Enhanced $B_s$-$\bar{B}_s$ lifetime difference and anomalous like-sign dimuon charge asymmetry from new physics in $B_s \to \tau^+\tau^-$

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New physics models that increase the decay rate of $B_s \to \tau^+\tau^-$ contribute to the absorptive part of $B_s^-\bar{B}_s$ mixing, and may enhance $\Delta \Gamma_s$ all the way up to its current experimental bound. In particular, the model with a scalar leptoquark can lead to a significant violation of the expectation $\Delta \Gamma_s \simeq \Delta \Gamma_s^{\text{SM}}$ (SM). It can even allow regions in the $\Delta \Gamma_s-\beta_s$ parameter space that are close to the best fit obtained by CDF and DØ through $B_s \to J/\psi \phi$. In addition, it can help explain the anomalous like-sign dimuon charge asymmetry observed recently by DØ. A measurement of $BR(B_s \to \tau^+\tau^-)$ is thus crucial for a better understanding of new physics involved in $B_s^-\bar{B}_s$ mixing.

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I. INTRODUCTION

In the standard model (SM), the Cabbibo-Kobayashi-Maskawa (CKM) mixing matrix is the only source of charge-parity (CP) violation. The data from the decays of $K$, $D$ and $B$ mesons have so far been consistent with this paradigm, however the flavor changing neutral current (FCNC) processes involving $b \to s$ transitions are expected to be sensitive to many sources of new physics (NP) [1]. This is why the $B_s$ meson is one of the most important and interesting portals for indirect detection of such NP models.

In this paper we shall concentrate on the oscillation parameters in the $B_s^-\bar{B}_s$ system. The average decay width $\Gamma_s \equiv (\Gamma_{sL} + \Gamma_{sH})/2 = (0.679^{+0.013}_{-0.011})$ ps$^{-1}$ and the mass difference $\Delta M_s \equiv M_{sH} - M_{sL} = (17.77 \pm 0.10 \pm 0.07)$ ps$^{-1}$ have already been measured to an accuracy of better than $\sim 2\%$ [2–4] and play an important role in constraining any new physics. Here the labels $L$ and $H$ stand respectively for the light and heavy mass eigenstates in the neutral $B_s$ system. The decay width difference $\Delta \Gamma_s = \Gamma_{sL} - \Gamma_{sH}$ and the $B_s^-\bar{B}_s$ mixing phase are relatively less certain. The SM predictions for these quantities are [5]

\[
\Delta \Gamma_s^{\text{SM}} = (0.096 \pm 0.039) \text{ ps}^{-1}, \tag{1}
\]

\[
\beta_s^{J/\psi \phi (\text{SM})} = \text{Arg} \left( \frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}} \right) \approx 0.019 \pm 0.001, \tag{2}
\]

where $2\beta_s^{J/\psi \phi}$ is the mixing phase relevant for $B_s \to J/\psi \phi$ decay. The recent CDF and DØ measurements [6–7], using the angular analysis in $B_s \to J/\psi \phi$ decay [8–9], give [10]

\[
\Delta \Gamma_s = \pm (0.15^{+0.054}_{-0.070}) \text{ ps}^{-1}, \tag{3}
\]

\[
\beta_s^{J/\psi \phi} = (0.39^{+0.18}_{-0.14}) \cup (1.18^{+0.14}_{-0.14}), \tag{4}
\]

where the second set in the last line is just the complement of $\pi/2$ for the first set. This reflects the ambiguity in the determination of $\beta_s^{J/\psi \phi}$. Note that the sign of $\Delta \Gamma_s$ is undetermined. The positive and negative signs correspond, respectively, to the two disconnected regions in the allowed parameter space for $\beta_s^{J/\psi \phi}$. Alternative ways of removing this sign ambiguity have been suggested in [11]. The correlated constraints are shown in Fig. 1. The SM prediction for $(\Delta \Gamma_s, \beta_s^{J/\psi \phi})$ is excluded by the data to 90% C.L.. Hence the exploration of new physics effects on these quantities becomes imperative.

While many new physics models can affect $\beta_s^{J/\psi \phi}$ and make its value anywhere in its conventional allowed range $[-\pi/2, \pi/2]$, the ability of new physics to influence $\Delta \Gamma_s$ is rather limited. Indeed, the width difference is

\[
\Delta \Gamma_s = 2|\Gamma_{12s}| \cos \phi_s, \tag{5}
\]

FIG. 1: The combined experimental constraints by CDF and DØ through $B_s \to J/\psi \phi$. Blue, red and green contours (from inner to outer) correspond to the 68%, 95% and 99% C.L. regions. The sinusoidal green band corresponds to the relation $\Delta \Gamma_s \approx 2\Delta \Gamma_s^{\text{SM}} \cos \phi_s$, valid when NP does not contribute to $\Gamma_{12s}$. The figure is taken from [6].
where $\phi_s \equiv \text{Arg}(-M_{12s}/\Gamma_{12s})$. Here $M_{12s}$ and $\Gamma_{12s}$ are the dispersive and absorptive parts, respectively, of the $B_s-\overline{B}_s$ mixing amplitude. In the SM

$$\phi_s = 0.0041 \pm 0.0007,$$

and hence $\Delta\Gamma^{\text{SM}} \approx 2|\Gamma_{12s}|$. The class of NP models which do not affect $\Gamma_{12s}$ then satisfy $\Delta\Gamma_s \leq \Delta\Gamma^{\text{SM}}$ [12]. These include the minimal flavour violating models [13] where the bases in the quark flavor space are the same as that in the SM, as well as models where the mixing box diagram contains only heavy degrees of freedom. The predictions of these models for $(\Delta\Gamma_s, \beta_s^{j/i})$ will then be restricted to the sinusoidal band shown in Fig. [1]. Note that only a small part of this band is within the 68% C.L. region, so that NP of this type will be unable to account for the measurements if the errors decrease with the best fit values staying unchanged.

However, there are well-motivated models where the $B_s-\overline{B}_s$ mixing box diagram contains two light degrees of freedom, resulting in an absorptive amplitude. Given the current strong constraints on the $B_s$ decays to hadrons, $e^+e^-$ and $\mu^+\mu^-$ [2], the only candidate for the intermediate light particle is $\tau$. In an earlier publication [14], we had implemented this idea with two examples: (i) the model with a scalar leptoquark, and (ii) R-parity violating supersymmetry. These models can have flavor dependent couplings of a light particle with a heavy new particle – in particular, $\tau$ can couple with the leptoquark or squark – and hence can contribute to $\Gamma_{12s}$. A significant enhancement of $\Delta\Gamma_s$ was shown to be possible in the former model [14]. In this paper we shall investigate the effect of the leptoquark on the correlation between $\Delta\Gamma_s$ and $\beta_s^{j/i}$, keeping in mind that any such new physics will also significantly affect the decay rate $B_s \to \tau^+\tau^-$. Recently, the DØ collaboration has claimed evidence for an anomalous like-sign dimuon charge asymmetry [15].

$$A_{\tau^+} = -0.00957 \pm 0.00251 \pm 0.00146.$$

CDF has also measured the same quantity using 1.6 fb$^{-1}$ of data and found $A_{\tau^+}^d = (8.0 \pm 9.0 \pm 6.8) \times 10^{-3}$ [16]. Combining these two, one gets

$$A_{\tau^+} = -(8.5 \pm 2.8) \times 10^{-3},$$

which differs from the SM prediction

$$A_{\tau^+}^{\text{SM}} = -0.00023^{+0.00005}_{-0.00006}$$

by about 3$\sigma$. Such an asymmetry can be used as a probe of the flavor structure of new physics [17]. It turns out that the same new physics that enhances $\Delta\Gamma_s$ can also help in explaining this anomaly. We shall elaborate on this in the latter part of this paper.

II. NEW PHYSICS IN $B_s \to \tau^+\tau^-$

Leptoquarks (LQ) are color-triplet objects that couple to quarks and leptons. They occur generically in GUTs [18], composite models [19], and superstring-inspired $E_6$ models [20]. Model-independent constraints on their properties are available [21], and the prospects of their discovery at the LHC have also been studied [22].

The direct production limits depend on the LQ model, as well as the SM fermions these LQs can couple to. The bounds on the second and third generation leptoquarks are, respectively, $M_{LQ} > 316, 245$ GeV, when they are pair produced [2, 23]. A third generation scalar leptoquark decaying only into a $b$-quark and a $\tau$ lepton has a mass bound of 210 GeV [24]. We shall conservatively take $M_{LQ} = 250$ GeV in this analysis. However our results hold even with much higher $M_{LQ}$, by appropriately scaling the coupling $|h_{\text{LQ}}|$ as shall be seen later.

We shall restrict ourselves to scalar leptoquarks that are singlets under the SU(2)$_L$ gauge group of the SM. This is because vector or most of the SU(2)$_L$ nonsinglet leptoquarks tend to couple directly to neutrinos, hence we expect that their couplings are tightly constrained from the neutrino mass and mixing data. This makes any significant effect on the $B_s-\overline{B}_s$ system unlikely.

The relevant interaction term for a scalar SU(2)$_L$ singlet leptoquark is of the form

$$\mathcal{L}_{\text{LQ}} = \lambda_{ij} \overline{d}_R e_i R \overline{s}_j \mathcal{S}_0 + \text{h.c.} ,$$

which gives almost identical results.

When $\lambda_{32}$ and $\lambda_{33}$ are nonzero, the interaction in eq. (10) generates an effective four-fermion $(S + P) \otimes (S + P)$ interaction leading to $b \to s\tau^+\tau^-$. This will contribute to $B_s-\overline{B}_s$ mixing (with $\tau$ and $\mathcal{S}_0$ flowing inside the box), to the leptonic decay $B_s \to \tau^+\tau^-$, and to the semileptonic decays $B \to X_s\tau^+\tau^-$. The relevant quantity here is the coupling product

$$h_{\text{LQ}}(b \to s\tau^+\tau^-) \equiv \lambda_{32}^* \lambda_{33}.$$
which is expected to be small for the $B_d$-$B_s$ system, one may conservatively put the upper bound for $B$ at 10%. The value of $B$ is only $O(10^{-8})$ in the SM. This decay has not been observed, nor is a direct measurement of an upper bound on its branching ratio available. A similar estimate of $B \approx 5\%$ is available in \[22\]. If indeed $|h_{LQ}|$ is large enough to cause such a significant enhancement in $B$, it is related to $B$ directly through

$$ B \approx \frac{|h_{LQ}|^2 f^2_{B_s} \Gamma_{B_s}^L M_{B_s}^2}{256 \pi M_{LQ}^3} \left( 1 - \frac{m_{B_s}^2}{M_{B_s}^2} \right), $$

\[
(13)
\]

where $f_{B_s}$ is the $B_s$ decay constant. It can be seen that for $M_{LQ} = 250$ GeV, $B \approx 10\%$ can accommodate $|h_{LQ}| \approx 0.3$.

We shall show in the next sections that the values of $|h_{LQ}|$ allowed by the above analysis can cause significant changes in the values of $\Delta \Gamma_s$ and $\beta_s^{J/\psi\phi}$, and can also enhance $A_{sl}$ by a sizeable amount.

\section{III. NEW PHYSICS IN $\Delta \Gamma_s$ AND $\beta_s^{J/\psi\phi}$}

In the presence of NP contribution, the expressions for the absorptive and dispersive parts of $B_s$-$\overline{B}_s$ mixing can be written as

$$ M_{12s}^{SM} = M_{12s}^{SM} + M_{12s}^{LQ} = M_{12s}^{SM} R_M e^{\phi_M}, $$

$$ \Gamma_{12s} = \Gamma_{12s}^{SM} + \Gamma_{12s}^{LQ} = \Gamma_{12s}^{SM} R_T e^{\phi_T}. $$

The standard model contributions, to leading order (LO) in $1/m_b$ and $\alpha_s(m_b)$, are given by \[20\] \[21\].

$$ M_{12s}^{SM} = (V_{tb} V_{ts}^*)^2 \frac{G_F^2}{2\pi^2} \chi_{B_s} \bar{\beta}_{B_s} M_{LQ}^2 S_0(x_t), $$

$$ \Gamma_{12s}^{SM} = -[(V_{tb} V_{ts}^*)^2 \Gamma_{cc} + (V_{us} V_{ub}^*)^2 \Gamma_{uu}] + 2(V_{ub} V_{uc} V_{td} V_{tc}) \Gamma_{uu}, $$

where $\chi_{B_s} \equiv M_{B_s} B_{B_s} f_{B_s}^2$, and $\Gamma_{ij}$, the absorptive parts of the box diagrams (without the CKM factors) with quarks $i$ and $j$ flowing inside the loop, are given in \[23\]. The short distance behavior is contained in $\bar{\beta}_{B_s}$, which incorporates the QCD corrections, and in the Inami-Lim function $S_0(x_t)$. The value of $\Gamma_{12s}$ has been calculated up to $O(1/m_t^4)$ in \[28\], wherein some NP contributions to $\Delta \Gamma_s$ have also been studied.

The leading order leptoquark contributions to the above quantities are \[14\].

$$ M_{12s}^{LQ} = \frac{h_{LQ}^2}{384 \pi^2 M_{LQ}^2} \chi_{B_s} \bar{\beta}_{B_s} S_0(x_t), $$

$$ \Gamma_{12s}^{LQ(0)} = \frac{h_{LQ}^2}{256 \pi M_{LQ}^2} \chi_{B_s} m_{B_s}^2 F(\tau), $$

where $S_0(x_t)$ is another Inami-Lim function, and the phase space factor is $F(\tau) = 0.64$. The details of the calculation may be found in \[14\].

While the next to leading order QCD corrections and the $1/m_b$ corrections do not affect $M_{12s}^{SM}$ significantly, they modify $\Gamma_{12s}^{SM}$ by $\approx 30\%$ from its LO value \[29\]. The QCD corrections are expected to be different for SM and LQ operators since the mediating heavy particle for the latter case is a color triplet. The $1/m_b$ corrections are also expected to differ since the light degrees of freedom that flow inside the mixing box are different too. While it is desirable to have an idea of these corrections, since we are only showing typical results from allowed leptoquark parameters, such corrections can be absorbed by just changing the value of $M_{LQ}$ and the phase of $h_{LQ}$. Therefore in our numerical analysis, we use the SM predictions for $\Gamma_{12s}^{SM}$ \[5\] that include the NLO QCD and $1/m_b$ corrections, however for $\Gamma_{12s}^{LQ}$ we only use the leading order contribution. For the sake of clarity, while calculating the combined SM and LQ contribution to $\Gamma_{12s}$, we use only the central value of the SM prediction. Including the $30\%$ error in the SM prediction will widen the bands for our results shown in Fig. \[2\].

In the presence of leptoquarks, eqs. \[5\] \[14\] \[15\] lead us to write the width difference as

$$ \Delta \Gamma_s = 2|\Gamma_{12s}^{SM} R_T \cos(\phi_M - \phi_T) - 2\beta_s^{SM}| $$

$$ \approx \Delta \Gamma_s^{SM} R_T \cos(\phi_M - \phi_T), $$

(20)

where the approximation uses $\beta_s^{SM} \approx 0$. The allowed values of $h_{LQ}$ permit $R_T \cos(\phi_M - \phi_T) > 1$, so that the value of $\Delta \Gamma_s$ can be enhanced in this model. Fig. \[2\] shows that the enhancement can be up to $\Delta \Gamma_s \approx 0.4 \text{ ps}^{-1}$ for $|h_{LQ}| \approx 0.3$.

The decay $B_s \rightarrow J/\psi \phi$ exhibits CP violation through the interference of mixing and decay. The CP violating phase measured through the time dependent angular distribution of this decay is

$$ \beta_s^{J/\psi\phi} \approx -\frac{1}{2} \arg \left( \frac{V_{ub} V_{us}^*}{M_{12s}} \right)^2 = \beta_s^{J/\psi\phi(\text{SM}) - \phi_M^2/2}. $$

(21)

where we have used the approximation $|\Gamma_{12s}| \ll |M_{12s}|$. Clearly at low values of $|h_{LQ}|$, the allowed range of $\phi_M$ will be restricted to be near zero, and hence $\beta_s^{J/\psi\phi}$ will be close to its SM value, which itself is close to zero. For higher $|h_{LQ}|$, however, the value of $\phi_M$ can be anything, and hence $\beta_s^{J/\psi\phi}$ can be anywhere in its conventional range $[-\pi/2, \pi/2]$. This is illustrated in Fig. \[2\].

Figure \[2\] overlays our predictions with the leptoquark model in the $\Delta \Gamma_s - \beta_s^{J/\psi\phi}$ plane on the results of the combined analysis of CDF and DØ. Clearly, the additional leptoquark contribution not only can enhance $\Delta \Gamma_s$ and $\beta_s$, but also can allow us to be well within the 68\% C.L. region of the current best fit.
Since $\beta$ mixing phase via $\tau^+\tau^-$ the like-sign dimuon charge asymmetry $A^{s}_{sl}$ measured by DØ [15] and CDF [16] is related to the semileptonic decay asymmetries $a^d_s$ and $a^a_{sl}$ in the $B_d$ and $B_s$ sectors, respectively, through [15] 

$$A^{s}_{sl} = (0.506 \pm 0.043) a^d_s + (0.494 \pm 0.043) a^a_{sl}.$$  \hspace{1cm} (22)

The coefficients here are valid even in the presence of NP. The average $A^{s}_{sl}$ from eq. (22), and the current experimental constraints of $a^a_{sl} = -0.0047 \pm 0.0046$ [10], yield

$$a^s_{sl} = -0.012 \pm 0.007,$$  \hspace{1cm} (23)

which is almost $2\sigma$ away from the SM prediction [3]

$$a^{s(SM)}_{sl} = (2.1 \pm 0.6) \times 10^{-5}. \hspace{1cm} (24)$$

This quantity is directly related to $\Delta \Gamma_s$ and the $B_s \rightarrow \tau \bar{\tau}$ mixing phase via

$$a^s_{sl} = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi^s_{sl} = -\frac{\Delta \Gamma_s}{\Delta M_s} \tan 2\beta^s_{sl}, \hspace{1cm} (25)$$

where $\phi^s_{sl} = \text{Arg}(-M_{12s}/\Gamma_{12s}) = \phi_s$ and we have defined $\beta^s_{sl}$ such that $\phi^s_{sl} = -2\beta^s_{sl}$. From eq. (25), we have

$$\beta^s_{sl} = -0.0020 \pm 0.0003. \hspace{1cm} (26)$$

In the presence of NP that affects $\Gamma_{12s}$, eqs. (14) and (15) yield the relation

$$\beta^s_{sl} = \frac{1}{2} \text{Arg} \left( \frac{\Gamma_{12s}}{M_{12s}} \right) = \beta^{s(SM)}_{sl} - \frac{\phi^s_{sl}}{2} + \frac{\phi^s_{s}}{2}. \hspace{1cm} (27)$$

Since $\beta^{s/\psi\phi(SM)} \approx 0 \approx \beta^{s(SM)}_{sl}$, eqs. (21) and (27) clearly show that $\beta^s_{sl}$ is in general different from $\beta^s_{\psi\phi}$. Note that when NP does not affect $\Gamma_{12s}$, the value of $\phi_s$ vanishes and only then can one say $\beta^s_{sl} \approx \beta^s_{\psi\phi}$. Therefore, it is not recommended to superimpose the parameter spaces of $(\Delta \Gamma_s, \beta^s_{sl})$ and $(\Delta \Gamma_s, \beta^s_{\psi\phi})$.

In Fig. 3 we show the constraints in the $(\Delta \Gamma_s, \beta^s_{sl})$ parameter space coming from the $A^{s}_{sl}$ (consequently, $a^a_{sl}$) measurement in [15], and $(\Delta \Gamma_s, \beta^s_{\psi\phi})$ predictions at some allowed $|h_{LQ}|$ values. It shows that the leptoquark contribution can give rise to $a^a_{sl}$ values well within the 95% C.L. region of the experimental data. Note that the predictions shown in Figs. 2 and 3 correspond to the same set of NP parameters. This again illustrates the need to clearly differentiate between $\beta^s_{sl}$ and $\beta^s_{\psi\phi}$.

V. SUMMARY AND CONCLUSIONS

The model with a scalar leptoquark, presented in this paper, belongs to the special class of NP models that affect the absorptive part $\Gamma_{12s}$ of $B_s \rightarrow \tau \bar{\tau}$ mixing. It can therefore evade the relation $\Delta \Gamma_s < \Delta \Gamma_s^{SM}$ and can give enhanced values of the lifetime difference in $B_s \rightarrow \tau \bar{\tau}$ system. The enhancement in $\Delta \Gamma_s$ also corresponds to an enhancement in the branching ratio $BR(B_s \rightarrow \tau^+ \tau^-)$. Recent measurements of $\Delta \Gamma_s$ and $\beta^s_{\psi\phi}$ by the CDF and DØ collaborations exclude the SM prediction to 90% C.L. We illustrate with the example of the scalar leptoquark model that $\Delta \Gamma_s$ as large as 0.4 ps$^{-1}$ may be achieved, and values in the $(\Delta \Gamma_s, \beta^s_{\psi\phi})$ parameter space close to the best fit from these measurements can be obtained. Indeed, if future experiments decrease the errors on these quantities while keeping the best fit values at their current positions, only models belonging to this class will be able to explain the deviation from the SM.

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asymmetry recently observed at DØ is also facilitated by this class of models, since these models give rise to large $\Delta \Gamma_s$ as well as large $\beta_s^\pm$ simultaneously. We point out that these models in general imply that $\beta_s^\pm \neq \beta_s^{\phi \phi}$, so one has to be careful when including NP in the analysis. Also, note that this mechanism affects $A_{sl}^\beta$ through the modification of $\Delta \Gamma_s$ and $\phi_s$, without the need of an explicit $b \to s\mu^+\mu^-$ coupling. This is a common feature of all models which have an absorptive part in the $B_s\bar{B_s}$ mixing diagram.

In order to confirm the compatibility of such models with the data, one needs further NLO calculations of the predictions of these models, as well as a better measurement of $B_s \to \tau^+\tau^-$ branching ratio, which will be crucial to constrain the leptoquark couplings. The $\tau$ from $B_s \to \tau^+\tau^-$ may be expected to have enough energy boost at the LHC to be detected. The $\tau$ polarization can also be measured: the $\tau$'s coming from leptoquarks are expected to be right handed. In addition, if we have an SU(2)$_L$ doublet leptoquark $S_{\pm}$, this will also give rise to the FCNC top decay $t \to c\tau^+\tau^-$ at the level of 1%, which will be another probe of the new physics of this class.

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