

Discriminating tauphilic leptoquark explanations of the B anomalies via $K \rightarrow \pi\nu\bar{\nu}$ and $B \rightarrow K\nu\bar{\nu}$

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Leptoquark models are prime candidates for new physics (NP) explanations of the longstanding anomalies in semileptonic B decays; $b \rightarrow c\tau\bar{\nu}$ [encoded in $R(D^{(*)})$] and $b \rightarrow s\ell\bar{\ell}$ ($\ell = e, \mu$) transitions. Furthermore, Belle II and NA62 reported weaker-than-expected limits on $B^+ \rightarrow K^+\nu\bar{\nu}$ and $K^+ \rightarrow \pi^+\nu\bar{\nu}$, respectively. While the $R(D^{(*)})$ and $b \rightarrow s\ell\bar{\ell}$ measurements can be explained with NP contributions at the $\mathcal{O}(10\%)$ level, the neutrino channels suggest that the NP effect could be comparable in size to the Standard Model one. In this context, we consider the two types of leptoquark models with minimal sets of the couplings that can best describe the semileptonic B anomalies and lead at the same time to effects in the neutrino modes, the singlet-triplet scalar leptoquark model ($S_1 + S_3$) and the singlet vector leptoquark model (U_1). More specifically, the neutrino channels pose nontrivial constraints on the parameter space, and we find that large effects (i.e., accounting for the current central value) in $B \rightarrow K^{(*)}\nu\bar{\nu}$ are only possible in the $S_1 + S_3$ setup, while both models can account for the central value of $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

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I. INTRODUCTION

Precision measurements have the potential to reveal the effects of physics beyond the Standard Model (SM). In particular, the study of kaon decays has been leading this frontier and can, in some instances, push the new physics (NP) mass scale to above 10^4 TeV [1,2]. Among these measurements, $s \rightarrow d\nu\bar{\nu}$ transitions are promising to reveal NP effects since they are dominated by calculable short-distance contributions, which are Glashow-Iliopoulos-Maiani (GIM) suppressed [3] and involve small Cabibbo-Kobayashi-Maskawa (CKM) elements [4], thus leading to quite small branching ratios of $\mathcal{O}(10^{-11})$ with controlled theoretical uncertainties [5]. Furthermore, the corresponding measurements have achieved sensitivities

of $\mathcal{O}(10^{-10})$, thus exceeding the precision of B physics by orders of magnitude.

The latest NA62 result for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ [6,7]

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}, \quad (1)$$

results in a more than 5σ rejection of the background-only hypothesis. This first observation of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ should be compared with the SM prediction [8–12]¹

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})_{\text{SM}} = (8.09 \pm 0.63) \times 10^{-11}. \quad (2)$$

From this, we obtain the observed signal strength with respect to the SM of²

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¹The numerical values of the CKM elements used for this prediction are given in Sec. III.

²For the neutral kaon mode, the upper limit $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-9}$, obtained by the KOTO experiment [13], should be compared with the SM prediction $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu})_{\text{SM}} = (2.58 \pm 0.30) \times 10^{-11}$ [12]. While this currently does not lead to competitive bounds, an improvement by three orders of magnitude is foreseen by the proposed KOTO II experiment [14].

$$\mu(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \equiv \frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}}} = 1.61^{+0.43}_{-0.39}. \quad (3)$$

Similar to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, an $\mathcal{O}(1)$ NP effect is preferred by $B \rightarrow K^{(*)} \nu \bar{\nu}$ data. More specifically, the Belle II collaboration announced an excess in their $B^+ \rightarrow K^+ \nu \bar{\nu}$ search [15], which, combined with the Belle [16,17] and BABAR measurements [18,19], results in a world average [15] of

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = (1.3 \pm 0.4) \times 10^{-5}. \quad (4)$$

This is three times larger than the SM value [20]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = (0.472 \pm 0.027) \times 10^{-5}. \quad (5)$$

They lead to a signal strength³

$$\mu(B^+ \rightarrow K^+ \nu \bar{\nu}) = 2.75 \pm 0.86, \quad (6)$$

which is consistent with the SM ($\mu = 1$) at $\approx 2\sigma$. Note that for $B \rightarrow K^* \nu \bar{\nu}$, only an upper limit $\mathcal{B}(B \rightarrow K^* \nu \bar{\nu}) < 2.7 \times 10^{-5}$ has been set by Belle [17] while the corresponding Belle II result is still pending.⁴

This situation in decays with neutrino final states is particularly interesting in light of the (possibly) related long-standing anomalies in the semileptonic B -meson decays [21].⁵ Already in 2012, the measurements of the lepton-flavor universality (LFU) in

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)} \ell \bar{\nu})} \quad (\ell = e, \mu), \quad (7)$$

deviated from the SM prediction. The current HFLAV world averages [28]

$$\begin{aligned} R(D) &= 0.342 \pm 0.026, \\ R(D^*) &= 0.287 \pm 0.012. \end{aligned} \quad (8)$$

are still $\approx 15\%$ larger than the SM expectations [29–32], which leads to $\approx 4\sigma$ deviation [33]. Furthermore, very recently, these tendencies were confirmed by the latest Belle II measurement [34,35]. Combining this measurement

³The upper limit $\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu}) < 2.6 \times 10^{-5}$, which has been set by the Belle [17], is much weaker than Eq. (6).

⁴Relative to the SM prediction an upper limit $\mu(B \rightarrow K^* \nu \bar{\nu}) \lesssim 2.7$ is obtained. This limit is not in conflict with Eq. (6). Note that NP models studied in this paper have a purely left-handed current, so the relative effect in all $b \rightarrow s \nu \bar{\nu}$ transitions is the same. However, since the relative efficiency in $B \rightarrow K^* \nu \bar{\nu}$ vs $B \rightarrow K \nu \bar{\nu}$ is not given in the experimental articles, we do not combine both modes our phenomenological analysis but rather just show the preferred regions from the latter and the exclusion limit from the former.

⁵See, e.g., Refs. [22–27] for articles studying the correlations between the neutrino modes and the B anomalies.

with the HFLAV value we obtain $\{3.8\sigma, 4.7\sigma, 4.9\sigma\}$ deviations, corresponding to p -value = $\{1.5 \times 10^{-4}, 2.4 \times 10^{-6}, 1.2 \times 10^{-6}\}$ ($\Delta\chi^2 = \{17.7, 25.9, 27.3\}$ with two degrees of freedom) from the SM predictions of {HFLAV2024 [28], Bernlochner *et al.* [32], Iguro-Watanabe [31]}, respectively.

Furthermore, in neutral-current semileptonic B decays, the LHCb collaboration observed already in 2013 [36,37] a tension in the angular observable P'_5 [38], which still persists and was even recently confirmed by the CMS collaboration [39]. This is accompanied by deficits in the total branching ratios of $\mathcal{B}(B \rightarrow K \mu \bar{\mu})$ [40–42] and $\mathcal{B}(B_s \rightarrow \phi \mu \bar{\mu})$ (together with angular observables in the latter) [43–45] and semi-inclusive observables [46]. In conjunction with updated tests of lepton flavor universality, the $R(K^{(*)})$ ratios [47] and the Q observables [48], which all agree with the SM predictions, this indicates a lepton-flavor-universal (U) effect in $b \rightarrow s \ell \bar{\ell}$.

In fact, the global fits to the Wilson coefficient C_9^U of the effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{ts}^* V_{tb} C_9^\ell (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell) + \text{H.c.}, \quad (9)$$

show statistically very significant indications for a nonzero new physics value [49–51].⁶

When attempting to construct a combined explanation of the charged and neutral current B anomalies [53,54], it is essential to keep in mind that to explain $R(D^{(*)})$, a tree-level effect is necessary which must be related to the tau lepton (and neutrino) [55–57]. Interestingly, this setup naturally leads to an LFU effect in C_9^U via off-shell photon-penguin involving the tau-lepton loop [58,59]. This mechanism providing a combined explanation can be achieved in the $SU(2)_L$ singlet-triplet scalar leptoquark model (S_1 and S_3) [60–62] and the $SU(2)_L$ singlet vector leptoquark model (U_1) [63–66].⁷

As the mechanism works the same way for both models, the question of how to disentangle them arises. In this paper, we will focus on $s \rightarrow d \nu \bar{\nu}$ and $b \rightarrow s \nu \bar{\nu}$ transitions, which, as we will see, have significantly different predictions in the two models. In particular, the $S_1 + S_3$ model requires a tuning between the S_1 and S_3 contributions $b \rightarrow s \nu \bar{\nu}$ for explaining $R(D^{(*)})$ while being compatible with the $B \rightarrow K^{(*)} \nu \bar{\nu}$ bounds.⁸ In general, the cancellation between the S_1 and S_3 neutrino contributions is expected to be imperfect and can result in a significant effect in $K \rightarrow \pi \nu \bar{\nu}$.

⁶Note that a sizable NP effect in C_{10}^μ is disfavored by the $B_s \rightarrow \mu \bar{\mu}$ measurement [52].

⁷Note that a photon penguin induced loop effect can also generate C_9^U in the generic 2HDM [67–69] or diquark models [70].

⁸In particular, these constraints rule out a full explanation of $R(D^{(*)})$ with the S_1 model as proposed in Ref. [71].

This is in stark contrast to the U_1 LQ model, where such an effect is only generated at the loop level (but unavoidable) [59].

Therefore, in this paper, we update these two promising leptoquark explanations of the semileptonic B anomalies, and investigate the correlations with $K \rightarrow \pi \nu \bar{\nu}$ and $B \rightarrow K \nu \bar{\nu}$. For this, the paper is organized as follows. The leptoquark models are briefly summarized in Sec. II. In Sec. III, we discuss the relevant observables and perform phenomenological analyses. Section IV is devoted to conclusions and discussions.

II. LEPTOQUARK MODELS

As the Introduction outlines, we will study the two leptoquark models $S_1 + S_3$ and U_1 , which provide combined explanations of the $R(D^{(*)})$ and $b \rightarrow s \ell \bar{\ell}$ anomalies.⁹ While S_1 and S_3 are scalars which transform under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ as $(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$ and $(\bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3})$ representations, respectively, U_1 is a vector with $(\mathbf{3}, \mathbf{1}, \frac{1}{3})$. In our study, we assume the leptoquarks to couple only to third-generation leptons (taus and tau neutrinos) and set all leptoquark masses to 2 TeV for concreteness, which is compatible with the collider bounds on the pair production of third-generation leptoquarks [73,74].¹⁰

A. Singlet-triplet scalar leptoquark model: $S_1 + S_3$

The $S_1 + S_3$ model was proposed in Ref. [60] and its phenomenology was studied in Refs. [61,62,75–79]. We consider the following Yukawa-like interaction [60–62]

$$\begin{aligned} \mathcal{L}_{S_1+S_3} = & (\lambda_{ij}^L \bar{Q}_i (i\sigma^2) L_j + \lambda_{ij}^R \bar{u}_i^c e_j) S_1 \\ & + \kappa_{ij} \bar{Q}_i^c (i\sigma^2) \sigma^I L_j S_3^I + \text{H.c.}, \end{aligned} \quad (10)$$

i.e., assuming lepton and baryon number conservation.¹¹ Here, Q (L) are quark (lepton) $SU(2)_L$ doublets, u (e) are up-type quark (charged lepton) singlets, σ^I ($I = 1, 2, 3$) are the Pauli matrices, and i, j are flavor indices.

Since $R(D^{(*)})$ requires a tree-level effect for an explanation of the anomalies, this results via $SU(2)_L$ invariance, in general also in an effect of the same order in $b \rightarrow s \nu \bar{\nu}$. As it is here compared to the loop-suppressed SM effect, this

⁹We do not consider the R_2 leptoquark model here. The reason is that even though it could as well explain $b \rightarrow s \ell \bar{\ell}$ via an off-shell photon penguin through a tau loop, the loop effects in $b \rightarrow s \nu \bar{\nu}$ are highly suppressed [72].

¹⁰The bounds from single resonant production and nonresonant searches will be discussed in Sec. III.

¹¹We also disregarded the scalar potential, which gives the $S_1 + S_3$ mixing [80–82] as the corresponding effect in meson physics are usually small.

excludes the possibility of (fully) accounting for data with S_1 or S_3 individually.¹² However, due to the relative sign difference in $b \rightarrow c \tau \bar{\nu}$ and $b \rightarrow s \nu \bar{\nu}$ in S_1 vs S_3 , it is possible to have constructive interference in the former but destructive interference in the latter. In fact, we find that the following flavor structure corresponds to a minimal set of the couplings, including only nonzero values for third-generation leptons, to explain the constructive interference in $b \rightarrow c \tau \bar{\nu}$ but the destructive interferences in both $b \rightarrow s \nu \bar{\nu}$ and $s \rightarrow d \nu \bar{\nu}$

$$\begin{aligned} \lambda_{ij}^L = \lambda_L \begin{pmatrix} 0 & 0 & r^3 \\ 0 & 0 & r \\ 0 & 0 & 1 \end{pmatrix}, \quad \lambda_{ij}^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23}^R \\ 0 & 0 & 0 \end{pmatrix}, \\ \kappa_{ij} = (1 - \epsilon) \lambda_L \begin{pmatrix} 0 & 0 & (1 - \delta) r^3 \\ 0 & 0 & -r \\ 0 & 0 & 1 \end{pmatrix}. \end{aligned} \quad (11)$$

Here, $\epsilon = 0$ leads to an exact cancellation in $b \rightarrow s \nu \bar{\nu}$ (at tree-level for equal masses of S_1 and S_3).¹³ On the other hand, δ implies an additional degree of freedom for κ_{13} coupling, resulting in a deviation from the CKM-like hierarchy encoded in $r \approx 0.2$. In the following, we will call $\epsilon = \delta = 0$ the alignment limit, where both contributions to $b \rightarrow s \nu \bar{\nu}$ and $s \rightarrow d \nu \bar{\nu}$ are exactly canceled at tree level. Note that thanks to this CKM-like alignment, leptoquark contributions to the D -meson mixing, $D_s^- \rightarrow \tau \bar{\nu}$, and $B \rightarrow \pi \tau \bar{\nu}$ decays are suppressed and thus do not provide relevant constraints once the relevant uncertainties are taken into account. Finally, note that we are working in the down basis. This means that after electroweak symmetry breaking, the CKM matrix appears in the couplings of leptoquarks to the left-handed up-quarks.

B. Singlet vector leptoquark model: U_1

References [53,83,84] pointed out that $SU(2)_L$ singlet vector-leptoquark with hypercharge 2/3, arising in the famous Pati-Salam model [85], has the potential to provide a combined explanation of the B anomalies. Its phenomenology as a simplified model was studied in Refs. [53,54,83,84,86–88] and Refs. [63–66,89–108] suggested different UV completions, as the original Pati-Salam model cannot be realized at the TeV scale due to the stringent constraints from $K_L \rightarrow \pi e \bar{\mu}$ etc.

¹²Note that while the S_1 LQ alone, even when supplemented with right-handed neutrinos [27], one cannot explain $R(D^{(*)})$ and $b \rightarrow s \ell \bar{\ell}$.

¹³Note that the misalignment between the S_1 and S_3 flavor structure could also be due to different masses and/or nontrivial mixing effects from the scalar potential.

Here we work in a simplified model¹⁴ with the quark-lepton interactions parametrized as

$$\mathcal{L}_{U_1} = (\kappa_{ij}^L \bar{Q}_i \gamma_\mu L_j + \kappa_{ij}^R \bar{d}_i \gamma_\mu e_j) U_1^\mu + \text{H.c.} \quad (12)$$

In addition to the notation introduced in Eq. (10), d is the $SU(2)_L$ singlet down-type quark. In the following, we will neglect the right-handed couplings κ_{ij}^R , which are unnecessary to explain the anomalies. We will focus on the situation in which the tauonic couplings are sizable while others are negligible, i.e., $\kappa_{i3}^L \neq 0$. Like for the $S_1 + S_3$ model, we work in the down-basis.

III. PHENOMENOLOGY

We now perform an updated phenomenological analysis of the $S_1 + S_3$ and the U_1 LQ models. In particular, we will investigate how we can distinguish the two models with the help of the neutrino modes $B \rightarrow K \nu \bar{\nu}$ and $K \rightarrow \pi \nu \bar{\nu}$ as these decays are sensitive to third-generation lepton interactions. We will use the formula for the various observables obtained in Refs. [61,62] for the $S_1 + S_3$ model and Refs. [59,98,110,111] for the U_1 model. The interested reader is referred to these articles for details, such as the definitions of the loop functions etc.

A. Observables and input

The SM predictions for several observables are sensitive to the numerical values of the CKM elements. In particular, $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ is proportional to A^4 , where A is the parameter of the Wolfenstein parametrization mainly determining $|V_{cb}|$. In this study, we follow the strategy of Ref. [12] and obtain $|V_{cb}|$ from the global fit including both the inclusive [112] and the exclusive determinations [113,114] from semileptonic $b \rightarrow c \ell \bar{\nu}$ transitions, resulting in

$$|V_{cb}| = (41.37 \pm 0.81) \times 10^{-3}. \quad (13)$$

Note that the CKM parameters fitted by the UTfit collaboration [115,116], are obtained from $(\bar{\rho}, \bar{\eta})$ without using the NP sensitive observables (ε_k , $B_{s,d} - \bar{B}_{s,d}$ mixing, and semileptonic B decays)

$$\lambda = 0.2251 \pm 0.0008, \quad (14)$$

$$A = 0.816 \pm 0.017, \quad (15)$$

¹⁴Even though a theory with a massive vector boson without an explicit Higgs sector is not renormalizable, it has been shown that several loop effects in flavor observables can be consistently calculated, leading to numerically relevant effects which result in additional correlations [59]. Furthermore, it has been shown in Refs. [107,109] that the effects of heavy leptons, necessarily present in UV-complete models, are numerically small (for these observables).

$$\bar{\rho} = 0.144 \pm 0.016, \quad (16)$$

$$\bar{\eta} = 0.343 \pm 0.012. \quad (17)$$

Using these parameters, we obtain

$$|\lambda_t| \equiv |V_{tb} V_{ts}^*| = 0.0406 \pm 0.0009, \quad (18)$$

$$|V_{ub}| = 0.00355 \pm 0.00015. \quad (19)$$

The resulting SM predictions for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $B^+ \rightarrow K^+ \nu \bar{\nu}$ are given in the Introduction. Note that $R(D^{(*)})$ is independent of CKM elements but that the $b \rightarrow s \ell \bar{\ell}$ fit feebly depends on them via the total branching ratios while the angular observables, like P'_5 are again independent.

Using the $|V_{ub}|$ value given above and the decay constant $f_{B^+} = 190.0(1.3)$ MeV from lattice QCD (with $N_f = 2 + 1 + 1$) [117], we obtain [118]

$$\mathcal{B}(B^- \rightarrow \tau \bar{\nu})_{\text{SM}} = (0.80 \pm 0.06) \times 10^{-4}. \quad (20)$$

On the experimental side, including the recent Belle II result [119], one has [120]

$$\mathcal{B}(B^- \rightarrow \tau \bar{\nu}) = (1.12 \pm 0.21) \times 10^{-4}. \quad (21)$$

While theory and experiment are consistent at 1.5σ , the foreseen sharpening of the experimental data offers the possibility to unveil NP at the same level as suggested by $R(D^{(*)})$. Furthermore, for

$$R(\pi) = \frac{\mathcal{B}(B \rightarrow \pi \tau \bar{\nu})}{\mathcal{B}(B \rightarrow \pi \ell \bar{\nu})}, \quad (22)$$

the SM prediction and experimental value are $R_\pi^{\text{SM}} = 0.719 \pm 0.028$ and $R_\pi^{\text{exp}} = 1.01 \pm 0.49$ [121]. Due to the large experimental uncertainty, these results are not in statistically significant tension with the SM, but it is interesting to note that they lie above the SM prediction as well.

Concerning $b \rightarrow s \ell \bar{\ell}$ data, there is a plethora of observables that are included in the global fit which find large significances for new physics in C_9^U , above the 5σ level [45,50,122,123] with best-fit values of around $C_9^U \approx -1$, i.e., a destructive effect of around 20% w.r.t. the SM. However, as C_9^U could, at least in principle, be mimicked by (additional unknown) hadronic SM effects [123], we will not confine ourselves to a specific range but rather show contour lines for the NP contribution to C_9^U in our plots. Note that both models predict the right sign in C_9^U , given a constructive effect in $R(D^{(*)})$.

In addition to the observables discussed in the introduction, we consider the constraints from the $\Delta F = 2$ processes for the $S_1 + S_3$ model. More specifically, we

have effects in $B_s - \bar{B}_s$, $B_d - \bar{B}_d$ and the kaon mixing, which are correlated in a CKM-like fashion due to our choice of the hierarchical coupling structure. As $B_s - \bar{B}_s$ mixing results in the most stringent bounds in this setup, we do not show the other two cases and use the global fit result of Ref. [124].¹⁵ For our (simplified) U_1 model, the calculation of $\Delta F = 2$ processes is plagued by divergences due to the lack of a Higgs mechanism generating its mass. As it has been shown that the bounds can be weakened in a UV-complete model by a GIM-like cancellation involving vectorlike leptons, we opted not to show the bounds in the plots. However, it should be kept in mind that these limits cannot be fully avoided but are rather model-dependent.

In both the $S_1 + S_3$ and the U_1 LQ model, we restrict our study to real couplings. In fact, the CP -violating complex phases are not helpful to explain $b \rightarrow c\ell\bar{\nu}$ anomaly [125]. Furthermore, while for the $S_1 + S_3$ model, $\arg(r\lambda_{23}^L(\lambda_{23}^R)^*)$ induces a nonzero electric dipole moment (EDM) of the tau lepton [126] and a charm-quark (chromo) EDM at the one-loop level [127, 128], the bounds are weak.¹⁶ Moreover, the presence of $\arg r$ induces CP -violating contributions to $\Delta F = 2$ processes, which could, however, also weaken the bounds.

B. $S_1 + S_3$ model

For the $S_1 + S_3$ model, we study the free parameters λ^L , λ_{23}^R , δ , and ϵ for $r = 0.2$ as motivated by the CKM hierarchy (and consent with kaon mixing), assuming all couplings are real, as discussed in the last section. Note that one can choose $\lambda^L > 0$ without loss of generality.

First, for the alignment limit $\epsilon = \delta = 0$, the effect in $b \rightarrow s\nu\bar{\nu}$ transitions vanishes at tree level due to the cancellation between the S_1 and S_3 contributions, which comes from the coupling structure in Eq. (11).¹⁷ In this limit, the discrepancy in $R(D^{(*)})$ can be explained via the combinations $\lambda_{33}^L\lambda_{23}^L$ and $\lambda_{33}^L\lambda_{23}^R$, the latter leading to scalar and tensor operators. However, the constraints from $B_s - \bar{B}_s$ mixing have to be respected. In fact, one can account for $R(D^{(*)})$ at the 1σ level without violating the bounds from $B_s - \bar{B}_s$ mixing for $m_1 = m_3 = 2$ TeV, $\lambda^L = 1.0$ and $\lambda_{23}^R = -0.5$ (see Fig. 3 in the appendix for details). For these values, we show the dependence on δ and ϵ in Fig. 1. Note that for $\epsilon \neq 0$, NP affects both $\mu(K^+ \rightarrow \pi^+\nu\bar{\nu})$ and $\mu(B^+ \rightarrow K^+\nu\bar{\nu})$.

Due to the $SU(2)_L$ invariance, $\lambda_{33}^L\lambda_{23}^L$ leads to a tree-level contribution to $b \rightarrow s\tau\bar{\tau}$ [110] processes which results in a huge enhancement of them. However, even though the

predictions are several orders of magnitude above the SM one, they are still significantly away from the current limits. Via the same combination of couplings, i.e., $\lambda_{33}^L\lambda_{23}^L$, the model also generates C_9^U via a tau-loop penguin with an off-shell photon. However, it is constrained from $B_s - \bar{B}_s$ mixing such that the current best-fit value for C_9^U cannot be achieved. Nevertheless, it is important that the effect is not negligible and is predicted to have the correct sign (i.e., negative) preferred by the global fit to $b \rightarrow s\ell\bar{\ell}$ data.

The red band in Fig. 1 is consistent with the NA62 result at 1σ and the yellow region is obtained by combining this measurement with $B^+ \rightarrow K^+\nu\bar{\nu}$, $R(D^{(*)})$ and $\mathcal{B}(B^- \rightarrow \tau\bar{\nu})$. We find that the shift in $\mathcal{B}(B^- \rightarrow \tau\bar{\nu})$ and $R(\pi)$ is small due to the partial cancellation between S_1 and S_3 contributions. The black-hatched region is excluded by $B_s - \bar{B}_s$ mixing. Besides, it is noted that the LHC constraint is imposed based on HighPT package [130] and found to be weak outside the plot range.¹⁸

Finally, note the constraining power of the NA62 measurement. While the B physics observables mainly depend on ϵ , δ changes $K \rightarrow \pi\nu\bar{\nu}$ and is more relevant than the bounds from kaon mixing for small values of r in the $S_1 + S_3$ model.

C. U_1 model

For the U_1 LQ model we have less free relevant parameters and fix $\kappa_L^{33} = 1.5$ and vary κ_L^{23} and κ_L^{13} in Fig. 2. We show the regions preferred by $R(D^{(*)})$, $K^+ \rightarrow \pi^+\nu\bar{\nu}$, and $B \rightarrow \tau\bar{\nu}$ in blue, red, and green bands, respectively. For $R(D^{(*)})$, we show both the 1σ and 2σ regions, while for the other observables, only the 1σ regions are shown. The global fit based in $R(D^{(*)})$, $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $B^+ \rightarrow K^+\nu\bar{\nu}$ and $B \rightarrow \tau\bar{\nu}$ is shown in yellow with 1σ . The predictions for C_9^U , $\mu(B \rightarrow K^{(*)}\nu\bar{\nu})$, $\mathcal{B}(B \rightarrow \tau\bar{\tau})$, and $\mathcal{B}(B \rightarrow K\tau\bar{\tau})$ are shown in terms of contour lines.

In Fig. 2, the orange and green dashed lines show the Belle II sensitivity for $\mathcal{B}(B \rightarrow \tau\bar{\tau})$ and $\mathcal{B}(B \rightarrow K\tau\bar{\tau})$ at 50 ab^{-1} of data [132]. Interestingly, the yellow region, which is preferred by current data, can be probed by $\mathcal{B}(B \rightarrow K\tau\bar{\tau})$, while the second favored region ($\kappa_{13}^L \approx -0.3$, which only consistent at the 2σ level) could be probed by $\mathcal{B}(B \rightarrow \tau\bar{\tau})$. Note that $K \rightarrow \pi\nu\bar{\nu}$ provides a unique bound and constrains the product of $\kappa_L^{23} \times \kappa_L^{13}$ on the plane such that only one of these regions is favored.

¹⁵Note that the kaon mixing is however constraining for larger values of r as can be seen in Fig. 3 the Appendix.

¹⁶The charm-quark tensor charge calculated with lattice QCD turns out to be small [129]. However, the charm EDM would contribute to the nucleon EDM, which can be observed in future experiments [111].

¹⁷However, note that the effect in $B \rightarrow \pi\nu\bar{\nu}$ only vanishes for $\delta = 2$.

¹⁸Note that S_1 could, in principle, give a chirally enhanced effect in $g-2$ of charged leptons via a top-quark loop [131]. However, this can lead to dangerously large effects in $\tau \rightarrow \mu\gamma$, etc., if one aims at a combined effect in the B anomalies [61]. Effects in EW oblique observables and Higgs signal strength originating from the scalar potential are mostly small, such that they can only be tested at future colliders [82]. We checked that the bounds from $\tau \rightarrow \mu\nu\bar{\nu}/\tau \rightarrow e\nu\bar{\nu}$ are satisfied.

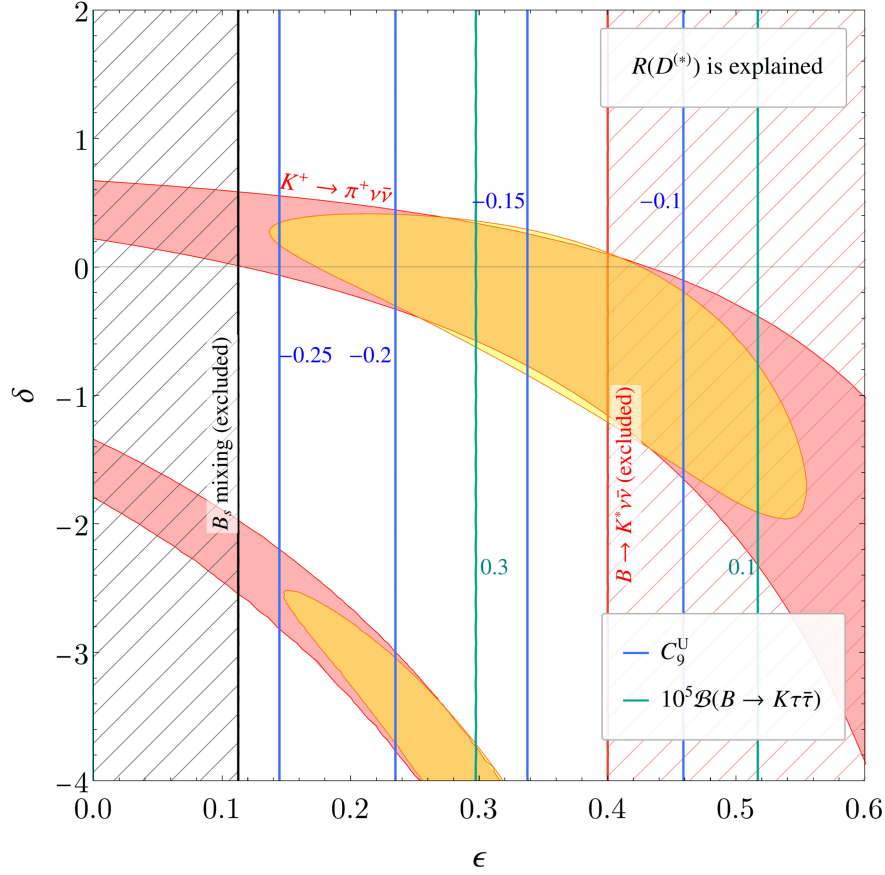


FIG. 1. The preferred and excluded region in the ϵ - δ plane for $m_{S_1} = m_{S_3} = 2$ TeV and $\lambda^L = 1$, $r = 0.2$, $\lambda_{23}^R = -0.5$ of the $S_1 + S_3$ LQ model, such that entire shown plane can accommodate $R(D^{(*)})$ at the 1σ level, i.e., $R(D) \approx 0.35$ and $R(D^*) \approx 0.28$. The blue and green contours represent C_9^U and $\text{Br}(B \rightarrow K\tau\bar{\tau}) \times 10^{-5}$, respectively. The red region is preferred by $K^+ \rightarrow \pi^+\nu\bar{\nu}$ (1σ), the yellow region is the global fit to $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $\mu(B^+ \rightarrow K^+\nu\bar{\nu})$. $B_s - \bar{B}_s$ and $B \rightarrow K^*\nu\bar{\nu}$ exclude the black and red hatched regions, respectively. Note that the NP effect in $B^- \rightarrow \tau\bar{\nu}$ is small with our CKM-like coupling structure.

In comparison to the $S_1 + S_3$ model, only smaller effects in $B \rightarrow K\nu\bar{\nu}$ are possible in the U_1 model. Furthermore, $B^- \rightarrow \tau\bar{\nu}$ is more relevant and large absolute values of C_9^U are possible. However, the latter depends crucially on the $B_s - \bar{B}_s$ mixing bound, which we ignored, as mentioned earlier, as it depends on the UV completion.

IV. CONCLUSION

The confirmation of the P'_5 and $R(D^{(*)})$ measurements together with the disappearance of the $R(K^{(*)})$ anomalies suggest that new physics might be only (or at least dominantly) directly related to tau leptons: A left-handed $\bar{c}b\bar{\tau}\nu$ operator affects the tau mode of $R(D^{(*)})$ and, via $SU(2)_L$ invariance, leads to an $\bar{s}b\bar{\tau}\tau$ operator which generates C_9^U via an off-shell photon penguin. This setup can be achieved within two leptoquark models: the $SU(2)_L$ singlet-triplet scalar leptoquark ($S_1 + S_3$) model and the (simplified) $SU(2)_L$ singlet vector leptoquark model U_1 .

Because the mechanics for explaining these anomalies is the same in both models, the question arises how they can

be discriminated. Here, the neutrino modes $b \rightarrow s\nu\bar{\nu}$ and $s \rightarrow d\nu\bar{\nu}$, which are both measured to be above the SM predictions (around a factor 2 larger with sizable errors) play a critical role as they involve tau neutrinos. In particular, kaon physics had been opening up the intensity frontier decades ago, and the latest NA62 result provided the first observation of the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

In particular, we find the following critical differences between the two models:

- (i) While the achievable size of C_9^U is smaller than the one suggested by the current global fits, it is important that the sign is predicted to be the preferred one. Note that for the same value of $R(D^{(*)})$ the $S_1 + S_3$ model results in a smaller contribution to C_9^U (and $b \rightarrow s\tau\bar{\tau}$ transitions) due to the presence of scalar and tensor amplitudes in $b \rightarrow c\tau\bar{\nu}$ transitions.
- (ii) The U_1 model only leads to a $\mathcal{O}(30\%)$ effects in $B \rightarrow K^{(*)}\nu\bar{\nu}$ as the effect is induced by a W loop. On the other hand, for the $S_1 + S_3$ model, where these decays receive tree-level leptoquark contributions,

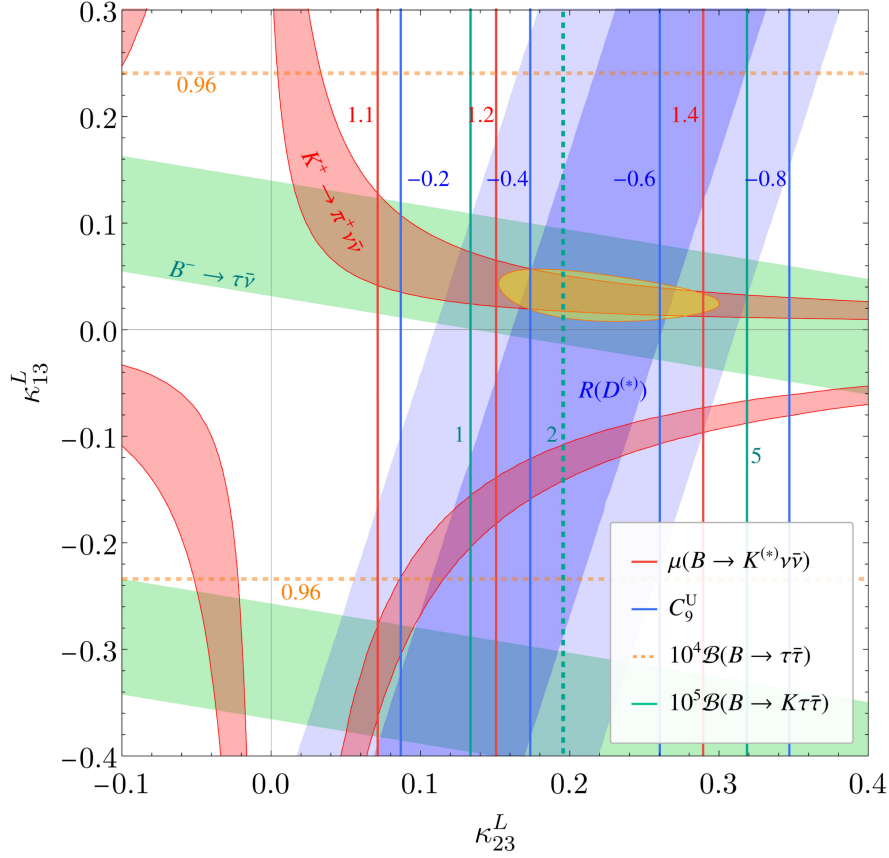


FIG. 2. For the U_1 LQ model we take $m_{U_1} = 2$ TeV and $\kappa_L^{33} = 1.5$. Then, the blue region can accommodate the $R(D^{(*)})$ (at 1σ , 2σ), while the red and green regions are consistent with $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $B^- \rightarrow \tau \bar{\nu}$. The yellow area represents the global fit for these observables, including $B^+ \rightarrow K^+ \nu \bar{\nu}$. The contours are the predictions for $\mu(B^+ \rightarrow K^+ \nu \bar{\nu})$, C_9^U , $\mathcal{B}(B \rightarrow \tau \bar{\tau})$, and $\mathcal{B}(B \rightarrow K \tau \bar{\tau})$ and the dashed lines show the Belle II sensitivity at 50 ab^{-1} of data [132].

$\mathcal{O}(100\%)$ effects can be easily obtained when the $S_1 + S_3$ alignment is slightly broken.

- (iii) While an enhancement in $b \rightarrow s \tau \bar{\tau}$ is observed in the $S_1 + S_3$ scenario, the one obtained in the U_1 model is, in general, larger due to the purely left-handed vector effect in $R(D^{(*)})$. Thus, Belle II can probe the U_1 leptoquark model only in the $B \rightarrow K \tau \bar{\tau}$ and $B \rightarrow \tau \bar{\tau}$ channels.
- (iv) In $B \rightarrow \tau \bar{\nu}$ and $B \rightarrow \pi \tau \bar{\nu}$, the $S_1 + S_3$ scenario predicts relatively small effect due to the constraints on r from the kaon mixing. On the other hand, the U_1 scenario can lead to an $\mathcal{O}(30\%)$ shift with respect to the SM when the model explains $R(D^{(*)})$ and the recent NA62 result. However, including λ_{13}^R as a free parameter, also $b \rightarrow u \tau \bar{\nu}$ transition can be significantly enhanced due to the scalar operator.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: ADDITIONAL ANALYSIS FOR $S_1 + S_3$ MODEL

In Fig. 3, we show the preferred and excluded regions in the $\lambda^L - r$ plane, where λ_{23}^R is fixed to be -0.5 . In the left panel, the alignment limit $\epsilon = \delta = 0$ is taken, while it is slightly broken ($\epsilon = 0.2$) in the right panel. The darker and lighter blue regions can accommodate the $R(D^{(*)})$ anomaly within 1 and 2σ levels. The red and green bands are consistent with the NA62 result and $\mathcal{B}(B^- \rightarrow \tau \bar{\nu})$ at 1σ

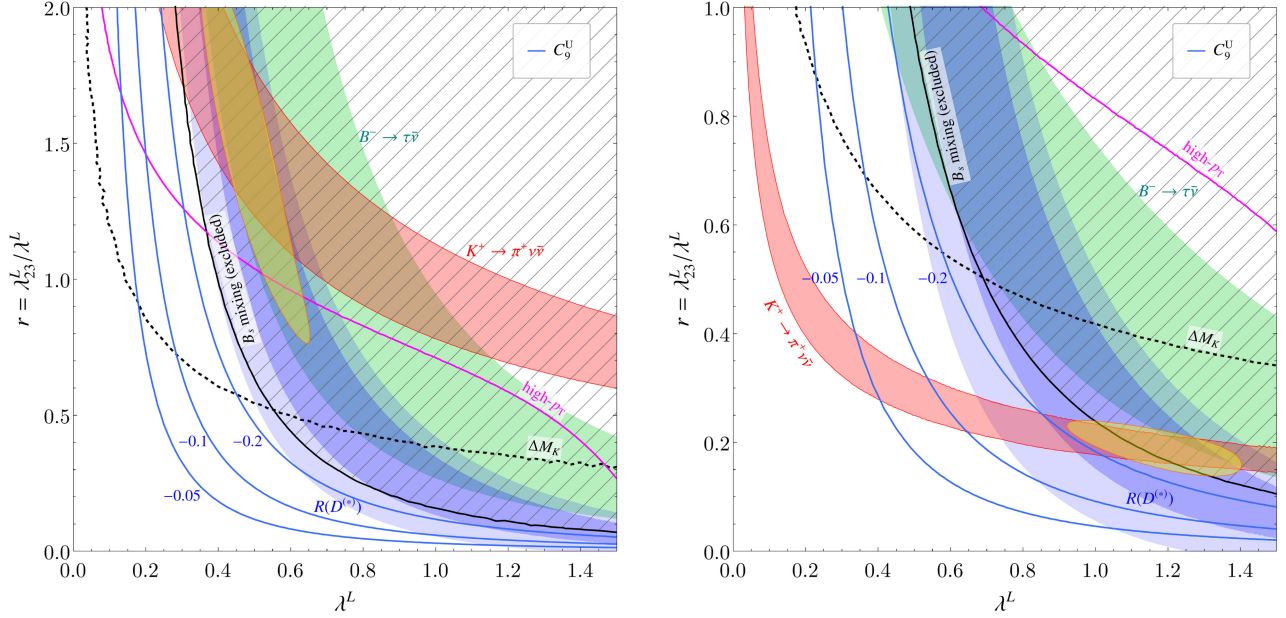


FIG. 3. Preferred and excluded regions for the $S_1 + S_3$ LQ model for the flavor structure given in Eq. (11). We take a common mass $m_{S_1} = m_{S_3} = 2$ TeV and $\lambda_{23}^R = -0.5$. In the left panel, we assume the alignment limit $\epsilon = \delta = 0$, while on the right panel, we take $\epsilon = 0.2$ but keep $\delta = 0$. The blue region can accommodate the $R(D^{(*)})$ anomaly at the $1, 2\sigma$ levels, while the red and green regions are consistent with the data of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $B^- \rightarrow \tau \bar{\nu}$. The yellow region represents the global fit for these observables (including $B^+ \rightarrow K^+ \nu \bar{\nu}$). The blue contours are the predictions of C_9^U . The hatched region is excluded by the $B_s - \bar{B}_s$ mixing bound at the 95% CL, and the dashed lines represent the bound from the kaon mixing. Furthermore, the upper-right regions of the magenta lines are excluded by the high- p_T search [130].

level, respectively. The global fit based on $R(D^{(*)})$, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $B^+ \rightarrow K^+ \nu \bar{\nu}$ and $B^- \rightarrow \tau \bar{\nu}$ is shown in the yellow ellipse. The blue contours represent the predictions of C_9^U . The hatched regions are excluded by $B_s - \bar{B}_s$ mixing, and bounds from the kaon mixing are shown by the dashed lines, which give a complementary constraint that is dominant for large values of r . Furthermore, it is noted that the LHC constraint, shown by the magenta lines, based on HighPT package [130] is found to be weak compared to the $\Delta F = 2$ bounds.

It is clearly shown that the alignment limit does not allow for a full explanation of $R(D^{(*)})$ due to the $\Delta F = 2$ bounds, while a slight violation of this limit ($\epsilon = 0.2$) is enough to be consistent within the 1σ level, giving rise to effects in the neutrino modes. Thus, a simultaneous explanation of $R(D^{(*)})$, $\mu(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\mu(B^+ \rightarrow K^+ \nu \bar{\nu})$ is possible in the yellow region in the right panel with the prediction of $C_9^U \approx -0.2$. We found that the shift in $\mathcal{B}(B^- \rightarrow \tau \bar{\nu})$ [and also $R(\pi)$] is negligible due to the partial cancellation between the S_1 and S_3 contributions.

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