Large forward-backward asymmetry in $B \to K\mu^+\mu^-$ from new physics tensor operators

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We study the constraints on possible new physics contributions to the forward-backward asymmetry of muons, $A_{\rm FB}(q^2)$, in $B \to K\mu^+\mu^-$. New physics in the form of vector/axial-vector operators does not contribute to $A_{\rm FB}(q^2)$, whereas new physics in the form of scalar/pseudoscalar operators can enhance $A_{\rm FB}(q^2)$ only by a few percent. However, new physics in the form of tensor operators can take the peak value of $A_{\rm FB}(q^2)$ to as high as 40% near the high-q^2 end point. In addition, if both scalar/pseudoscalar and tensor operators are present, then $A_{\rm FB}(q^2)$ can be more than 15% for the entire high-q^2 region $q^2 > 15$ GeV^2. The observation of significant $A_{\rm FB}$ would imply the presence of new physics tensor operators, whereas its q^2 dependence could further indicate the presence of new scalar/pseudoscalar physics.

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I. INTRODUCTION

Flavor changing neutral interactions (FCNI) are forbidden at tree level in the standard model (SM). Therefore they have the potential to test higher order corrections to the SM and also constrain many of its possible extensions. Among all FCNI, rare B decays play an important role in searching new physics beyond the SM. The quark level FCNI $b \to s\mu^+\mu^-$ is responsible for (i) the inclusive semileptonic decay $B \to X_s\mu^+\mu^-$, (ii) the exclusive semileptonic decay $B \to (K, K^*)\mu^+\mu^-$, and (iii) the purely leptonic decay $B_s \to \mu^+\mu^-$. These decays have been studied within the SM in Refs. [1–5]. The SM predictions for their branching ratios are

$$B(B \to X_s\mu^+\mu^-) = (4.15 \pm 0.71) \times 10^{-6}, \quad (1)$$

$$B(B \to K\mu^+\mu^-) = (0.35 \pm 0.12) \times 10^{-6}, \quad (2)$$

$$B(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.39) \times 10^{-6}, \quad (3)$$

$$B(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}. \quad (4)$$

The correlations between these branching ratios in the SM as well as some new physics models have been studied in [6–8].

Both the inclusive and exclusive semileptonic decays have been observed experimentally [9–14] with branching ratios close to their SM predictions. These data severely constrain new physics in the form of vector/axial-vector operators, so an order of magnitude enhancement in the branching ratio of $B_s \to \mu^+\mu^-$ due to such new physics is ruled out [15]. On the other hand, if new physics is in the form of scalar/pseudoscalar operators, then the branching ratio of $B \to K^*\mu^+\mu^-$, $B(B \to K^*\mu^+\mu^-)$, does not put any useful constraints on the new physics couplings and allows an order of magnitude enhancement in the $B(B_s \to \mu^+\mu^-)$ decay. Thus $B(B_s \to \mu^+\mu^-)$ is sensitive to an extended Higgs sector. However, such an extended Higgs sector cannot lead to large deviations of semileptonic branching ratios from their SM predictions [6,16].

In [17], the forward-backward (FB) asymmetry of leptons in semileptonic decays of mesons was introduced as an observable sensitive to the physics beyond the SM. In particular, the FB asymmetry of muons, $A_{\rm FB}$, in $B \to K\mu^+\mu^-$ is important because its value is negligibly small in the SM [18]. This is due to the fact that the hadronic current for the $B \to K$ transition does not have any axial-vector contribution; it can have a nonzero value only if it receives contributions from new physics. The sensitivity of $A_{\rm FB}$ for testing the nonstandard Higgs sector has been studied in the literature in detail [6,19–22]. However, in [23], it was shown that the present upper bound on the branching ratio of $B_s \to \mu^+\mu^-$ [24] restricts the average (or integrated) FB asymmetry, $\langle A_{\rm FB}\rangle$, to about 1% as long as the only new physics is in the form of scalar/pseudoscalar operators. Such a small FB asymmetry is very difficult to measure in experiments, and hence searching for new scalar/pseudoscalar physics through $\langle A_{\rm FB}\rangle$ will be a futile exercise.

The forward-backward asymmetry can also get contributions from tensor operators. In the SM, the tensor operators in $b \to s\mu^+\mu^-$ arise at higher order in the electroweak operator product expansion from finite external momenta in the matching calculations; however, their contribution is negligibly small and we shall not consider them in this paper. However, in models beyond the SM, tensor operators may contribute significantly to the decay and to the asymmetry $A_{\rm FB}$. For example, in the minimal supersymmetric standard model (MSSM), the tensor operators arise from photino and Z-ino box diagrams at the leading order operator product expansion [25]. Tensor operators can also be induced by scalar operators under

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renormalization group running [8,26]. In leptoquark models, tensor operators are induced by the interactions of leptoquarks with the SM Higgs field [27].

Tensor operators have been studied in the literature in the context of the decay $B \to K\mu^+\mu^-$ [25,28,29]. In Refs. [28,29], the polarization of the final state leptons in $B \to K\mu^+\mu^-$ was studied. In [25], the effect of these operators on $\langle A_{FB}\rangle$ was studied in detail for the low-q^2 region (1 GeV$^2 < q^2 < 7$ GeV^2). It was also shown that the integrated asymmetry $\langle A_{FB}\rangle$ can be as high as 3% at 90% C.L. if new physics is only in the form of tensor operators, whereas it can rise to 15% if both scalar/pseudoscalar and tensor new physics operators are present. This asymmetry $\langle A_{FB}\rangle$ has been measured by *BABAR* [12] and Belle [30,31] to be

$$\langle A_{FB}\rangle = (0.15^{+0.21}_{-0.23} \pm 0.08) \qquad (BABAR), \tag{5}$$

$$\langle A_{FB}\rangle = (0.10 \pm 0.14 \pm 0.01) \qquad (\text{Belle}). \tag{6}$$

These measurements are consistent with zero. However, they can be as high as ~40% within 2σ error bars. Future experiments like a super-B factory or the LHC will increase the statistics by more than 2 orders of magnitude. For example, at ATLAS the number of expected $B \to K\mu^+\mu^-$ events even after analysis cuts is expected to be ~4000 with 30 fb^{-1} data [32], which will be collected within the first three years. Thus, $\langle A_{FB}\rangle$ can soon be probed to values as low as 5%.

With higher statistics, one will even be able to determine the distribution of A_{FB} as a function of the invariant dilepton mass squared q^2, which can provide a stronger handle on this quantity than just its average value $\langle A_{FB}\rangle$. Moreover, since the theoretical predictions for the rate of $B \to K\mu^+\mu^-$ are rather uncertain in the intermediate q^2 region (7 GeV$^2 < q^2 < 12$ GeV^2) owing to the vicinity of charmed resonances, it is important to look at the quantity $A_{FB}(q^2)$ in the complete q^2 range so that its robust features may be identified. Indeed, it turns out that with the new physics considered in this paper, $A_{FB}(q^2)$ is high near the high-q^2 end point.

In this paper we study $A_{FB}(q^2)$ in the complete q^2 region and explore the possibility of large FB asymmetry in some specific regions of the dilepton invariant mass spectrum. This paper is organized as follows. In Sec. II we present the theoretical expressions for the FB asymmetry of $B \to K\mu^+\mu^-$ considering new physics in the form of scalar/pseudoscalar and tensor operators. In Sec. III we study $A_{FB}(q^2)$ due to new physics only in the form of scalar/pseudoscalar operators, whereas in Sec. IV we consider $A_{FB}(q^2)$ due to new physics only in the form of tensor operators. In Sec. V we calculate $A_{FB}(q^2)$ when both the scalar/pseudoscalar and tensor operators are present. Finally, in Sec. VI we present the conclusions.

II. FORWARD-BACKWARD ASYMMETRY OF MUONS IN $B \to K\mu^+\mu^-$

We consider new physics in the form of scalar/pseudoscalar and tensor operators. The effective Lagrangian for the quark level transition $b \to s\mu^+\mu^-$ can be written as

$$L(b \to s\mu^+\mu^-) = L_{SM} + L_{SP} + L_T, \tag{7}$$

where

$$L_{SM} = \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^\star\Big\{C_9^{\text{eff}}(\bar{s}\gamma_\mu P_L b)\bar{\mu}\gamma_\mu\mu + C_{10}(\bar{s}\gamma_\mu P_L b)\bar{\mu}\gamma_\mu\gamma_5\mu - 2\frac{C_7^{\text{eff}}}{q^2} m_b(\bar{s}i\sigma_{\mu\nu}q^\nu P_R b)\bar{\mu}\gamma_\mu\mu\Big\}, \tag{8}$$

$$L_{SP} = \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^\star\{R_S\bar{s}P_R b\bar{\mu}\mu + R_P\bar{s}P_R b\bar{\mu}\gamma_5\mu\}, \tag{9}$$

$$L_T = \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^\star\{C_T\bar{s}\sigma_{\mu\nu}b\bar{\mu}\sigma^{\mu\nu}\mu + iC_{TE}\bar{s}\sigma_{\mu\nu}b\bar{\mu}\sigma_{\alpha\beta}\mu\epsilon^{\mu\nu\alpha\beta}\}. \tag{10}$$

Here $P_{L,R} = (1 \mp \gamma_5)/2$ and q_μ is the sum of 4-momenta of μ^+ and μ^-. R_S and R_P are new physics scalar/pseudoscalar couplings, whereas C_T and C_{TE} are new physics tensor couplings.

Within the SM, the Wilson coefficients in Eq. (8) have the following values:

$$C_7^{\text{eff}} = -0.310, \quad C_9^{\text{eff}} = +4.138 + Y(q^2), \quad C_{10} = -4.221, \tag{11}$$

where the function $Y(q^2)$ is given by [33,34]

$$Y(q^2) = g(m_c, q^2)(3C_1 + C_2 + 3C_3 + C_4 + 3C_5 + C_6) - \tfrac{1}{2}g(0, q^2)(C_3 + 3C_4) - \tfrac{1}{2}g(m_b, q^2)(4C_3 + 4C_4 + 3C_5 + C_6) + \tfrac{2}{9}(3C_3 + C_4 + 3c_5 + C_6). \tag{12}$$

Here we take the values of the relevant Wilson coefficients to be

$$C_1 = -0.249, \quad C_2 = 1.107, \quad C_3 = 0.011, \quad C_4 = -0.025, \quad C_5 = 0.007, \quad C_6 = -0.031, \tag{13}$$

all of which are computed at the scale $\mu = m_b = 5$ GeV. The function g is given by

$$g(m_i, q^2) = -\frac{8}{9}\ln(m_i/m_b^{\rm pole}) + \frac{8}{27} + \frac{4}{9}y_i - \frac{2}{9}(2+y_i) \times \sqrt{|1-y_i|}\Big\{\Theta(1-y_i)\Big[\ln\Big(\frac{1+\sqrt{1-y_i}}{1-\sqrt{1-y_i}}\Big) - i\pi\Big] + \Theta(y_i-1)2\tan^{-1}\Big(\frac{1}{\sqrt{y_i-1}}\Big)\Big\}, \quad (14)$$

with $y_i \equiv 4m_i^2/q^2$.

The normalized FB asymmetry is defined as

$$A_{\rm FB}(z) = \frac{\int_0^1 d\cos\theta \frac{d^2\Gamma}{dz d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d^2\Gamma}{dz d\cos\theta}}{\int_0^1 d\cos\theta \frac{d^2\Gamma}{dz d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d^2\Gamma}{dz d\cos\theta}}, \quad (15)$$

with $z \equiv q^2/m_B^2$. In order to calculate the FB asymmetry, we first need to calculate the differential decay width. The decay amplitude for $B(p_1) \to K(p_2)\mu^+(p_+)\mu^-(p_-)$ is given by

$$\begin{aligned} M(B\to K\mu^+\mu^-) = \frac{\alpha G_F}{2\sqrt{2}\pi}V_{tb}V_{ts}^\star\Big[&\langle K(p_2)|\bar{s}\gamma_\mu b|B(p_1)\rangle\{C_9^{\rm eff}\bar{u}(p_-)\gamma_\mu v(p_+) + C_{10}\bar{u}(p_-)\gamma_\mu\gamma_5 v(p_+)\} \\ &- 2\frac{C_7^{\rm eff}}{q^2}m_b\langle K(p_2)|\bar{s}i\sigma_{\mu\nu}q^\nu b|B(p_1)\rangle\bar{u}(p_-)\gamma_\mu v(p_+) \\ &+ \langle K(p_2)|\bar{s}b|B(p_1)\rangle\{R_S\bar{u}(p_-)v(p_+) + R_P\bar{u}(p_-)\gamma_5 v(p_+)\} \\ &+ 2C_T\langle K(p_2)|\bar{s}\sigma_{\mu\nu}b|B(p_1)\rangle\bar{u}(p_-)\sigma^{\mu\nu}v(p_+) \\ &+ 2iC_{TE}\epsilon^{\mu\nu\alpha\beta}\langle K(p_2)|\bar{s}\sigma_{\mu\nu}b|B(p_1)\rangle\bar{u}(p_-)\sigma_{\alpha\beta}v(p_+)\Big], \end{aligned} \quad (16)$$

where $q_\mu = (p_1 - p_2)_\mu = (p_+ + p_-)_\mu$. The relevant matrix elements are

$$\langle K(p_2)|\bar{s}\gamma_\mu b|B(p_1)\rangle = (2p_1 - q)_\mu f_+(z) + \Big(\frac{1-k^2}{z}\Big)q_\mu[f_0(z) - f_+(z)], \quad (17)$$

$$\langle K(p_1)|\bar{s}i\sigma_{\mu\nu}q^\nu b|B(p_1)\rangle = [(2p_1-q)_\mu q^2 - (m_B^2 - m_K^2)q_\mu] \times \frac{f_T(z)}{m_B+m_K}, \quad (18)$$

$$\langle K(p_2)|\bar{s}b|B(p_1)\rangle = \frac{m_B(1-k^2)}{\hat{m}_b}f_0(z), \quad (19)$$

$$\langle K(p_2)|\bar{s}\sigma_{\mu\nu}b|B(p_1)\rangle = -i[(2p_1-q)_\mu q_\nu - (2p_1-q)_\nu q_\mu] \times \frac{f_T}{m_B+m_K}, \quad (20)$$

where $k \equiv m_K/m_B$ and $\hat{m}_b \equiv m_b/m_B$.

Using the above matrix elements, the double differential decay widths can be calculated as

$$\begin{aligned} \frac{d^2\Gamma}{dz d\cos\theta} = \frac{G_F^2\alpha^2}{2^{11}\pi^5}|V_{tb}V_{ts}^*|^2 m_B^5\phi^{1/2}\Big[&z\Big\{\frac{\hat{m}_\mu}{m_B}{\rm Re}(CE^*) + \frac{1}{4m_B^2}(|E|^2 + \beta_\mu^2|D|^2)\Big\} + \phi\Big\{\frac{1}{4}(|A|^2+|B|^2) + 2\hat{m}_\mu m_B{\rm Re}AF^*\Big\} \\ &+ (1-k^2)\Big\{2\hat{m}_\mu^2{\rm Re}(BC^*) + \frac{\hat{m}_\mu}{m_B}{\rm Re}(BE^*)\Big\} + \hat{m}_\mu^2\{(2+2k^2-z)|B|^2 + z|C|^2\} + \phi z m_B^2(1-\beta_\mu^2)|F|^2 \\ &+ \phi\beta_\mu^2\Big\{zm_B^2(|F|^2+4|G|^2) - \frac{1}{4}(|A|^2+|B|^2)\Big\}\cos^2\theta - \phi^{1/2}\beta_\mu\Big\{\frac{\hat{m}_\mu}{m_B}{\rm Re}(AD^*) + 4m_\mu(1-k^2){\rm Re}(BG^*) \\ &+ 4z\hat{m}_\mu m_B{\rm Re}(CG^*) + 2z{\rm Re}(GE^*) + \frac{z}{4}{\rm Re}(DF^*)\Big\}\cos\theta\Big], \end{aligned} \quad (21)$$

where

$$\hat{m}_\mu \equiv m_\mu/m_B, \qquad \phi \equiv 1 + k^4 + z^2 - 2(k^2 + k^2 z + z), \qquad \beta_\mu \equiv \sqrt{1 - \frac{4\hat{m}_\mu^2}{z}}, \quad (22)$$

and θ is the angle between the momenta of the K meson and μ^- in the dilepton center of mass frame. The parameters A, B, C, D, E, F, G are combinations of the Wilson coefficients and the form factors, given by

$$\begin{aligned}
A &\equiv 2C_9^{\rm eff} f_+(z) - 4C_7^{\rm eff}\hat{m}_b \frac{f_T(z)}{1+k},\\
B &\equiv 2C_{10} f_+(z),\\
C &\equiv 2C_{10}\frac{1-k^2}{z}[f_0(z)-f_+(z)],\\
D &\equiv 2R_S \frac{m_B(1-k^2)}{\hat{m}_b} f_0(z),\\
E &\equiv 2R_P \frac{m_B(1-k^2)}{\hat{m}_b} f_0(z),\\
F &\equiv -4C_T \frac{f_T(z)}{m_B(1+k)},\\
G &\equiv 4C_{TE} \frac{f_T(z)}{m_B(1+k)}.
\end{aligned} \tag{23}$$

The kinematical variables in Eq. (21) are bounded as

$$-1 \le \cos\theta \le 1, \qquad 4\hat{m}_\mu^2 \le z \le (1-k)^2. \tag{24}$$

The form factors $f_{+,0,T}$ can be calculated in the light cone QCD approach. Their z dependence is given by [18]

$$f(z) = f(0)\exp(c_1 z + c_2 z^2 + c_3 z^3), \tag{25}$$

where the parameters $f(0)$, c_1, c_2, and c_3 for each form factor are given in Table I.

TABLE I. Form factors for the $B \to K$ transition [18].

	$f(0)$	c_1	c_2	c_3
f_+	$0.319^{+0.052}_{-0.041}$	1.465	0.372	0.782
f_0	$0.319^{+0.052}_{-0.041}$	0.633	−0.095	0.591
f_T	$0.355^{+0.016}_{-0.055}$	1.478	0.373	0.700

The FB asymmetry arises from the $\cos\theta$ term in the last two lines of Eq. (21). We get

$$A_{\rm FB}(z) = \frac{2\Gamma_0 \beta_\mu \phi N(z)}{d\Gamma/dz}, \tag{26}$$

where

$$\Gamma_0 = \frac{G_F^2 \alpha^2}{2^{12}\pi^5}|V_{tb}V_{ts}^*|^2 m_B^5, \tag{27}$$

$$\begin{aligned}
N(z) = &-4m_\mu(1-k^2)\,{\rm Re}(BG^*) - \frac{\hat{m}_\mu}{m_B}\,{\rm Re}(AD^*)\\
&- 4z\hat{m}_\mu m_B\,{\rm Re}(CG^*) - \frac{z}{4}\,{\rm Re}(DF^*)\\
&- 2z\,{\rm Re}(EG^*),
\end{aligned} \tag{28}$$

$$\begin{aligned}
\frac{d\Gamma}{dz} = \Gamma_0 \phi^{1/2} \times \Big[&\phi\Big(1 - \frac{1}{3}\beta_\mu^2\Big)(|A|^2 + |B|^2) + 4\hat{m}_\mu^2|B|^2(2+2k^2-z) + 4\hat{m}_\mu^2 z|C|^2 + 8\hat{m}_\mu^2(1-k^2)\,{\rm Re}(BC^*)\\
&+ 8\hat{m}_\mu m_B \phi\,{\rm Re}(AF^*) + \frac{z}{m_B^2}(|E|^2 + \beta_\mu^2|D|^2) + \frac{4\hat{m}_\mu}{m_B}(1-k^2)\,{\rm Re}(BE^*) + \frac{4\hat{m}_\mu}{m_B} z\,{\rm Re}(CE^*)\\
&+ \frac{4}{3}\phi z m_B^2\{3|F|^2 + 2\beta_\mu^2(2|G|^2 - |F|^2)\}\Big].
\end{aligned} \tag{29}$$

In our analysis we assume that there are no additional CP phases apart from the single Cabibbo-Kobayashi-Maskawa (CKM) phase. Under this assumption the new physics couplings are all real.

III. $A_{\rm FB}$ FROM NEW SCALAR/PSEUDOSCALAR OPERATORS

If new physics is only in the form of scalar/pseudoscalar operators, then $A_{\rm FB}(z)$ is obtained by putting $C_T = C_{TE} = 0$ in Eq. (16). We get

$$A_{\rm FB}(z) = \frac{\beta_\mu \phi^{1/2} a_{{\rm SM},S}(z) R_S}{b_{\rm SM}(z) + b_{{\rm SM},S}(z)R_P + b_S(z)(R_S^2 + R_P^2)}, \tag{30}$$

where

$$a_{{\rm SM},S}(z) = -\frac{4\hat{m}_\mu}{\hat{m}_b}(1-k^2) f_0(z)\,{\rm Re}(A), \tag{31}$$

$$\begin{aligned}
b_{\rm SM}(z) = &\,\phi(1 - \tfrac{1}{3}\beta_\mu^2)(|A|^2 + |B|^2)\\
&+ 4\hat{m}_\mu^2|B|^2(2+2k^2-z) + 4\hat{m}_\mu^2 z|C|^2\\
&+ 8\hat{m}_\mu^2(1-k^2)\,{\rm Re}(BC^*),
\end{aligned} \tag{32}$$

$$b_{{\rm SM},S}(z) = \frac{16\hat{m}_\mu}{\hat{m}_b}(1-k^2)^2 C_{10} f_0^2(z), \tag{33}$$

$$b_S(z) = \frac{4z}{\hat{m}_b^2}(1-k^2)^2 f_0^2(z). \tag{34}$$

Therefore, in order to estimate $A_{\rm FB}(z)$ we need to know the scalar/pseudoscalar couplings R_S and R_P.

We constrain R_S and R_P through the decay $B_s \to \mu^+\mu^-$. The branching ratio of $B_s \to \mu^+\mu^-$ due to $L_{\rm SM} + L_{\rm SP}$ is given by [23]

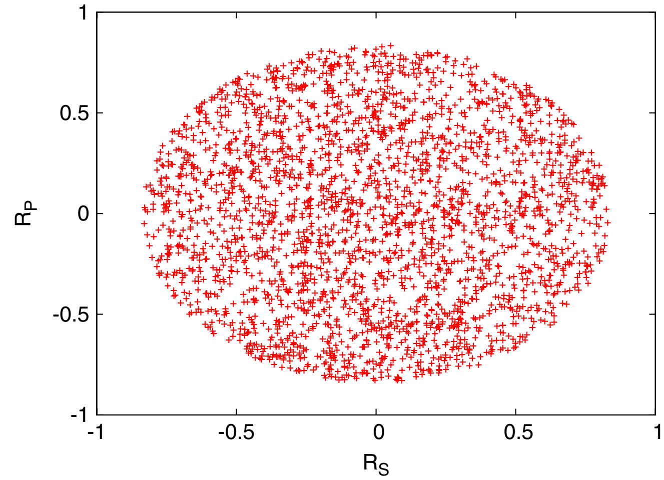

FIG. 1 (color online). $R_S - R_P$ parameter space allowed by the present upper bound on the branching ratio of $B_s \to \mu^+\mu^-$.

$$B(B_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2 m_{B_s}^3 \tau_{B_s}}{64\pi^3} |V_{tb}V_{ts}^*|^2 f_{B_s}^2 \times [R_S^2 + (R_P + 2\hat{m}_\mu C_{10})^2]. \quad (35)$$

The present upper bound on $B(B_s \to \mu^+\mu^-)$ is [24]

$$B(B_s \to \mu^+\mu^-) < 0.58 \times 10^{-7} \qquad (95\% \text{ C.L.}), \quad (36)$$

which is still more than an order of magnitude away from its SM prediction. Therefore, we will neglect the SM contribution while obtaining constraints on the $R_S - R_P$ parameter space. The allowed values of R_S and R_P at 2σ are shown in Fig. 1. The input values of the parameters, used throughout this paper, are given in Table II.

The maximum value of $A_{\rm FB}(z)$ is obtained for $R_P = 0$ and $R_S = \pm 0.84$. At these parameter values, $A_{\rm FB}(z)$ is shown in Fig. 2 for the central and $\pm 2\sigma$ values of the form factors. As can be observed, the errors in the form factors have almost no impact on the value of $A_{\rm FB}(z)$ obtained. The peak value of $A_{\rm FB}(z)$ is observed to be $\approx$ 2%, whereas in most of the z range $A_{\rm FB}(z) < 1\%$. Measurements of $A_{\rm FB}(z)$ in the presence of only scalar/pseudoscalar operators will therefore be very challenging.

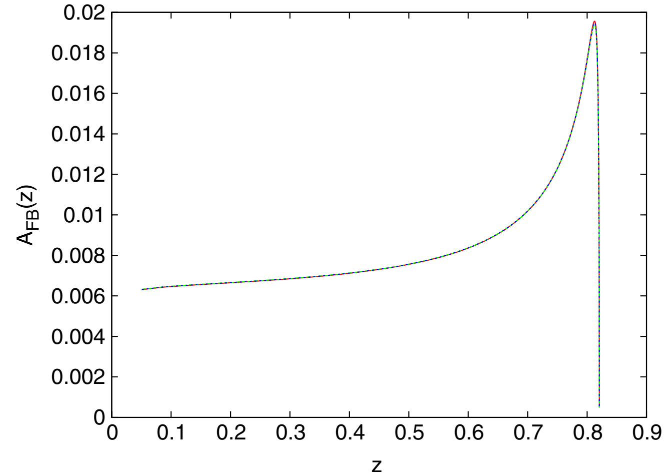

FIG. 2 (color online). The forward-backward asymmetry $A_{\rm FB}(z = q^2/m_B^2)$ for the new physics only in the form of scalar/pseudoscalar operators. The plot corresponds to $R_P = 0$ and $R_S = -0.84$. The red (solid) curve corresponds to the central values of the form factors given in Table I, whereas the green (dashed) and blue (dotted) curves correspond to their values at $+2\sigma$ and -2σ, respectively. In this scenario, all the curves overlap, indicating that the dependence on form factors is negligibly small.

IV. $A_{\rm FB}$ FROM NEW TENSOR OPERATORS

If new physics is only in the form of tensor operators, then $A_{\rm FB}(z)$ is obtained by putting $R_S = R_P = 0$ in Eq. (16). We get

$$A_{\rm FB}(z) = \frac{\beta_\mu \phi^{1/2} a_{{\rm SM},T}(z) C_{TE}}{b_{\rm SM}(z) + b_{{\rm SM},T}(z) C_T + b_T(z)(C_T + 4C_{TE}^2)}, \quad (37)$$

where

$$a_{{\rm SM},T}(z) = -64\hat{m}_\mu (1-k) C_{10} f_T(z) f_0(z), \quad (38)$$

$$b_{{\rm SM},T}(z) = -\frac{32\hat{m}_\mu \phi \,{\rm Re}(A) f_T(z)}{1+k}, \quad (39)$$

TABLE II. Numerical inputs used in our analysis. Unless explicitly specified, they are taken from the Review of Particle Physics [35].

$G_F = 1.166 \times 10^{-5}$ GeV^{-2}	$m_{B_s} = 5.366$ GeV
$\alpha = 1.0/129.0$	$m_B = 5.279$ GeV
$\alpha_s(m_b) = 0.220$ [36]	$V_{tb} = 1.0$
$\tau_{B_s} = 1.45 \times 10^{-12}$ s	$\lvert V_{ts}\rvert = (40.6 \pm 2.7) \times 10^{-3}$
$m_\mu = 0.105$ GeV	$\lvert V_{tb}V_{ts}^*/V_{cb}\rvert = 0.967 \pm 0.009$ [37]
$m_K = 0.497$ GeV	$m_c/m_b = 0.29$ [1]
$m_b = 4.80$ GeV [1]	$B(B \to X_c \ell \nu) = 0.1061 \pm 0.0016 \pm 0.0006$ [38]

$$b_T(z) = \frac{64\phi z f_T^2(z)}{3(1+k)^2}, \tag{40}$$

and $b_{\rm SM}(z)$ is given already in Eq. (32).

In order to estimate $A_{\rm FB}(z)$, we need to know the tensor couplings C_T and C_{TE}. In [39], it was shown that the most stringent bound on tensor couplings comes from the data on the branching ratio of the inclusive decay $B \to X_s \mu^+ \mu^-$. The branching ratio of $B \to X_s(p_s)\mu^+(p_{\mu^+})\mu^-(p_{\mu^-})$ is given by [40]

$$B(B \to X_s l^+ l^-) = B_0[I_{\rm SM} + (C_T^2 + 4C_{TE}^2)I_T], \tag{41}$$

where

$$I_{\rm SM} = \int dz \bigg[\frac{8u(z)}{z}\bigg\{1 - z^2 + \frac{1}{3}u(z)^2\bigg\}C_7^{\rm eff} - 2u(z)\bigg\{z^2 + \frac{1}{3}u(z)^2 - 1\bigg\}(C_9^{\rm eff2} + C_{10}^2) - 16u(z)(z-1)C_9^{\rm eff}C_7^{\rm eff}\bigg], \tag{42}$$

$$I_T = 16\int dz u(z)\bigg[\frac{-2}{3}u(z)^2 - 2z + 2\bigg], \tag{43}$$

$$u(z) = (1-z). \tag{44}$$

Here $z \equiv q^2/m_b^2 = (p_{\mu^+} + p_{\mu^-})^2/m_b^2 = (p_b - p_s)^2/m_b^2$. The limits of integration for z are now

$$z_{\rm min} = 4m_\mu^2/m_b^2, \qquad z_{\rm max} = \bigg(1 - \frac{m_s}{m_b}\bigg)^2, \tag{45}$$

as opposed to the ones given in Eq. (24) for the exclusive decay. The normalization factor B_0 is given by

$$B_0 = B(B \to X_c e\nu)\frac{3\alpha^2}{16\pi^2}\frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2}\frac{1}{f(\hat{m}_c)\kappa(\hat{m}_c)}, \tag{46}$$

where the phase space factor $f(\hat{m}_c = \frac{m_c}{m_b})$ and the $O(\alpha_s)$ QCD correction factor $\kappa(\hat{m}_c)$ of $b \to ce\nu$ are given by [41]

$$f(\hat{m}_c) = 1 - 8\hat{m}_c{}^2 + 8\hat{m}_c{}^6 - \hat{m}_c{}^8 - 24\hat{m}_c{}^4 \ln\hat{m}_c, \tag{47}$$

$$\kappa(\hat{m}_c) = 1 - \frac{2\alpha_s(m_b)}{3\pi}\bigg[\bigg(\pi^2 - \frac{31}{4}\bigg)(1-\hat{m}_c)^2 + \frac{3}{2}\bigg]. \tag{48}$$

Equation (41) can be written as

$$B(B \to X_s\mu^+\mu^-) = B_{\rm SM}(B \to X_s\mu^+\mu^-) + B_T(B \to X_s\mu^+\mu^-), \tag{49}$$

where

$$B_{\rm SM}(B \to X_s\mu^+\mu^-) = B_0 I_{\rm SM}, \tag{50}$$

$$B_T(B \to X_s\mu^+\mu^-) = B_0 I_T(C_T^2 + 4C_{TE}^2). \tag{51}$$

The present world average for $B(B \to X_s\mu^+\mu^-)$ is [14]

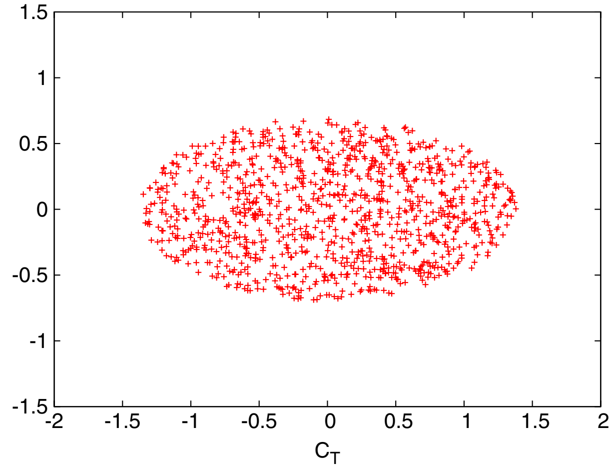

FIG. 3 (color online). (C_T, C_{TE}) parameter space at 2σ allowed by the measurement of the branching ratio of $B \to X_s\mu^+\mu^-$.

$$B_{\rm exp}(B \to X_s\mu^+\mu^-)_{q^2 > 0.04\ {\rm GeV}^2} = (4.3^{+1.3}_{-1.2}) \times 10^{-6}. \tag{52}$$

We keep the same invariant mass cut, $q^2 > 0.04\ {\rm GeV}^2$, in order to enable comparison with the experimental data. With this range of q^2, the SM branching ratio for $B \to X_s\mu^+\mu^-$ in next-to-next-to-leading order is [1]

$$B_{\rm SM}(B \to X_s\mu^+\mu^-)_{q^2 > 0.04\ {\rm GeV}^2} = (4.15 \pm 0.71) \times 10^{-6}, \tag{53}$$

whereas $B_0 I_T = (1.47 \pm 0.22) \times 10^{-6}$. Using Eqs. (49),

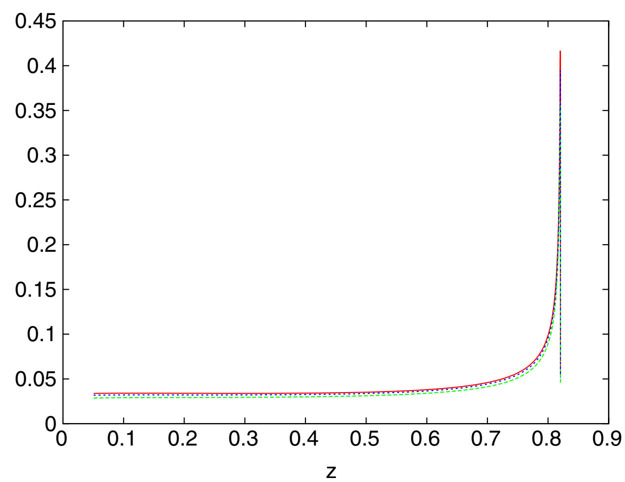

FIG. 4 (color online). The forward-backward asymmetry $A_{\rm FB}(z = q^2/m_B^2)$ for the new physics only in the form of tensor operators. The plot corresponds to $C_T = 0$ and $C_{TE} = +0.69$. The red (solid) curve corresponds to the central values of the form factors given in Table I, whereas the green (dashed) and blue (dotted) curves correspond to their values at $+2\sigma$ and -2σ, respectively. The dependence on the form factors is clearly extremely small.

(52), and (53), we get

$$C_T^2 + 4C_{TE}^2 = 0.10 \pm 1.01. \quad (54)$$

The allowed parameter space for C_T, C_{TE} at 2σ is shown in Fig. 3.

The maximum value of $A_{FB}(z)$ is obtained for $C_T = 0$ and $C_{TE} = \pm 0.69$. For these parameter values, $A_{FB}(z)$ is shown in Fig. 4 for the central and $\pm 2\sigma$ values of the form factors. In most of the z range, $A_{FB}(z) \lesssim 3\%$; however, its peak value at the high-q^2 end point is $\sim 40\%$. Thus there can be a large deviation from the SM prediction in the high-q^2 region.

V. A_{FB} FROM THE COMBINATION OF SCALAR/PSEUDOSCALAR AND TENSOR OPERATORS

We now consider the scenario where new physics in the form of both scalar/pseudoscalar and tensor operators is present. In this case the expression for $A_{FB}(z)$ is given by Eq. (16). Maximum values of $A_{FB}(z)$ are obtained for $R_S = C_T = 0$ and $R_P = -0.84$, $C_{TE} = 0.69$. For these values, we have plotted $A_{FB}(z)$ vs z in Fig. 5. The peak value of $A_{FB}(z)$ is $\sim 40\%$ at 2σ and is obtained at the high-q^2 end point. Thus, there can be large FB asymmetry in the high-q^2 region. In this region, the light cone QCD sum rules are inapplicable directly, and extrapolations need to be used. However, the errors induced by these extrapolations are expected to be less than the intrinsic sum rule uncertainty [42], which has already been taken care of through the uncertainties in $f_{0,+,T}$ [18].

Let $\mathcal{R}$ be the high-q^2 region, with $q_0 < q^2 < q^2_{\rm max}$, where $q^2_{\rm max}$ is the endpoint. The restriction to high q^2 would decrease the number of events selected; however,

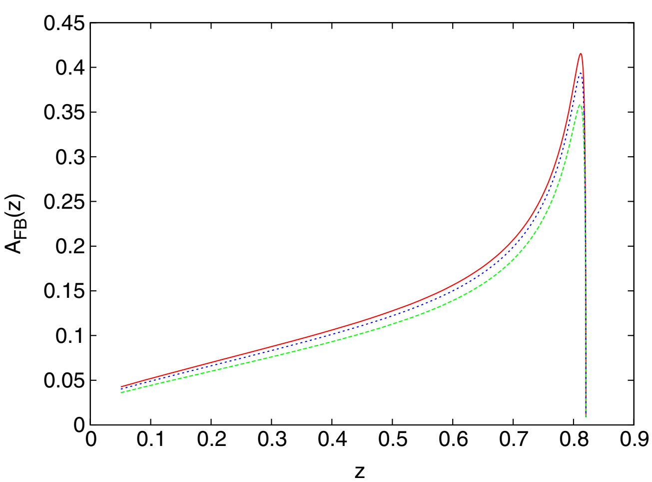

FIG. 5 (color online). The forward-backward asymmetry $A_{FB}(z = q^2/m_B^2)$ for new physics when both scalar/pseudoscalar and tensor operators are present. The plot corresponds to $R_S = C_T = 0$ and $R_P = -0.84$, $C_{TE} = +0.69$. The red (solid) curve corresponds to the central values of the form factors given in Table I, whereas the green (dashed) and blue (dotted) curves correspond to their values at $+2\sigma$ and -2σ, respectively.

since the average A_{FB} in this region, $\langle A_{FB}^{\mathcal{R}}\rangle$, is larger, it can still be observed. The number of events of $B \to K\mu^+\mu^-$ required to determine this asymmetry to $n\sigma$ is

$$N_{B\to K\mu^+\mu^-} \gtrsim \frac{n^2}{\langle A_{FB}^{\mathcal{R}}\rangle^2 f^{\mathcal{R}}}, \quad (55)$$

where $f^{\mathcal{R}}$ is the fraction of the total number of $B \to K\mu^+\mu^-$ events that lie in the region $\mathcal{R}$. When $\mathcal{R}$ corresponds to the whole q^2 range available, then the expression reduces to $N_{B\to K\mu^+\mu^-} \gtrsim n^2/\langle A_{FB}\rangle^2$, as expected.

Taking $\mathcal{R}$ to be the region $q^2 > 15\ {\rm GeV}^2$, and for the values of parameters which maximize $A_{FB}(z)$ (listed in the caption of Fig. 5), we find that about 600 total $B \to K\mu^+\mu^-$ events are required to observe FB asymmetry at 2σ. For $q^2 > 19\ {\rm GeV}^2$, the corresponding number of events increases to 1600. These numbers are easily obtainable at a super-B factory as well as at the LHC, so the structure of the $A_{FB}(q^2)$ peak can be studied at these experiments.

VI. CONCLUSIONS

In the standard model, the forward-backward asymmetry A_{FB} of muons in $B \to K\mu^+\mu^-$ is negligible. New physics in the form of vector/axial-vector operators cannot contribute to A_{FB} either. However, new physics in the form of scalar/pseudoscalar or tensor operators can enhance A_{FB} to the percent level or more, thus bringing it within the reach of the LHC or a super-B factory. In this paper, we concentrate on the magnitude as well as q^2 dependence of A_{FB} with these kinds of new physics.

We find that if new physics is in the form of scalar/pseudoscalar operators only, then the peak value of $A_{FB}(q^2)$ can only be $\lesssim 2\%$, and hence rather challenging to detect. However, if new physics is only in the form of tensor operators, then the peak value of $A_{FB}(q^2)$ can be as high as 40%. Such a high enhancement is obtained only near the high-q^2 end point, i.e. for $q^2 > 19\ {\rm GeV}^2$, below which $A_{FB}(q^2) \lesssim 5\%$. In the presence of both scalar/pseudoscalar and tensor operators, the interference terms between them can boost $A_{FB}(q^2)$ to more than 15% for the whole region $q^2 > 15\ {\rm GeV}^2$.

The measurement of the distribution of A_{FB} as a function of q^2 can not only reveal new physics, but also indicate its possible Lorentz structure. A large enhancement in A_{FB} by itself would confirm the presence of new physics tensor operators. If the enhancement is only at large q^2 values, the scalar/pseudoscalar new physics operators probably play no major role. On the other hand, if the enhancement as a function of q^2 is significant at low q^2 and increases gradually with increasing q^2, the presence of scalar/pseudoscalar new physics operators would be indicated.

The high-q^2 region in the $A_{FB}(q^2)$ distribution is relatively cleaner compared to the intermediate q^2 region ($7\ {\rm GeV}^2 < q^2 < 12\ {\rm GeV}^2$) which is influenced by the charm resonances. This region also happens to be highly sensitive to new physics, especially in the form of tensor operators, as we have shown here. Exploration of this region in the upcoming experiments is therefore of crucial importance.

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