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Probing new physics in $B \to K^*\tau^+\tau^-$ decay

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We analyze the implications of current $b \to s\ell\ell$ ($\ell = e,\ \mu$) measurements on several observables under the assumption that the possible new physics can have both universal as well as nonuniversal couplings to leptons. For these new physics solutions, we intend to identify observables with large deviations from the Standard Model (SM) predictions as well as to discriminate between various new physics scenarios. For this we consider the $B \to K^*\tau^+\tau^-$ branching fraction, the longitudinal fraction, the tau forward-backward asymmetry and the optimized angular observables. Further, we construct the lepton-flavor differences ($Q_{\tau\mu}$) between these tau observables and their muonic counterparts in decay along with the lepton-flavor ratios ($R_{\tau\mu}$) of all of these observables. We find that the current data allows for deviations ranging from 25% up to an order of magnitude from the SM value in a number of observables. A precise measurement of these observables can also discriminate between a number of new physics solutions.

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1. Introduction

Measurements in decays resulting from the quark-level process $b \to s\ell^+\ell^-$, with ℓ being either an electron or a muon, exhibit promising indications of physics beyond the Standard Model (SM). These measurements are primarily associated with the decay modes of $B \to K^* \mu^+ \mu^-$ and $B_s \to \phi \mu^+ \mu^-$. However, a recent update from the LHCb Collaboration on December 20, 2022, which included previously missing systematic effects [1], has brought the measurements of R_K and R_{K^*} in line with the SM predictions [2, 3]. These updates disfavors the explanation of anomalies solely by introducing new physics within the muon sector. Instead, they point towards the need for couplings that are nearly universal in nature [4]. A legitimate question to ask at this stage is whether, in addition to universal couplings, the current data permits non-universal couplings as well. In this work, we explore this possibility and look for the possible implications of such framework in a number of observables in $B \to K^*\tau^+\tau^-$ decay [5]. The universal couplings will generate new physics effects in $b \to s\tau^+\tau^-$ decay as Wilson Coefficients (WCs) in e, μ and τ sectors being the same. Further, we also obtain bounds on lepton flavor universality violating (LFUV) observables in $\tau - \mu$ sector in the context of $B \to K^*\ell^+\ell^-$ ($\ell = \mu,\ \tau$) decays [5, 6].

2. Methodology

We consider a framework where apart from having nonuniversal couplings affecting only $b \to s\mu^+\mu^-$ decay, one can also have universal WCs equally affecting all $b \to s\ell\ell$ processes, $\ell = e,\ \mu,\ \tau$ [7]. We assume new physics in the form of vector and axial-vector for which the effective Hamiltonian for $b \to s\ell^+\ell^-$ decay can be written as

$$\begin{aligned} \mathcal{H}_{\text{eff}}^{\text{NP}} &= -\frac{\alpha_{\text{em}} G_F}{\sqrt{2}\pi} V_{ts}^* V_{tb} \Big[C_{9\ell} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell) + C_{10\ell} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \\ &\quad + C'_{9\ell} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell) + C'_{10\ell} (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \Big] + H.c.\ , \end{aligned}$$

where $C_{(9,10)\ell}$ and $C'_{(9,10)\ell}$ are NP WCs having both universal and non-universal components:

$$\begin{aligned} C_{(9,10)e} &= C_{(9,10)\tau} = C^U_{(9,10)}\ , \quad C'_{(9,10)e} = C'_{(9,10)\tau} = C'^U_{(9,10)}\ , \\ C_{(9,10)\mu} &= C^U_{(9,10)} + C^V_{(9,10)\mu}\ , \quad C'_{(9,10)\mu} = C'^U_{(9,10)} + C'^V_{(9,10)\mu}\ . \end{aligned}$$

Table 1 presents the 1σ range of WCs and their respective pull values for the favored scenarios, as determined in [8]. These values were derived through a comprehensive global fit to all available data, excluding measurements related to $\Lambda_b \to \Lambda\mu\mu$. In the same table, we also offer our fit results utilizing the methodology of ref. [9]. These results incorporate the recently updated measurements of R_K and R_{K^*} by the LHCb Collaboration in December 2022. Furthermore, we account for the revised world average of the branching ratio for $B_s \to \mu^+\mu^-$, considering the latest measurement from the CMS Collaboration [10]. Furthermore, our analysis incorporates observables from $b \to se^+e^-$ sector. For the sake of comparison, we present our fitting results based on data that predates the updates from December 2022. The comprehensive list of 179 observables used in the fitting process can be found in reference [5]. It is evident from Table 1 that the previously favored scenarios remain favored, albeit with smaller pull values. This outcome is in line with expectations, considering that the overall tension between experimental measurements and the SM has diminished.

Solutions	WCs	1σ range [8]	pull [8]	1σ range (old)	pull	1σ range (new)	pull
S-V	$C_{9\mu}^V$	(-1.02, -0.11)		(-0.98,0.003)		(-1.31, -0.53)	
	$C_{10\mu}^V$	(0.08, 0.84)	6.6	(0.15,0.97)	7.7	(-0.66 ,0.07)	4.5
	$C_9^U = C_{10}^U$	(-0.73, 0.07)		(-0.76,0.08)		(-0.13 ,0.58)	
S-VI	$C_{9\mu}^V = -C_{10\mu}^V$	(-0.59,-0.44)		(-0.60,-0.45)		(-0.33,-0.20)	
	$C_9^U = C_{10}^U$	(-0.56,-0.26)	6.9	(-0.44,-0.18)	7.7	(-0.43, -0.17)	4.1
S-VII	$C_{9\mu}^V$	(-1.07,-0.63)		(-1.15,-0.77)		(-0.43, -0.08)	
	C_9^U	(-0.52,0.01)	6.7	(-0.35,0.15)	7.4	(-1.07, -0.58)	5.5
S-VIII	$C_{9\mu}^V = -C_{10\mu}^V$	(-0.41,-0.27)		(-0.47,-0.32)		(-0.18, -0.05)	
	C_9^U	(-0.99,-0.63)	7.2	(-0.87,-0.45)	7.9	(-1.15,-0.77)	5.6
S-IX	$C_{9\mu}^V = -C_{10\mu}^V$	(-0.63,-0.43)		(-0.61, -0.43)		(-0.27,-0.12)	
	C_{10}^U	(-0.44,-0.05)	6.3	(-0.32,0.07)	7.4	(-0.09,0.27)	3.6
S-X	$C_{9\mu}^V$	(-1.13,-0.84)		(-1.10,-0.82)		(-0.72,-0.41)	
	C_{10}^U	(0.13,0.42)	6.9	(0.19,0.50)	7.8	(0.05,0.34)	4.6
S-XI	$C_{9\mu}^V$	(-1.20,-0.91)		(-1.23,-0.95)		(-0.82, -0.51)	
	$C_{10}^{\prime U}$	(-0.35,-0.10)	6.9	(-0.37,-0.16)	7.8	(-0.26,-0.04)	4.6
S-XIII	$C_{9\mu}^V$	(-1.27,-0.96)		(-1.27,-0.98)		(-0.96,-0.60)	
	$C_{9\mu}^{\prime V}$	(0.13,0.60)		(0.20,0.59)		(0.22,0.63)	
	C_{10}^U	(0.10,0.47)		(0.14,0.52)		(0.01,0.38)	
	$C_{10}^{\prime U}$	(-0.15,0.21)	6.7	(-0.17,0.14)	8.1	(-0.08,0.24)	5.1

Table 1: Allowed new physics solutions [8]. In our fit, the pull is defined as $\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm bf}}$ where $\chi^2_{\rm bf}$ is the χ^2 at the best-fit value in the presence of new physics and $\chi^2_{\rm SM}$ is the value of χ^2 in the SM. The value of $\chi^2_{\rm SM}$ is ≈ 217 before December 2022 (denoted by 'old'). In the updated fit (denoted by 'new'), the value of $\chi^2_{\rm SM}$ reduces to ≈ 184.

3. Results

Within this section, we present predictions for a range of observables in the context of $B \to K^*\tau^+\tau^-$ decays. These predictions encompass the SM expectations as well as various scenarios of new physics outlined in Table 1. Our objective is to investigate any deviations from the SM and to differentiate between various allowed beyond SM scenarios. The observables are classified into three categories: τ observables, $\tau - \mu$ lepton-flavor differences ($Q^{\tau\mu}$) and $\tau - \mu$ lepton-flavor ratios ($R^{\tau\mu}$). The τ observables include differential branching ratio of $B \to K^*\tau^+\tau^-$, f_L and A_{FB}. We also consider the optimized angular observables $P_{1,2,3}$ and $P'_{4,5,6,8}$. From these observables, we construct the $\tau - \mu$ lepton-flavor difference and ratio observables. These predictions are obtained using `flavio` [11] where the observables are preimplemented based on refs. [12, 13].

In Figure 1, we depict the graph illustrating the differential branching ratio for the $B \to K^*\tau^+\tau^-$ decay. Our findings suggest that none of the permissible scenarios can produce a significant increase in the branching fraction. However, for the S-VII and S-VIII solutions, there is a potential for a suppression of approximately 25% in the value of $\mathcal{B}(B \to K^*\tau^+\tau^-)$. Additionally, our analysis

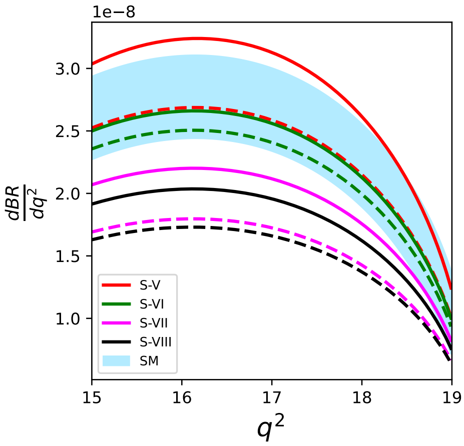

Figure 1: Plot for the q^2 distribution in the SM as well as for several new physics solutions for the branching fraction of $B \to K^*\tau^+\tau^-$. The light blue band is due to theoretical uncertainties. The thick and dotted lines represent maximum deviation from the SM for each new physics solutions.

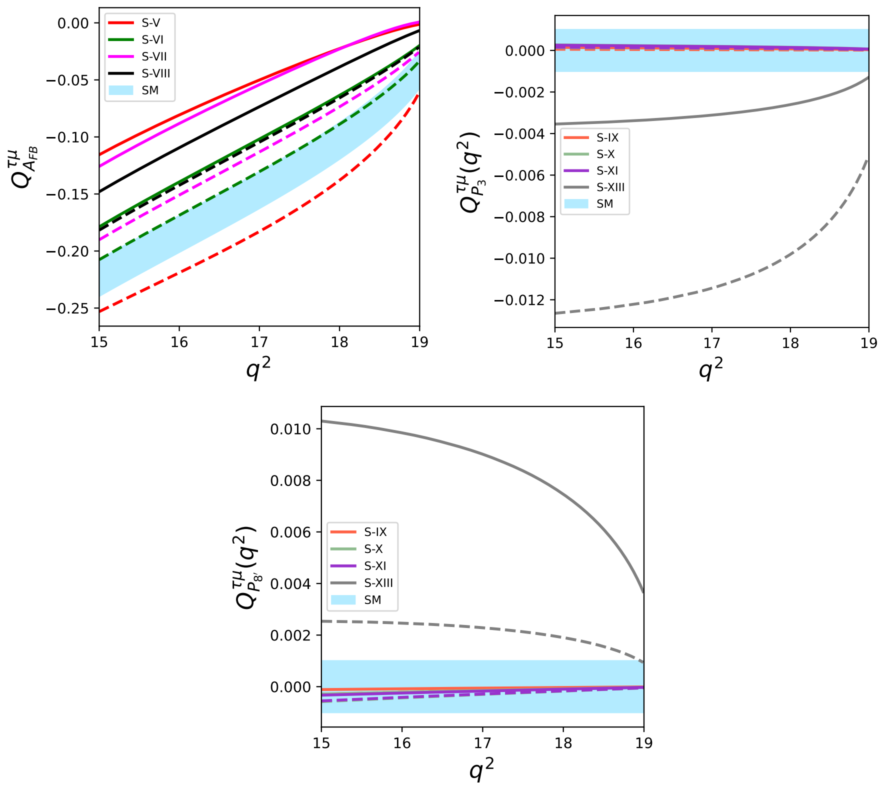

Figure 2: Plot for the q^2 distribution in the SM as well as for several new physics solutions for the $\tau - \mu$ lepton-flavor difference observables for the forward backward asymmetry A_{FB} and for P_3 and P_8'.

reveals that both the K^* longitudinal polarization fraction and the tau forward-backward asymmetry A_{FB} are predicted to be in close proximity to their SM predictions for all permissible solutions. Furthermore, we observe that there are no discernible new physics effects allowed in any of the optimized angular observables for any of the new physics scenarios.

We now shift our focus to the lepton-flavor difference observables $Q^{\tau\mu}$, and in Figure 2, we present predictions for some of these observables where significant deviations from the SM are possible. Notably, the observable $Q^{\tau\mu}_{A_{FB}}$ exhibits promising characteristics, as it can be enhanced compared to the SM predictions for the S-V and S-VII solutions. These solutions have the potential to elevate the value of $Q^{\tau\mu}_{A_{FB}}$ by up to twofold above its SM prediction. Furthermore, the S-XIII solution can induce an order of magnitude enhancement in the magnitudes of the $Q^{\tau\mu}_{P'_3}$ and $Q^{\tau\mu}_{P'_8}$ observables. Additionally, it also allows for a threefold increase in the magnitude of $Q^{\tau\mu}_{P'_4}$. However, deviations from the SM are negligible for the other solutions.

Finally, we consider $\tau - \mu$ lepton-flavor ratios of the branching fractions, the longitudinal fractions, the forward backward asymmetries and the $P_i^{(\prime)}$ angular observables in $B \to K^*\tau^+\tau^-$ and $B \to K^*\mu^+\mu^-$ decays. The prediction for these observables in the SM as well as for favored new physics solutions for which interesting deviations from SM are possible are given in Figure 3. It is

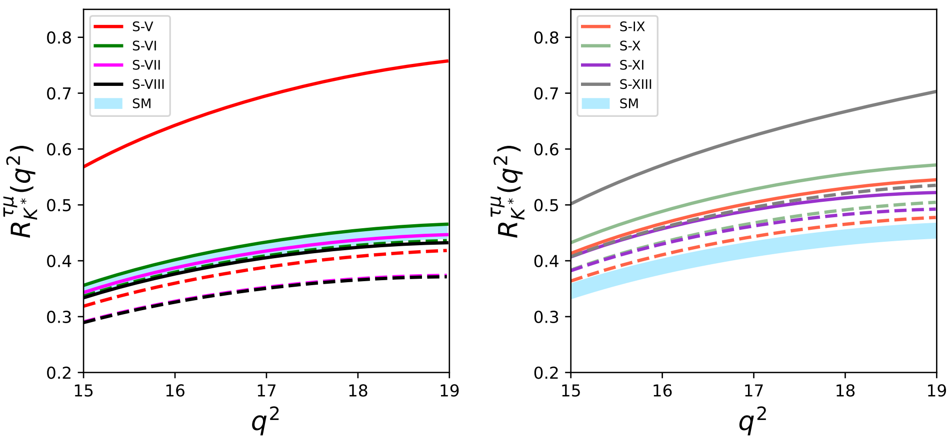

Figure 3: Plot for the q^2 distribution in the SM as well as for several new physics solutions for the $\tau - \mu$ lepton-flavor ratio observable for the the branching fraction.

apparent from Figure 3 that the S-V solution can engender largest enhancement in $R^{\tau\mu}_{K^*}$, by 60%, from the SM. The scenarios S-VII and S-VIII can suppress the value of $R^{\tau\mu}_{K^*}$, ~15% below the SM. The S-XIII solution can enhance $R^{\tau\mu}_{K^*}$ by ~40%. The S-IX, S-X and S-XI solutions can also induce enhancement in $R^{\tau\mu}_{K^*}$. However these enhancements cannot exceed by more than ~20%. Further, it can be espied from the right panel of Figure 3 that none of the solutions depicted in the figure can lead to suppression in $R^{\tau\mu}_{K^*}$ below the SM value. Further, we find that amongst the flavor ratio of optimized observables, $R^{\tau\mu}_{P_2}$ and $R^{\tau\mu}_{P'_5}$ can show maximum deviation, up to 25%, from the SM. This deviation is possible for new physics scenario S-V. For other ratios, only marginal deviation is allowed [5].

4. Conclusions

In our study, we investigate the impact of the most recent measurements in $b \to s\ell^+\ell^-$ decays, where ℓ can be either an electron or a muon, on a range of observables in the decay process

$B \to K^*\tau^+\tau^-$. We consider the possibility that new physics contributions in $b \to s\ell^+\ell^-$ can have both universal and non-universal couplings to leptons. Our analysis is conducted in a model-independent manner using the framework of effective field theory. The primary objective of this work is twofold. Firstly, we aim to pinpoint observables where substantial new physics effects are permitted by scenarios that provide a good fit to all available data in $b \to s\ell^+\ell^-$ transitions. Secondly, we seek to distinguish between the various new physics solutions. In our analysis, we consider a number of observables related to $B \to K^*\tau^+\tau^-$. These include the branching fraction, the K^* longitudinal fraction f_L, the tau forward backward asymmetry A_{FB} as well as optimized angular observables $P_{1,2,3}$ and $P'_{4,5,6,8}$. We then construct LFUV difference and ratio observables between τ and μ by comparing the branching fractions, f_L, A_{FB}, and optimized angular observables ($P_i^{(')}$) of $B \to K^*\tau^+\tau^-$ and $B \to K^*\mu^+\mu^-$ decays. Our findings indicate that within the framework we consider, the current data does permit significant new physics effects in several observables related to $B \to K^*\tau^+\tau^-$ decays. These effects can range from 20% to 30% above the SM level, all the way up to an order of magnitude enhancement. Consequently, the $B \to K^*\tau^+\tau^-$ decay mode possesses significant potential to probe physics beyond the SM.

References

[1] [LHCb], [arXiv:2212.09152 [hep-ex]].

[2] G. Hiller and F. Kruger, Phys. Rev. D **69**, 074020 (2004) [arXiv:hep-ph/0310219 [hep-ph]].

[3] G. Isidori, D. Lancierini, S. Nabeebaccus and R. Zwicky, JHEP **10**, 146 (2022) [arXiv:2205.08635 [hep-ph]].

[4] N. R. Singh Chundawat, Phys. Rev. D **107** (2023), 075014 [arXiv:2207.10613 [hep-ph]].

[5] N. R. Singh Chundawat, Phys. Rev. D **107**, no.5, 055004 (2023) [arXiv:2212.01229 [hep-ph]].

[6] A. K. Alok, N. R. Singh Chundawat and A. Mandal, To appear in Phys. Lett. B (2023) [arXiv:2303.16606 [hep-ph]].

[7] M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan and J. Matias, Phys. Rev. D **99**, no.7, 075017 (2019) [arXiv:1809.08447 [hep-ph]].

[8] M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias and M. Novoa-Brunet, [arXiv:2104.08921 [hep-ph]].

[9] A. K. Alok, N. R. Singh Chundawat, S. Gangal and D. Kumar, Eur. Phys. J. C **82** (2022) no.10, 967 [arXiv:2203.13217 [hep-ph]].

[10] M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini and M. Valli, Phys. Rev. D **107**, no.5, 055036 (2023) [arXiv:2212.10516 [hep-ph]].

[11] D. M. Straub, arXiv:1810.08132 [hep-ph].

[12] A. Bharucha, D. M. Straub and R. Zwicky, JHEP **08**, 098 (2016) [arXiv:1503.05534 [hep-ph]].

[13] N. Gubernari, A. Kokulu and D. van Dyk, JHEP **01**, 150 (2019) [arXiv:1811.00983 [hep-ph]].