Beyond the standard model effective field theory with $b \to c\tau^- \bar{\nu}$

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Electroweak interactions assign a central role to the gauge group $SU(2)_L \times U(1)_Y$, which is either realized linearly (SMEFT) or nonlinearly (e.g., HEFT) in the effective theory obtained when new physics above the electroweak scale is integrated out. Although the discovery of the Higgs boson has made SMEFT the default assumption, nonlinear realization remains possible. The two can be distinguished through their predictions for the size of certain low-energy dimension-6 four-fermion operators: for these, HEFT predicts $O(1)$ couplings, while in SMEFT they are suppressed by a factor $v^2/\Lambda_{\rm NP}^2$, where v is the Higgs vev. One such operator, $O_V^{LR} \equiv (\bar{\tau}\gamma^\mu P_L \nu)(\bar{c}\gamma_\mu P_R b)$, contributes to $b \to c\tau^-\bar{\nu}$. We show that present constraints permit its non-SMEFT coefficient to have a HEFTy size. We also note that the angular distribution in $\bar{B} \to D^*(\to D\pi')\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$ contains enough information to extract the coefficients of all new-physics operators. Future measurements of this angular distribution can therefore tell us if non-SMEFT new physics is really necessary.

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I. INTRODUCTION

The Standard Model (SM) of particle physics provides a spectacular description of the physics so far found at the Large Hadron Collider (LHC). But it also cannot be complete because it leaves several things unexplained (like neutrino masses, dark matter and dark energy, etc.), and it makes some of cosmology's initial conditions (such as primordial fluctuations and baryon asymmetry) seem unlikely. To have hitherto escaped detection, any new particles must either couple extremely weakly or be very massive (or possibly both).

This—together with the eventual need for something to unitarize gravity at high energies—underpins the widespread belief that the SM is the leading part of an effective field theory (EFT) describing the low-energy limit of something more fundamental. EFTs are largely characterized by their particle content and symmetries (see, e.g., Refs. [1,2]). Since the discovery of the Higgs boson, the known particle content at energies above the top-quark mass, m_t, suffices to linearly realize the electroweak gauge group $SU(2)_L \times U(1)_Y$. Whether the known particles actually *do* linearly realize this symmetry is what distinguishes SMEFT, which linearly realizes it (see, e.g., Refs. [3,4]) from alternatives like HEFT, which do not, despite also including a "Higgs" scalar (see, e.g., Refs. [5–13]).

The question of whether the symmetry is realized linearly or nonlinearly can only be answered experimentally. One proposal for doing this [14] seeks new particles whose presence requires nonlinear realization. In the present paper, we show how to use indirect b-physics signals to extract evidence for nonlinearly realized new physics.

How symmetries are realized in an EFT comes up when power-counting how effective interactions are suppressed at low energies. For instance, an effective interaction like $g_z Z_\mu(\bar{u}\gamma^\mu P_R u) \in \mathcal{L}_{\rm eff}$, which describes a nonstandard $Z\bar{u}_R u_R$ coupling, naively arises at mass-dimension 4 when $SU(2)_L \times U(1)_Y$ is nonlinearly realized [15,16], but instead arises at dimension-6 through an operator $\Lambda_h^{-2}(H^\dagger D_\mu H)(\bar{u}\gamma^\mu P_R u)$ when it is linearly realized, implying a coupling $g_z \sim v^2/\Lambda_h^2$ that is suppressed by the ratio of Higgs vev v to a UV scale Λ_h.

The assumption underlying SMEFT is that the scale Λ_h appearing here is the same order of magnitude as the scale

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Λ that suppresses all other dimension-6 operators If $\Lambda_h \sim \Lambda$ then the lower bound on Λ required to have generic dimension-6 SMEFT operators not be detected also implies an upper bound on the effective dimension-4 non-SMEFT coupling g_z. While this assumption is not unreasonable, it *is* an assumption, since nothing in the power-counting of EFTs requires the scale Λ_h that accompanies powers of a field like H to be the same as the scale Λ that appears with derivatives [1,2]. (For example, these scales are very different in supergravity theories, and this is why it is consistent to have complicated target-space metrics appearing in the kinetic energies of fields while working only to two-derivative order. Similar observations have also been made for SMEFT [17].)

Because it is an assumption, it should be tested. It is ultimately an experimental question which kind of symmetry realization provides a better description of Nature. Our purpose in this paper is to identify how to do so using a class of B-physics measurements. Despite being at relatively low energies, B-meson properties suggest themselves for this purpose because they can be precisely studied and because there are at present several observables that seem to disagree with the predictions of the SM.

II. SMEFT VS LEFT AT LOW ENERGIES

A complicating issue arises when using B physics to distinguish SMEFT from non-SMEFT effective interactions because the EFT relevant at such low-energies necessarily already integrates out many of the heavier SM particles ($W^{\pm}$, Z^0, H, t). But once these particles are removed the remaining EFT necessarily nonlinearly realizes $SU(2)_L\times U(1)_Y$, while linearly realizing its $U(1)_{em}$ subgroup. This is why heavy top-quark loops can generate otherwise SM-forbidden effective interactions such as $\delta\mathcal{L}_{\rm eff} \ni \delta M_W^2 W_\mu^* W^\mu + \delta M_Z^2 Z_\mu Z^\mu$ that violate the SM condition $M_W = M_Z \cos\theta_W$, or more broadly contribute to oblique corrections or modification of gauge couplings [15].

The exercise of separating these more mundane sources of symmetry breaking from those coming from higher energies has been studied in the literature. For instance, the theory obtained below the W mass has been called LEFT (low-energy effective field theory) or WET (weak effective field theory), and in Ref. [18], Jenkins, Manohar and Stoffer (JMS) present a complete and nonredundant basis of operators in this theory up to dimension 6. For the particularly interesting class of dimension-6 four-fermion operators that conserve baryon and lepton number, they also identify how these effective interactions can be obtained (at tree level) from the similarly complete and nonredundant list of operators given for SMEFT in Ref. [19]. (For a fuller discussion of the relationships among these various EFTs see Ref. [20] and references therein.)

JMS find that most dimension-6 LEFT operators can be generated in this way starting from dimension-6 operators in SMEFT. However, a handful of dimension-6 LEFT operators are not invariant under $SU(2)_L \times U(1)_Y$, and so are not contained among dimension-6 SMEFT operators. Tree graphs can also generate these "non-SMEFT" operators, but in this case only do so starting from SMEFT operators with mass dimension greater than 6. It is these non-SMEFT operators that interest us in our applications to B physics.

The existence of non-SMEFT operators affects the search for new physics at low energies, such as when analyzing discrepancies from the SM using four-fermion effective operators in LEFT. One current example is in observables involving the decay $b \to c\tau^-\bar{\nu}$. Assuming only left-handed neutrinos, five four-fermion $b \to c\tau^-\bar{\nu}$ operators are possible:

$$\begin{aligned} O_V^{LL,LR} &\equiv (\bar{\tau}\gamma^\mu P_L \nu), (\bar{c}\gamma_\mu P_{L,R} b), \\ O_S^{LL,LR} &\equiv (\bar{\tau} P_L \nu)(\bar{c} P_{L,R} b), \\ O_T &\equiv (\bar{\tau}\sigma^{\mu\nu} P_L \nu)(\bar{c}\sigma_{\mu\nu} P_L b), \end{aligned} \tag{1}$$

where $P_{L,R}$ are the left-handed and right-handed projection operators. As we will see below, O_V^{LR} is a non-SMEFT operator: it is generated at tree level starting from a dimension-8 SMEFT operator. Because of this, the coefficient of O_V^{LR} would naively be suppressed by the small factor v^2/Λ^4 if SMEFT were true at UV scales. It is usually excluded when seeking new physics in $b \to c\tau^-\bar{\nu}$ (see, e.g., Refs. [21,22]).

To test how the gauge symmetries are realized, one must measure the coefficients of such non-SMEFT operators, and see if their size is consistent with SMEFT power counting. If the SMEFT-predicted suppression in the coefficients is not present it would point to a more complicated realization of $SU_(2)_L \times U(1)_Y$ in the UV than is usually assumed.

The first step in performing such an analysis is to identify all the non-SMEFT dimension-6 operators in LEFT. We list these in Table I, along with the higher-dimension SMEFT operators from which they can be obtained at tree level. Operators appearing in the "LEFT operator" column are denoted by $\mathcal{O}$ and are as defined in Ref. [18]. Operators appearing in the "Tree-level SMEFT origin" column are denoted by Q. The one with dimension 6 (the operator Q_{Hud}) is as defined in Ref. [19]. The dimension-8 SMEFT operators have been tabulated in Refs. [23,24]; our nomenclature for these operators is taken from Ref. [24]. JMS also identified these non-SMEFT operators, simply saying they had no direct dimension-6 SMEFT counterpart, and our list agrees with their findings.

Of course, there is nothing sacred about tree level, and in principle loops can also generate effective operators as one evolves down to lower energies (as the example of non-SM gauge-boson masses generated by top-quark loops mentioned above shows). Whether such loops are important in

TABLE I. Non-SMEFT four-fermion operators in LEFT and the dimension-8 SMEFT operators to which they are mapped at tree level. In the LEFT operator column, the subscripts p, r, s, t are weak-eigenstate indices; they are suppressed in the operator labels. The superscripts "1" and "8" of four-quark operators denote the color transformation of the quark pairs. In the Tree-level SMEFT origin column, ℓ and q denote left-handed $SU(2)_L$ doublets, while e, u and d denote right-handed $SU(2)_L$ singlets. Here, $\tilde{H} = i\sigma_2 H^*$ denotes the conjugate of the Higgs doublet H.

LEFT operator	Tree-level SMEFT origin	Dimensions
	Semileptonic operators	
$\mathcal{O}^{V,LR}_{\nu edu}: (\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{H.c.}$	$Q_{Hud}: i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r) + \text{H.c.}$	$6 \to 6$
	$Q_{\ell^2 udH^2}: (\bar{\ell}_p d_r H)(\tilde{H}^\dagger \bar{u}_s \ell_t) + \text{H.c.}$	$6 \to 8$
$\mathcal{O}^{S,RR}_{ed}: (\bar{e}_{Lp}e_{Rr})(\bar{d}_{Ls}d_{Rt})$	$Q^{(3)}_{\ell eqdH^2}: (\bar{\ell}_p e_r H)(\bar{q}_s d_t H)$	$6 \to 8$
$\mathcal{O}^{S,RL}_{eu}: (\bar{e}_{Rp}e_{Lr})(\bar{u}_{Ls}u_{Rt})$	$Q^{(5)}_{\ell equH^2}: (\bar{\ell}_p e_r H)(\tilde{H}^\dagger \bar{q}_s u_t)$	$6 \to 8$
$\mathcal{O}^{T,RR}_{ed}: (\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} d_{Rt})$	$Q^{(4)}_{\ell eqdH^2}: (\bar{\ell}_p \sigma_{\mu\nu} e_r H)(\bar{q}_s \sigma^{\mu\nu} d_t H)$	$6 \to 8$
	Four-lepton operators	
$\mathcal{O}^{S,RR}_{ee}: (\bar{e}_{Lp}e_{Rr})(\bar{e}_{Ls}e_{Rt})$	$Q^{(3)}_{\ell^2 e^2 H^2}: (\bar{\ell}_p e_r H)(\bar{\ell}_s e_t H)$	$6 \to 8$
	Four-quark operators	
$\mathcal{O}^{V1,LR}_{uddu}: (\bar{u}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{H.c.}$	$Q_{Hud}: i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r) + \text{H.c.}$	$6 \to 6$
	$Q^{(5)}_{q^2 udH^2}: (\bar{q}_p d_r H)(\tilde{H}^\dagger \bar{u}_s q_t) + \text{H.c.}$	$6 \to 8$
$\mathcal{O}^{V8,LR}_{uddu}: (\bar{u}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$Q^{(6)}_{q^2 udH^2}: (\bar{q}_p T^A d_r H)(\tilde{H}^\dagger \bar{u}_s T^A q_t) + \text{H.c.}$	
$\mathcal{O}^{S1,RR}_{uu}: (\bar{u}_{Lp}u_{Rr})(\bar{u}_{Ls}u_{Rt})$	$Q^{(5)}_{q^2 u^2 H^2}: (\bar{q}_p u_r \tilde{H})(\bar{q}_s u_t \tilde{H})$	$6 \to 8$
$\mathcal{O}^{S8,RR}_{uu}: (\bar{u}_{Lp}T^A u_{Rr})(\bar{u}_{Ls}T^A u_{Rt})$	$Q^{(6)}_{q^2 u^2 H^2}: (\bar{q}_p T^A u_r \tilde{H})(\bar{q}_s T^A u_t \tilde{H})$	
$\mathcal{O}^{S1,RR}_{dd}: (\bar{d}_{Lp}d_{Rr})(\bar{d}_{Ls}d_{Rt})$	$Q^{(5)}_{q^2 d^2 H^2}: (\bar{q}_p d_r H)(\bar{q}_s d_t H)$	$6 \to 8$
$\mathcal{O}^{S8,RR}_{dd}: (\bar{d}_{Lp}T^A d_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$	$Q^{(6)}_{q^2 d^2 H^2}: (\bar{q}_p T^A d_r H)(\bar{q}_s T^A d_t H)$	

any particular instance depends on the size of any loop-suppressing couplings and the masses that come with them. As the top-quark example also shows, generating non-SMEFT operators from loops involving SMEFT operators necessarily involves a dependence on $SU(2)_L \times U(1)_Y$-breaking masses, implying a suppression (and a lowering of operator dimension) when these masses are small. The authors of Ref. [25] have computed how SM loops dress individual SMEFT operators, and show that such loops do not generate non-SMEFT operators in LEFT at the one-loop level.

Reference [26] computes the running of the LEFT operators that are unsuppressed by such factors, arising due to dressing by photon and gluon loops, and shows that non-SMEFT dimension-6 operators of this type also can arise from the mixing of dimension-5 dipole operators of the form $(\bar{\psi}\sigma^{\mu\nu}\psi)X_{\mu\nu}$ in LEFT, where $X_{\mu\nu} = G_{\mu\nu}, F_{\mu\nu}$ are gauge field strengths. The two required insertions of these dipole operators ensure that they do not change the tree-level counting of powers of $1/\Lambda$, in their coefficients.

III. APPLICATIONS TO *B* PHYSICS

Although the Table shows quite a few non-SMEFT operators that can, in principle, be used to search for non-SMEFT new physics, one of these is particularly interesting: the operator O^{LR}_V of Eq. (1),

$$\mathcal{O}^{V,LR}_{\nu\tau bc} \equiv (\bar{\tau}_L\gamma^\mu \nu_L)(\bar{c}_R\gamma_\mu b_R) + \text{H.c.}, \tag{2}$$

that contributes to the decay $b \to c\tau^-\bar{\nu}$ [27].

Notice that Table I offers two possible SMEFT operators from which this operator can be obtained at tree level, one of which is the dimension-6 SMEFT operator Q_{Hud}. Naively this seems to imply that $\mathcal{O}^{V,LR}_{\nu\tau bc}$ is actually a SMEFT operator after all. But there is a subtlety here: Q_{Hud} is a lepton-flavor-universal operator that generates equal effective couplings for the operators $\mathcal{O}^{V,LR}_{\nu ebc}$, $\mathcal{O}^{V,LR}_{\nu\mu bc}$ and $\mathcal{O}^{V,LR}_{\nu\tau bc}$ [28]. An effective operator that generates *only* $\mathcal{O}^{V,LR}_{\nu\tau bc}$ without the other two violates lepton-flavor universality, and this can only come from the dimension-8 operator given in the Table. (A similar reasoning applies also to $\mathcal{O}^{V1,LR}_{uddu}$ and $\mathcal{O}^{V8,LR}_{uddu}$, where superscripts 1 and 8 give the color transformation of the quark pairs.) Furthermore, at the 1-loop level, $\mathcal{O}^{V,LR}_{\nu\tau bc}$ does not mix with any other LEFT operators [26].

The five four-fermion operators given in Eq. (1) imply that the most general LEFT effective Hamiltonian describing $b \to c\tau^-\bar{\nu}$ decay with left-handed neutrinos is

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} O_V^{LL} - \frac{C_V^{LL}}{\Lambda^2} O_V^{LL} - \frac{C_V^{LR}}{\Lambda^2} O_V^{LR}, \\ - \frac{C_S^{LL}}{\Lambda^2} O_S^{LL} - \frac{C_S^{LR}}{\Lambda^2} O_S^{LR} - \frac{C_T}{\Lambda^2} O_T. \quad (3)$$

The first term is the SM contribution; the remaining five terms are the various new-physics contributions. Within LEFT, these are all dimension-6 operators and so, in the absence of other information, for a given new-physics scale Λ, their dimensionless coefficients (the Cs) are all at most $O(1)$. By contrast, the coefficient C_V^{LR} is instead proportional to v^2/Λ_h^2 if the new physics is described at higher energies by SMEFT (since $\mathcal{O}_V^{LR}$ then really descends from a Higgs-dependent interaction with dimension 8), and so is predicted to be small if $\Lambda_h \sim \Lambda$.

The beauty of $b \to c\tau^-\bar{\nu}$ decays is that, in principle, they provide sufficiently many observables to measure each of the couplings in Eq. (3) separately, thereby allowing a test of the prediction that C_V^{LR} should be negligible (assuming that the presence of new physics is confirmed). If the effective couplings do not follow the SMEFT pattern, non-SMEFT new physics must be involved.

What is currently known about C_V^{LR}? At present several observables have been measured that involve the decay $b \to c\tau^-\bar{\nu}$. These include

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \quad \mathcal{R}(J/\psi) \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}, \\ F_L(D^*) \equiv \frac{\Gamma(B \to D_L^*\tau\nu)}{\Gamma(B \to D^*\tau\nu)}, \quad P_\tau(D^*) \equiv \frac{\Gamma^{+1/2} - \Gamma^{-1/2}}{\Gamma^{+1/2} + \Gamma^{-1/2}}, \quad (4)$$

where $\Gamma^\lambda \equiv \Gamma(B \to D^*\tau^\lambda\nu)$. $P_\tau(D^*)$ measures the τ polarization asymmetry while $F_L(D^*)$ measures the longitudinal D^* polarization. These observables are useful for distinguishing new-physics models with different Lorentz structures and (interestingly) the measurements of most of these observables seem to be in tension with the predictions of the SM. References [21,22]) perform fits to the data using the interactions of Eq. (3) (though with a different operator normalization than is used here), but with O_V^{LR} assumed not to be present (precisely because it is a non-SMEFT operator).

We make two observations about how to use these measurements to probe the size of $\mathcal{O}_V^{LR}$, one using existing data and one using new observables—proposed elsewhere [29]—to exploit future data to access more information about the effective coefficients appearing in Eq. (3).

IV. FITS TO CURRENT DATA

We have repeated the fit of Refs. [21,22]), though this time including $\mathcal{O}_V^{LR}$ for comparison. The values of the experimental observables used in the fit are those found in Ref. [22]. One observable that is not used is $\mathcal{B}(B_c \to \tau\nu)$. This decay has not yet been measured, but it has been argued that its branching ratio has an upper limit in order to be compatible with the B_c lifetime. Unfortunately this upper bound varies enormously in different analyses, from 10% [30] to 60% [21]. Because of this uncertainty, we do not use this upper bound as a constraint, but simply compute the prediction for $\mathcal{B}(B_c \to \tau\nu)$ in each new physics scenario. For the theoretical predictions of the observables in the presence of new physics, we use the program FLAVIO [31] and the fit itself is done using MINUIT [32–34].

TABLE II. Fit results for the scenarios in which C_V^{LL}, C_V^{LR} or both C_V^{LL} and C_V^{LR} are allowed to be nonzero. At the best-fit point the prediction for $\mathcal{B}(B_c \to \tau\nu)$ is ~2.8% for all scenarios.

New-physics coefficient	Best fit	p value (%)	pull$_{\rm SM}$
C_V^{LL}	-3.1 ± 0.7	51	4.1
C_V^{LR}	2.8 ± 1.2	0.3	2.3
(C_V^{LL}, C_V^{LR})	$(-3.0 \pm 0.8, 0.6 \pm 1.2)$	35	3.7

Because the data is not yet rich enough to permit an informative simultaneous fit to all five effective couplings[1] we instead perform fits in which only one or two of the effective couplings are nonzero. We choose $\Lambda = 5$ TeV and consider the following three scenarios for nonzero new-physics coefficients: either C_V^{LL} or C_V^{LR} are turned on by themselves, or both C_V^{LL} and C_V^{LR} are turned on together. The results of fits using these three options are presented in Table II, and Fig. 1 presents the (correlated) allowed values of C_V^{LL} and C_V^{LR} for the joint fit. We see that the scenario that adds only C_V^{LL} provides an excellent fit to the data. On the other hand, the fit is poor when C_V^{LR} alone is added (though it is still much better than for the SM itself). The fit remains acceptable when both C_V^{LL} and C_V^{LR} are allowed to be nonzero. In all scenarios, $\mathcal{B}(B_c \to \tau\nu)$ is predicted to be <3%, which easily satisfies all constraints.

It is clear that the current data is insufficient to constrain the value for C_V^{LR} in a useful way. Both the SMEFT prediction $C_V^{LR} \sim v^2/\Lambda^2 = O(10^{-3})$ and $C_V^{LR} \sim \mathcal{O}(1)$ are consistent with the joint fit with both C_V^{LL} and C_V^{LR} nonzero; the best-fit value $C_V^{LR} = 0.6 \pm 1.2$ is consistent with both zero and large $O(1)$ values.[2] At present, the data are consistent with the non-SMEFT coefficient C_V^{LR} being much larger than the SMEFT prediction.

[1]Fits involving the other new-physics coefficients were performed in Ref. [22]. We have redone these fits in order to verify that we reproduce the results of this paper.

[2]We note that the central values satisfy $C_V^{LR}/C_V^{LL} \simeq -0.2$. In Ref. [35], it was assumed that the $b \to c\tau^-\bar{\nu}$ anomaly could be explained by the addition of a W' with general couplings. When they performed a fit with LL and LR couplings, they also found a ratio of $LR/LL \simeq -0.2$.

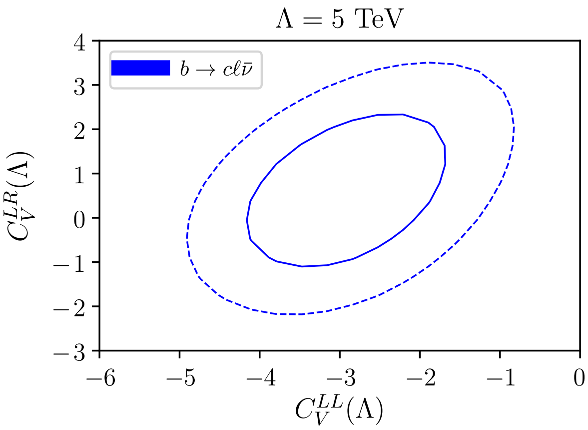

FIG. 1. (Correlated) allowed values of C_V^{LL} and C_V^{LR} at 1σ (inner region) and 2σ (outer region).

It is worth noting that the same is *not* true for other non-SMEFT operators. From the operators listed in Table I, consider for example the specific operators $(\bar{\mu}_L\mu_R)(\bar{s}_L b_R)$ and $(\bar{\mu}_R\mu_L)(\bar{s}_R b_L)$ in the class $\mathcal{O}_{ed}^{S,RR}$, or the $\mathcal{O}_{ed}^{T,RR}$ operators of the type $(\bar{\mu}_L\sigma_{\mu\nu}\mu_R)(\bar{s}_L\sigma^{\mu\nu}b_R)$ and $(\bar{\mu}_R\sigma_{\mu\nu}\mu_L)\times(\bar{s}_R\sigma^{\mu\nu}b_L)$. These all contribute in a chirally unsuppressed way to the decay $b\to s\mu^+\mu^-$ (unlike the case in the SM), and so the addition of any of these operators can dramatically change the prediction for $\mathcal{B}(B_s^0\to\mu^+\mu^-)$. But the measured value $\mathcal{B}(B_s^0\to\mu^+\mu^-) = (2.9\pm 0.4)\times 10^{-9}$ [36] is close to the SM prediction, so that the coefficients of these operators cannot be larger than order $O(10^{-4})$, consistent with SMEFT expectations. Things are similar for the analogous operators contributing to $b\to se^+e^-$, for which the upper limit of $\mathcal{B}(B_s^0\to e^+e^-) < 9.4\times 10^{-9}$ [36] constrains the coefficients of these operators to be $< O(10^{-3})$, again consistent with SMEFT.

V. FUTURE PROSPECTS

The above discussion shows that the non-SMEFT operator O_V^{LR} can have a large effective coupling, $C_V^{LR}\sim O(1)$ without causing observational difficulties with $b\to c\tau^-\bar{\nu}$ decays, though there are large errors. But even if the experimental errors on the currently measured observables were to improve dramatically, the five observables of Eq. (4) are never enough to measure all of these parameters in the most general case. This is simply because these five measurements cannot pin down all ten of the parameters that can appear in the five complex couplings given in Eq. (3).

Fortunately, there are potentially many more observables whose measurement can remedy this situation. Reference [29] has proposed to measure the angular distribution in $\bar{B}\to D^*(\to D\pi')\tau^-(\to\pi^-\nu_\tau)\bar{\nu}_\tau$. This decay includes three final-state particles whose four-momenta can be measured: D, π' and π^-. Using this information, the differential decay rate can be constructed. This depends on two nonangular variables, q^2 and E_π, as well as a number of angular variables. Here, q^2 is the invariant mass-squared of the $\tau^-\bar{\nu}_\tau$ pair and E_π is the energy of the π^- in the τ decay. The idea is then to separate the data into $q^2 - E_\pi$ bins, and then to perform an angular analysis in each of these bins. Each angular distribution consists of twelve different angular functions; nine of these terms are CP-conserving, and three are CP-violating. There are therefore a large number of observables in this differential decay rate; the exact number depends on how many $q^2 - E_\pi$ bins there are.

Eq. (1) lists five new-physics operators, but only four of these actually contribute to $\bar{B}\to D^*\tau^-\bar{\nu}_\tau$. To see why, consider the following linear combinations of the two scalar operators:

$$O_{LS} \equiv O_S^{LR} + O_S^{LL} = (\bar{\tau}P_L\nu)(\bar{c}b),$$
$$O_{LP} \equiv O_S^{LR} - O_S^{LL} = (\bar{\tau}P_L\nu)(\bar{c}\gamma_5 b). \qquad (5)$$

Of these, only O_{LP} contributes to $\bar{B}\to D^*\tau^-\bar{\nu}_\tau$.

With complex coefficients, there are therefore eight unknown theoretical parameters in the remaining four effective interactions. Observables are functions of these parameters, as well as q^2 and E_π. Thus, if the angular distribution in $\bar{B}\to D^*(\to D\pi')\tau^-(\to\pi^-\nu_\tau)\bar{\nu}_\tau$ can be measured, it may be possible to extract all of the new physics coefficients from a fit to observations. If the real or imaginary part of C_V^{LR} were found to be much larger than the SMEFT expectation, it would suggest the presence of non-SMEFT physics at higher energies.

Note that the decay $b\to c\mu^-\bar{\nu}$ can also be analyzed in a similar way (even though there is no hint of new physics in this reaction (but see Ref. [37] for an alternative point of view)). The angular distribution for $b\to c\mu^-\bar{\nu}$ described in Ref. [38] provides enough observables to perform a fit for the coefficients of all dimension-6 new-physics operators, including the non-SMEFT one.

In summary, we reproduce here the list of non-SMEFT four-fermion operators and identify their provenance, assuming that they arise at tree level starting from even-higher-dimension SMEFT operators, in order to pin down the SMEFT estimate for the size of their effective couplings. We show that fits to current observations allow one of these couplings—that of the semileptonic $b\to c\tau^-\bar{\nu}$ operator $\mathcal{O}_V^{LR}$—to be $\mathcal{O}(1)/\Lambda^2$ for $\Lambda\sim 5$ TeV, which is consistent with couplings that are several orders of magnitude larger than would be predicted by SMEFT. We also identify a sufficiently large class of $b\to c\tau^-\bar{\nu}$ observables whose measurement would in principle allow all of the relevant effective couplings to be determined, including that of $\mathcal{O}_V^{LR}$. There is a good prospect that these measurements can be done in the future.

Finally, suppose it were eventually established that non-SMEFT new physics is present in $b\to c\tau^-\bar{\nu}$. The obvious question then is: What could this non-SMEFT new physics be? Although serious exploration of models probably awaits evidence for such a signal, some preliminary attempts have been made in the literature. One example is Ref. [39], which studies the non-SMEFT operators in $b \to s\mu^+\mu^-$ and $b \to c\tau^-\bar{\nu}$ in the context of HEFT, and argues that such operators can be generated by a nonstandard Higgs sector containing additional strongly interacting scalars. We regard a more systematic exploration of non-SMEFT physics in the UV to be well worthwhile, and look forward to that happy day when experimental results are what drives it.

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