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Physics beyond the Standard Model through $b \to s\mu^+\mu^-$ transition

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Abstract. A comprehensive study of the impact of new-physics operators with different Lorentz structures on decays involving the $b \to s\mu^+\mu^-$ transition is performed. The effects of new vector–axial vector (VA), scalar–pseudoscalar (SP) and tensor (T) interactions on the differential branching ratios, forward–backward asymmetries ($A_{\rm FB}$'s), and direct CP asymmetries of $\bar{B}^0_{\rm s} \to \mu^+\mu^-$, $\bar{B}^0_{\rm d} \to X_{\rm s}\mu^+\mu^-$, $\bar{B}^0_{\rm s} \to \mu^+\mu^-\gamma$, $\bar{B}^0_{\rm d} \to \bar{K}\mu^+\mu^-$, and $\bar{B}^0_{\rm d} \to \bar{K}^*\mu^+\mu^-$ are examined. In $\bar{B}^0_{\rm d} \to \bar{K}^*\mu^+\mu^-$, we also explore the longitudinal polarization fraction $f_{\rm L}$ and the angular asymmetries $A_{\rm T}^{(2)}$ and $A_{\rm LT}$, the direct CP asymmetries in them, as well as the triple-product CP asymmetries $A_{\rm T}^{(\rm im)}$ and $A_{\rm LT}^{(\rm im)}$. While the new VA operators can significantly enhance most of the observables beyond the Standard Model predictions, the SP and T operators can do this only for $A_{\rm FB}$ in $\bar{B}^0_{\rm d} \to \bar{K}\mu^+\mu^-$.

Keywords. *B* Physics; CP violation; beyond Standard Model.

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1. Introduction

While the CKM+GIM picture of flavour and CP violation describes the existing data extremely well, a number of anomalies observed in the last few years indicate that New Physics (NP) could be already in sight. For example, the present experimental world avarage $(1.68 \pm 0.31) \times 10^{-4}$ [1] for the branching ratio (BR) of $B^+ \to \tau^+\nu_\tau$ based on results by BABAR and Belle is roughly 2.5σ higher than the SM value $(0.81 \pm 0.15) \times 10^{-4}$ [2]. Some possible hints of NP have recently surfaced also in modes involving $b \to s$ transitions. These include the large transverse polarization in $B \to \phi K^*$ [3,4], the $B \to \pi K$ puzzle [5], the mixing-induced CP asymmetry in $B_{\rm d} \to J/\psi K_{\rm S}$ [1] and the large CP asymmetry in $B_{\rm s} \to J/\psi\phi$ [6]. Finally, the recent observation of the anomalous dimuon charge asymmetry by the DØ Collaboration [7] points towards some new physics in $B_{\rm s}$ mixing (for example, see ref. [8]). Here, we consider the addition of NP vector–axial vector (VA), scalar–pseudoscalar (SP), and tensor (T) operators that contribute to $b \to s\mu^+\mu^-$, and compute their effects on the decays $\bar{B}^0_{\rm s} \to \mu^+\mu^-$, $\bar{B}^0_{\rm d} \to X_{\rm s}\mu^+\mu^-$, $\bar{B}^0_{\rm s} \to \mu^+\mu^-\gamma$, $\bar{B}^0_{\rm d} \to \bar{K}\mu^+\mu^-$, and $\bar{B}^0_{\rm d} \to \bar{K}^*\mu^+\mu^-$. The results discussed in the following sections are based on [9–11].

2. Effective Hamiltonian

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

$$\begin{aligned}\mathcal{H}_{\text{eff}}^{\text{SM}} &= -\frac{4G_{\text{F}}}{\sqrt{2}} V_{ts}^* V_{tb} \\ &\quad \times \Bigg\{ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} [\bar{s}\sigma_{\mu\nu}(m_{\text{s}} P_{\text{L}} + m_{\text{b}} P_{\text{R}})b] F^{\mu\nu} \\ &\quad + C_9 \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\gamma^\mu P_{\text{L}} b)\, \bar{\mu}\gamma_\mu\mu + C_{10} \frac{\alpha_{\text{em}}}{4\pi} (\bar{s}\gamma^\mu P_{\text{L}} b)\, \bar{\mu}\gamma_\mu\gamma_5\mu \Bigg\}, \qquad (1)\end{aligned}$$

where $P_{\text{L,R}} = (1 \mp \gamma_5)/2$. We now add new physics to the effective Hamiltonian so that it becomes:

$$\mathcal{H}_{\text{eff}}(b \to s\mu^+\mu^-) = \mathcal{H}_{\text{eff}}^{\text{SM}} + \mathcal{H}_{\text{eff}}^{\text{VA}} + \mathcal{H}_{\text{eff}}^{\text{SP}} + \mathcal{H}_{\text{eff}}^{\text{T}},$$

where

$$\begin{aligned}\mathcal{H}_{\text{eff}}^{\text{VA}} &= -\frac{4G_{\text{F}}}{\sqrt{2}} \frac{\alpha_{\text{em}}}{4\pi} V_{ts}^* V_{tb} \Big\{ R_{\text{V}}(\bar{s}\gamma^\mu P_{\text{L}} b)\bar{\mu}\gamma_\mu\mu + R_{\text{A}}(\bar{s}\gamma^\mu P_{\text{L}} b)\bar{\mu}\gamma_\mu\gamma_5\mu \\ &\quad + R'_{\text{V}}(\bar{s}\gamma^\mu P_{\text{R}} b)\, \bar{\mu}\gamma_\mu\mu + R'_{\text{A}}(\bar{s}\gamma^\mu P_{\text{R}} b)\, \bar{\mu}\gamma_\mu\gamma_5\mu \Big\}, \qquad (2)\end{aligned}$$

$$\begin{aligned}\mathcal{H}_{\text{eff}}^{\text{SP}} &= -\frac{4G_{\text{F}}}{\sqrt{2}} \frac{\alpha_{\text{em}}}{4\pi} V_{ts}^* V_{tb} \Big\{ R_{\text{S}}(\bar{s}P_{\text{R}} b)\bar{\mu}\mu + R_{\text{P}}(\bar{s}P_{\text{R}} b)\bar{\mu}\gamma_5\mu \\ &\quad + R'_{\text{S}}(\bar{s}P_{\text{L}} b)\bar{\mu}\mu + R'_{\text{P}}(\bar{s}P_{\text{L}} b)\bar{\mu}\gamma_5\mu \Big\}, \qquad (3)\end{aligned}$$

$$\mathcal{H}_{\text{eff}}^{\text{T}} = -\frac{4G_{\text{F}}}{\sqrt{2}} \frac{\alpha_{\text{em}}}{4\pi} V_{ts}^* V_{tb} \Big\{ C_{\text{T}}(\bar{s}\sigma_{\mu\nu} b)\bar{\mu}\sigma^{\mu\nu}\mu + iC_{\text{TE}}(\bar{s}\sigma_{\mu\nu} b)\bar{\mu}\sigma_{\alpha\beta}\mu\epsilon^{\mu\nu\alpha\beta} \Big\} \qquad (4)$$

are the new contributions. Here, R_{V}, R_{A}, R'_{V}, R'_{A}, R_{S}, R_{P}, R'_{S}, R'_{P}, C_{T} and C_{TE} are the NP effective couplings. We do not consider NP in the form of C_7 or its chiral counterpart C'_7 (see for example, [12] for model-independent bounds on C_7 and C'_7).

The constraints on these NP couplings in $b \to s\mu^+\mu^-$ come mainly from the upper bound on the branching ratio $\text{B}(\bar{B}_{\text{s}}^0 \to \mu^+\mu^-)$ and the measurements of the total branching ratios $\text{B}(\bar{B}_{\text{d}}^0 \to X_{\text{s}}\mu^+\mu^-)$ and $\text{B}(\bar{B}_{\text{d}}^0 \to \bar{K}\mu^+\mu^-)$.

3. Results and discussion

We observe that new VA operators are the ones that influence the observables strongly in most cases. They typically can interfere with the SM terms constructively or destructively, thus enhancing or suppressing the differential branching ratios by up to factors of 2 or 3. They also are able to enhance almost all the asymmetries, the notable exception being A_{FB} in $\bar{B}_{\text{d}}^0 \to \bar{K}\mu^+\mu^-$, where the VA operators cannot contribute. But for most of the other observables, this kind of NP can potentially be observed. This can be traced to the large magnitudes of the NP couplings still allowed by data, which in turn can be traced to the possibility of interference between the new VA operators with the SM operators that allows more freedom for the new VA couplings. Typically, the $R_{\rm V,A}$ couplings are constrained more weakly than the $R'_{\rm V,A}$ couplings, since the corresponding operators have the same structure as those of the SM, allowing strong destructive interferences. Consequently, the operators with $R_{\rm V,A}$ couplings are more likely to show themselves over and above the SM background. We point out that the exception to this rule is the $A_{\rm FB}$ in $\bar{B}_{\rm d}^0 \to \bar{K}^*\mu^+\mu^-$ at large q^2, where the $R'_{\rm V,A}$ couplings can cause a larger enhancement. The SP operators, on the other hand, are handicapped by the stringent constraints from the upper bound on $\mathrm{B}(\bar{B}_{\rm s}^0 \to \mu^+\mu^-)$. If only $R_{\rm S,P}$ or $R'_{\rm S,P}$ couplings are present, the constraints become even more severe. It is for this reason that, even when the SP contributions are unsuppressed by $m_\mu/m_{\rm b}$, they are not often large enough to stand apart from the SM background. The couplings of the T operators, viz. $C_{\rm T}$ and $C_{\rm TE}$, are not as suppressed as those of the SP operators. Therefore, they typically contribute significantly to the DBRs. However, the interference terms of these operators with the SM operators often suffer from the $m_\mu/m_{\rm b}$ helicity suppression, and hence they tend to suppress the magnitudes of the asymmetries. The combination of multiple Lorentz structures in general gives rise to the combination of features of the individual Lorentz structures involved. A remarkable exception is the combination of SP and T operators in the forward–backward asymmetry in $\bar{B}_{\rm d}^0 \to \bar{K}\mu^+\mu^-$. This asymmetry, which vanishes in the SM, can be enhanced to $\sim$5% at low q^2 with only SP operators, and can be enhanced to $\sim$30% with T operators but only at $q^2 \approx m_{\rm B}^2$. However, the presence of both SP and T operators allows the asymmetry to be $\sim$40% in the whole high-q^2 region.

For the CP-violating observables the SM predicts $A_{\rm CP}(q^2) \lesssim 10^{-3}$ for all the modes, while VA NP operators allow this quantity to be as large as $\sim$10% (for $\bar{B}_{\rm d}^0 \to X_{\rm s}\mu^+\mu^-$, $\bar{B}_{\rm d}^0 \to \bar{K}\mu^+\mu^-$ and $\bar{B}_{\rm d}^0 \to \bar{K}^*\mu^+\mu^-$) and even up to $\sim$30% for $\bar{B}_{\rm s}^0 \to \mu^+\mu^-\gamma$. Even $\Delta A_{\rm FB}$, expected to be $\lesssim 10^{-4}$ in the SM, can be enhanced up to $\sim$10% (for $\bar{B}_{\rm d}^0 \to X_{\rm s}\mu^+\mu^-$) and up to $\sim$40% (for $\bar{B}_{\rm s}^0 \to \mu^+\mu^-\gamma$). While $\Delta A_{\rm FB}$ in $\bar{B}_{\rm d}^0 \to \bar{K}\mu^+\mu^-$ stays zero even with VA NP, its value in $\bar{B}_{\rm d}^0 \to \bar{K}^*\mu^+\mu^-$ may be enhanced to $\sim$10% from its SM expectation of $\lesssim 10^{-4}$. In $\bar{B}_{\rm d}^0 \to \bar{K}^*\mu^+\mu^-$ the SM predicts $\Delta f_{\rm L} \lesssim 10^{-4}$, while VA NP operators allow this quantity to be enhanced up to $\sim$10%. $\Delta A_{\rm T}^{(2)}$, $\Delta A_{\rm LT}$, $A_{\rm T}^{(\rm im)}$, and $A_{\rm LT}^{(\rm im)}$ are all zero in the SM. VA NP operators can enhance $\Delta A_{\rm T}^{(2)}$ up to $\sim$12%, $A_{\rm T}^{(\rm im)}$ even up to $\sim$50%, and $A_{\rm LT}^{(\rm im)}$ up to $\sim$10%. $\Delta A_{\rm LT}$ cannot be enhanced more than $\sim$3% even in the presence of VA NP operators. Note that while in almost all the cases the impact of the left-handed VA NP couplings $R_{\rm V,A}$ is dominant, for the TP asymmetry $\Delta A_{\rm T}^{(\rm im)}$, the $R'_{\rm V,A}$ couplings play a dominating role.

With the large amount of data expected from the LHC experiments and *B*-factories in the coming years, we may be able to detect confirmed NP signals in the above processes. In that case, a combined analysis of all these decay modes, as carried out here, would enable us to identify the Lorentz structure of the NP operators.

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