

In the scenario with $Z$ mediated flavor changing neutral current occurring at the tree level due to the addition of a vector-like isosinglet down-type quark $d'$ to the SM particle spectrum, we perform a $\chi^2$ fit using the flavor physics data and obtain the best fit value along with errors of the tree level $Z\bar{b}s$ coupling, $U_{sb}$. The fit indicates that the new physics coupling is constrained to be small: we obtain $|U_{sb}| \leq 3.40 \times 10^{-4}$ at 3σ. Still this does allow for the possibility of new physics signals in some of the observables such as semileptonic CP asymmetry in $B_s$ decays.
I. INTRODUCTION

The Standard Model (SM) of the electroweak interactions successfully explains most of the experimental data to date. However in recent years, there have been quite a few measurements of quantities in $B$ decays which differ from the predictions of the SM. For example, in $B \rightarrow \pi K$, the SM has some difficulty in accounting for all the experimental measurements [1]. The measured indirect (mixing-induced) CP asymmetry in some $b \rightarrow s$ penguin decays is found not to be identical to that in $B \rightarrow J/\psi K_s$ [23], counter to the expectations of the SM. The measurement of indirect CP asymmetry in $B_s \rightarrow J/\psi\phi$ by the CDF and DØ collaborations shows a deviation from the SM prediction [5,7]. 1.

The observation of the anomalous dimuon charge asymmetry by the DØ collaboration [9–11] also points towards some CP asymmetry in $\bar{B}_s \rightarrow \psi\phi$, where $\psi\phi$ is a $2\pi$ state. The recent LHCb update does not confirm this result [18]. Their measurement of the $A_{FB}$ distribution is consistent with the SM prediction, except in the high-$q^2$ region.

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A minimal extension of SM can be obtained by adding a vector-like isosinglet up-type or down-type quark to the SM particle spectrum [19–34]. Such exotic fermions can appear in grand unified theories as well in models with large extra dimensions. Here we consider the extension of SM by adding a vector like down-type quark $d'$.

The ordinary $Q_{em} = −1/3$ quarks mix with the $d'$.

Because the $d'$ has a different $I_{3L}$ from $d_L$, $s_L$, and $b_L$, $Z$-mediated FCNC’s (ZFCNC) appear at tree level in the left-handed sector. In particular, a $Zbs$ coupling can be generated:

$$Z_{FCNC}^2 = -\frac{g}{2\cos\theta_W} U_{sb} \bar{s} \gamma^\mu P_L b Z_\mu + h.c. \quad (1)$$

This coupling leads to a new physics contribution to $b \rightarrow s$ transition (such as $B_s - \bar{B}_s$ mixing, $b \rightarrow s \mu^+ \mu^-$ & $b \rightarrow s \nu \bar{\nu}$ decays, etc) at the tree level. This tree level coupling $U_{sb}$ can be constrained by various measurements in the $b \rightarrow s$ sector.

In this paper we consider observables such as $B_s - \bar{B}_s$ mixing, branching ratios of $B \rightarrow X_s \mu^+ \mu^-$, $\bar{B}_s \rightarrow \mu^+ \mu^-$ and $B \rightarrow X_s \nu \bar{\nu}$ to constrain the new physics coupling $U_{sb}$. Instead of obtaining the usual scatter plot which shows the allowed ranges of the $U_{sb}$ parameter space, we perform a $\chi^2$ fit which provides us the best fit value of $U_{sb}$ along with the errors. We then study the effect of tree level $Zbs$ coupling on the indirect CP asymmetry in $B_s \rightarrow \psi\phi$, anomalous dimuon charge asymmetry $a_{sl}^s$, forward-backward (FB) asymmetry in $B \rightarrow X_s \mu^+ \mu^-$ and the branching ratio of $B_s \rightarrow \tau^+ \tau^-$. We show that the various measurements in the $b \rightarrow s$ sector put strong constraint on the allowed values of $U_{sb}$. However it is still possible to have new physics signals in some $b \rightarrow s$ observables.

The paper is organized as follows. In Sec. [II] we discuss the methodology for the fit. In Sec. [III] we present the results of the fit. In Sec. [IV] we obtain predictions for various $b \rightarrow s$ observables. Finally in Sec. [V] we present our conclusions.

II. METHOD

As $U_{sb}$ denotes the $Zbs$ coupling generated in the ZFCNC model, the parameters of the model are therefore the magnitude and the phase of this coupling, $|U_{sb}|$ and $\phi_{sb} \equiv \arg U_{sb}$.

In order to obtain constraints on the new physics coupling $U_{sb}$, we perform a $\chi^2$ fit using the CERN minimization code MINUIT [35]. The fit includes observables that have relatively small hadronic uncertainties: (i) the branching ratio of $B \rightarrow X_s \mu^+ \mu^-$ in the low- and high-$q^2$ regions, (ii) the branching ratio of $B_s \rightarrow \mu^+ \mu^-$, (iii) the ratio of the branching ratio of $B_s \rightarrow \mu^+ \mu^-$ and the mass difference in $B_s$ system, (iv) the branching ratio of $B \rightarrow X_s \nu \bar{\nu}$. We include both experimental errors and theoretical uncertainties in the fit. In the following subsections, we discuss various observables used as a constraint.

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2 The recent LHCb update does not confirm this result [18]. Their measurement of the $A_{FB}$ distribution is consistent with the SM prediction, except in the high-$q^2$ region.
A. $\bar{B} \to X_s \mu^+ \mu^-$

The effective Hamiltonian for the quark-level transition $b \to s \mu^+ \mu^-$ in the SM can be written as

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu),$$

where the form of the operators $O_i$ and the expressions for calculating the coefficients $C_i$ are given in Ref. [36]. The operator $O_i$, $i = 1, 6$ can contribute indirectly to $b \to s \mu^+ \mu^-$ and their effects are included in the effective Wilson coefficients $C_9$ and $C_7$ [36, 37].

The $Zbs$ coupling generated in the ZFCNC model changes the values of the Wilson coefficients $C_{9,10}$. The Wilson coefficients $C_{9,10}^{\text{tot}}$ in the ZFCNC model can be written as

$$C_9^{\text{tot}} = C_9^{\text{eff}} - \pi \frac{U_{sb}}{V_{ts}^* V_{tb}} (4 \sin^2 \theta_W - 1),$$

$$C_{10}^{\text{tot}} = C_{10} - \pi \frac{U_{sb}}{V_{ts}^* V_{tb}}.$$

Here $V_{ts}^* V_{tb} \simeq -0.0403 e^{-i\pi^*}$. We use the SM Wilson coefficients as given in Ref. [37].

The calculation of branching ratio gives

$$\text{BR}(\bar{B} \to X_s \mu^+ \mu^-) = \frac{\alpha^2 \text{BR}(\bar{B} \to X_c e\bar{\nu}) |V_{ts}^* V_{tb}|^2}{4\pi^2 f(m_c^2) \kappa(m_c)} \frac{1}{|V_{cb}|^2} \int D(z) dz,$$

where

$$D(z) = (1-z)^2 \left[ (1+2z) \left( |C_9^{\text{tot}}|^2 + |C_{10}^{\text{tot}}|^2 \right) + 4 \left( 1 + \frac{2z}{z} \right) |C_7^{\text{eff}}|^2 + 12 \text{Re}(C_7^{\text{eff}} C_9^{\text{tot*}}) \right] .$$

Here $z \equiv q^2/m_b^2 \equiv (p_{\mu^+} + p_{\mu^-})^2/m_b^2$ and $m_{\ell q} = m_q/m_b$ for all quarks $q$. The expressions for the phase-space factor $f(m_c)$ and the 1-loop QCD correction factor $\kappa(m_c)$ are given in [38].

The theoretical prediction for the branching ratio of $\bar{B} \to X_s \mu^+ \mu^-$ in the intermediate $q^2$ region ($7 \text{GeV}^2 \leq q^2 \leq 12 \text{GeV}^2$) is rather uncertain due to the nearby charmed resonances. The predictions are relatively cleaner in the low-$q^2$ ($1 \text{GeV}^2 \leq q^2 \leq 6 \text{GeV}^2$) and the high-$q^2$ ($14.4 \text{GeV}^2 \leq q^2 \leq m_{\pi}^2$) regions. We therefore consider both low-$q^2$ high-$q^2$ region in the fit.

We define $\chi^2$ as

$$\chi^2_{\bar{B} \to X_s \mu^+ \mu^-: \text{low}} = \frac{(D_{\text{low}} - 5.69947)^2}{1.82522},$$

$$\chi^2_{\bar{B} \to X_s \mu^+ \mu^-: \text{high}} = \frac{(D_{\text{high}} - 1.56735)^2}{0.635465},$$

where

$$D_{\text{low}} = \int_{\frac{m_b}{2\sqrt{s}}} \frac{m_c}{\sqrt{s}} D(z) dz = \frac{4\pi^2 f(m_c^2) \kappa(m_c)}{\alpha^2 \text{BR}(\bar{B} \to X_c e\bar{\nu}) |V_{ts}^* V_{tb}|^2} |V_{cb}|^2 = 5.69947 \pm 1.82522,$$

$$D_{\text{high}} = \int_{\frac{m_b}{2\sqrt{s}}} \frac{m_c}{\sqrt{s}} \frac{1}{m_c^2} D(z) dz = \frac{4\pi^2 f(m_c^2) \kappa(m_c)}{\alpha^2 \text{BR}(\bar{B} \to X_c e\bar{\nu}) |V_{ts}^* V_{tb}|^2} |V_{cb}|^2 = 1.56735 \pm 0.635465 .$$

Here we have added an overall corrections of 30% to the theoretical prediction of $\text{BR}(\bar{B} \to X_s \mu^+ \mu^-)$, which includes the non-perturbative corrections.

B. $\bar{B}_s \to \mu^+ \mu^-$

The purely leptonic decay $\bar{B}_s \to \mu^+ \mu^-$ is chirally suppressed within the SM. The SM prediction for the branching ratio is $(3.35 \pm 0.32) \times 10^{-9}$ [48]. Recently LHCb collaboration reported a very strong upper bound on the branching ratio of $\bar{B}_s \to \mu^+ \mu^-$, which is $3.8 \times 10^{-9}$ at 90% C.L. [49].
The branching ratio of $B_s \rightarrow \mu^+ \mu^-$ in the ZFCNC model is given by

$$BR(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2 M_{B_s} m_{\mu}^2 f_{B_s}^2 |V_{ts}^* V_{tb}|^2}{16 \pi^3} \sqrt{1 - \frac{4 m_{\mu}^2}{M_{B_s}^2}} |C_{10}^{tot}|^2 .$$  

(11)

We define $\chi^2$ as

$$\chi^2_{B_s \rightarrow \mu^+ \mu^-} = \left( \frac{|C_{10}^{tot}|^2 - 0.0}{13.5408} \right) ^2 ,$$  

(12)

with

$$|C_{10}^{tot}|^2 = \frac{16 \pi^3 \cdot BR(B_s \rightarrow \mu^+ \mu^-)}{G_F^2 \alpha^2 M_{B_s} m_{\mu}^2 f_{B_s}^2 |V_{ts}^* V_{tb}|^2 \sqrt{1 - \frac{4 m_{\mu}^2}{M_{B_s}^2}}} = 0.0 \pm 13.5408 .$$  

(13)

### C. Ratio of BR($B_s \rightarrow \mu^+ \mu^-$) and the mass difference in the $B_s$ system

The mass difference $\Delta M_s$ is given by

$$\Delta M_s = 2 |M_{12}^{SM}| .$$  

(14)

The SM contribution to $M_{12}^{SM}$ is

$$M_{12}^{SM} = \frac{G_F^2}{12 \pi^2} (V_{ts}^* V_{tb})^2 M_W^2 M_{B_s} \eta_B f_{B_s}^2 B_B E(x_t) ,$$  

(15)

where $x_t = m_t^2 / M_W^2$ and $\eta_B$ is the QCD correction. The loop function $E(x_t)$ is given by

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

(16)

The mass difference $\Delta M_s$ in the ZFCNC model is given by

$$\Delta M_s = \frac{G_F^2}{6 \pi^2} |V_{ts}^* V_{tb}|^2 M_W^2 M_{B_s} \eta_B f_{B_s}^2 B_B E(x_t) |\Delta s| .$$  

(17)

$\Delta s$ is given by

$$\Delta s = 1 + a \left( \frac{U_{sb}}{V_{ts}^* V_{tb}} \right) - b \left( \frac{U_{sb}}{V_{ts}^* V_{tb}} \right)^2 ,$$  

(18)

where

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

(19)
The loop function $C(x_t)$ is given by \[ C(x_t) = \frac{x_t}{4} \left[ 4 - x_t + \frac{3x_t \ln x_t}{1 - x_t} \right]. \] (20)

The term in Eq. (17) proportional to $a$ is obtained from a diagram with both SM and new physics $Z$ vertices; that proportional to $b$ corresponds to the diagram with two new physics $Z$ vertices.

Dividing Eq. (14) by Eq. (17), we get

$$\frac{\text{BR}(\bar{B}_s \to \mu^+\mu^-)}{\Delta M_s} = \frac{3\alpha^2\tau_{B_s}m_\mu^2}{8\pi M_{W_s}^2\eta_{B_s}|E(x_t)|}\sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}\frac{|C_{10}^\text{tot}|^2}{|\Delta_s|}}.$$ (21)

We define $\chi^2$ as

$$\chi^2_{\text{BR mix}} = \left( \frac{|C_{10}^\text{tot}|^2}{13.6328} - 0.0 \right)^2,$$ (22)

with

$$\frac{|C_{10}^\text{tot}|^2}{|\Delta_s|} = \frac{\text{BR}(\bar{B}_s \to \mu^+\mu^-) 8\pi M_{W_s}^2\eta_{B_s}|E(x_t)|}{\Delta M_s\sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}}} = 0.0 \pm 13.6328.$$ (23)

### D. $\bar{B} \to X_s\nu\bar{\nu}$

The effective Hamiltonian for the decay $\bar{B} \to X_s\nu\bar{\nu}$ is given by

$$H_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} V_{ts}^* V_{tb} X_0(x_t)(\bar{s}b)_{V - A} (\bar{\nu}\nu)_{V - A} + \text{h.c.},$$ (24)

with

$$X_0(x_t) = \frac{x_t}{8} \left[ \frac{2 + x_t}{x_t - 1} + \frac{3x_t - 6}{(x_t - 1)^2}\ln x_t \right].$$ (25)

The presence of tree level $Zbs$ coupling changes the value of the structure function $X_0(x_t)$. The structure function within the ZFCNC model can be written as

$$X_0'(x_t) = X_0(x_t) + \left( \frac{\pi \sin^2 \theta_W}{\alpha V_{ts}^* V_{tb}} \right) U_{sb}.$$ (26)

The branching ratio of $\bar{B} \to X_s\nu\bar{\nu}$ is given by \[ \frac{\tilde{C}^2}{\tilde{\eta}} \] (27)

where $\tilde{C}^2$ is given by

$$\tilde{C}^2 = \frac{\alpha^2}{2\pi^2 \sin^2 \theta_W} |V_{ts}^* V_{tb} X_0' (x_t)|^2.$$ (28)

We define $\chi^2$ as

$$\chi^2_{\bar{B} \to X_s\nu\bar{\nu}} = \left( \frac{|V_{ts}^* V_{tb} X_0'(x_t)|^2 - 0.0}{0.069157} \right)^2,$$ (29)

with

$$|V_{ts}^* V_{tb} X_0'(x_t)|^2 = \frac{\text{BR}(\bar{B} \to X_s\nu\bar{\nu}) 2\pi^2 \sin^4 \theta_W |V_{tb}|^2 f(\hat{m}_c)\kappa(\hat{m}_c)}{\tilde{\eta} \tilde{\alpha^2}} = 0.0 \pm 0.069157.$$ (30)

Here we have used the present upper bound $\text{BR}(\bar{B} \to X_s\nu\bar{\nu}) < 64 \times 10^{-5}$ at 90% C.L. \[ 46 \] which can be written as $(0.0 \pm 40) \times 10^{-5}$.

Therefore the total $\chi^2$ can be written as

$$\chi^2_{\text{total}} = \chi^2_{\bar{B} \to X_s\mu^+\mu^- : \text{low}} + \chi^2_{\bar{B} \to X_s\mu^+\mu^- : \text{high}} + \chi^2_{\bar{B} \to \mu^+\mu^-} + \chi^2_{\text{BR mix}} + \chi^2_{\bar{B} \to X_s\nu\bar{\nu}}.$$ (31)
| Parameter       | Value                          |
|-----------------|-------------------------------|
| $|U_{sb}|$        | $0.90 \pm 0.83 \times 10^{-3}$ |
| $\phi_{sb}$     | $(0.00 \pm 181.34)^0$         |
| $\chi^2/d.o.f.$ | 1.72/3                        |

**TABLE II:** The results of the fit to the parameters of ZFCNC model.

| Observables | Predictions |
|-------------|-------------|
|             | SM          | ZFCNC       |
| $\phi_s^a$ (rad) | 0           | (0.00 ± 0.03) |
| $|\Delta_s|$  | 1           | 1.01 ± 0.01  |
| $a_{sl}^s \times 10^7$ | (1.92 ± 0.67) | (1.98 ± 13.88) |
| $\text{Br}(B_s \rightarrow \tau^+ \tau^-) \times 10^7$ | 5.74 ± 0.27 | 3.34 ± 1.92 |
| $(q^2)_{\text{incl}}^\text{max} \text{ GeV}^2$ | 3.33 ± 0.25 | 3.38 ± 0.26 |

**TABLE III:** ZFCNC predictions for potential observables.

### III. RESULTS OF THE FIT

The results of these fits are presented in Table II. It may be observed that the $\chi^2$ per degree of freedom is small, indicating that the fit is good. We observe that the present flavor data put strong constraint on $Z\bar{b} s$ coupling. At $3\sigma$, we obtain $|U_{sb}| \leq 3.40 \times 10^{-4}$.

### IV. PREDICTIONS

#### A. Semileptonic asymmetry $a_{sl}^s$

The expression for the semileptonic asymmetry $a_{sl}^s$ is given by

$$a_{sl}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin \phi_s = \frac{|\Gamma_{12}^s|}{|M_{12}^{s,SM}|} \sin \phi_s,$$

where the CP violating phase $\phi_s$ is defined by the following equation,

$$\phi_s \equiv \text{Arg} \left( -\frac{M_{12}^s}{\Gamma_{12}^s} \right).$$

The parameter $\Delta_s$ takes into account the new physics effects in mixing and is defined as

$$M_{12}^s = M_{12}^{s,SM} (1 + \frac{M_{12}^{s,NP}}{M_{12}^{s,SM}}) = M_{12}^{s,SM} \Delta_s = M_{12}^{s,SM} |\Delta_s| e^{i\phi_s^\Delta}.$$  

Thus $\phi_s$ can be written as

$$\phi_s = \phi_s^\Delta + \phi_s^\text{SM},$$

where $\phi_s^\text{SM} = (3.84 \pm 1.05) \times 10^{-3}$ [51]. Also, one has [52, 53]

$$\frac{|\Gamma_{12}^s|}{|M_{12}^{s,SM}|} = (5.0 \pm 1.1) \times 10^{-3}.$$  

The predictions for $\phi_s^\Delta$, $|\Delta_s|$ and $a_{sl}^s$ in ZFCNC model are given in Table III. We see that it is possible to have large deviations in $\phi_s$ (and hence $a_{sl}^s$) from its SM predictions.
B. Zero of Forward-Backward asymmetry

The FB asymmetry of muons in $\bar{B} \to X_s \mu^+ \mu^-$ is obtained by integrating the double differential branching ratio $\frac{d^2BR}{dz d \cos \theta}$ with respect to the angular variable $\cos \theta$,

$$A_{FB}(z) = \frac{\int_0^1 d \cos \theta \frac{d^2BR}{dz d \cos \theta} - \int_{-1}^0 d \cos \theta \frac{d^2BR}{dz d \cos \theta}}{\int_0^1 d \cos \theta \frac{d^2BR}{dz d \cos \theta} + \int_{-1}^0 d \cos \theta \frac{d^2BR}{dz d \cos \theta}},$$

(37)

where $\theta$ is the angle between the momentum of the $\bar{B}$-meson and that of $\mu^+$ in the dimuon center-of-mass frame.

Within the ZFCNC model, the FB asymmetry in $\bar{B} \to X_s \mu^+ \mu^-$ is given by

$$A_{FB}(z) = -\frac{3}{8} E(z) D(z),$$

(38)

where $D(z)$ is given in Eq. 6 and $E(z)$ by

$$E(z) = \text{Re}(C_9^{\text{tot}} C_{10}^{\text{tot}*}) z + 2 \text{Re}(C_7^{\text{eff}} C_{10}^{\text{tot}*}) \sqrt{1 - 4m_{\tau}^2/M_{\bar{B}_s}^2 |\Delta_{s}|} \Delta M_s,$$

(39)

Zero of $A_{FB}(z)$ is determined by

$$E(z) = \text{Re}(C_9^{\text{tot}} C_{10}^{\text{tot}*}) z + 2 \text{Re}(C_7^{\text{eff}} C_{10}^{\text{tot}*}) = 0.$$

(40)

The prediction for $(q^2)^{\text{incl}}$ in ZFCNC model is given in Table III. One can see that large deviations from SM prediction is not possible.

C. $\mathcal{B}(\bar{B}_s \to \tau^+ \tau^-)$

The branching ratio of $\bar{B}_s \to \tau^+ \tau^-$ in the ZFCNC model is given by

$$\mathcal{B}(\bar{B}_s \to \tau^+ \tau^-) = \frac{3\alpha^2 \tau_{\bar{B}_s} m_{\tau}^2}{8\pi M_{\bar{B}_s}^2 \eta_{\bar{B}_s} \mathcal{B}(\bar{B}_s \to E(x_t))} \sqrt{1 - \frac{4m_{\tau}^2}{M_{\bar{B}_s}^2} |\Delta_{s}|} \Delta M_s,$$

(41)

The prediction for $\mathcal{B}(\bar{B}_s \to \tau^+ \tau^-)$ in ZFCNC model is given in Table III. We see that it is possible to have large suppression in $\mathcal{B}(\bar{B}_s \to \tau^+ \tau^-)$ as compared to its SM prediction.

V. CONCLUSION

In this paper, we consider a minimal extension of the SM by adding a vector-like isosinglet down-type quark $d'$ to the SM particle spectrum. As a consequence, $Z$-mediated FCNC’s appear at tree level in the left-handed sector. In particular, we are interested in $Zbs$ coupling which leads to a new physics contribution to $b \to s$ transition such as $B_s-\bar{B}_s$ mixing, $b \to s\mu^+ \mu^-$, $b \to s\nu \bar{\nu}$ decays, etc at the tree level. Using inputs from several observables in flavor physics, we perform a $\chi^2$ fit to constrain the tree level $Zbs$ coupling, $U_{sb}$. The fit takes into account both the theoretical as well as the experimental uncertainties.

We conclude the following:

- $\chi^2$ per degree of freedom is small, indicating that the fit is good. This is expected as the SM itself is in good agreement with the data.
- The present data put strong constraint on the $Zbs$ coupling. At $3\sigma$, $|U_{sb}| \leq 3.40 \times 10^{-4}$.
- Despite the strong constraint on the $Zbs$ coupling, it is possible to have new physics signals in some $b \to s$ observables such as semileptonic $CP$ asymmetry in $B_s$ decays.
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