

Neutral Gauge Boson Contributions to the Dimuon Charge Asymmetry in B Decays

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ABSTRACT: Recently, the DØ Collaboration measured the CP-violating like-sign dimuon charge asymmetry in neutral B decays, finding a 3.2σ difference from the standard-model (SM) prediction. A non-SM charge asymmetry a_{sl}^s suggests a new-physics (NP) contribution to B_s - \bar{B}_s mixing. In this case, in order to explain the measured value of a_{sl}^s within its 1σ range, NP must be present in Γ_{12}^s , the absorptive part of the mixing. In this paper, we examine whether such an explanation is possible in models with flavor-changing Z (ZFCNC) or Z' (Z'FCNC) gauge bosons. The models must also reproduce the measured values of the indirect CP asymmetry $S_{\psi\phi}$ in $B_s \rightarrow J/\psi\phi$, and $\Delta\Gamma_s$, the B_s - \bar{B}_s width difference. We find that the ZFCNC model cannot reproduce the present measured values of $S_{\psi\phi}$ and a_{sl}^s within their 1σ ranges. On the other hand, in the Z'FCNC model, the values of all three observables can be simultaneously reproduced.

KEYWORDS: Flavor-Changing Gauge Boson, B_s - \bar{B}_s mixing, Beyond Standard Model.

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1. Introduction

Flavor-changing neutral-current (FCNC) processes occur only at the loop level in the standard model (SM), and are therefore a very sensitive probe of physics beyond the SM. Interestingly, recently there have been several measurements of quantities in B decays, especially in the $b \rightarrow s$ transition, which differ from the predictions of the SM. For example, i) the value of $\sin 2\beta$ measured in several $b \rightarrow s$ penguin decays is found to be smaller than that obtained in $B_d \rightarrow J/\psi K_S$ [1], ii) in $B \rightarrow \pi K$, the SM has some difficulty in accounting for all the experimental measurements [2], iii) the forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$ shows a small deviation from the SM, especially at low momentum transfer squared [3], iv) the measurement of CP violation in $B_s \rightarrow J/\psi \phi$ suggests the presence of a new-physics (NP) CP-violating phase in B_s - \bar{B}_s mixing [4]. Although these effects are not significant enough to claim NP, at least they indicate that flavor physics will still play a very important role in the search for NP in the LHC era. The LHCb will provide much more precise data on the above-mentioned observables.

Recently the DØ Collaboration reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the B system [5]. The asymmetry is

$$A_{\text{sl}}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \quad (1.1)$$

where $N_b^{\pm\pm}$ is the number of events of $b\bar{b} \rightarrow \mu^\pm\mu^\pm X$. From the analysis of 6.1 fb^{-1} of data, DØ found

$$A_{\text{sl}}^b = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3} , \quad (1.2)$$

where the first (second) error is statistical (systematic). This exhibits a 3.2σ deviation from the SM prediction, $A_{\text{sl}}^{b,\text{SM}} = (-2.3_{-0.6}^{+0.5}) \times 10^{-4}$ [6]. The asymmetry can be written as a linear combination of B_d and B_s contributions [7]

$$A_{\text{sl}}^b = (0.506 \pm 0.043)a_{\text{sl}}^d + (0.494 \pm 0.043)a_{\text{sl}}^s , \quad (1.3)$$

where the semileptonic “wrong-charge” asymmetry a_{sl}^q ($q = d, s$) is given by

$$a_{\text{sl}}^q = \frac{\Gamma(\overline{B}_q \rightarrow \mu^+ X) - \Gamma(B_q \rightarrow \mu^- X)}{\Gamma(\overline{B}_q \rightarrow \mu^+ X) + \Gamma(B_q \rightarrow \mu^- X)} . \quad (1.4)$$

Thus, the discrepancy may indicate a NP contribution to B_d - \overline{B}_d mixing and/or B_s - \overline{B}_s mixing [7].

Using the current experimental value of $a_{\text{sl}}^{d,\text{exp}} = -0.0047 \pm 0.0046$ [5, 8] and the SM prediction $a_{\text{sl}}^{d,\text{SM}} = (-4.8_{-1.2}^{+1.0}) \times 10^{-4}$, Eq. (1.3) leads to $a_{\text{sl}}^s = -0.0146 \pm 0.0075$. The CDF Collaboration also measured A_{sl}^b , but with much larger errors: $A_{\text{sl}}^b = (8.0 \pm 9.0 \pm 6.8) \times 10^{-3}$ [9]. Finally, DØ directly measured a_{sl}^s : $a_{\text{sl}}^{s,\text{exp}} = -(1.7 \pm 9.1_{-1.5}^{+1.4}) \times 10^{-3}$ [10]. Combining all these results, we get

$$(a_{\text{sl}}^s)_{\text{ave}} = -(12.7 \pm 5.0) \times 10^{-3} , \quad (1.5)$$

which is still about 2.5σ away from the SM prediction of $a_{\text{sl}}^{s,\text{SM}} = (2.1 \pm 0.6) \times 10^{-5}$.

The DØ measurement thus suggests the presence of NP in B_s - \overline{B}_s mixing, and we explore this possibility below. We begin with a general review of the mixing. In the B_s system, the mass eigenstates B_L and B_H (L and H indicate the light and heavy states, respectively) are admixtures of the flavor eigenstates B_s and \overline{B}_s :

$$\begin{aligned} |B_L\rangle &= p|B_s\rangle + q|\overline{B}_s\rangle , \\ |B_H\rangle &= p|B_s\rangle - q|\overline{B}_s\rangle , \end{aligned} \quad (1.6)$$

with $|p|^2 + |q|^2 = 1$. As a result, the initial flavor eigenstates oscillate into one another according to the Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} |B_s(t)\rangle \\ |\overline{B}_s(t)\rangle \end{pmatrix} = \left(M^s - i \frac{\Gamma^s}{2} \right) \begin{pmatrix} |B_s(t)\rangle \\ |\overline{B}_s(t)\rangle \end{pmatrix} , \quad (1.7)$$

where $M = M^\dagger$ and $\Gamma = \Gamma^\dagger$ correspond respectively to the dispersive and absorptive parts of the mass matrix. The off-diagonal elements, $M_{12}^s = M_{21}^{s*}$ and $\Gamma_{12}^s = \Gamma_{21}^{s*}$, are generated by B_s - \overline{B}_s mixing. We define

$$\Gamma_s \equiv \frac{\Gamma_H + \Gamma_L}{2}, \quad \Delta M_s \equiv M_H - M_L, \quad \Delta \Gamma_s \equiv \Gamma_L - \Gamma_H . \quad (1.8)$$

Expanding the mass eigenstates and q/p in Γ_{12}^s/M_{12}^s , we find, to a very good approximation [11],

$$\begin{aligned}\Delta M_s &= 2|M_{12}^s|, \\ \Delta\Gamma_s &= 2|\Gamma_{12}^s| \cos\phi_s, \\ \frac{q}{p} &= -e^{-i\phi_M^s} \left(1 - \frac{|M_{12}^s|}{2|\Gamma_{12}^s|} \sin\phi_s\right),\end{aligned}\tag{1.9}$$

where $\phi_M^s \equiv \arg M_{12}^s$ and $\phi_s \equiv \arg(-M_{12}^s/\Gamma_{12}^s)$. Then a_{sl}^s is given by [6]

$$a_{\text{sl}}^s = \text{Im} \left(\frac{\Gamma_{12}^s}{M_{12}^s} \right) = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_s.\tag{1.10}$$

In the SM, we have

$$a_{\text{sl}}^s = (4.97 \pm 0.94) \times 10^{-3} \sin\phi_s.\tag{1.11}$$

Within the SM, the phase of M_{12}^s is given by $\arg[(V_{tb}V_{ts}^*)^2]$ and that of Γ_{12}^s is dominated by $\arg[(V_{cb}V_{cs}^*)^2]$. The state-of-the-art calculation gives $\phi_s = 0.0041 \pm 0.0008$ [6]. As noted above, the SM cannot explain the $D\bar{O}$ result; this is due to its far-too-small weak phases. From here on, we neglect the SM weak phases.

Suppose now that NP contributes to M_{12}^s but not to Γ_{12}^s . We introduce a new parameter Δ_s to take this into account: $M_{12}^s = M_{12}^{s,\text{SM}} + M_{12}^{s,\text{NP}} = M_{12}^{s,\text{SM}} \Delta_s = M_{12}^{s,\text{SM}} |\Delta_s| e^{i\phi_M^s}$. We have

$$a_{\text{sl}}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^{s,\text{SM}}|} \frac{\sin\phi_M^s}{|\Delta_s|} = (4.97 \pm 0.94) \times 10^{-3} \frac{\sin\phi_M^s}{|\Delta_s|}.\tag{1.12}$$

The experimental value of the mass difference in the $B_s\text{-}\bar{B}_s$ system, $\Delta M_s = (17.77 \pm 0.12) \text{ ps}^{-1}$, constrains $|\Delta_s| = 0.92 \pm 0.32$. Then Eqs. (1.5) and (1.12) give $\sin\phi_M^s = -2.56 \pm 1.16$, implying that the full 1σ range of the experimental result lies outside the physical region. It is therefore not possible to explain the 1σ range of the $D\bar{O}$ measurement if NP contributes only to M_{12}^s .

This problem can be solved if the new physics contributes to Γ_{12}^s . Here we introduce a second new parameter Ξ_s : $\Gamma_{12}^s = \Gamma_{12}^{s,\text{SM}} + \Gamma_{12}^{s,\text{NP}} = \Gamma_{12}^{s,\text{SM}} \Xi_s = \Gamma_{12}^{s,\text{SM}} |\Xi_s| e^{i\phi_\Gamma^s}$. We then have

$$\begin{aligned}a_{\text{sl}}^s &= \frac{|\Gamma_{12}^{s,\text{SM}}|}{|M_{12}^{s,\text{SM}}|} \frac{|\Xi_s|}{|\Delta_s|} \sin(\phi_M^s - \phi_\Gamma^s) \\ &= (4.97 \pm 0.94) \times 10^{-3} \frac{|\Xi_s|}{|\Delta_s|} \sin(\phi_M^s - \phi_\Gamma^s).\end{aligned}\tag{1.13}$$

Now Eq. (1.5) can be reproduced if $|\Xi_s|$ is sufficiently large.

The difficulty is that, in many NP models, the contribution to Γ_{12}^s is not large enough to compete with that of the SM, which is dominated by the tree-level $b \rightarrow$

$sc\bar{c}$ process. Two exceptions are R-parity-violating supersymmetric models [12] and leptoquark models [13] (other analyses of Eq. (1.5) in various NP models can be found in Refs. [7, 14]).

In this paper we examine the contribution of flavor-changing neutral gauge bosons to Γ_{12}^s . We consider two types of models. They involve tree-level $Z\bar{b}s$ or $Z'\bar{b}s$ couplings. As we will see, the non-universal Z' model can enhance Γ_{12}^s enough to explain the 1σ range of Eq. (1.5).

The paper is organised as follows. The NP contribution to Γ_{12}^s is discussed in Sec. 2. In Sec. 3, we describe the models with flavor-changing Z and Z' couplings. The numerical results are presented in Sec. 4. We conclude in Sec. 5.

2. Contributions to Γ_{12}^s

In the SM, the dominant contribution to $\Gamma_{12}^{s,\text{SM}}$ comes from the charged-current $b \rightarrow sc\bar{c}$ operator with a c -quark loop. It is given by

$$\Gamma_{12}^{s,\text{SM}} = -\frac{G_F^2 m_b^2 \lambda_c^2}{3\pi} \sqrt{1-4x_c} \times \left\{ \left[K_1(1-x_c) + \frac{1}{2}K_2(1-4x_c) \right] \langle O_{LL} \rangle + (K_1 - K_2)(1+2x_c) \langle \tilde{O}_{RR} \rangle \right\}, \quad (2.1)$$

where $\lambda_c = V_{cb}V_{cs}^*$, $x_c = m_c^2/m_b^2$, and $K_1 = 3C_1^2 + 2C_1C_2$, $K_2 = C_2^2$. The values for the C_i are $C_1(m_b) = 1.086$, $C_2(m_b) = -0.197$ (Tables 4, 5 of Ref. [15]). We use the vacuum insertion approximation to calculate the hadronic matrix elements [16]:

$$\begin{aligned} \langle O_{LL} \rangle &\equiv \langle B_s | \bar{s} \gamma_\mu P_L b \bar{s} \gamma^\mu P_L b | \bar{B}_s \rangle = \frac{1}{3} m_{B_s} f_{B_s}^2, \\ \langle \tilde{O}_{RR} \rangle &\equiv \langle B_s | \bar{s} P_R b \bar{s} P_R b | \bar{B}_s \rangle = -\frac{5}{24} m_{B_s} f_{B_s}^2 \left(\frac{m_{B_s}}{m_b + m_s} \right)^2, \end{aligned} \quad (2.2)$$

where $P_{L,R} = (1 \mp \gamma_5)/2$ and $f_{B_s} = (238.8 \pm 9.5)$ MeV [17]. An updated theoretical prediction can be found in Ref. [6], whose results we use in our numerical calculations.

Any NP contribution to $\Gamma_{12}^{s,\text{NP}}$ must come from a new operator of the form $b \rightarrow sf\bar{f}$, where f is a light fermion. If $\Gamma_{12}^{s,\text{NP}}$ is to be significant, it must be at least comparable to $\Gamma_{12}^{s,\text{SM}}$. Now, most NP light fermionic operators are constrained to be small. In particular, (i) e and μ loop contributions are strongly bounded by the $b \rightarrow se^+e^-$ and $b \rightarrow s\mu^+\mu^-$ processes, (ii) the $b \rightarrow su\bar{u}$ and $b \rightarrow sd\bar{d}$ operators are constrained by the measurement of $B(\bar{B} \rightarrow \pi K)$, (iii) $B(\bar{B} \rightarrow \phi K)$ constrains $b \rightarrow ss\bar{s}$. On the other hand, the bounds on the NP $b \rightarrow s\tau^+\tau^-$ transition are very weak. For example, the present upper bound on $B(\bar{B}_s \rightarrow \tau^+\tau^-)$ is only $\lesssim 5\%$ [18], to be compared with the SM prediction of $B(\bar{B}_s \rightarrow \tau^+\tau^-) \sim 10^{-8}$. Also, the current upper bound on $B(\bar{B} \rightarrow X_s \tau^+\tau^-)$ is just $\lesssim 5\%$ [18]. For this reason, in the NP models we consider, we examine the contribution to $\Gamma_{12}^{s,\text{NP}}$ coming from $b \rightarrow s\tau^+\tau^-$.

Another potential important effect on $\Gamma_{12}^{s,\text{NP}}$ comes from the NP $b \rightarrow sc\bar{c}$ operator. Although the constraints from $\bar{B} \rightarrow DD_s$, $\bar{B}_d \rightarrow J/\psi K_S$, etc. are such that the NP c -quark loop contribution cannot be large enough to compete with $\Gamma_{12}^{s,\text{SM}}$, the SM-NP interference term can be significant.

The decay width difference $\Delta\Gamma_s$ has been measured independently. The angular analysis of $\bar{B}_s \rightarrow J/\psi\phi$ gives [8, 19, 20]

$$\Delta\Gamma_s = \pm(0.154_{-0.070}^{+0.054}) \text{ ps}^{-1}, \quad (2.3)$$

to be compared with the the SM prediction [6]

$$\Delta\Gamma_s^{\text{SM}} = (0.096 \pm 0.039) \text{ ps}^{-1}. \quad (2.4)$$

If NP contributes to $\Gamma_{12}^{s,\text{NP}}$, it is present in the width difference, whose expression is given by

$$\Delta\Gamma_s = \Delta\Gamma_s^{\text{SM}} |\Xi_s| \cos(\phi_M^s - \phi_\Gamma^s). \quad (2.5)$$

The measurement of $\Delta\Gamma_s$ therefore constrains $\Gamma_{12}^{s,\text{NP}}$.

There is another measurement which must be taken into account. The CDF [21] and DØ [22] Collaborations have measured indirect CP violation in $\bar{B}_s \rightarrow J/\psi\phi$. They obtain $S_{\psi\phi} = -2\beta_s$, and find [8]

$$\beta_s = 0.39_{-0.14}^{+0.18} \quad \text{or} \quad 1.18_{-0.18}^{+0.14}. \quad (2.6)$$

This disagrees with the SM prediction

$$\beta_s^{\text{SM}} = 0.019 \pm 0.001 \quad (2.7)$$

at 2σ . (Note: the recent CDF measurement agrees with the SM better than the previous DØ and CDF measurements.) Now, we have assumed that the NP affects M_{12}^s , so that there is a weak phase in B_s - \bar{B}_s mixing, ϕ_M^s . Depending on which NP operator(s) contribute to $\Gamma_{12}^{s,\text{NP}}$, there may also be a contribution to the decay of $\bar{B}_s \rightarrow J/\psi\phi$. Thus, the NP is constrained in that the CDF/DØ measurement must be reproduced.

To detail the contribution of the NP to the indirect CP asymmetry in $\bar{B}_s \rightarrow J/\psi\phi$, we follow the procedure of Ref. [23]. First, we note that $\bar{B}_s \rightarrow J/\psi\phi$ is really three separate decays, one for each polarization state λ of the final-state vector particles; longitudinal: $\lambda = 0$, transverse: $\lambda = \{||, \perp\}$. Second, in Ref. [24] it is argued that all strong phases associated with NP amplitudes are negligible. In this case, for each polarization one can combine all NP matrix elements into a single NP amplitude, with a single weak phase φ_λ :

$$\sum \langle (J/\psi\phi)_\lambda | \mathcal{O}_{\text{NP}} | B_s \rangle = b_\lambda e^{i\varphi_\lambda}. \quad (2.8)$$

We now assume that this single NP amplitude contributes to the decay of $\bar{B}_s \rightarrow J/\psi\phi$. The decay amplitude for each of the three possible polarization states may then be written as

$$\begin{aligned} A_\lambda &\equiv \text{Amp}(B_s \rightarrow J/\psi\phi)_\lambda = a_\lambda e^{i(\delta_\lambda^a - \delta_\perp^a)} + b_\lambda e^{i\varphi_\lambda} e^{-i\delta_\perp^a} , \\ \bar{A}_\lambda &\equiv \text{Amp}(\bar{B}_s \rightarrow J/\psi\phi)_\lambda = a_\lambda e^{i(\delta_\lambda^a - \delta_\perp^a)} + b_\lambda e^{-i\varphi_\lambda} e^{-i\delta_\perp^a} , \end{aligned} \quad (2.9)$$

where a_λ and b_λ represent the SM and NP amplitudes, respectively, φ_λ is the new-physics weak phase, and the δ_λ^a are the SM strong phases. All strong phases are given relative to δ_\perp^a . a_λ is defined to be positive for every polarization. b_λ can also be taken to be positive: if it is negative, the minus sign can be absorbed in the weak phase by redefining $\varphi_\lambda \rightarrow \varphi_\lambda + \pi$. We emphasize this fact by writing the ratio b_λ/a_λ as the positive-definite quantity $|r_\lambda|$. Note that strong phases are generated by rescattering, and this costs a factor of about 25. The strong phase of the SM color-suppressed $\bar{b} \rightarrow \bar{c}c\bar{s}$ diagram C is generated by rescattering of the color-allowed $\bar{b} \rightarrow \bar{c}c\bar{s}$ tree diagram T . Since $|C/T|$ is expected to be in the range 0.2-0.6, the SM strong phase is on the small side, but is not negligible.

Putting all this together, we find that the indirect CP asymmetry in $\bar{B}_s \rightarrow J/\psi\phi$ measures

$$S_{\psi\phi} = \sin \phi_M^s + 2|r_\lambda| \cos \phi_M^s \sin \varphi_\lambda \cos \delta_\lambda^a . \quad (2.10)$$

(We have neglected the SM contribution to the weak phase of B_s - \bar{B}_s mixing, which is expected to be only $\sim 2\%$ [Eq. (2.7)].) If the NP contribution to $\Gamma_{12}^{s,\text{NP}}$ comes only from $b \rightarrow s\tau^+\tau^-$, then $r_\lambda = 0$ and $S_{\psi\phi} = \sin \phi_M^s$. However, if the NP $b \rightarrow s\bar{c}\bar{c}$ operator is involved in $\Gamma_{12}^{s,\text{NP}}$, then $r_\lambda \neq 0$ and the full expression for $S_{\psi\phi}$ above must be used.

Finally, we note that the phases of a_{sl}^s and $S_{\psi\phi}$ are different when there is a NP contribution to Γ_{12}^s and/or $\bar{B}_s \rightarrow J/\psi\phi$. In addition, the relation between them [25],

$$a_{\text{sl}}^s = -\frac{|\Delta\Gamma_s|}{|\Delta M_s|} S_{\psi\phi} / \sqrt{1 - S_{\psi\phi}^2} , \quad (2.11)$$

is violated in this case.

3. New-Physics Models

3.1 Z-mediated FCNC's

In the model with Z-mediated FCNC's (ZFCNC), a new vector-like isosinglet down-type quark d' is added to the particle spectrum [26, 27, 28]. Such quarks appear in E_6 GUT theories, for example. The ordinary $Q_{em} = -1/3$ quarks mix with the d' . Because the d'_L has a different I_{3L} from d_L , s_L and b_L , FCNC's appear at tree level in the left-handed sector. In particular, a $Z\bar{b}s$ coupling can be generated:

$$\mathcal{L}_{FCNC}^Z = -\frac{g}{2 \cos \theta_W} U_{sb} \bar{s} \gamma^\mu P_L b Z_\mu + \text{h.c.} \quad (3.1)$$

This coupling leads to a NP contribution to B_s - \bar{B}_s mixing at tree level.

The SM contribution to M_{12}^s is

$$M_{12}^{s,\text{SM}} = \frac{G_F^2}{12\pi^2} M_W^2 \lambda_t^2 \eta_B B_{B_s} f_{B_s}^2 M_{B_s} E(x_t) , \quad (3.2)$$

where $\lambda_t = V_{tb}V_{ts}^*$, $x_t = m_t^2/M_W^2$, $\eta_B \simeq 0.551$ is the QCD correction, and we take the hadronic parameter $f_{B_s} B_{B_s}^{1/2} = 295 \pm 36$ MeV. The loop function $E(x_t)$ is given by

$$E(x_t) = \frac{-4x_t + 11x_t^2 - x_t^3}{4(1-x_t)^2} + \frac{3x_t^3 \ln x_t}{2(1-x_t)^3} . \quad (3.3)$$

The mass difference ΔM_s in the ZFCNC model is given by [28]

$$\Delta M_s = \Delta M_s^{\text{SM}} \left| 1 + a \left(\frac{U_{sb}}{\lambda_t} \right) - b \left(\frac{U_{sb}}{\lambda_t} \right)^2 \right| , \quad (3.4)$$

where

$$a = 4 \frac{C(x_t)}{E(x_t)} , \quad b = \frac{2\sqrt{2}\pi^2}{G_F M_W^2 E(x_t)} . \quad (3.5)$$

The loop functions $E(x_t)$ and $C(x_t)$ are given by [28]

$$\begin{aligned} E(x_t) &= \frac{-4x_t + 11x_t^2 - x_t^3}{4(1-x_t)^2} + \frac{3x_t^3 \ln x_t}{2(1-x_t)^3} , \\ C(x_t) &= \frac{x_t}{4} \left[\frac{4-x_t}{1-x_t} + \frac{3x_t \ln x_t}{(1-x_t)^2} \right] . \end{aligned} \quad (3.6)$$

The term in Eq. (3.4) proportional to a is obtained from a diagram with both SM and NP Z vertices; that proportional to b corresponds to the diagram with two NP Z vertices.

This coupling will also lead to contributions to Γ_{12}^s due to the generation of the Z -mediated operator $b \rightarrow sf\bar{f}$ ($f = \tau, c$). The amplitude is

$$\frac{G_F}{\sqrt{2}} U_{sb} \bar{s} \gamma_\mu (1 - \gamma_5) b \bar{f} \gamma^\mu (I_3 - Q \sin^2 \theta_W) (1 \mp \gamma_5) f . \quad (3.7)$$

There are diagrams with two NP vertices, and with one SM and one NP vertex. The dominant contribution is due to SM-NP interference, yielding

$$\begin{aligned} \Gamma_{12}^{s,Z} &= -\frac{G_F^2 m_b^2 \lambda_c U_{sb}}{\pi} \sqrt{1-4x_c} \times \left[\left\{ \frac{1}{2}(1-x_c) - \frac{2}{3} \sin^2 \theta_W (1+2x_c) \right\} \langle O_{LL} \rangle \right. \\ &\quad \left. + \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) (1+2x_c) \langle \tilde{O}_{RR} \rangle \right] . \end{aligned} \quad (3.8)$$

3.2 Z' -mediated FCNC's

In the model with Z' -mediated FCNC's (Z' FCNC), the gauge group contains an additional $U(1)'$, which leads to a Z' [29]. Within some string-construction or GUT models such as E_6 , it is possible to have family non-universal Z' couplings. In the physical basis, FCNC's generally appear at tree level in both the left-handed (LH) and right-handed (RH) sectors. In particular, the interaction Lagrangian can contain $Z'\bar{b}s$ couplings:

$$\mathcal{L}_{FCNC}^{Z'} = -\frac{g}{\cos\theta_W} \left[\bar{s}\gamma^\mu P_L B_{sb}^L b + (L \leftrightarrow R) \right] Z'_\mu + \text{h.c.} , \quad (3.9)$$

which lead to a tree-level contribution to B_s - \bar{B}_s mixing. (Note: the $U(1)'$ coupling constant is g' . However, the above Lagrangian is written in terms of the SM coupling; the ratio of the two couplings is absorbed into the B_{sb} 's. This makes the comparison of NP and SM effects more straightforward.)

The effective Hamiltonian for M_{12}^s in the Z' FCNC model at the scale m_b is calculated from the tree-level diagrams [30, 31]:

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & \frac{4G_F}{\sqrt{2}} \frac{m_Z^2}{m_{Z'}^2} \left[\eta^{6/23} (B_{sb}^L)^2 O_{LL}(m_b) + \eta^{6/23} (B_{sb}^R)^2 O_{RR}(m_b) + 2\eta^{3/23} B_{sb}^L B_{sb}^R O_{LR}(m_b) \right. \\ & \left. + \frac{4}{3} (\eta^{3/23} - \eta^{-24/23}) B_{sb}^L B_{sb}^R \tilde{O}_{LR}(m_b) \right] , \end{aligned} \quad (3.10)$$

where $\eta = \alpha_s(M_{Z'})/\alpha_s(m_b)$ and

$$\begin{aligned} O_{LL} &= \bar{s}\gamma_\mu P_L b \bar{s}\gamma^\mu P_L b , \\ O_{RR} &= \bar{s}\gamma_\mu P_R b \bar{s}\gamma^\mu P_R b , \\ O_{LR} &= \bar{s}\gamma_\mu P_L b \bar{s}\gamma^\mu P_R b , \\ \tilde{O}_{LR} &= \bar{s}P_L b \bar{s}P_R b . \end{aligned} \quad (3.11)$$

In addition to the SM operator O_{LL} , the operators O_{RR} and O_{LR} are generated at the scale $M_{Z'}$. The operator \tilde{O}_{LR} is generated through renormalization down to the scale m_b .

The matrix element $M_{12}^{s,Z'}$ for B_s - \bar{B}_s mixing is given by

$$M_{12}^{s,Z'} = \langle B_s | \mathcal{H}_{\text{eff}} | \bar{B}_s \rangle . \quad (3.12)$$

The hadronic matrix elements are again calculated using the vacuum insertion approximation [16]. $\langle B_s | O_{LL} | \bar{B}_s \rangle$ is given in Eq. (2.2), $\langle O_{RR} \rangle \equiv \langle B_s | O_{RR} | \bar{B}_s \rangle = \langle B_s | O_{LL} | \bar{B}_s \rangle$, and

$$\begin{aligned} \langle O_{LR} \rangle &\equiv \langle B_s | O_{LR} | \bar{B}_s \rangle = -\left[\frac{1}{4} + \frac{1}{6} \left(\frac{m_{B_s}}{m_b + m_s} \right)^2 \right] m_{B_s} f_{B_s}^2 , \\ \langle \tilde{O}_{LR} \rangle &\equiv \langle B_s | \tilde{O}_{LR} | \bar{B}_s \rangle = \left[\frac{1}{24} + \frac{1}{4} \left(\frac{m_{B_s}}{m_b + m_s} \right)^2 \right] m_{B_s} f_{B_s}^2 . \end{aligned} \quad (3.13)$$

The Z' contribution to Γ_{12}^s through τ pairs is obtained from the formulae given in Refs. [32, 33]:

$$\begin{aligned} \Gamma_{12}^{s,Z'} = & -\frac{4G_F^2 m_b^2}{3\pi} \left(\frac{m_Z^2}{m_{Z'}^2}\right)^2 \sqrt{1-4x_\tau} \times \\ & \left[\left\{ (B^{LL})^2 + (B^{RR})^2 + (B^{LR})^2 + (B^{RL})^2 \right\} \left\{ (1-x_\tau)\langle O_{LL} \rangle + (1+2x_\tau)\langle \tilde{O}_{RR} \rangle \right\} \right. \\ & + 2 \left\{ B^{LL}B^{RL} + B^{RR}B^{LR} \right\} \left\{ (1-x_\tau)\langle O_{LR} \rangle + (1+2x_\tau)\langle \tilde{O}_{LR} \rangle \right\} \\ & + 6 \left\{ B^{LL}B^{LR} + B^{RR}B^{RL} \right\} x_\tau \langle O_{LL} \rangle \\ & \left. + 6 \left\{ B^{LL}B^{RR} + B^{LR}B^{RL} \right\} x_\tau \langle O_{LR} \rangle \right], \end{aligned} \quad (3.14)$$

where $B^{ij} = B_{sb}^i B_{\tau\tau}^j$ ($i, j = L, R$), $x_\tau = m_\tau^2/m_b^2$. Comparing Eqs. (2.1) and (3.14), we can see that if $B^{ij} \sim (\lambda_c m_{Z'}^2/m_Z^2)^2 \sim \mathcal{O}(1)$, $\Gamma_{12}^{s,Z'}$ can be comparable to $\Gamma_{12}^{s,SM}$. We will see that these $\mathcal{O}(1)$ couplings are still allowed by $B(\bar{B}_s \rightarrow \tau^+ \tau^-)$ and $B(\bar{B} \rightarrow X_s \tau^+ \tau^-)$.

Although the c -quark loop contribution with both couplings from NP cannot be large enough to compete with the SM contribution, there can be an interference term between the SM and the NP in this case. This term is given by

$$\begin{aligned} \Gamma_{12}^{s,Z'+SM} = & -\frac{G_F^2 m_b^2 \lambda_c}{\pi} \left(\frac{m_Z^2}{m_{Z'}^2}\right) \sqrt{1-4x_c} \\ & \times \left[4B_{sb}^L B_{cc}^L \left\{ (1-x_c)\langle O_{LL} \rangle + (1+2x_c)\langle \tilde{O}_{LR} \rangle \right\} + 6B_{sb}^L B_{cc}^R x_c \langle O_{LL} \rangle + 12B_{sb}^R B_{cc}^R \langle O_{LR} \rangle \right. \\ & \left. + 4B_{sb}^R B_{cc}^L \left\{ (1-x_c)\langle O_{LR} \rangle + (1+2x_c)\langle \tilde{O}_{LR} \rangle \right\} \right]. \end{aligned} \quad (3.15)$$

Here again Eq. (3.15) can be comparable with $\Gamma_{12}^{s,SM}$ when $B_{sb}^i B_{cc}^j \sim \mathcal{O}(1)$ ($i, j = L, R$).

4. Numerical Results

4.1 ZFCNC

In the numerical study of the ZFCNC model, we scan the allowed values of the couplings after imposing the constraints from $|\Delta_s| \equiv \Delta M_s/\Delta M_s^{SM}$ [Eq. (3.4)] and $B(\bar{B} \rightarrow X_s \mu^+ \mu^-)$ ¹. The general expression for the branching ratio of $\bar{B} \rightarrow X_s l^+ l^-$,

¹There can be other constraints, such as those from the forward-backward asymmetry in $B \rightarrow K^* l^+ l^-$ [35]. However, we do not include these in our analysis, since, as can be seen below in Fig. 2, the two constraints used are sufficient to rule out the ZFCNC model as an explanation of $S_{\psi\phi}$ and a_{sl}^s .

where $l = e, \mu, \tau$, is given by [34]

$$B(\bar{B} \rightarrow X_s l^+ l^-) = B_0 \int_{4m_l^2/m_b^2}^{(1-m_s/m_b)^2} \left(B_{SM}(z) + B_{SM-VA}(z) + B_{VA}(z) \right) dz. \quad (4.1)$$

The expressions for B_0 , B_{SM} , B_{SM-VA} , and B_{VA} are given in Ref. [34]. We do not repeat them here. We note only that the integrand depends on the NP couplings R_V, R_A, R'_V and R'_A . In the ZFCNC model, the NP couplings $R'_{V,A} = 0$, and the $R_{V,A}$ are given by [36]

$$R_V = \frac{2\pi}{\alpha} \frac{U_{sb}}{V_{tb}V_{ts}^*} \left(-\frac{1}{2} + 2 \sin^2 \theta_W \right), \quad R_A = \frac{\pi}{\alpha} \frac{U_{sb}}{V_{tb}V_{ts}^*}. \quad (4.2)$$

We define q^μ as the sum of the 4-momenta of the μ^+ and μ^- in $\bar{B} \rightarrow X_s \mu^+ \mu^-$. The theoretical predictions for the branching ratio of this decay are not reliable over the whole q^2 region due to the presence of charm resonances at intermediate q^2 ($7 \text{ GeV}^2 \leq q^2 \leq 12 \text{ GeV}^2$). The predictions are relatively more robust for low q^2 ($1 \text{ GeV}^2 \leq q^2 \leq 6 \text{ GeV}^2$) and high q^2 ($14.4 \text{ GeV}^2 \leq q^2 \leq m_b^2$). However, the two regions have different sensitivities to the short-distance physics. The dominant contribution to $\bar{B} \rightarrow X_s \mu^+ \mu^-$ in the low- q^2 region comes from a virtual photon, whereas the dominant contribution in the high- q^2 region comes from the Z and W . Since we are interested specifically in the $Z\bar{b}s$ coupling, we use the branching ratio in the high- q^2 region to constrain the ZFCNC parameter space.

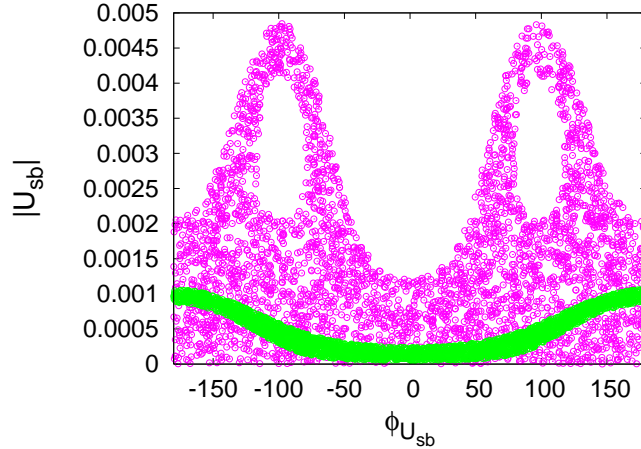


Figure 1: The $\phi_{U_{sb}}-|U_{sb}|$ parameter space allowed by $|\Delta_s|$ (magenta) and $B(\bar{B} \rightarrow X_s \mu^+ \mu^-)$ (green).

As described earlier, U_{sb} denotes the $Z\bar{b}s$ coupling generated in the ZFCNC model [Eq. (3.1)]. The parameters of the model are therefore the magnitude and the phase of this coupling, $|U_{sb}|$ and $\phi_{U_{sb}} \equiv \arg U_{sb}$. Fig. 1 shows the allowed region in $(\phi_{U_{sb}}, |U_{sb}|)$ space due to the measurements of $|\Delta_s|$ (magenta) and $B(\bar{B} \rightarrow X_s \mu^+ \mu^-)$

(green). Using constraints only from $|\Delta_s|$, we see that the full range of $\phi_{U_{sb}}$ is obtained only when $|U_{sb}| \lesssim 0.001$, while $|U_{sb}|$ can be as large as 0.005 in the constrained regions of $\phi_{U_{sb}}$. However, if we include the constraints from $B(\bar{B} \rightarrow X_s \mu^+ \mu^-)$, the $(\phi_{U_{sb}}, |U_{sb}|)$ space is reduced considerably. From Fig. 1, one sees that $B(\bar{B} \rightarrow X_s \mu^+ \mu^-)$ limits the upper value of $|U_{sb}|$ to be around 0.001.

Using these allowed couplings, we can calculate the observables $S_{\psi\phi}$, a_{sl}^s and $\Delta\Gamma_s$, and compare these values with the measurements. The 1σ ranges of these observables are

$$\begin{aligned} S_{\psi\phi} &: [-0.91, -0.47] , \\ a_{sl}^s &: [-17.7, -7.7] \times 10^{-3} , \\ \Delta\Gamma_s &: \pm[0.084, 0.208] \text{ ps}^{-1} . \end{aligned} \quad (4.3)$$

In addition, we can examine correlations between the observables.

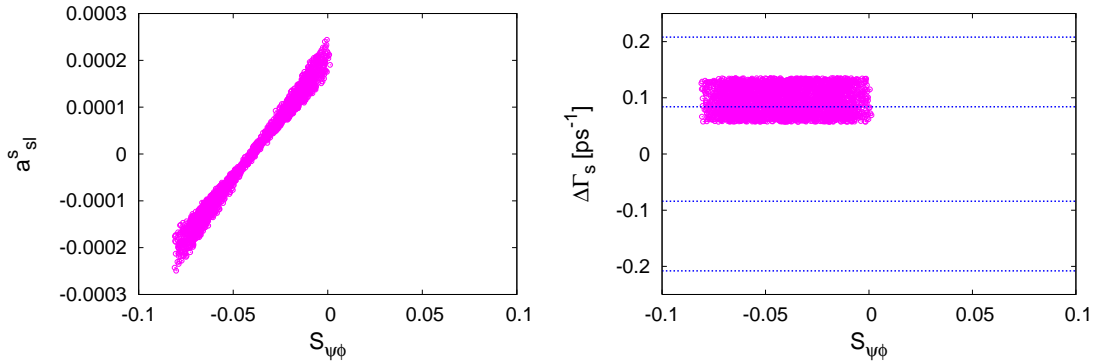


Figure 2: The a_{sl}^s - $S_{\psi\phi}$ correlation plot (left panel) and the $\Delta\Gamma_s$ - $S_{\psi\phi}$ correlation plot (right panel). The horizontal lines in the right panel indicate the 1σ experimental allowed range for $\Delta\Gamma_s$.

As a consequence of the strong constraint on the size and phase of U_{sb} , we see in Fig. 2 that it is not possible to explain the present 1σ ranges of $S_{\psi\phi}$ and a_{sl}^s in the ZFCNC model. Still, this model can produce values for these observables which are closer to the experimental data. In particular, one can have $a_{sl}^s \sim -3 \times 10^{-4}$, which is about 10 times larger in magnitude than the SM prediction of $\sim 2 \times 10^{-5}$. And $S_{\psi\phi}$ can be decreased to -0.08 , as compared to the SM value of -0.04 .

4.2 Z'FCNC

As discussed earlier, a large NP contribution to $\Gamma_{12}^{s,\text{NP}}$, and hence to a_{sl}^s , may come from the NP $b \rightarrow s\tau^+\tau^-$ and/or $b \rightarrow sc\bar{c}$ operators. Since the two operators need not be related to one another, a large NP effect on $b \rightarrow s\tau^+\tau^-$ but not on $b \rightarrow sc\bar{c}$, or vice versa, is conceivable. Thus, in analyzing the Z'FCNC model, we examine

whether it is possible to explain the present 1σ measurement of a_{sl}^s if only one of the NP operators is present.

4.2.1 NP $b \rightarrow s\tau^+\tau^-$ operator only

We first consider the case where the NP contribution to $\Gamma_{12}^{s,\text{NP}}$ comes only from the $b \rightarrow s\tau^+\tau^-$ operator. In our numerical study we scan the allowed values of the Z' FCNC couplings imposing the constraints from $|\Delta_s|$, $B(\bar{B} \rightarrow X_s \tau^+ \tau^-) < 5\%$ and $B(\bar{B}_s \rightarrow \tau^+ \tau^-) < 5\%$. $|\Delta_s|$ can be obtained using Eqs. (3.10) and (3.12), and $B(\bar{B} \rightarrow X_s \tau^+ \tau^-)$ is given by Eq. (4.1) with $l = \tau$. The branching ratio of $\bar{B}_s \rightarrow \tau^+ \tau^-$ is [34]

$$B(\bar{B}_s \rightarrow \tau^+ \tau^-) = \frac{G_F^2 \alpha^2 m_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\tau^2}{m_{B_s}^2}} \left| \frac{2m_\tau}{m_{B_s}^2} (C_{10} + R_A - R'_A) \right|^2. \quad (4.4)$$

In the Z' FCNC model, the NP couplings are given by

$$\begin{aligned} R_V &= -\frac{4\pi m_Z^2/m_{Z'}^2}{\alpha V_{tb} V_{ts}^*} B_{sb}^L (B_{\tau\tau}^L + B_{\tau\tau}^R), \\ R_A &= \frac{4\pi m_Z^2/m_{Z'}^2}{\alpha V_{tb} V_{ts}^*} B_{sb}^L (B_{\tau\tau}^L - B_{\tau\tau}^R), \\ R'_V &= -\frac{4\pi m_Z^2/m_{Z'}^2}{\alpha V_{tb} V_{ts}^*} B_{sb}^R (B_{\tau\tau}^L + B_{\tau\tau}^R), \\ R'_A &= \frac{4\pi m_Z^2/m_{Z'}^2}{\alpha V_{tb} V_{ts}^*} B_{sb}^R (B_{\tau\tau}^L - B_{\tau\tau}^R). \end{aligned} \quad (4.5)$$

These couplings are constrained by the above observables. However, the key point is that, because the bounds on the NP $b \rightarrow s\tau^+\tau^-$ transition are still weak, the constraints are not severe.

Fig. 3 shows the a_{sl}^s - $S_{\psi\phi}$ and $\Delta\Gamma_s$ - $S_{\psi\phi}$ correlation plots for the case where only B_{sb}^L and $B_{\tau\tau}^{L,R}$ couplings are present. We make the following observations:

- $S_{\psi\phi}$ can take any value between -1 and 1 .
- The Z' FCNC model gives values for a_{sl}^s within its 1σ range.
- One can simultaneously reproduce the present measurements of all three observables, $S_{\psi\phi}$, a_{sl}^s and $\Delta\Gamma_s$, within their 1σ ranges.

Obviously, one obtains the same conclusions if a nonzero B_{sb}^R is also present.

4.2.2 NP $b \rightarrow sc\bar{c}$ operator only

We now consider the case where the NP contribution to $\Gamma_{12}^{s,\text{NP}}$ comes only from the $b \rightarrow sc\bar{c}$ operator. In our numerical study we scan the allowed values of the Z' FCNC

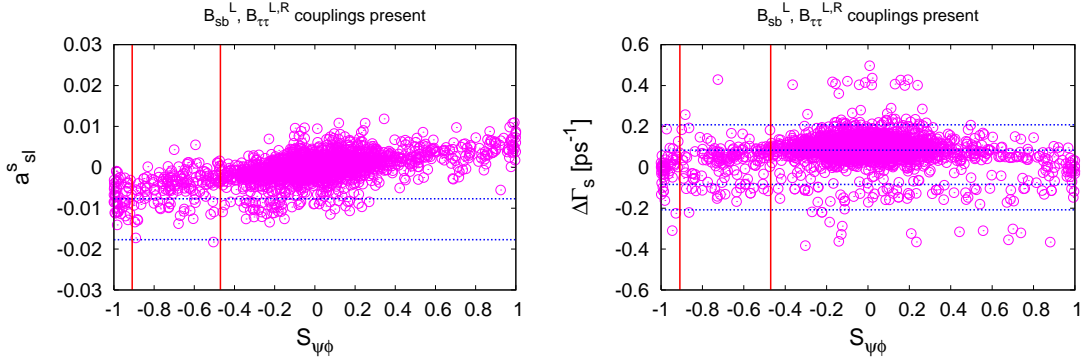


Figure 3: The a_{sl}^s - $S_{\psi\phi}$ correlation plot (left panel) and the $\Delta\Gamma_s$ - $S_{\psi\phi}$ correlation plot (right panel), for the case where only B_{sb}^L and $B_{\tau\tau}^{L,R}$ couplings are present. The horizontal and vertical lines indicate the 1σ experimental allowed ranges for the observables.

couplings imposing the constraints from $|\Delta_s|$ and the indirect CP asymmetry in $\bar{B}_d \rightarrow J/\psi K_S$. This latter constraint arises as follows. In the presence of NP in the decay $b \rightarrow sc\bar{c}$, the effective measured $\sin 2\beta$ in $\bar{B}_d \rightarrow J/\psi K_S$ is given by [23]

$$\sin 2\beta^{meas} = \sin 2\beta + 2|r| \cos 2\beta \sin \varphi \cos \delta^a . \quad (4.6)$$

Here, the NP parameters are defined similarly to those in Eq. (2.10): $|r|$ is the ratio of magnitudes of the NP and SM $b \rightarrow sc\bar{c}$ amplitudes, φ is the NP weak phase, and δ^a is the SM strong phase. The true value of $\sin 2\beta$ is taken from the fit to the sides of the unitarity triangle: $\sin 2\beta = 0.731 \pm 0.038$, while the experimental measurement gives $\sin 2\beta^{meas} = 0.668 \pm 0.028$ [37]. Using these values, $|r|$ is estimated to be [23]

$$|r| = (4.6 \pm 3.5)\% . \quad (4.7)$$

Thus, at 1σ , $|r| \leq 8.1\%$ is permitted. This upper bound on $|r|$, along with the measurement of $|\Delta_s|$, constrain the NP couplings.

Fig. 4 shows the a_{sl}^s - $S_{\psi\phi}$ and $\Delta\Gamma_s$ - $S_{\psi\phi}$ correlation plots for the case where only B_{sb}^L and $B_{cc}^{L,R}$ couplings are present. The results are the same as for the case where a NP $b \rightarrow s\tau^+\tau^-$ operator was added:

- $S_{\psi\phi}$ can take any value between -1 and 1 .
- The Z' FCNC model gives values for a_{sl}^s within its 1σ range.
- One can simultaneously reproduce the present measurements of all three observables, $S_{\psi\phi}$, a_{sl}^s and $\Delta\Gamma_s$, within their 1σ ranges.

We therefore see that the Z' FCNC model can reproduce the present measurements of $S_{\psi\phi}$, $\Delta\Gamma_s$ and a_{sl}^s within their 1σ ranges if the NP contribution comes only from either the $b \rightarrow s\tau^+\tau^-$ or $b \rightarrow sc\bar{c}$ operators.

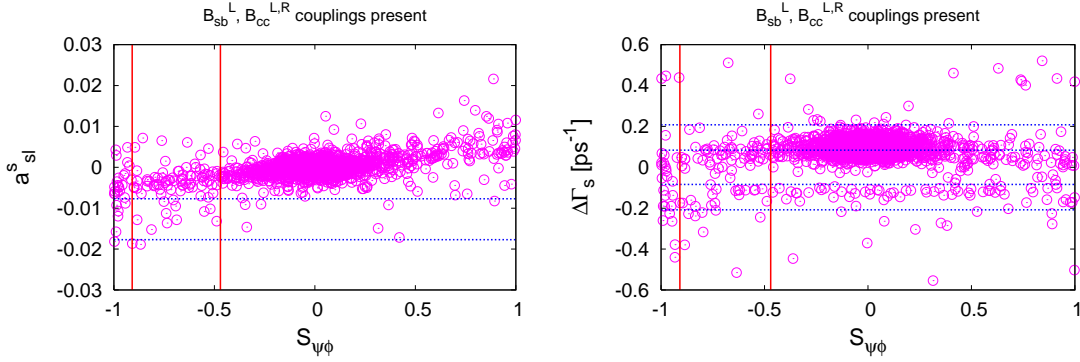


Figure 4: The a_{sl}^s - $S_{\psi\phi}$ correlation plot (left panel) and the $\Delta\Gamma_s$ - $S_{\psi\phi}$ correlation plot (right panel), for the case where only $B_{sb}^{L,R}$ and $B_{cc}^{L,R}$ couplings are present. The horizontal and vertical lines indicate the 1σ experimental allowed ranges for the observables.

5. Conclusions

Recently, the DØ Collaboration measured the CP-violating like-sign dimuon charge asymmetry in neutral B decays and found a 3.2σ difference from the prediction of the standard model (SM). Combining the DØ result with other measurements, we obtain the semileptonic charge asymmetry for B_s mesons, $(a_{sl}^s)_{\text{ave}} = -(12.7 \pm 5.0) \times 10^{-3}$, which is still $\sim 2.5\sigma$ away from the SM prediction.

A non-SM a_{sl}^s can be explained theoretically by a new-physics (NP) contribution to B_s - \bar{B}_s mixing, specifically to M_{12}^s and Γ_{12}^s , the dispersive and absorptive parts of the mixing. It is usually assumed that Γ_{12}^s is dominated by the SM tree-level $b \rightarrow s\bar{c}c$ coupling, and that it is not affected by the NP. Instead, NP is considered only in M_{12}^s . However, in this case, the measured value of $(a_{sl}^s)_{\text{ave}}$ within its 1σ range cannot be explained. Thus, NP in Γ_{12}^s is necessary.

There are some NP models (leptoquarks, R-parity-violating SUSY) whose contributions to Γ_{12}^s can compete with the SM. In this paper, we examine models with flavor-changing neutral gauge bosons (Z or Z') to see if they can explain $(a_{sl}^s)_{\text{ave}}$. The models must also reproduce the measured values of the indirect CP asymmetry $S_{\psi\phi}$ in $\bar{B}_s \rightarrow J/\psi\phi$ and $\Delta\Gamma_s$.

In our models we assume that the main contribution to Γ_{12}^s comes from diagrams involving τ and/or c loops. The point is that the current constraints on NP $b \rightarrow sf\bar{f}$ ($f = \tau, c$) transitions are quite weak. We find that the model with flavor-changing Z couplings (ZFCNC) cannot reproduce the present measured values of $S_{\psi\phi}$ and a_{sl}^s within their 1σ ranges. Still, the ZFCNC model can lead to modified values for $S_{\psi\phi}$ and a_{sl}^s which are closer to the experimental data than the SM predictions.

On the other hand, in the model with flavor-changing Z' couplings (Z' FCNC), even after imposing the current experimental constraints, the present measurements of $S_{\psi\phi}$, a_{sl}^s and $\Delta\Gamma_s$, can all be simultaneously reproduced within their 1σ ranges.

Indeed, the full range of $S_{\psi\phi}$ is allowed. We therefore see that the Z' FCNC model is another type of NP which can explain the measured value of the $D\bar{0}$ dimuon charge asymmetry in the B system.

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