

Exploring observable effects of scalar operators beyond SMEFT in the angular distribution of $B \rightarrow K^{*0} \tau^+ \tau^-$

Siddhartha Karmakar^{*} and Amol Dighe[†]

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India

 (Received 13 September 2024; accepted 2 December 2024; published 30 December 2024)

The $SU(2)_L \times U(1)_Y$ invariance of the Standard Model effective field theory (SMEFT) imposes relations among different low-energy effective field theory Wilson coefficients (WCs), any deviations from which would signal the presence of physics beyond SMEFT. In this work, we investigate two such relations ($C_S = -C_P$, $C'_S = C'_P$) among the scalar and the pseudoscalar new physics WCs that can contribute to $b \rightarrow s \tau \tau$ processes. We show that, even when new physics violating these relations would not be measurable in the branching ratios of $B_s \rightarrow \tau^+ \tau^-$ and $B \rightarrow K^{(*)} \tau^+ \tau^-$ at HL-LHC and FCC-ee, it can still manifest itself in the angular distribution of $B \rightarrow K^{*0} \tau^+ \tau^-$. We identify the combinations of angular observables in this decay channel that are sensitive to scenarios beyond SMEFT. We find that the two observables S_6^C and A_7 , and their combination, have the potential to identify physics beyond SMEFT.

DOI: [10.1103/PhysRevD.110.115041](https://doi.org/10.1103/PhysRevD.110.115041)

I. INTRODUCTION

Physics beyond the Standard Model (BSM) is often parametrized model independently in terms of the Standard Model effective field theory (SMEFT) [1,2]. The effective Lagrangian in SMEFT is written as

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} C^{(5)} O^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right). \quad (1)$$

Here $O_i^{(d)}$ are the effective operators with mass dimension $d > 4$ which are composed of the Standard Model (SM) fields, and the Wilson coefficients (WCs) $C_i^{(d)}$ encode the corresponding new physics (NP) effects. All the operators in SMEFT are invariant under the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$.

In flavor physics, the relevant energy scale is near the mass of the B meson. At this scale, the heavier particles, i.e., Z , $W^\pm$ gauge bosons, the Higgs boson (h), and the top quark, are integrated out. The resulting effective field theory is the low-energy effective field theory (LEFT) [3,4]. As LEFT is relevant below the electroweak (EW) scale, all the operators in LEFT need to be invariant only under $SU(3)_C \times U(1)_{em}$. When LEFT operators are

matched to SMEFT operators, the $SU(2)_L \times U(1)_Y$ invariance of SMEFT imposes several relations among the WCs in LEFT. Such relations and their phenomenological implications have recently been studied in [5–24].

However, SMEFT is not the only effective field theory (EFT) above the EW scale. There are more general EFTs, completely consistent with the current data, which may obey only a subset of the full SM gauge symmetry or have a different EW symmetry breaking mechanism. For example, in the Higgs effective field theory (HEFT) [25–29], the EW symmetry $SU(2)_L \times U(1)_Y$ is nonlinearly realized. Although SMEFT is a more commonly used EFT in literature due to its minimality, there is no experimental evidence yet to prefer it over HEFT, which is a more general EFT framework. The motivation for exploring deviations from SMEFT stems from the possibility that NP may manifest itself in ways not fully captured by SMEFT. For example, correlations among certain observables, implicit in SMEFT, may not actually exist if the realization of the electroweak symmetry is not linear. In such cases, the analyses performed using SMEFT will not be fully consistent and a more general framework such as HEFT may have to be employed.

Searches for beyond-SMEFT physics in ATLAS and CMS have focused on the precise measurements of Higgs couplings with fermions and gauge bosons [30]. In this work, our goal is to study the possibility of identifying the effects of physics beyond SMEFT in the $b \rightarrow s \tau \tau$ channel.

The motivation for focusing on the $b \rightarrow \tau$ sector emerges from several recently observed flavor anomalies in B meson decays that indicate the possibility of BSM physics. For example, the measurements of $R(D^{(*)})$ [31–34] and $R(J/\psi)$ [35] involve the charged-current transition $b \rightarrow c \tau \nu_\tau$, while the observables $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$ [36],

^{*}Contact authors: siddhartha@theory.tifr.res.in

[†]Contact authors: amol@theory.tifr.res.in

$\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$ [37], $\mathcal{B}(B \rightarrow K \nu \bar{\nu})$ [38], and P'_5 [39–41] involve the neutral-current transitions $b \rightarrow s \ell \ell$. Although these anomalies can be addressed within the framework of SMEFT, the possibility that they originate from physics beyond SMEFT remains open. In our earlier study [42], we have explored the possibility of identifying the beyond-SMEFT effects in the charged-current transition $b \rightarrow c \tau \nu_\tau$, using angular observables in $\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda \pi) \tau \bar{\nu}_\tau$ and constraints from $R(D^{(*)})$, $R(J/\psi)$, $\mathcal{B}(B_c \rightarrow \tau^+ \tau^-)$.

In this work, we focus on the processes mediated by $b \rightarrow s \tau \tau$. In recent literature [12,20,24,43–47], it has been pointed out that a common explanation of observed excess in $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$ and the deviations in the lepton flavor universality (LFU) ratios $R(D^{(*)})$ would predict excess branching fractions for the modes $B_s \rightarrow \tau^+ \tau^-$, $B \rightarrow K^{(*)} \tau^+ \tau^-$, etc. Other LFU ratios such as $R_{K^{(*)}}^{\tau/\mu}$ [48] would also probe BSM physics. It should be noted that, in addition to the branching fractions, the NP will also affect the angular distributions in the $B \rightarrow K^{(*)} \tau^+ \tau^-$ modes. In fact, even in the cases where the NP effects are not evident in the branching ratios or are obscured by hadronic uncertainties, they may still show up in the angular distributions. In our analysis, we study the possibility of identifying the NP effects—specifically the effects beyond SMEFT—in the angular observables of $B \rightarrow K^{(*)} \tau^+ \tau^-$, even when they are not measurable in the branching ratios.

Two of the SMEFT-predicted relations among the WCs of scalar and pseudoscalar LEFT operators are

$$\mathcal{C}_S = -\mathcal{C}_P \quad \text{and} \quad \mathcal{C}'_S = \mathcal{C}'_P. \quad (2)$$

We study the possible violation of these relations and the prospects of identifying the physics beyond SMEFT through future measurements of the processes $B_s \rightarrow \tau^+ \tau^-$ and $B \rightarrow K^{(*)} \tau^+ \tau^-$, which may get contributions from the semileptonic scalar and pseudoscalar operators in the $b \rightarrow s \tau \tau$ channel.

Currently, the branching ratios of these modes are not well measured. The present experimental bounds are $\mathcal{B}(B_s \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3}$ [49], $\mathcal{B}(B^+ \rightarrow K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3}$ [50], and $\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) < 3.1 \times 10^{-3}$ [51]. These bounds are much weaker as compared to the SM expectations, which are $\mathcal{O}(10^{-7})$ for all these modes [52]. However, these bounds will improve by 1 or 2 orders of magnitude in Belle-II [53] and HL-LHC [54]. Moreover, FCC-ee is expected to measure $\mathcal{B}(B \rightarrow K^{(*)} \tau^+ \tau^-)$ at the SM level with the estimated yield for $B \rightarrow K^{*0} \tau^+ \tau^-$ of $\mathcal{O}(1000)$ in its phase 1 of running [55,56]. This will allow us to carry out angular analyses for these modes.

In this work, we envisage the scenario where the NP effects may not be apparent directly in the branching ratios of $B_s \rightarrow \tau^+ \tau^-$ and $B \rightarrow K^{(*)} \tau^+ \tau^-$ at the level of precision possible at HL-LHC and FCC-ee. Taking these branching ratios to be consistent with the SM, we calculate constraints

for the WCs in LEFT contributing to $b \rightarrow s \tau \tau$ processes based on the projected measurements of these branching ratios. Given these constraints, we explore if the angular observables in $B \rightarrow K^{*0} \tau^+ \tau^-$ are sensitive to any deviations from the SMEFT-predicted relations. We look for combinations of these angular observables that will be able to identify physics beyond SMEFT. Note that angular distributions of $B \rightarrow K^{*0} \tau^+ \tau^-$ have been studied earlier in [57–60]; however, their potential for identifying beyond-SMEFT effects has not yet been explored.

In Sec. II, we list the effective operators in SMEFT and in LEFT that contribute to the $b \rightarrow s \tau \tau$ processes and discuss the predictions of SMEFT for the LEFT WCs. In Sec. III, we present the projected constraints on the WCs in LEFT with and without the underlying SMEFT assumptions, taking the NP WCs to be real. In Sec. IV, we discuss the angular observables in $B \rightarrow K^{*0} \tau^+ \tau^-$ and try to identify suitable observables, and their combinations, for distinguishing the scenarios within and beyond SMEFT. In Sec. V, we extend this exercise to the case of complex WCs, pointing out an additional CP -odd observable sensitive to physics beyond SMEFT. Finally, we summarize our results in Sec. VI.

II. SMEFT-PREDICTED RELATIONS FOR WILSON COEFFICIENTS IN LEFT

In this section, we list the dimension-six semileptonic operators in LEFT contributing to the $b \rightarrow s \tau \tau$ transition at the tree level. Based on the matching of these operators to SMEFT, we present the resulting relations among the WCs in LEFT.

The leading order effective Lagrangian in LEFT for $b \rightarrow s \tau^+ \tau^-$ process, considering only semileptonic operators, is [61]

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i \mathcal{C}_i \mathcal{O}_i, \quad (3)$$

where the operators $\mathcal{O}_i$ include the following:

$$\begin{aligned} \mathcal{O}_9^{(\prime)} &= [\bar{s} \gamma^\mu P_{L(R)} b] [\tau \gamma_\mu \tau], & \mathcal{O}_P^{(\prime)} &= [\bar{s} P_R(L) b] [\tau \gamma_5 \tau], \\ \mathcal{O}_S^{(\prime)} &= [\bar{s} P_R(L) b] [\tau \tau], & \mathcal{O}_{10}^{(\prime)} &= [\bar{s} \gamma^\mu P_{L(R)} b] [\tau \gamma_\mu \gamma_5 \tau], \\ \mathcal{O}_T &= [\bar{s} \sigma^{\mu\nu} b] [\tau \sigma_{\mu\nu} \tau], & \mathcal{O}_{T5} &= [\bar{s} \sigma^{\mu\nu} b] [\tau \sigma_{\mu\nu} \gamma_5 \tau]. \end{aligned} \quad (4)$$

Semileptonic operators in SMEFT contributing to $b \rightarrow s \tau \tau$ channel are

$$\mathcal{O}_{lq}^{(1)} = (\bar{q} \gamma^\mu q) (\bar{\ell} \gamma_\mu \ell), \quad \mathcal{O}_{lq}^{(3)} = (\bar{q} \gamma^\mu \tau_l q) (\bar{\ell} \gamma_\mu \tau^l \ell), \quad (5)$$

$$\mathcal{O}_{qe} = (\bar{q} \gamma^\mu q) (\bar{e} \gamma_\mu e), \quad \mathcal{O}_{ld} = (\bar{d} \gamma^\mu d) (\bar{\ell} \gamma_\mu \ell), \quad (6)$$

$$\mathcal{O}_{ledq} = (\bar{\ell} e) (\bar{d} q), \quad (7)$$

where q and ℓ are left-handed quark and lepton doublets, whereas d and e are right-handed down-type quark and right-handed electron, respectively. The matching equations among the WCs of scalar and tensor operators in SMEFT and LEFT are [6,62]

$$\mathcal{C}_S^{\alpha\beta ij} = \frac{v^2}{4\Lambda^2} \mathcal{C}_{ledq}^{\beta\alpha ji*}, \quad \mathcal{C}_P^{\alpha\beta ij} = -\frac{v^2}{4\Lambda^2} \mathcal{C}_{ledq}^{\beta\alpha ji*}, \quad (8)$$

$$\mathcal{C}_S^{\prime\alpha\beta ij} = \frac{v^2}{4\Lambda^2} \mathcal{C}_{ledq}^{\alpha\beta ij}, \quad \mathcal{C}_P^{\prime\alpha\beta ij} = \frac{v^2}{4\Lambda^2} \mathcal{C}_{ledq}^{\alpha\beta ji*}, \quad (9)$$

$$\mathcal{C}_T^{\alpha\beta ij} = \mathcal{C}_{T5}^{\alpha\beta ij} = 0. \quad (10)$$

These matching equations imply the following relations [6,24,62]:

$$\mathcal{C}_S = -\mathcal{C}_P, \quad \mathcal{C}'_S = \mathcal{C}'_P, \quad \mathcal{C}_T = \mathcal{C}_{T5} = 0. \quad (11)$$

These relations result from the conservation of $U(1)_Y$ hypercharge in the corresponding SMEFT operators. When considering operators up to dimension six, these relations hold true irrespective of which SMEFT operators are present at the UV scale. However, in a more general EFT above the EW scale, such as HEFT, the EW gauge symmetry $SU(2)_L \times U(1)_Y$ is realized nonlinearly, and therefore, the $U(1)_Y$ hypercharge need not be conserved in each HEFT operator separately. In this scenario, the resulting LEFT operators may not follow the SMEFT-predicted relations.

The matching of LEFT scalar operators to such a nonlinear EFT is detailed in [6],

$$\mathcal{C}_{S,P} = \mathcal{N}(\pm \mathbf{c}_S + \mathbf{c}_{Y1}), \quad \mathcal{C}'_{S,P} = \mathcal{N}(\mathbf{c}'_S \pm \mathbf{c}'_{Y1}), \quad (12)$$

where $\mathcal{N}$ is a normalization constant. Here $\mathbf{c}_S^{(\ell)}$ and $\mathbf{c}_{Y1}^{(\ell)}$ are the WCs of the corresponding operators $\mathbf{o}_S^{(\ell)}$ and $\mathbf{o}_{Y1}^{(\ell)}$ in the nonlinear EFT basis in unitary gauge,

$$[\mathbf{o}_S]^{\alpha\beta ij} = -4(\bar{d}_L^i \gamma_\mu e_L^\alpha)(\bar{e}_R^\beta \gamma^\mu d_R^j), \quad (13)$$

$$[\mathbf{o}'_S]^{\alpha\beta ij} = -4(\bar{e}_L^\beta \gamma_\mu d_L^j)(\bar{d}_R^i \gamma^\mu e_R^\alpha), \quad (14)$$

$$[\mathbf{o}_{Y1}]^{\alpha\beta ij} = (\bar{e}_L^\alpha e_R^\beta)(\bar{d}_L^i d_R^j), \quad (15)$$

$$[\mathbf{o}'_{Y1}]^{\alpha\beta ij} = (\bar{e}_R^\alpha e_L^\beta)(\bar{d}_R^i d_L^j). \quad (16)$$

Here (α, β) and (i, j) correspond to the generation indices for leptons and quarks, respectively. The implication of Eq. (12) is that the relations in Eq. (11) are no longer maintained. The deviations from the correlations arise due to the WCs $\mathbf{c}_{Y1}$ and $\mathbf{c}'_{Y1}$ and can be parametrized as

$$\Delta\mathcal{C} \equiv \mathcal{C}_S + \mathcal{C}_P = 2\mathcal{N}\mathbf{c}_{Y1}, \quad (17)$$

$$\Delta\mathcal{C}' \equiv \mathcal{C}'_S - \mathcal{C}'_P = 2\mathcal{N}\mathbf{c}'_{Y1}. \quad (18)$$

Nonzero values of $\Delta\mathcal{C}$ and $\Delta\mathcal{C}'$ indicate effects beyond SMEFT. For the tensor operators, the WCs $\mathcal{C}_T$ and $\mathcal{C}_{T5}$ are zero in SMEFT, so any nonzero value of these WCs will suggest physics beyond SMEFT. In our numerical analysis, we focus exclusively on the NP vector and scalar operators.

III. CONSTRAINTS ON THE LEFT WCs

The NP contributions to $b \rightarrow s\tau\tau$ transition may arise from the vector and scalar Wilson coefficients $\mathcal{C}_9^{(\ell)}$, $\mathcal{C}_{10}^{(\ell)}$, $\mathcal{C}_S^{(\ell)}$, and $\mathcal{C}_P^{(\ell)}$. To put constraints on these WCs, we consider the branching ratios $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ and $\mathcal{B}(B \rightarrow K^{(*)}\tau^+\tau^-)$. The SM predictions, current upper bounds, and projected future bounds for these modes are presented in Table I. We envisage the scenario where the NP effects may not be apparent directly in the branching ratios of $B \rightarrow K^{(*)}\tau^+\tau^-$; however, they may affect the angular distribution of these decays. Based on these projected measurements, we calculate constraints on the WCs, both in the SMEFT and beyond-SMEFT scenarios.

For the WCs associated with the vector operators, the best constraints come from $\mathcal{B}(B \rightarrow K^*\tau^+\tau^-)$. While constraining these WCs corresponding to the vector operators, we consider the “VA” scenario where we take all the scalar WCs to be zero. Since $\mathcal{O}(1000)$ such events are expected in the phase 1 of FCC-ee [55], we project the future precision on $\mathcal{B}(B \rightarrow K^{(*)}\tau^+\tau^-)$ conservatively to be within 10% of its SM value. That is, we estimate constraints on the vector WCs with the condition

$$|\mathcal{B}_{\text{NP}} - \mathcal{B}_{\text{SM}}| < 0.1 \times \mathcal{B}_{\text{SM}}, \quad (19)$$

TABLE I. SM values (column 2), current bounds (column 3), and expected precisions after HL-LHC and the phase 1 of FCC-ee (column 4) for the branching ratios of $B_s \rightarrow \tau^+\tau^-$ and $B \rightarrow K^{(*)}\tau^+\tau^-$.

Observables	SM [52]	Current bounds	HL-LHC + FCC-ee [55]
$\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$	$(7.73 \pm 0.49) \times 10^{-7}$	$< 6.8 \times 10^{-3}$ [49]	$< 10^{-5}$
$\mathcal{B}(B^+ \rightarrow K^+\tau^+\tau^-)$	$(1.66 \pm 0.17) \times 10^{-7}$	$< 2.25 \times 10^{-3}$ [50]	SM $\pm 10\%$
$\mathcal{B}(B^+ \rightarrow K^{*+}\tau^+\tau^-)$	$(1.55 \pm 0.20) \times 10^{-7}$	$< 3.1 \times 10^{-3}$ [51]	SM $\pm 10\%$
$\mathcal{B}(B^+ \rightarrow K^{*0}\tau^+\tau^-)$	$(1.43 \pm 0.18) \times 10^{-7}$	$< 3.1 \times 10^{-3}$ [51]	SM $\pm 10\%$

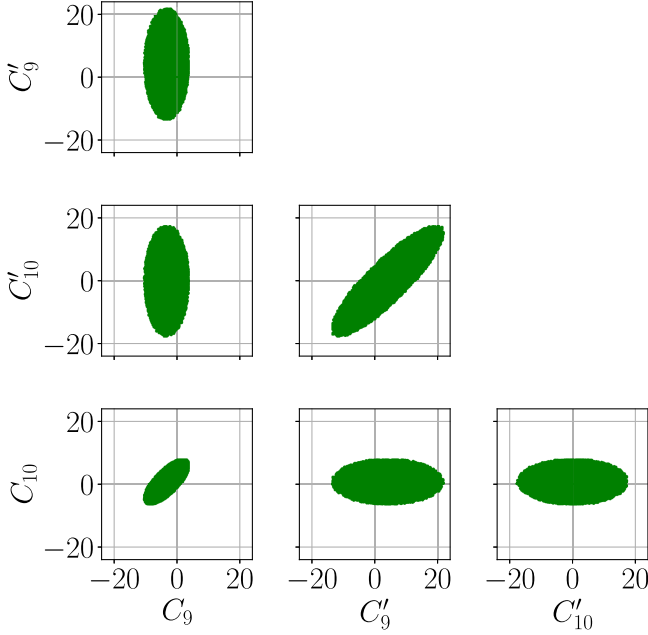


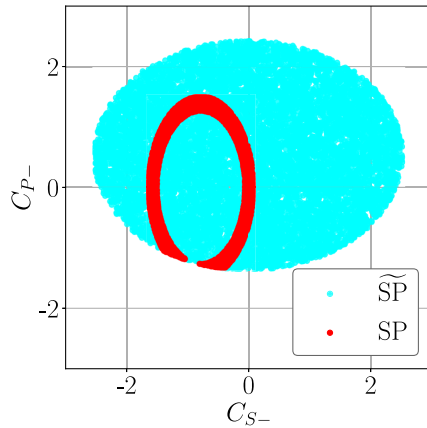
FIG. 1. Projected bounds on C_9 , C_{10} , C'_9 , and C'_{10} from the expected observation of $\mathcal{B}(B \rightarrow K^* \tau \tau)$ at FCC-ee to be within 10% of its SM value. While considering any combination of two parameters, the remaining parameters are varied over all their possible values.

where $\mathcal{B}$ stands for $\mathcal{B}(B \rightarrow K^{(*)} \tau^+ \tau^-)$. We use the PYTHON package FLAVIO [52] to calculate the theoretical prediction for $\mathcal{B}(B \rightarrow K^{(*)} \tau^+ \tau^-)$. The resulting constraints on the WCs C_9 , C_{10} , C'_9 , and C'_{10} are shown in Fig. 1.

For the scalar operators, we define

$$C_{S+} \equiv C_S + C'_S, \quad C_{P+} \equiv C_P + C'_P, \quad (20)$$

$$C_{S-} \equiv C_S - C'_S, \quad C_{P-} \equiv C_P - C'_P. \quad (21)$$



In terms of the above quantities, the SMEFT-predicted relations for the WCs of the scalar operators become

$$C_{S+} = -C_{P-} \quad \text{and} \quad C_{P+} = -C_{S-}. \quad (22)$$

When these relations are obeyed, we call the scenario “SP.” Violations of the SMEFT-predicted relations can be parametrized in terms of the quantities ΔC_1 and ΔC_2 , where

$$\Delta C_1 \equiv C_{S+} + C_{P-}, \quad \Delta C_2 \equiv C_{P+} + C_{S-}. \quad (23)$$

Note that ΔC_1 and ΔC_2 can be related to the quantities ΔC and $\Delta C'$ defined in Eqs. (17) and (18) as

$$\Delta C_1 \equiv \Delta C + \Delta C', \quad \Delta C_2 \equiv \Delta C - \Delta C'. \quad (24)$$

When $\Delta C_1 \neq 0$ and/or $\Delta C_2 \neq 0$, we call that scenario “ $\widetilde{\text{SP}}$.” In SP and $\widetilde{\text{SP}}$ scenarios, the NP WCs corresponding to the vector operators are taken to be zero.

In [63], current bounds on the scalar operators are calculated indirectly from $b \rightarrow s \gamma$, $b \rightarrow s l^+ l^-$ processes and directly from $B_s \rightarrow \tau^+ \tau^-$, $B^+ \rightarrow K^+ \tau^+ \tau^-$, and $B^+ \rightarrow X_s \tau^+ \tau^-$ processes. These bounds are rather weak,

$$|C_S \pm C_P| < 0.4 \frac{2\pi}{\alpha_e}, \quad |C'_S \pm C'_P| < 0.4 \frac{2\pi}{\alpha_e}. \quad (25)$$

In our analysis, we take $\mathcal{B}(B_s \rightarrow \tau^+ \tau^-) < 10^{-5}$, which is the expected upper bound at the HL-LHC and FCC-ee [55], and the expected measurement of $\mathcal{B}(B \rightarrow K \tau^+ \tau^-)$ at FCC-ee to be within the precision of 10% of the SM value. With these assumptions, we find the allowed region for the four parameters C_{S+} , C_{P+} , C_{S-} , and C_{P-} for the two scenarios SP and $\widetilde{\text{SP}}$. We present the projections of these allowed regions in Fig. 2. Note that the observable $\mathcal{B}(B \rightarrow K \tau^+ \tau^-)$ is more sensitive to C_{S+} and C_{P+} , whereas $\mathcal{B}(B_s \rightarrow \tau^+ \tau^-)$

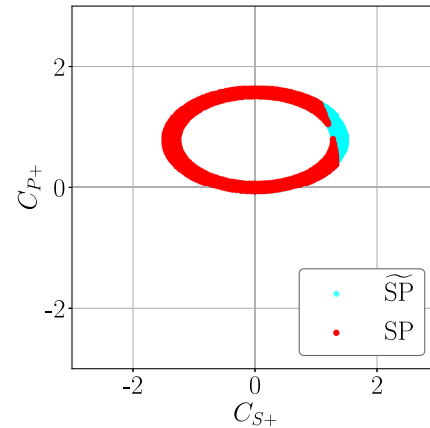


FIG. 2. Projected bounds on the NP scalar WCs in the (C_{S-}, C_{P-}) and (C_{S+}, C_{P+}) planes, from the expected upper bound on $\mathcal{B}(B_s \rightarrow \tau \tau) < 10^{-5}$ and the expected measurement of $\mathcal{B}(B^+ \rightarrow K^+ \tau \tau)$ with 10% of its SM value. Note that the SP regions (red) are subsets of $\widetilde{\text{SP}}$ region (cyan), i.e., all the red regions have cyan regions underneath.

is more sensitive to C_{S-} and C_{P-} . The upper bound $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) < 10^{-5}$ constrains C_{S-} and C_{P-} to a circular cyan region. On the other hand, the constraint on $\mathcal{B}(B \rightarrow K\tau^+\tau^-)$ leads to an annular red region in the (C_{S+}, C_{P+}) plane.

Note that, in Figs. 1 and 2, we have not accounted for uncertainties due to form factors and other input parameters. When these uncertainties are included, the allowed regions broaden, although their overall shapes remain largely unchanged. We shall later include the uncertainties and study their effects.

Based on the allowed WC values, our next goal is to find observables whose values for the $\widetilde{\text{SP}}$ scenario will be distinguishable from those for the VA and SP scenarios.

IV. ANGULAR OBSERVABLES IN $B^0 \rightarrow K^{*0}\tau^+\tau^-$

In this section, we study the effects of the $\widetilde{\text{SP}}$ scenario, in comparison to the SM, VA, and SP scenarios, on the angular observables in $B \rightarrow V(\rightarrow P_1 P_2)\tau^+\tau^-$ decays. Here V and $P_{1(2)}$ are vector and pseudoscalar mesons, respectively. The angular distribution for $B \rightarrow V(\rightarrow P_1 P_2)\tau^+\tau^-$ decay is given as [64]

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_V d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_V, \phi), \quad (26)$$

where

$$\begin{aligned} I(q^2, \theta_l, \theta_V, \phi) = & I_1^s \sin^2\theta_V + I_1^c \cos^2\theta_V + (I_2^s \sin^2\theta_V + I_2^c \cos^2\theta_V) \cos 2\theta_l + I_3 \sin^2\theta_V \sin^2\theta_l \cos 2\phi \\ & + I_4 \sin 2\theta_V \sin 2\theta_l \cos \phi + I_5 \sin 2\theta_V \sin \theta_l \cos \phi + (I_6^s \sin^2\theta_V + I_6^c \cos^2\theta_V) \cos \theta_l \\ & + I_7 \sin 2\theta_V \sin \theta_l \sin \phi + I_8 \sin 2\theta_V \sin 2\theta_l \sin \phi + I_9 \sin^2\theta_V \sin^2\theta_l \sin 2\phi. \end{aligned} \quad (27)$$

Here the direction of V in the rest frame of B is taken to be the z axis. The angle between the z axis and the direction of P_1 in the rest frame of V is denoted by θ_V . The angle between the $-z$ axis and the direction of τ^- in the center-of-mass frame of the lepton pair is denoted by θ_l . The azimuthal angle ϕ is the angle between the decay planes formed by the decay products (P_1, P_2) and (τ^+, τ^-) in the rest frame of B . In our analysis, $V \equiv K^{*0}$, $P_1 \equiv K^+$, and $P_2 \equiv \pi^-$.

We calculate the values of the following observables as functions of q^2 using the software package FLAVIO [52]:

$$S_i^{(a)} = \frac{(I_i^{(a)} + \bar{I}_i^{(a)})}{d(\Gamma + \bar{\Gamma})/dq^2}, \quad A_{FB} = \frac{3}{8}(2S_6^s + S_6^c), \quad F_L = S_1^c, \quad (28)$$

where $\bar{I}_i^{(a)}$ and $\bar{\Gamma}$ are the corresponding angular coefficient and decay width for the CP -conjugate process. The explicit expressions of these angular observables are available in [64]. In Table II, we present the observables that are sensitive to each NP parameter.

TABLE II. Wilson coefficients of NP vector and scalar operators and observables sensitive to each of them.

NP WCs	Sensitive observables
$C_9^{(\prime)}, C_{10}^{(\prime)}$	$S_1^{s,c}, S_2^{s,c}, S_3, S_4, S_5, S_6^s, A_7, A_{FB}, \mathcal{B}(B \rightarrow K^{*0}\tau^+\tau^-)$
C_{S-}	$S_1^c + S_2^c, S_6^c, A_{FB}, \mathcal{B}(B_s \rightarrow \tau^+\tau^-)$
C_{P-}	$F_L, \mathcal{B}(B_s \rightarrow \tau^+\tau^-)$
C_{S+}, C_{P+}	$\mathcal{B}(B \rightarrow K\tau^+\tau^-)$

We calculate these observables in $B^0 \rightarrow K^{*0}\tau^+\tau^-$ for the SM and the NP scenarios VA, SP, and $\widetilde{\text{SP}}$. Note that when we calculate the expected values of the observables in the VA scenario, we consider points for $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$ from the allowed regions as shown in Fig. 1, while keeping all WCs for the scalar operators as zero. Similarly, while calculating observables in the SP ($\widetilde{\text{SP}}$) scenario, we put $C_9^{(\prime)} = C_{10}^{(\prime)} = 0$ and take $C_{S,P}^{(\prime)}$ points from the red (cyan) regions shown in Fig. 2. We find that the angular observables A_{FB} , F_L , and S_6^c show significant sensitivity to the SP and $\widetilde{\text{SP}}$ scenarios. In Fig. 3, we present the expected values of A_{FB} , F_L , and S_6^c in SM and in the NP scenarios VA, SP, and $\widetilde{\text{SP}}$. For all these four observables, we have considered 2σ uncertainties due to form factors and other input parameters, and the WCs corresponding to the NP scenarios are varied within their allowed regions.

As shown in Fig. 3, the observables A_{FB} and F_L by themselves would not be able to distinguish the effects of $\widetilde{\text{SP}}$ from VA and SP scenarios or even from the SM. However, the observable S_6^c is suppressed for both SM and VA and may have significant nonzero values for SP and $\widetilde{\text{SP}}$ scenarios. Moreover, some values of S_6^c that are possible in $\widetilde{\text{SP}}$ are not achievable in the SP scenario. Thus, S_6^c is a good probe for distinguishing between scenarios within SMEFT (VA and SP) and beyond SMEFT ($\widetilde{\text{SP}}$). For example, even a small negative value of S_6^c will hint toward physics beyond SMEFT.

Next, we ask whether it is possible to distinguish the different scenarios even in the case of S_6^c having a positive value. To answer this, we consider the pairs of angular

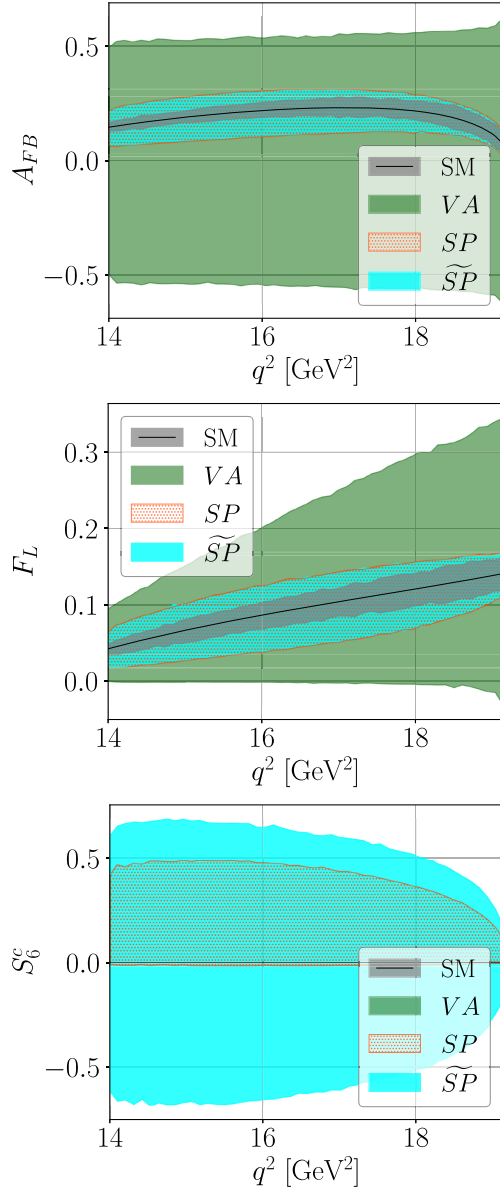


FIG. 3. The allowed values of angular observables A_{FB} (top), F_L (middle), and S_6^c (bottom) in $B^0 \rightarrow K^{0*} \tau^+ \tau^-$ in the scenarios SM, VA, SP, and $\widetilde{SP}$ with 2σ theoretical uncertainties included.

observables (A_{FB} , S_6^c) and (F_L , S_6^c). The left panels of Fig. 4 show the possible points in the respective planes for a fixed value of q^2 and in the absence of any uncertainties in the input parameters. This indicates that, in principle, the combination S_6^c with another observable would be more efficient than S_6^c alone in identifying the beyond-SMEFT effects. However, the necessity of binning over q^2 reduces the efficacy of such combinations as shown in the central panels of Fig. 4. The inclusion of 2σ uncertainties due to form factors and input parameters further limits the ability of these combinations of observables as probes of physics beyond SMEFT. This may be seen from the right panels of Fig. 4. Thus, one would need narrow q^2 bins (hence a large

number of events) and better control over theory parameters in order to effectively exploit such combinations.

Note that our analysis assumes that the branching ratio $B(B \rightarrow K^{(*)} \tau \tau)$ is measured to be within 10% of its SM prediction. This implicitly assumes that the SM prediction itself is known to a precision better than 10%. However, achieving precise predictions for $B(B \rightarrow K^{(*)} \tau \tau)$ within the SM is complicated due to as-yet unresolved long-distance contributions in $C_9^{\text{eff}}(q^2)$, particularly due to the $c\bar{c}$ hadronic effects. Despite recent progress [65–67], these contributions have significant uncertainties, as the $B \rightarrow K^{(*)}$ form factors rely heavily on the light-cone sum rules, which inherently carry phenomenological model dependences. We hope to minimize the effects of these limitations by focusing our analysis on angular observables at higher q^2 values ($q^2 > 14 \text{ GeV}^2$), where hadronic uncertainties may be less pronounced due to a reduced influence from resonant states and nonperturbative effects. Nevertheless, it needs to be borne in mind that the hadronic uncertainties can have a potential impact on the disentanglement of NP effects and improved calculations of hadronic form factors are required to implement our proposed analysis procedure efficiently.

V. RESULTS WITH COMPLEX NP WILSON COEFFICIENTS

In our analysis so far, we have considered all the WCs to be real. However, the WCs in LEFT can be complex in general. Note that, even if all the WCs in SMEFT (or HEFT) in the UV scale are real in the flavor basis, phases will appear in low-energy WCs through Cabibbo-Kobayashi-Maskawa elements while matching. The basic idea and results of our analysis are independent of whether the WCs are real or complex. However, it is worthwhile to see the effects of complex WCs on the angular observables, especially the ones that are asymmetric under CP transformation.

In this section, we consider the WCs $C_9^{(\prime)}$, $C_{10}^{(\prime)}$, $C_{S\pm}$, and $C_{P\pm}$ to be complex. In Fig. 5, we present the allowed regions for complex $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$ in the VA scenario. The methodology for obtaining these constraints is the same as discussed in Sec. III. Note that we allow all of these parameters to be nonzero at the same time, however, we do not show the correlations among them in Fig. 5. The regions are symmetric about the real axis as expected.

In Fig. 6, we show the allowed regions for complex $C_{S\pm}$ and $C_{P\pm}$ in the SP and $\widetilde{SP}$ scenarios. It is observed that the allowed regions in C_{S+} and C_{P+} parameter spaces in the two scenarios SP and $\widetilde{SP}$ overlap almost completely. However, for C_{S-} and C_{P-} , there are regions in this complex parameter space that are only accessible in the scenario beyond SMEFT ($\widetilde{SP}$).

The results for the observables A_{FB} , F_L , and S_6^c are similar to the ones discussed in Sec. IV with allowed

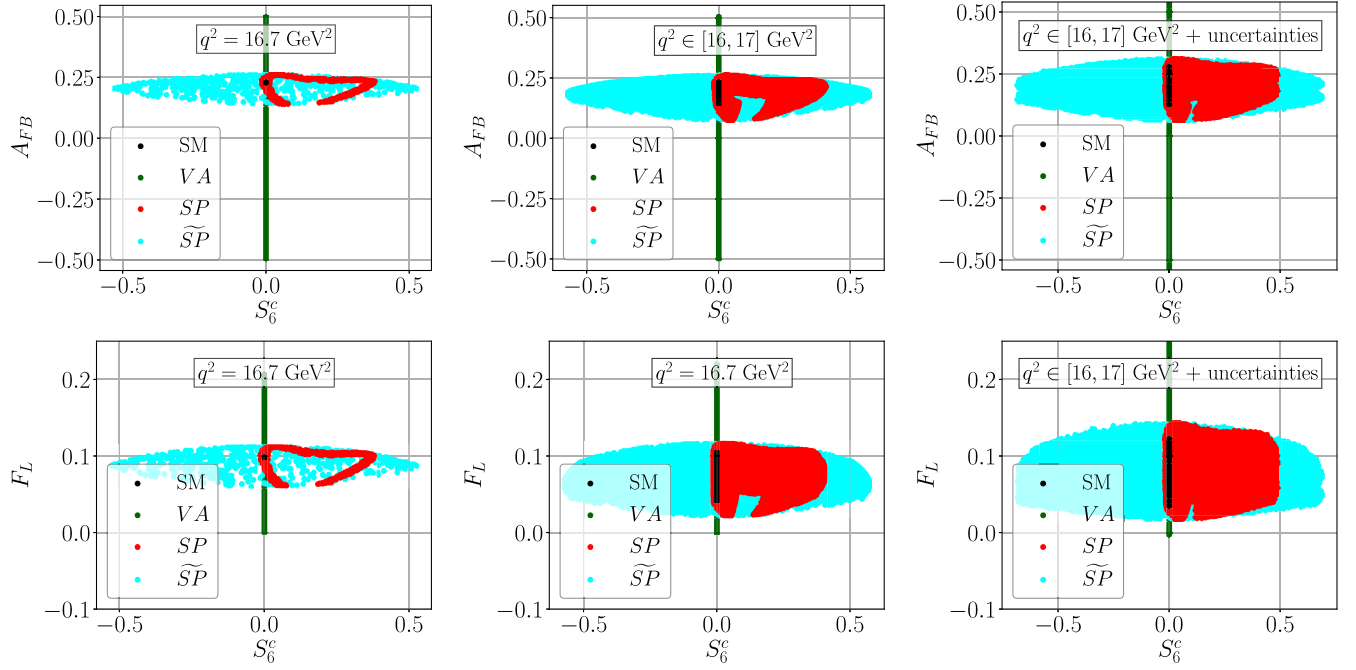


FIG. 4. The combinations of the pairs of angular observables (A_{FB} , S_6^c) and (F_L , S_6^c) in $B^\pm \rightarrow K^{0*}\tau^+\tau^-$, for the SM and for the three NP scenarios VA, SP, and $\widetilde{SP}$. The left column corresponds to the fixed benchmark value $q^2 = 16.7 \text{ GeV}^2$. The middle column is for the bin $q^2 \in [16, 17] \text{ GeV}^2$. The right column is for the same q^2 bin, but after including the 2σ uncertainties due to form factors and other input parameters.

regions becoming wider. We do not show the results with these individual observables in this section. The results for the combinations (A_{FB} , S_6^c) and (F_L , S_6^c) are shown in Fig. 7. These indicate that, for complex WCs, a significantly negative value of S_6^c ($S_6^c \lesssim -0.2$) as well as a large

positive value of S_6^c ($S_6^c \gtrsim 0.5$) would suggest physics beyond SMEFT. The observables A_{FB} and F_L do not seem to be offering any extra advantage to identify $\widetilde{SP}$.

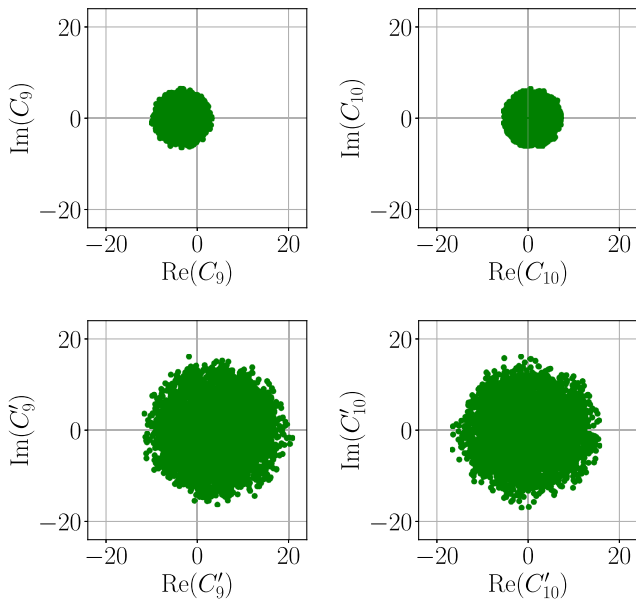


FIG. 5. Projected bounds on the complex parameters C_9 , C_{10} , C'_9 , and C'_{10} from the expected observation of $\mathcal{B}(B \rightarrow K^*\tau\tau)$ at FCC-ee to be within 10% of its SM value.

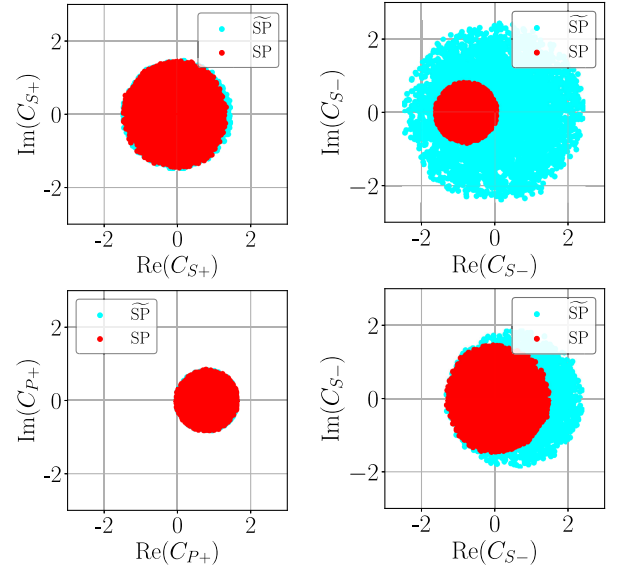


FIG. 6. Projected bounds for the complex parameters C_{S-} , C_{P-} , C_{S+} , and C_{P+} from the expected upper bound on $\mathcal{B}(B_s \rightarrow \tau\tau)$ and the expected measurement of $\mathcal{B}(B^+ \rightarrow K^+\tau\tau)$ at HL-LHC/FCC-ee. Note that the SP regions (red) are subsets of $\widetilde{SP}$ region (cyan), i.e., all the red regions have cyan regions underneath.

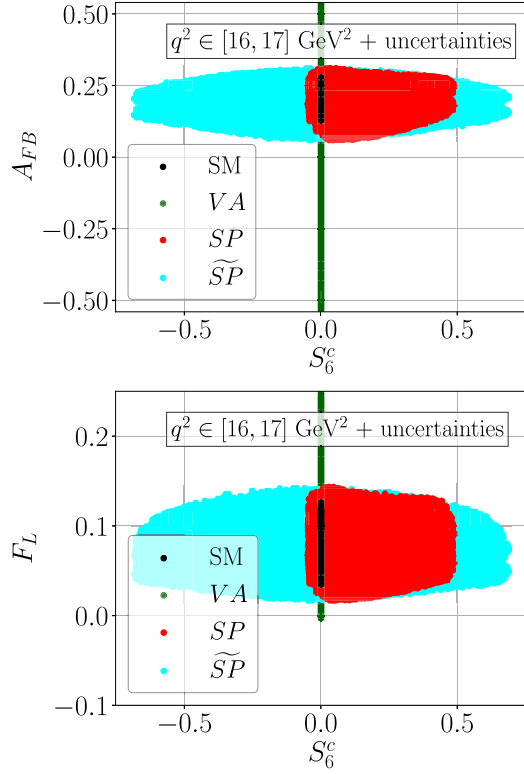


FIG. 7. The combinations of the pairs of angular observables (A_{FB} , S_6^c) and (F_L , S_6^c) in $B^\pm \rightarrow K^{0*}\tau^+\tau^-$, for the SM and for the three NP scenarios VA, SP, and $\widetilde{SP}$ with complex NP parameters. These plots are for the bin $q^2 \in [16, 17]$ GeV^2 with the inclusion of 2σ theoretical uncertainties.

We further explore the CP asymmetric observable A_7 defined as

$$A_7 = \frac{I_7 - \bar{I}_7}{d(\Gamma + \bar{\Gamma})/dq^2}. \quad (29)$$

In the SM as well as in the NP scenarios where all the WCs are real, A_7 is highly suppressed. However, for complex WCs, it may become significantly nonzero. The value of this observable as a function of q^2 is shown in the top panel of Fig. 8. Clearly, A_7 has the ability to identify the $\widetilde{SP}$ scenario by itself. The combination of A_7 and S_6^c can be more effective at this task than the two observables separately, even after taking into account the q^2 binning of 1 GeV^2 and 2σ theoretical uncertainties, as can be seen in the bottom panel of Fig. 8.

VI. CONCLUDING REMARKS

The SMEFT is often taken to be the default EFT above the EW scale. However, more general EFTs, such as HEFT where the EW gauge symmetry $SU(2)_L \times U(1)_Y$ is non-linearly realized, are still not ruled out. In this paper, we

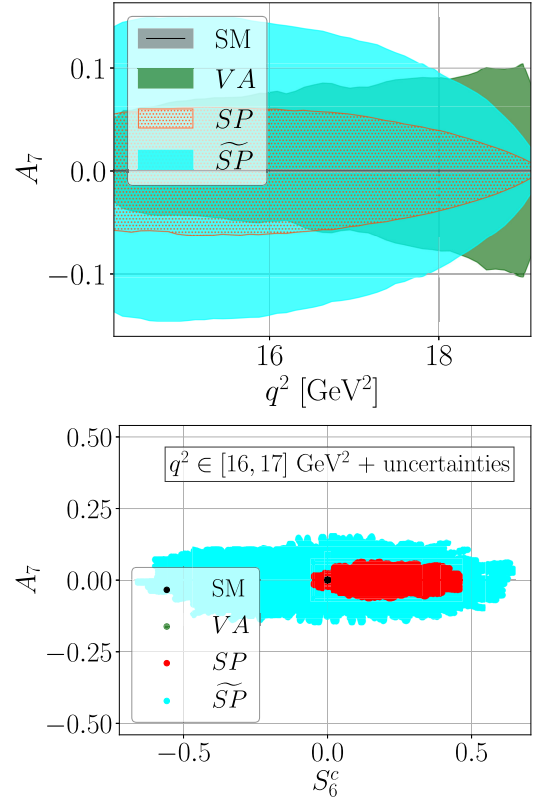


FIG. 8. Allowed values of A_7 as a function of q^2 (top) and the combination of A_7 and S_6^c in the bin $q^2 \in [16, 17]$ GeV^2 (bottom) for complex NP WCs, with 2σ theoretical uncertainties included.

study the possibility of probing beyond-SMEFT physics in low-energy processes mediated via the $b \rightarrow s\tau\tau$ transition.

When relevant operators in the LEFT are mapped to the EFT above the EW scale, certain relations that are satisfied in SMEFT may not hold if a more general EFT such as HEFT is valid over the EW scale. For the neutral-current transition $b \rightarrow s\tau\tau$, some such relations are $C_S = -C_P$, $C'_S = C'_P$, which are predicted by SMEFT. We identify observables that are sensitive to any deviations from these relations and explore the possibility of distinguishing these deviations from not only SM, but also from other NP scenarios that are still within SMEFT.

We consider three NP scenarios (i) VA, where only NP vector operators are nonzero, (ii) SP, where only NP scalar operators are nonzero, but SMEFT-predicted relations are obeyed, and (iii) $\widetilde{SP}$, where only NP scalar operators are nonzero and the SMEFT-predicted relations are not imposed. We calculate constraints on the NP WCs in these three scenarios using projected observations of $\mathcal{B}(B_s \rightarrow \tau^+\tau^-)$ and $\mathcal{B}(B \rightarrow K^{(*)}\tau^+\tau^-)$ with the precision expected in HL-LHC and the phase 1 of FCC-ee. We take these measurements to be consistent with the SM; specifically, we consider an upper bound $\mathcal{B}(B_s \rightarrow \tau^+\tau^-) < 10^{-5}$ and a measurement of $\mathcal{B}(B \rightarrow K^{(*)}\tau^+\tau^-)$ within 10% of its SM prediction.

We calculate the values of angular observables in $B \rightarrow K^{0*} \tau^+ \tau^-$, as functions of q^2 , in the SM and the three NP scenarios mentioned above, possible with the allowed real values of the NP WCs. We find that the angular observable S_6^c will be the most efficient in distinguishing the beyond-SMEFT scenario $\widetilde{SP}$ from the SM as well as from the other NP scenarios. A significant negative value of S_6^c ($\lesssim -0.2$) or a large positive value of S_6^c ($\gtrsim 0.5$) would suggest physics beyond SMEFT. The observables A_{FB} and F_L can help in this identification, in principle. However, with a 1 GeV² binning in q^2 and the inclusion of current theoretical uncertainties, the usefulness of these observables would seem rather constrained.

We further consider the possibility that the NP WCs can take complex values and repeat the above analysis. This allows us to access an additional angular observable A_7 which is sensitive to beyond-SMEFT effects. Moreover, the combination of A_7 and S_6^c would be more effective compared to the two observables by themselves. Thus, we demonstrate that the angular observables can reveal the NP which would stay hidden if only the branching ratios were observed.

Although the measurements of the two branching ratios considered in our analysis will only be available after the full run of HL-LHC (for $B_s \rightarrow \tau^+ \tau^-$) and phase 1 of FCC-ee (for $B \rightarrow K^{(*)} \tau^+ \tau^-$), the analysis proposed is a promising way to identify scenarios beyond SMEFT through neutral-current semileptonic decays of B mesons and underscores the importance of efficient τ detection in future collider experiments.

ACKNOWLEDGMENTS

We would like to thank Susobhan Chattopadhyay, Rick S. Gupta, Gagan B. Mohanty, and Tuhin S. Roy for useful discussions. We would also like to thank Ajay Salve and Kapil Ghadiali for technical assistance. This work is supported by the Department of Atomic Energy, Government of India, under Project Identification No. RTI 4002. We acknowledge the use of computational facilities of the Department of Theoretical Physics at Tata Institute of Fundamental Research, Mumbai.

DATA AVAILABILITY

No data were created or analyzed in this study.

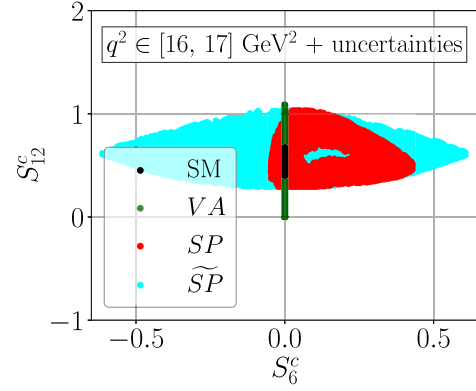


FIG. 9. Allowed values of the pair of observables (S_{12}^c , S_6^c) for the bin $q^2 \in [16, 17]$ GeV² with 2σ theoretical uncertainties included.

APPENDIX: THE ANGULAR OBSERVABLE $S_1^c + S_2^c$

In Table II we have mentioned that the observable $S_{12}^c \equiv S_1^c + S_2^c$ is sensitive to C_{S-} . Indeed, it gets a contribution from $|C_{S-}|^2$ at the leading order, while the contributions from C_{P-} and the vector WCs are suppressed by a factor of $m_\tau^2/q^2 \sim 1/5$. In this appendix, we study the effectiveness of S_{12}^c in distinguishing the $\widetilde{SP}$ scenario from SM and the other NP scenarios. We present this observable separately because it is not directly available in FLAVIO.

We calculate S_{12}^c following the expressions in [64] and taking the $B \rightarrow K^*$ form factors from [68]. We consider the scenario where all the NP WCs are real. It is observed that S_{12}^c by itself will not be able to distinguish the $\widetilde{SP}$ scenario from SP, though it can distinguish it from VA. The combination of S_{12}^c and S_6^c could offer an advantage over these two observables separately in certain regions of parameter space. This may be seen in Fig. 9.

It may be worthwhile to comment on the observable S_{12}^c in the context of $b \rightarrow s \mu \mu$. In this case, the contributions from C_{P-} and the vector WCs are strongly suppressed, i.e., by $m_\mu^2/q^2 \sim 1/1500$. However, since the NP WCs in $b \rightarrow s \mu \mu$ are severely constrained [69], it would not be possible to identify the beyond-SMEFT scenario in the muon mode with the analysis proposed in this article.

- [1] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, Dimension-six terms in the Standard Model Lagrangian, *J. High Energy Phys.* **10** (2010) 085.
- [2] G. Isidori, F. Wilsch, and D. Wyler, The Standard Model effective field theory at work, *Rev. Mod. Phys.* **96**, 015006 (2024).

- [3] G. Buchalla, A. J. Buras, and M. E. Lautenbacher, Weak decays beyond leading logarithms, *Rev. Mod. Phys.* **68**, 1125 (1996).
- [4] E. E. Jenkins, A. V. Manohar, and P. Stoffer, Low-energy effective field theory below the electroweak Scale: Operators and matching, *J. High Energy Phys.* **03** (2018) 016.

- [5] R. Alonso, B. Grinstein, and J. Martin Camalich, $SU(2) \times U(1)$ gauge invariance and the shape of new physics in rare B decays, *Phys. Rev. Lett.* **113**, 241802 (2014).
- [6] O. Catà and M. Jung, Signatures of a nonstandard Higgs boson from flavor physics, *Phys. Rev. D* **92**, 055018 (2015).
- [7] A. Azatov, D. Bardhan, D. Ghosh, F. Sgarlata, and E. Venturini, Anatomy of $b \rightarrow c\tau\nu$ anomalies, *J. High Energy Phys.* **11** (2018) 187.
- [8] J. Fuentes-Martin, A. Greljo, J. Martin Camalich, and J. D. Ruiz-Alvarez, Charm physics confronts high- p_T lepton tails, *J. High Energy Phys.* **11** (2020) 080.
- [9] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Lepton universality and lepton flavor conservation tests with dineutrino modes, *Eur. Phys. J. C* **82**, 164 (2022).
- [10] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Rare charm $c \rightarrow u\bar{\nu}\bar{\nu}$ dineutrino null tests for e^+e^- machines, *Phys. Rev. D* **103**, 015033 (2021).
- [11] S. Bißmann, C. Grunwald, G. Hiller, and K. Kröninger, Top and beauty synergies in SMEFT-fits at present and future colliders, *J. High Energy Phys.* **06** (2021) 010.
- [12] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Interplay of dineutrino modes with semileptonic rare B-decays, *J. High Energy Phys.* **12** (2021) 061.
- [13] R. Bause, H. Gisbert-Mullor, M. Golz, and G. Hiller, Dineutrino modes probing lepton flavor violation, *Proc. Sci., EPS-HEP2021* (2022) 563.
- [14] S. Bruggisser, R. Schäfer, D. van Dyk, and S. Westhoff, The flavor of UV physics, *J. High Energy Phys.* **05** (2021) 257.
- [15] R. Bause, H. Gisbert, M. Golz, and G. Hiller, Model-independent analysis of $b \rightarrow d$ processes, *Eur. Phys. J. C* **83**, 419 (2023).
- [16] S. Sun, Q.-S. Yan, X. Zhao, and Z. Zhao, Constraining rare B decays by $\mu + \mu^- \rightarrow t\bar{c}$ at future lepton colliders, *Phys. Rev. D* **108**, 075016 (2023).
- [17] C. Grunwald, G. Hiller, K. Kröninger, and L. Nollen, More synergies from beauty, top, Z and Drell-Yan measurements in SMEFT, *J. High Energy Phys.* **11** (2023) 110.
- [18] A. Greljo, J. Salko, A. Smolkovič, and P. Stangl, SMEFT restrictions on exclusive $b \rightarrow u\ell\nu$ decays, *J. High Energy Phys.* **11** (2023) 023.
- [19] S. Fajfer, J. F. Kamenik, and I. Nisandzic, On the $B \rightarrow D^*\tau\bar{\nu}_\tau$ Sensitivity to new physics, *Phys. Rev. D* **85**, 094025 (2012).
- [20] R. Bause, H. Gisbert, and G. Hiller, Implications of an enhanced $B \rightarrow K\nu\nu$ branching ratio, *Phys. Rev. D* **109**, 015006 (2024).
- [21] S. Bhattacharya, S. Jahedi, S. Nandi, and A. Sarkar, Probing flavour constrained SMEFT operators through tc production at the Muon collider, *J. High Energy Phys.* **07** (2024) 061.
- [22] F.-Z. Chen, Q. Wen, and F. Xu, Correlating $B \rightarrow K^{(*)}\nu\bar{\nu}$ and flavor anomalies in SMEFT, *Eur. Phys. J. C* **84**, 1012 (2024).
- [23] E. Fernández-Martínez, X. Marcano, and D. Naredo-Tuero, Global lepton flavour violating constraints on new physics, *Eur. Phys. J. C* **84**, 666 (2024).
- [24] S. Karmakar, A. Dighe, and R. S. Gupta, SMEFT predictions for semileptonic processes, *arXiv:2404.10061*.
- [25] R. Alonso, M. B. Gavela, L. Merlo, S. Rigolin, and J. Yepes, The effective chiral Lagrangian for a light dynamical “Higgs Particle,” *Phys. Lett. B* **722**, 330 (2013).
- [26] G. Buchalla, O. Catà, and C. Krause, Complete electroweak chiral Lagrangian with a light Higgs at NLO, *Nucl. Phys. B* **880**, 552 (2014).
- [27] A. Pich, I. Rosell, J. Santos, and J. J. Sanz-Cillero, Fingerprints of heavy scales in electroweak effective Lagrangians, *J. High Energy Phys.* **04** (2017) 012.
- [28] T. Cohen, N. Craig, X. Lu, and D. Sutherland, Is SMEFT enough?, *J. High Energy Phys.* **03** (2021) 237.
- [29] C. P. Burgess, S. Hamoudou, J. Kumar, and D. London, Beyond the standard model effective field theory with $B \rightarrow c\tau^-\bar{\nu}$, *Phys. Rev. D* **105**, 073008 (2022).
- [30] J. Alison *et al.*, Higgs boson potential at colliders: Status and perspectives, *Rev. Phys.* **5**, 100045 (2020).
- [31] BABAR Collaboration, Evidence for an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays, *Phys. Rev. Lett.* **109**, 101802 (2012).
- [32] BABAR Collaboration, Measurement of an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons, *Phys. Rev. D* **88**, 072012 (2013).
- [33] Belle Collaboration, Measurement of the branching ratio of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle, *Phys. Rev. D* **92**, 072014 (2015).
- [34] LHCb Collaboration, Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$, *Phys. Rev. Lett.* **115**, 111803 (2015).
- [35] LHCb Collaboration, Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \rightarrow J/\psi\mu^+\nu_\mu)$, *Phys. Rev. Lett.* **120**, 121801 (2018).
- [36] LHCb Collaboration, Differential branching fractions and isospin asymmetries of $B \rightarrow K^{(*)}\mu^+\mu^-$ decays, *J. High Energy Phys.* **06** (2014) 133.
- [37] LHCb Collaboration, Measurement of lepton universality parameters in $B^+ \rightarrow K^+\ell^+\ell^-$ and $B^0 \rightarrow K^{*0}\ell^+\ell^-$ decays, *Phys. Rev. D* **108**, 032002 (2023).
- [38] Belle-II Collaboration, Evidence for $B^+ \rightarrow K^+\nu\bar{\nu}$ decays, *Phys. Rev. D* **109**, 112006 (2024).
- [39] LHCb Collaboration, Measurement of form-factor-independent observables in the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$, *Phys. Rev. Lett.* **111**, 191801 (2013).
- [40] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, Implications from clean observables for the binned analysis of $B^- \rightarrow K^-\mu^+\mu^-$ at large recoil, *J. High Energy Phys.* **01** (2013) 048.
- [41] S. Descotes-Genon, J. Matias, and J. Virto, Understanding the $B \rightarrow K^*\mu^+\mu^-$ anomaly, *Phys. Rev. D* **88**, 074002 (2013).
- [42] S. Karmakar, S. Chattopadhyay, and A. Dighe, Identifying physics beyond SMEFT in the angular distribution of $\Lambda b \rightarrow \Lambda c(\rightarrow \Lambda\pi)\tau\nu^-\tau$ decay, *Phys. Rev. D* **110**, 015010 (2024).
- [43] R. Alonso, B. Grinstein, and J. Martin Camalich, Lepton universality violation and lepton flavor conservation in B -meson decays, *J. High Energy Phys.* **10** (2015) 184.
- [44] A. Crivellin, D. Müller, and T. Ota, Simultaneous explanation of $R(D^{(*)})$ and $b \rightarrow s\mu^+\mu^-$: The last scalar leptoquarks standing, *J. High Energy Phys.* **09** (2017) 040.
- [45] L. Calibbi, A. Crivellin, and T. Li, Model of vector leptoquarks in view of the B -physics anomalies, *Phys. Rev. D* **98**, 115002 (2018).
- [46] B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer, and J. Matias, Searching for new physics with $b \rightarrow s\tau^+\tau^-$ processes, *Phys. Rev. Lett.* **120**, 181802 (2018).

- [47] L. Allwicher, D. Becirevic, G. Piazza, S. Rosauero-Alcaraz, and O. Sumensari, Understanding the first measurement of $B(B \rightarrow K\ell\nu^-)$, *Phys. Lett. B* **848**, 138411 (2024).
- [48] A. K. Alok, N. R. Singh Chundawat, and A. Mandal, Investigating the potential of $R_{K^{(*)}}^{\tau\mu}$ to probe lepton flavor universality violation, *Phys. Lett. B* **847**, 138289 (2023).
- [49] LHCb Collaboration, Search for the decays $B_s^0 \rightarrow \tau^+\tau^-$ and $B^0 \rightarrow \tau^+\tau^-$, *Phys. Rev. Lett.* **118**, 251802 (2017).
- [50] BABAR Collaboration, Search for $B^+ \rightarrow K^+\tau^+\tau^-$ at the BABAR experiment, *Phys. Rev. Lett.* **118**, 031802 (2017).
- [51] Belle Collaboration, Search for the decay $B_0 \rightarrow K^*0\tau^+\tau^-$ at the Belle experiment, *Phys. Rev. D* **108**, L011102 (2023).
- [52] D. M. Straub, flavio: A Python package for flavour and precision phenomenology in the Standard Model and beyond, [arXiv:1810.08132](https://arxiv.org/abs/1810.08132).
- [53] Belle-II Collaboration, The Belle II physics book, *Prog. Theor. Exp. Phys.* **2019**, 123C01 (2019).
- [54] LHCb Collaboration, Physics case for an LHCb Upgrade II —Opportunities in flavour physics, and beyond, in the HL-LHC era, [arXiv:1808.08865](https://arxiv.org/abs/1808.08865).
- [55] FCC Collaboration, FCC physics opportunities: Future circular collider conceptual design report volume 1, *Eur. Phys. J. C* **79**, 474 (2019).
- [56] A. Apollonio *et al.*, FCC-ee operation model, availability & performance, in Proceedings of the 62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (JACOW, Geneva, Switzerland, 2019), WEPAB03.
- [57] T. M. Aliev and M. Savci, Lepton polarization and CP violating effects in $B \rightarrow K^*\tau^+\tau^-$ decay in standard and two Higgs doublet models, *Phys. Lett. B* **481**, 275 (2000).
- [58] S. R. Choudhury, N. Gaur, A. S. Cornell, and G. C. Joshi, Lepton polarization correlations in $B \rightarrow K^*\tau^+\tau^-$, *Phys. Rev. D* **68**, 054016 (2003).
- [59] N. R. Singh Chundawat, New physics in $B \rightarrow K^*\tau^+\tau^-$: A model independent analysis, *Phys. Rev. D* **107**, 055004 (2023).
- [60] A. K. Alok, N. R. S. Chundawat, J. Kumar, A. Mandal, and U. Tamponi, Genuine lepton-flavor-universality-violating observables in the $\tau-\mu$ sector of $B \rightarrow (K, K^*)\ell\ell$ decays, *Phys. Rev. D* **110**, 055024 (2024).
- [61] D. Das, On the angular distribution of $\Lambda_b \rightarrow \Lambda(\rightarrow N\pi)\tau^+\tau^-$ decay, *J. High Energy Phys.* **07** (2018) 063.
- [62] J. Aebischer, A. Crivellin, M. Fael, and C. Greub, Matching of gauge invariant dimension-six operators for $b \rightarrow s$ and $b \rightarrow c$ transitions, *J. High Energy Phys.* **05** (2016) 037.
- [63] C. Bobeth and U. Haisch, New physics in $\Gamma_{12}^s: (\bar{s}b)(\bar{\tau}\tau)$ operators, *Acta Phys. Pol. B* **44**, 127 (2013).
- [64] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub, and M. Wick, Symmetries and asymmetries of $B \rightarrow K^*\mu^+\mu^-$ decays in the Standard Model and beyond, *J. High Energy Phys.* **01** (2009) 019.
- [65] N. Gubernari, M. Reboud, D. van Dyk, and J. Virto, Dispersive analysis of $B \rightarrow K^{(*)}$ and $B_s \rightarrow \phi$ form factors, *J. High Energy Phys.* **12** (2023) 153.
- [66] G. Isidori, Z. Polonsky, and A. Tinari, An explicit estimate of charm rescattering in $B^0 \rightarrow K^0\bar{\ell}\ell$, [arXiv:2405.17551](https://arxiv.org/abs/2405.17551).
- [67] S. Mutke, M. Hoferichter, and B. Kubis, Anomalous thresholds in $B \rightarrow (P, V)\gamma^*$ form factors, *J. High Energy Phys.* **07** (2024) 276.
- [68] A. Bharucha, D. M. Straub, and R. Zwicky, $B \rightarrow V\ell^+\ell^-$ in the Standard Model from light-cone sum rules, *J. High Energy Phys.* **08** (2016) 098.
- [69] F. Beaujean, C. Bobeth, and S. Jahn, Constraints on tensor and scalar couplings from $B \rightarrow K\bar{\mu}\mu$ and $B_s \rightarrow \bar{\mu}\mu$, *Eur. Phys. J. C* **75**, 456 (2015).