How large can the branching ratio of $B_s \rightarrow \tau^+\tau^-$ be?

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Motivated by the large like-sign dimuon charge asymmetry observed recently, whose explanation would require an enhanced decay rate of $B_s \rightarrow \tau^+\tau^-$, we explore how large a branching ratio of this decay mode is allowed by the present constraints. We use bounds from the lifetimes of $B_d$ and $B_s$, constraints from the branching ratios of related $b \rightarrow s\tau^+\tau^-$ modes, as well as measurements of the mass difference, width difference and CP-violating phase in the $B_s\bar{B}_s$ system. Using an effective field theory approach, we show that a branching ratio as high as 15% may be allowed while being consistent with the above constraints. The measurement of this decay, therefore, may be within the reach of current experiments, and can point toward a specific class of new physics models. We also explore the possible enhancement of this decay in models with leptoquarks and $Z'$, and find that in the latter case the branching ratio may be as much as 5%, which may alleviate the dimuon anomaly to some extent.

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I. INTRODUCTION

In 2010, the DØ Collaboration reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the $B$ system [1,2], which was strengthened by the updated measurement [3]. The weighted average with the older CDF results [4] gives

$$A_{SL}^q = -(74.1 \pm 19.3) \times 10^{-4},$$

which is a $3.8\sigma$ deviation from the Standard Model (SM) prediction $A_{SL}^{q, SM} = -(2.3 \pm 0.4) \times 10^{-4}$ [5].

The measured dimuon charge asymmetry is a linear combination of the semileptonic asymmetries $a_q^d$ and $a_q^{sL}$ in the $B_d$ and $B_s$ sectors, respectively. Therefore, the new physics (NP) may contribute through either of these two sectors. However, since

$$a_q^q = \frac{\Delta \Gamma_q^{\tau}}{\Delta m_q^{\tau}} \tan \phi_q^{SL} \quad (q = d, s),$$

where $\Delta \Gamma_q^{\tau}$ is the width difference in the $B_q\bar{B}_q$ system and $\phi_q^{SL}$ is the CP-violating phase in the semileptonic decays, an enhancement in $a_q^{SL}$ is necessarily accompanied by an enhancement in $\tan \phi_q^{SL}$ and/or in $\Delta \Gamma_q^{\tau}$. In the $B_d$ sector, since $\Delta \Gamma_d < 0.075$ in SM already, a further large enhancement would amount to fine-tuning. Also, an enhancement in $\Delta \Gamma_d$ would imply the NP contribution of a few percent to the branching ratios of decay modes common to $B_d$ and $\bar{B}_d$, which is ruled out by the measurements of such modes [6]. In the $B_s$ sector on the other hand, $\phi_s^{SL} \approx 0.004$ in SM [5], and the branching ratios of some of the decay modes, notably of $B_s \rightarrow \tau^+\tau^-$, have not yet been strongly constrained. Therefore NP that contributes to $B_s \rightarrow \tau^+\tau^-$ would be a prime candidate to account for the dilepton anomaly [7].

Indeed, it has been shown that the only effective four-Fermi operators that can account for such an enhanced $A_{SL}^q$ are $(\bar{b} \ell s)(\tau \Gamma\tau)$ and $(\bar{b} \ell s)(\bar{e} \Gamma \ell)$ [8]. We, therefore, investigate how large the branching ratio $B(B_s \rightarrow \tau^+\tau^-)$ can be.

Since the desired NP is expected to contribute to $B_s$ and $B_d$ decays to different extents, it may lead to a difference in the lifetimes of $B_d$ and $B_s$, which is otherwise expected to be $\lesssim 1\%$ in SM [5]. The recent LHCb measurements [9] yield $\tau_{B_d}/\tau_{B_s} = 1.002 \pm 0.014 \pm 0.012$. This indicates that at the $2\sigma$ level, the branching ratio $B(B_d \rightarrow \tau^+\tau^-)$ up to 3.5% is still allowed, even if there is no NP contribution to $B_d$ decays. If NP contributes to $B_d$ decays, this bound will be further relaxed. Note that this would be a large enhancement: the value of this branching ratio in SM is $\approx 7 \times 10^{-7}$ [10].

Measurements from other modes of the form $b \rightarrow s\tau^+\tau^-$, like $B_d \rightarrow X_s\tau^+\tau^-$, $B_s \rightarrow K\tau^+\tau^-$ and $B_d \rightarrow K^*\tau^+\tau^-$, can restrict the NP contribution to $B_s \rightarrow \tau^+\tau^-$ since they involve the same effective four-Fermi operator. However the experimental information on such decay modes is very poor. The only direct bound available at present is the 90% BaBar limit of [11]

$$B(B^+ \rightarrow K^+\tau^+\tau^-)|_{q^2 > 14.23 \text{ GeV}^2} < 0.33\%.$$ (3)

It was suggested in [10] that a dedicated experimental analysis of the LEP data using the missing energy spectrum as in [12] could be used to constrain $B(B_d \rightarrow X_s\tau^+\tau^-)$ and $B(B_s \rightarrow \tau^+\tau^-)$ to 5%; however such an analysis has not been performed to our knowledge. The bound on $B(B_d \rightarrow X_s\tau^+\tau^-)$ obtained in [13] also weakens considerably when the theoretical uncertainties in $B(B \rightarrow K\nu \ell + \text{anything})$ are taken into account. The charm counting in $B_d$ decays yields $B(B_d \rightarrow \text{no charm}) \lesssim 14\%$ at $2\sigma$ [13]. This would give $B(B_d \rightarrow X_s\tau^+\tau^-) \lesssim 12.5\%$, by subtracting the SM contribution of 1.5% to charmless $B$ decays [14]. The compatibility between these bounds and a large $B(B_s \rightarrow \tau^+\tau^-)$ needs to be investigated in a model-independent framework as well as in the context of spe-
cific models, which we shall do in this paper.

The models with scalar leptoquarks [7, 10, 15] and with flavor-dependent $Z'$ couplings [16–18] have been proposed in the literature in order to enhance the $b \to s\tau^+\tau^-$ decay rates, to account for the dimuon anomaly as well as the measurements of width difference in the $B_s\bar{B}_s$ system and the CP-violating phase $B_s \to J/\psi\phi$. We explore the two models above to check whether they are still able to account for all the data, at the same time allowing for an enhanced dimuon asymmetry.

II. MODEL-INDEPENDENT ANALYSIS: HAMILTONIAN FOR $B_s$-$\bar{B}_s$ MIXING

The NP that contributes to the decay modes $b \to s\tau^+\tau^-$ directly influences $B_s$-$\bar{B}_s$ mixing, by contributing to the dispersive ($M_{12}^s$) as well as absorptive ($\Gamma_{12}^s$) part of the effective Hamiltonian for this mixing. These contributions may result in an enhanced value of the lifetime difference $\Delta \Gamma_s$ and the CP-violating phase $\delta_{s12}^S = \text{Arg}[M_{12}$/$\Gamma_{12}$] and, hence, will be restricted by the recent measurements of $B_s \to J/\psi\phi$ at the LHCb [19]. In this section, we shall explore what the data have to say about the NP contributions to $M_{12}^s$ and $\Gamma_{12}^s$.

FIG. 1. The goodness-of-fit contours in the $[M_{12}^S | -\Gamma_{12}^S]$ plane, where the phases of $M_{12}^S$ and $\Gamma_{12}^S$ are varied over. The red, blue, green and brown regions have $\chi^2$ values less than 2.3, 6.18, 11.83, and 19.35, respectively, corresponding to regions allowed at 1$\sigma$, 2$\sigma$, 3$\sigma$, and 4$\sigma$, respectively. The same convention is followed in all figures.

We follow the recent analysis [20], with the inclusion of newly available data. We parameterize the NP by

$$M_{12}^s = M_{12}^{S}\, M_{12}^{NP}, \quad \Gamma_{12}^s = \Gamma_{12}^{S}\, \Gamma_{12}^{NP},$$

where we take the central values of $M_{12}^{S}$ and $\Gamma_{12}^{S}$ to be $M_{12}^{S} = 8.65 \text{e}^{-0.04i}$ ps$^{-1}$ and $\Gamma_{12}^{S} = 0.0435 \text{e}^{-0.04i}$ ps$^{-1}$. We investigate constraints on the two complex quantities (four parameters) $M_{12}^{NP}$ and $\Gamma_{12}^{NP}$ from the measured values of $\Delta m_s$, $\Delta \Gamma_s$, $A_{SL}^{\mu}$ and the CP-violating phase in the $B_s \to J/\psi\phi$ decay ($\phi_{J/\psi\phi}$). The results of the $\chi^2$ fit projected in the $[M_{12}^S | -\Gamma_{12}^S]$ plane are shown in Fig. 1. We assume all the measurements to be independent for simplicity, add the theoretical and experimental errors in quadrature, and vary over the phases of the two quantities $M_{12}^{NP}$ and $\Gamma_{12}^{NP}$.

The origin in this figure is the SM, which has $\chi^2 \simeq 15$. This dramatically quantifies the failure of the SM to accommodate all the current data. There are two regions in the parameter space that are consistent with the current data, one of which is also consistent with $M_{12}^{NP} = 0$, i.e. there is no need for NP to contribute to the dispersive part of the Hamiltonian. On the other hand, consistency with the data even to 3$\sigma$ (i.e. $\chi^2 < 11.83$) seems to require a nonzero NP contribution $\Gamma_{12}^{NP}$.

The 2$\sigma$ preferred range of $|\Gamma_{12}^{NP}|$ is (0.05, 0.25) ps$^{-1}$. Even the lower end of this range yields $B(B_s \to \tau^+\tau^-) \approx 15\%$ if $\Gamma_{12}^{NP}$ is coming entirely from $B_s \to \tau^+\tau^-$. Thus, the model-independent constraints from $B_s$-$\bar{B}_s$ mixing on $B(B_s \to \tau^+\tau^-)$ are rather weak and easily allow values as large as $\sim 15\%$.

III. MODEL INDEPENDENT ANALYSIS: HAMILTONIAN FOR $b \to s\tau^+\tau^-$ DECAY

Within the SM, the effective Hamiltonian for the quark-level transition $b \to s\tau^+\tau^-$ is

$$H_{\text{eff}}^{SM} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \times$$

$$\left\{ \sum_{i=1}^{6} C_i(\mu) \mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \right. + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma^\mu P_L b) \bar{\tau}\gamma_\mu \tau + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma^\mu P_L b) \bar{\tau}\gamma_\mu \gamma_5 \tau \left. \right\},$$

where $P_{L,R} = (1 \mp i\gamma_5)/2$. The operators $\mathcal{O}_i$ ($i = 1, \ldots, 6$) correspond to the $P_i$ of Ref. [21], and $m_b = m_b(\mu)$ is the running $b$-quark mass in the $\overline{MS}$ scheme. We use the SM Wilson coefficients as given in Ref. [22].

We now parameterize NP through the addition of new operators with distinct Lorentz structures to the effective Hamiltonian for $b \to s\tau^+\tau^-$. We consider only scalar-pseudoscalar and vector-axial vector operators and exclude tensor ones. The new effective Hamiltonian is

$$H_{\text{eff}}(b \to s\tau^+\tau^-) = H_{\text{eff}}^{SM} + H_{\text{eff}}^{VA} + H_{\text{eff}}^{SP},$$

where the new operators are

$$H_{\text{eff}}^{VA} = -\frac{g_{SV}^2}{\Lambda^2} \left[ C_V (\bar{s}\gamma^\mu P_L b) + C'_V (\bar{s}\gamma^\mu P_R b) \right] (\bar{\tau}\gamma_\mu \tau),$$

$$H_{\text{eff}}^{SP} = -\frac{g_{SP}^2}{\Lambda^2} \left[ C_S (\bar{s}P_L b) + C'_S (\bar{s}P_R b) \right] (\bar{\tau}\gamma_\mu \tau),$$

$$H_{\text{eff}}^{SP} = -\frac{g_{SP}^2}{\Lambda^2} \left[ C_P (\bar{s}P_L b) + C'_P (\bar{s}P_R b) \right] (\bar{\tau}\gamma_\mu \tau).$$

In the above expressions, $g_{SV}$ and $\Lambda$ are the NP coupling constant and mass scale, respectively. The $C_i, C'_i$ ($i =$
V, A, S, P) are the unknown NP Wilson coefficients. Note that $C_V$ and $C'_V$ do not contribute to the decay $B_d \to \tau^+\tau^-$, but can contribute to the other $b \to s\tau^+\tau^-$ modes. The indirect bounds on these NP operators from $b \to s\gamma$ and $b \to sℓ^+\ell^-$ ($ℓ = e, \mu$) were considered in [13] and found to be weaker than the direct bounds obtained from the ratio $\tau_{B_s}/\tau_{B_d}$.

In terms of all the Wilson coefficients, the branching ratio for this decay is given by

$$B(B_s \to \tau^+\tau^-) = \frac{G_F^2\alpha_{em}^2m_B^5f_B^2\tau_B}{64\pi^3}\left(1 - \frac{4m_d^2}{m_{B_s}^2}\right) \times$$

$$\left\\{\left(1 - \frac{4m_d^2}{m_{B_s}^2}\right)\left|\frac{C_S - C'_S}{m_b + m_s}\right|^2 + \left|\frac{C_P - C'_P}{m_b + m_s}\right|^2 + \frac{2m_\tau}{m_{B_s}^2}\left(|V_{tb}V_{ts}^*|C_{10} + |\xi (C_A - C'_A)|^2\right)\right\}, \tag{8}$$

where $\xi = (g_{3P}/\Lambda^2)(\sqrt{2}/4G_F)(4\pi/\alpha_{em})$. We now examine the decays $B_d \to K^+\tau^+\tau^-$, $B_d \to K^+\tau^+\tau^-$, and $B_d \to X_s\tau^+\tau^-$ in the presence of NP operators. The theoretical expressions are taken from [23, 24], with the replacement of $m_\mu$ with $m_s$. We first consider one NP coupling at a time. We fix the value of the coupling by requiring that $B(B_s \to \tau^+\tau^-) \sim 3.5\%$.

Note that when a single NP operator is present that enhances $B(B_s \to \tau^+\tau^-)$ to percent levels, since the SM contribution is negligible, the branching ratio would depend only on the magnitude of the NP coupling and not on its phase. The relevant branching ratios obtained by using the values for the NP couplings that yield $B(B_s \to \tau^+\tau^-) = 3.5\%$ are shown in Table I.

| Model | $B_d \to K^+\tau^+$ | $B_d \to K^+\tau^+$ | $B_d \to X_s\tau^+$ |
|-------|-----------------|-----------------|-----------------|
| SM    | $0.96 \times 10^{-7}$ | $1.15 \times 10^{-7}$ | $3.6 \times 10^{-7}$ |
| $C_A$ | 0.35 %          | 0.19 %          | 0.80 %          |
| $C'_A$ | 0.35 %          | 0.19 %          | 0.80 %          |
| $C_S$ | 0.04 %          | 0.01 %          | 0.05 %          |
| $C'_S$ | 0.04 %          | 0.01 %          | 0.05 %          |
| $C_P$ | 0.12 %          | 0.03 %          | 0.15 %          |
| $C'_P$ | 0.12 %          | 0.03 %          | 0.15 %          |

TABLE I. Branching ratios of $B_d \to K^+\tau^+$, $B_d \to K^+\tau^+$, and $B_d \to X_s\tau^+$, when $B(B_s \to \tau^+\tau^-) = 3.5\%$ and only one type of NP coupling is present. A kinematic cut $q^2 \geq 14.23$ GeV$^2$ has been imposed in our theoretical calculations for the exclusive modes. We have set $g_{3P} = g_{3V} = 0.65$ and $\Lambda = 1$ TeV. The theoretical errors on the branching ratios may be taken to be $\sim 25\%$.

From Table I we see that if there is only a single NP operator, the branching ratio of all these decay modes is less than 0.8%, and if the NP operator is scalar or pseudoscalar, it is even less than 0.2%. Therefore, the effect on the lifetime ratio $\tau_{B_s}/\tau_{B_d}$ will be small. In any case, the increase in $B_d$ decay rate tends to increase this ratio and, hence, bring it closer to its central value of 1.002. It is also clear that the current 90% upper bound on the BR of $B_d \to K\tau^+\tau^-$ is consistent with $B(B_s \to \tau^+\tau^-)$ as long as the single NP operator is not of the axial vector kind.

Now we shall consider the implications of the presence of more than one NP operator. This is of course a more realistic scenario, since in any specific NP model, more than one effective operator is generally produced. For example, if the NP is leptoquark [7, 10, 15], in general we expect both $(S \pm P)$ and $(V \pm A)$ operators to be generated. And if the NP is a flavor-dependent $Z'$ [16], one obtains all the $(V \pm A)$ operators.

The decay $B_d \to K^+\tau^+\tau^-$ depends on the combinations $(C_A + C'_A), (C_S + C'_S),$ and $(C_P + C'_P)$ [23, 24], while the $B_s \to \tau^+\tau^-$ decay depends on the combinations $(C_A - C'_A), (C_S - C'_S),$ and $(C_P - C'_P)$. Therefore, it is always possible to enhance $B(B_s \to \tau^+\tau^-)$ without affecting $B_d \to K^+\tau^+\tau^-$ significantly. On the other hand, $B_d \to K^+\tau^+\tau^-$ depends on the same combination of NP operators as $B_s \to \tau^+\tau^-$, except through the $F_1$ term (see Eqs. (A.7) and (A.12) of [23]) that depends on $(C_A + C'_A)$, but always adds positively to the decay rate. Therefore, the increased branching ratio of $B_s \to \tau^+\tau^-$ is expected to also increase the branching ratio of $B_d \to K^+\tau^+\tau^-$. The branching ratio of $B_d \to X_s\tau^+\tau^-$ will also naturally increase. Therefore, the latter two decay modes will be directly useful to constrain $B(B_s \to \tau^+\tau^-)$ even when multiple NP operators are present.

Since NP of the kind $b \to s\tau^+\tau^-$ contributes to both $B_s$ and $B_d$ decays (through $B_s \to \tau^+\tau^-$ and $B_d \to X_s\tau^+\tau^-$, respectively), the lifetime ratio $\tau_{B_s}/\tau_{B_d}$ can be consistent with the observation even if $B(B_s \to \tau^+\tau^-)$ and $B(B_d \to X_s\tau^+\tau^-)$ are large, since their contributions to the decay widths tend to cancel each other. The bound on $B(B_d \to K^+\tau^+\tau^-)$ also offers constraints, however, these are only marginal, due to the arguments given above. Note that the consistency with the bounds on $B_s \to \tau^+\tau^-$, $B_d \to X_s\tau^+\tau^-$, and $B_d \to K^+\tau^+\tau^-$ does not need fine-tuning. For example, for $|C_A - C'_A| = 3.8$ (which leads to $B(B_s \to \tau^+\tau^-)\sim 15\%$), any set of values of $|C_A + C'_A|$ and $|C_V + C'_V|$ in the range $[0, 1.4]$ are allowed by the upper bound on $B(B_d \to K^+\tau^+\tau^-)$. The value of $|C_V|$ and $|C'_V|$ may now be chosen to be $\sim 3$ in order to make $B(B_s \to X_s\tau^+\tau^-)\sim 12\%$, so that the $\tau_{B_s}/\tau_{B_d}$ constraint is satisfied. Note that further constraints on $B(B_d \to X_s\tau^+\tau^-)$ would decrease the upper limit on $B(B_s \to \tau^+\tau^-)$ from $\sim 15\%$.

IV. LEPTOQUARK

Leptoquarks (LQ) are particles whose quantum numbers are such that they couple to both the quarks and the leptons of the SM. Vector leptoquarks are predicted in many NP models like models of grand unification based on SU(5) [25] and SO(10) [26, 27] while scalar lepto-
quarks can arise in models of supersymmetry with R-parity violation [28–31] and in extended technicolor models [32] where leptoquark states appear as bound states of technifermions. With the pre-LHCb data, a third-generation scalar leptoquark was shown to provide an explanation of the dimuon anomaly. In fact, we have checked that if a large value of $\Gamma_{\tau\tau}$ will be needed in the LQ model. A further analysis of the constraints in [35] are, therefore, not applicable in our case. A further analysis of $Z'$ exchange has a large imaginary part for small $M_{Z'}$. The constraints in [35] are, therefore, not applicable in our case. A further analysis of $Z'\rightarrow\tau^+\tau^-$, allowing for an imaginary contribution to the effective coupling, may yield stronger constraints.

In Fig. 3 we show the predictions of the $Z'$ model in the $(\phi_s^{J/\psi}, \Delta m_s)$ and $\phi_s^{SL}$ planes for some sample values of the couplings for illustration. (Note that $\phi_s^{J/\psi} \neq \phi_s^{SL}$ [7, 37].) The figure shows that there are values of the couplings that can be consistent with the $J/\psi\phi$ data as well as the dimuon asymmetry data to within 2σ. The values of $B(B_s \rightarrow \tau^+\tau^-)$ in these allowed regions can be as high as $\sim 20\%$. However, constraints from the measurements of $\tau_{B_s}/\tau_{B_d}$, $B(B_d \rightarrow X_s\tau^+\tau^-)$ even for very low values of leptoquark mass. This means that the LQ model cannot do better than the SM as far as the explanation of the dimuon anomaly is concerned.

V. FLAVOR CHANGING $Z'$

In this section we consider a flavor-changing $Z'$ [16–18] gauge boson and examine whether it can offer an explanation of the dimuon anomaly while still being consistent with the recent LHCb data. We consider the Lagrangian density

$$\mathcal{L}_{Z'} \supset (R^{s_B} [\bar{s}_L P_L b] Z^{\mu} + \text{h.c.}) + \Gamma_{T}^{\tau \tau} [\bar{\tau}_L \gamma_{\mu} P_L \tau] Z^{\mu}. \quad (10)$$

Note that $\Delta m_s$ gets tree-level $Z'$ contribution from $\mathcal{L}_{Z'}$ and is proportional to $(R^{s_B})^2$. This restricts the value of $R^{s_B}$ to be very small. On the other hand, $\Gamma_{12}$ is sensitive to the combination of couplings $\lambda = R^{s_B} R^{\tau \tau}$, and we have already seen in Fig. 1 that a large value of $\Gamma_{12}$ is required for a solution of the dimuon anomaly. This means that a large value of $\lambda$ will be needed in the $Z'$ model. With a small $R^{s_B}$, this could imply a very large value of $R^{\tau \tau}$, where the calculations would become nonperturbative and, hence, unreliable. The situation would become worse with increasing values of $Z'$ mass. Therefore we have to stay away from the nonperturbative region.

Lower experimental bounds on the $Z'$ mass can be a serious problem. Direct searches of pair production of $\tau^+\tau^-$ at the Tevatron have provided a lower bound on the $Z'$ mass to be 399 GeV at 95% C.L. [34]. However since this bound assumes SM-like couplings of $Z'$ to all quarks, it can be bypassed if the $Z'$ is assumed to couple very weakly (or not at all) to the first-generation quarks. This allows us to consider a very light $Z'$, with mass as low as $M_{Z'} = 7$ GeV. Note that since $M_{Z'} \approx M_{B_s}$, the decay width of $Z'$ can affect the results (at large couplings, the width may be as large as a few GeV) and has been taken into account in our calculations.

Note that, in principle, bounds on the effective coupling in $Z \rightarrow \tau^+\tau^-$ as obtained in [35] can put correlated constraints on $R^{\tau \tau}$ and $M_{Z'}$. However, the fit therein assumes a small imaginary part of the effective coupling, while the one-loop correction [36] to $Z \rightarrow \tau^+\tau^-$ through a $Z'$ exchange has a large imaginary part for small $M_{Z'}$. The constraints in [35] are, therefore, not applicable in our case. A further analysis of $Z \rightarrow \tau^+\tau^-$, allowing for an imaginary contribution to the effective coupling, may yield stronger constraints.

A 95% C.L. lower bound of 210 GeV on the mass of a third-generation scalar leptoquark decaying to a $b\tau$ final state was reported in [33]. Here, we show our results for the leptoquark mass $M_{LQ} = 250$ GeV. It is worth mentioning that the above bound depends on specific assumptions and can be evaded if those assumptions are changed, however our conclusions do not change even if lower masses are considered.

In Fig. 2 we show the prediction of the leptoquark model for two values of $|h_{LQ}|$ in the $(\phi_s^{J/\psi}, \Delta m_s)$ plane, superimposed on the recent results from the LHCb [19]. The phase of $h_{LQ}$ has been varied over. It is observed that a significant enhancement of $\Delta m_s$ above the SM prediction is not possible in this model.

A $\chi^2$ fit in the (Arg$[h_{LQ}]$, $|h_{LQ}|$) parameter space, using the constraints on $\Delta m_s$ [6] in addition to those on $\Delta \Gamma_s$ and $\phi_s^{J/\psi}$ mentioned above, yields the maximum value of $|h_{LQ}|$ to be only around 0.05 (for $M_{LQ} = 250$ GeV at 95% C.L.). This gives $B(B_s \rightarrow \tau^+\tau^-) \lesssim 0.3\%$. A leptoquark model, thus, cannot raise to $B(B_s \rightarrow \tau^+\tau^-)$ to the level of a percent. It is, therefore, also not enough to explain the dimuon anomaly. In fact, we have checked that if $A_{SL}^b$ is included in the fit, then the $\chi^2 \geq \chi^2_{SM} \approx 15$
FIG. 3. The upper panel shows the predictions of the $t^{0}$ ratio $B_{m}$, the strongest constraints here come from strong constraints on the value of this branching ratio to significant higher-order corrections.)

FIG. 4. Goodness-of-fit contours in the $(|R^{b}|, |R^{s}|)$ plane overlaid with the experimental constraints from $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ values of 3.5%, 7%, 12%, and 20% are also shown.

$B(B_{d} \rightarrow K^{+}\tau^{-}\tau^{-})$ still continue to apply. In the case of a specific model such as this, the constraints would be more severe than those in Sec. III since the effective couplings $(C_{V}, C_{A})$ are now related to each other.

We have investigated the possible enhancement of $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ that may help explain the observed anomalous like-sign dimuon asymmetry. Taking into account the constraints from the lifetime ratio of $B_{s}$ and $B_{d}$, as well as the measurements of related $b \rightarrow s\tau^{+}\tau^{-}$ decay modes, we find that an enhancement up to $B(B_{s} \rightarrow \tau^{+}\tau^{-}) \sim 15\%$ is allowed at 2$\sigma$. This bound may decrease with further constraints on $B(B_{d} \rightarrow X_{s}\tau^{+}\tau^{-})$.

Within the context of specific models, an enhancement of $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ to more than 0.3% is not possible with the leptoquark model, but the model with a light flavor-changing $Z'$ that does not couple to light quarks can increase it to 5%. This helps alleviate the $A_{SL}^{b}$ anomaly to some extent, but cannot account for it entirely, and contribution from NP in the $B_{d} \rightarrow B_{d}$ mixing may also be needed, as was recently conjectured in [38].

VI. CONCLUDING REMARKS

We have investigated the possible enhancement of $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ that may help explain the observed anomalous like-sign dimuon asymmetry. Taking into account the constraints from the lifetime ratio of $B_{s}$ and $B_{d}$, as well as the measurements of related $b \rightarrow s\tau^{+}\tau^{-}$ decay modes, we find that an enhancement up to $B(B_{s} \rightarrow \tau^{+}\tau^{-}) \sim 15\%$ is allowed at 2$\sigma$. This bound may decrease with further constraints on $B(B_{d} \rightarrow X_{s}\tau^{+}\tau^{-})$.

Within the context of specific models, an enhancement of $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ to more than 0.3% is not possible with the leptoquark model, but the model with a light flavor-changing $Z'$ that does not couple to light quarks can increase it to 5%. This helps alleviate the $A_{SL}^{b}$ anomaly to some extent, but cannot account for it entirely, and contribution from NP in the $B_{d}$ sector may also be needed.

Our results with leptoquarks are similar to those in [13], however the updated LHCb data used by us has made the constraints on leptoquark parameters even stronger. On the other hand, the light $Z'$ employed by us allows much larger values of the branching ratio than that predicted therein. Accounting for the dimuon anomaly to within 1$\sigma$, as indicated in [16], is not possible even with a light $Z'$, because of the new stronger LHCb constraints and the requirement of perturbative couplings.

If $B(B_{s} \rightarrow \tau^{+}\tau^{-})$ is at the percent level, it will soon be within the reach of experiments, and could play an important role in our understanding of physics beyond the SM. The direct measurement of this branching ratio should, hence, be a high-priority.
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