tau\,\bar{\nu})/\mathcal{B}(B \to J/\psi\mu\,\bar{\nu})$ by LHCb collaboration, is 1.7σ away from its SM prediction [60].

The quark level transition $b \to c\tau\bar{\nu}$ occurs at tree level in the SM. The new physics operators which can account for $R_{D^{(*)}}$ anomaly are identified in ref [87]. In Ref. [89] it was shown that there are only four independent new physics solutions which can explain the present data in the $b \to c\tau\bar{\nu}$ sector. Methods to discriminate between these new physics solutions were suggested in Ref. [90]. The new physics WCs of these solutions are about 10% of the SM values. Since this transition occurs at tree level in the SM, it is very likely that the new physics operators also occur at tree level. In the SM, the relation between the interaction eigenstates and mass eigenstates leads to the cancellation of FCNCs at tree level through GIM mechanism. However the relation between the interaction eigenstates of new physics and the mass eigenstates need not be the same as that in the SM. In such a situation, the new physics will lead to tree level neutral current $b \to sl^+l^-$ transitions. In Ref. [212], a model is constructed where the tree level FCNC terms due to new physics are significant for $b \to s\,\tau^+\,\tau^-$ but are suppressed for $b \to sl^+l^-$ where $l = e$ or $l = \mu$. The branching ratios for the decay modes such as $B \to K^{(*)}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$ and $B_s \to \phi\tau^+\tau^-$ will have a large enhancement in this model [212].

On the experimental front, as of now, we only have upper bounds on the decays induced by the quark level transition $b \to s\,\tau^+\,\tau^-$. The current upper bound on the branching ratio of $B_s \to \tau^+\tau^-$ is 6.8×10^{-3} [213] whereas for the semileptonic decay $B \to K\tau^+\tau^-$, the current upper bound is 2.25×10^{-3} [214]. These bounds are weak, however, there are bright experimental prospects for these decays at LHCb and Belle II. On the theoretical side, $b \to s\,\tau^+\,\tau^-$ sector has received less attention. The branching ratio of $B_s \to \tau^+\tau^-$ is known precisely in the SM whereas other decay modes, in particular semileptonic decays are less explored.

In this chapter, we study the effects of new model of Ref. [212] on the branching ratio of $B_s^* \to \tau^+\tau^-$ and the τ polarization asymmetry $\mathcal{A}_{LP}(\tau)$. The impact of tree level new physics on the branching ratio of $B_s^* \to \tau^+\tau^-$ and $\mathcal{A}_{LP}(\tau)$ is studied in the next section whereas the conclusions are presented in Sec. 6.3.

6.2 Effect of new physics in $B_s^* \to \tau^+\tau^-$

As mentioned in the introduction, anomalies are also observed in the $b \to c\tau\bar{\nu}$ transitions. An new physics model, which can account for these anomalies, is likely to contain new physics amplitude for $b \to s\tau^+\tau^-$ transition also. Hence the branching ratio of $B_s^* \to \tau^+\tau^-$ and τ longitudinal polarization asymmetry $\mathcal{A}_{LP}(\tau)$ will contain signatures of such new physics. In the SM, the predictions for these quantities are

$$\mathcal{B}(B_s^* \to \tau^+\tau^-) = (6.87 \pm 4.23) \times 10^{-12}, \tag{6.1}$$

$$\mathcal{A}_{LP}^+(\tau)|_{SM} = -\mathcal{A}_{LP}^-(\tau)|_{SM} = 0.8860 \pm 0.0006. \tag{6.2}$$

The authors of Ref. [212] constructed a model of new physics which accounts for the anomalies in $b \to c\tau\bar{\nu}$. This model contains tree level FCNC terms for $b \to s\,\tau^+\,\tau^-$ but not for $b \to sl^+l^-$ ($l = e, \mu$). Therefore, the WCs $C_9^{NP}(\mu\mu)$ and $C_{10}^{NP}(\mu\mu)$ have no relation to the WCs $C_9^{NP}(\tau\tau)$ and $C_{10}^{NP}(\tau\tau)$. The amplitude for $b \to s\mu^+\mu^-$ transition remains small enough that the constraints from R_K and R_{K^*} are satisfied. The WCs for the $b \to s\tau^+\tau^-$ transition have the form

$$\begin{aligned} C_9(\tau\tau) &= C_9^{SM} - C^{NP}(\tau\tau), \\ C_{10}(\tau\tau) &= C_{10}^{SM} + C^{NP}(\tau\tau), \end{aligned} \tag{6.3}$$

in this model, where

$$C^{NP}(\tau\tau) = \frac{2\pi}{\alpha}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{SM}}} - 1\right). \tag{6.4}$$

The ratio R_X/R_X^{SM} is the weighted average of current experimental values of R_D, R_{D^*} and $R_{J/\psi}$. From the current measurements of these quantities, we estimate this ratio to be $\simeq 1.22 \pm 0.06$. This, in turn, leads to $C^{NP}(\tau\tau) \sim \mathcal{O}(100)$. Thus the new physics contribution completely dominates the WCs and leads to greatly enhanced branching ratios for various B/B_s meson decays involving $b \to s\,\tau^+\,\tau^-$ transition [212].

In this framework, the effects of scalar/pseudoscalar and tensor new physics were neglected. This is because these operators are disfavoured by the current data in $b \to sl^+\,l^-$ ($l = e,\,\mu$) and $b \to c\tau\nu$ sectors. The global analysis of $b \to sl^+\,l^-$ data favours solutions in the form of vector and axial-vector operators. In $b \to c\tau\nu$ sector, the scalar operators are tightly constrained from the total lifetime of the B_c meson [117, 122, 215]. The tensor operators are disfavoured by the measurement of D^* polarization fraction in $B \to D^*\,\tau\,\bar{\nu}$ [196].

We calculate $\mathcal{B}(B_s^* \to \tau^+\tau^-)$ and $\mathcal{A}_{LP}(\tau)$ as a function of R_X/R_X^{SM}. The plot of $\mathcal{B}(B_s^* \to \tau^+\tau^-)$ $vs.$ R_X/R_X^{SM} is shown in left panel of Fig. 6.1. We note, from this plot, that $\mathcal{B}(B_s^* \to \tau^+\tau^-)$ can be enhanced up to 10^{-9} which is about three orders of magnitude larger than the SM prediction. The plot of $\mathcal{A}_{LP}(\tau)$ $vs.$ R_X/R_X^{SM} is shown in the right panel of Fig. 6.1. It can be seen that $\mathcal{A}_{LP}(\tau)$ is suppressed by about 5% in comparison to its SM value.

The recent data on $R_{D^{(*)}}$ [189] show less tension with the SM which leads to smaller values of R_X/R_X^{SM}. As long as this ratio is greater than 1.05, the branching ratio of $B_s^* \to \tau^+\tau^-$ is enhanced by an order of magnitude at least. When $R_X/R_X^{SM} \sim 1.01$, $\mathcal{A}_{LP}(\tau)$ exhibits some very interesting behaviour. In this case, the tree level FCNC new physics contribution is similar in magnitude to the SM contribution (which occurs only at loop level). Due to the interference between these two amplitudes, $\mathcal{A}_{LP}(\tau)$ changes sign and becomes almost (-1). Hence a measurement of this asymmetry provides an effective tool for the discovery of tree level FCNC amplitudes of this model [212] when their magnitude becomes quite small.

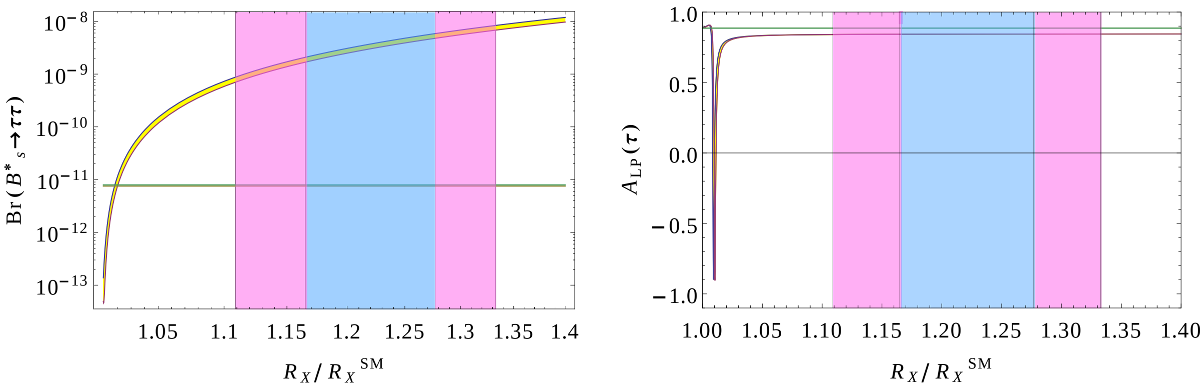

Figure 6.1: Left and right panels correspond to $\mathcal{B}(B_s^* \to \tau^+\tau^-)$ and $\mathcal{A}_{LP}(\tau)$ respectively. In both panels the yellow band represents 1σ range of these observables. The 1σ and 2σ ranges of R_X/R_X^{SM} are indicated by blue and pink bands respectively. The green horizontal line corresponds to the SM value.

6.3 Conclusions

We study the impact of the anomalies in $b \to c\tau\bar{\nu}$ transitions on the branching ratio of $B_s^* \to \tau^+\tau^-$ and $\mathcal{A}_{LP}(\tau)$. In Ref. [212], a model was constructed where tree level new physics leads to both $b \to s\tau^+\tau^-$ and $b \to c\tau\bar{\nu}$ with moderately large new physics couplings. Within this new physics model, we find that the present data in $R_{D^{(*)},J/\psi}$ sector imply about three orders of magnitude enhancement in the branching ratio of $B_s^* \to \tau^+\tau^-$ and a 5% suppression in $\mathcal{A}_{LP}(\tau)$ compared to their SM predictions. We also show that $\mathcal{A}_{LP}(\tau)$ undergoes drastic changes when the new physics amplitude is similar in magnitude to the SM amplitude.

To measure $\mathcal{A}_{LP}(\tau)$ in experiments, the final state leptons have to decay into secondary particles. But for muon, the measurement would be quite difficult as it does not decay within the detector. In the case of $\mathcal{A}_{LP}(\tau)$, it may be possible for LHCb to reconstruct τ where the τ decays into multiple hadrons. This technique has been already used to identify the τ leptons in $B \to D^*\tau\bar{\nu}$ decay. Therefore a precise reconstruction from the decay products of the τ is necessary to measure the τ longitudinal polarization asymmetry in $B_s^* \to \tau^+\tau^-$.