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Crivellin, Andreas ; Kirk, Matthew

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Letter

Diquark explanation of $b \to s\ell^+\ell^-$

Andreas Crivellin[*]

Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH–8057 Zürich, Switzerland
and Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland

Matthew Kirk[†]

Departament de Física Quàntica i Astrofísica (FQA), Institut de Ciències del Cosmos (ICCUB),
Universitat de Barcelona (UB), Spain

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The discrepancies between $b \to s\ell^+\ell^-$ data and the corresponding Standard Model predictions point to the existence of new physics with a significance at the 5σ level. While previously a lepton flavor universality violating effect was preferred, the new $R(K^{(*)})$ and $B_s \to \mu^+\mu^-$ measurements are now compatible with the Standard Model, favoring a lepton flavor universal beyond the Standard Model contribution to C_9. Since heavy new physics is generally chiral, and because of the stringent constraints from charged lepton flavor violation, this poses a challenge for model building. In this article, we point out a novel possibility: a diquark, i.e., a colored scalar, induces the Wilson coefficient of the $(\bar{s}\gamma^\mu P_L b)(\bar{c}\gamma_\mu P_L c)$ operator at tree-level, which then mixes into O_9 via an off-shell photon penguin. This setup allows for a lepton flavor universal effect of $C_9 \approx -0.5$, without violating bounds from ΔM_s, $\Delta\Gamma$, $B \to X_s\gamma$ and $D^0 - \bar{D}^0$ mixing. This scenario predicts a small and negative C_9' and a light diquark, preferably with a mass around 500 GeV, as compatible with the CMS di-dijet analysis, and a deficit in the inclusive $b \to c\bar{c}s$ rate.

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Introduction. While the Standard Model (SM) Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1] of quark flavor violation was established by the B factories Belle [2] and *BABAR* [3], there is still room for new physics (NP) at the order of 10% in flavor changing neutral current (FCNC) processes. Such FCNC observables are loop suppressed and thus particularly sensitive to beyond-the-SM contributions. In fact, there are long-lasting hints for NP in $b \to s\ell^+\ell^-$ observables. However, the picture changed radically with the release of the latest LHCb results for the ratios $R(K^{(*)}) = \mathrm{Br}[B \to K^{(*)}\mu^+\mu^-]/\mathrm{Br}[B \to K^{(*)}e^+e^-]$ [4,5], superseding their previous measurements [6–8]. While previously all global fits [9–15] preferred lepton flavor universality (LFU) violating NP [16,17], now data is not only consistent with LFU but even stringently limits deviations from it.

Nonetheless, the case for physics beyond the SM in $b \to s\ell^+\ell^-$ transitions remains very strong (see Ref. [18] for a recent review). The main tensions with the SM predictions are within the angular $B \to K^*\mu^+\mu^-$ observable P_5' [19–22], the total branching ratio and angular observables in $B_s \to \phi\mu^+\mu^-$ [23–25] as well as in $\mathrm{Br}[B \to K\mu^+\mu^-]$ [26,27],[1] with tensions at the 2–4σ level in each of these modes. In fact, while SM predictions are challenging, due to the hadronic form factors involved [33–38] (including nonlocal charm-loop contributions [39–41]), the first lattice calculation over the full q^2 range of $\mathrm{Br}[B \to K\mu^+\mu^-]$ leads to a stronger tension of 4.7σ [42]. Furthermore, P_5', being an optimized angular observable [43–45] possess a reduced sensitivity to the form factors and semi-inclusive decays at high q^2, that are independent of hadronic form factors, are fully compatible with the other observables [46]. Finally, dispersive methods based on analyticity confirm previous error estimates for the form factors [47,48] (including their nonlocal parts).

Combining the processes discussed above in a global fit together with all other available data on $b \to s\ell^+\ell^+$ transitions leads to a coherent picture. In fact, while before the $R(K^{(*)})$ update, the most strongly favored scenarios were at least two-dimensional [49], now a single one-dimensional scenario is clearly favored: the C_9^U scenario

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[*] andreas.crivellin@psi.ch
[†] mjkirk@icc.ub.edu

[1] Measurements of these decays were also performed by the ATLAS, CMS and Belle collaborations [28–32] but with less precise results.

with a significance around 5σ [50–53]. This means that a left-handed $b-s$ current and a vectorial flavor-universal lepton current ($B_s \to \mu^+\mu^-$ [54–57] constrains an axial current) is needed.

This poses a challenge for model building since both tree-level leptoquark effects [58,59] as well as loop contributions of new scalars and fermions [60–63], in general, give a chiral lepton current and have difficulties respecting the stringent bounds from $\mu \to e$ flavor violating [64] unless multiple generations are involved [65]. This leaves Z' models [66–68] as well as leptoquarks which generate a LFU effect in C_9^U via a tau-loop with an off-shell photon [68–73] as the remaining (simple) options. However, also in these cases $B_s - \bar{B}_s$ mixing [74], LEP and LHC constraints [75,76] make a full explanation challenging.

An alternative scenario that can naturally generate C_9^U is a NP contribution to the Wilson coefficient of the $(\bar{s}\gamma^\mu P_L b)(\bar{c}\gamma_\mu P_{L,R} c)$ operator [77] that mix into C_9 via an off-shell photon penguin [78]. As a tree-level effect in $\bar{s}b\bar{c}c$ operators is necessary, only Z' bosons, heavy gluons, Higgses [79–82] or diquarks (DQs) come into mind [83]. For the first two options the possible effect is stringently limited by $B_s - \bar{B}_s$ mixing (to which these particles also contribute at tree-level [84]) and there is only a small region in parameter space left that works for 2HDMs [82]. Therefore, we will consider the DQs in this article which have not been studied so far. Out of the 8 different scalar DQs [85,86], there is only a single representation that couples to left-handed down-type quarks, can have flavor-diagonal couplings to up-type quarks and does not lead to tree-level effects in $\Delta F = 2$: the scalar $SU(3)_c$ triplet, $SU(2)_L$ singlet with hypercharge $-1/3$ which we call ϕ.[2]

DQs are not only theoretically well motivated, e.g., by E_6 models [87] or the R-parity violating MSSM [88], but also lead to interesting LHC signatures [89–99]: They are candidates from an explanation [100] of the ATLAS dijet [101] and the CMS di-dijet [102] excesses. In fact, the nonresonant CMS analysis shows a weaker-than-expected limit for a diquark $SU(3)_c$ triplet with a mass around 500 GeV.

In the next section, we will define our model and perform the matching on the effective theory before we continue with the phenomenological analysis in Sec. III can conclude in Sec. IV.

Setup and observables. There are 8 representations of scalar DQs with couplings to quarks $SU(2)_L$ singlets or doublets which can have either symmetric or antisymmetric couplings in flavor space. In order to get a sizable effect in $b \to s\ell^+\ell^-$ via the operator $(\bar{s}\gamma^\mu P_L b)(\bar{c}\gamma_\mu P_{L,R} c)$, we need (1) simultaneous couplings to up-type and down-type quarks, (2) flavor diagonal couplings to up-quarks (i.e., not antisymmetric ones), (3) left-handed down-quarks must be involved, (4) no tree-level effect in $B_s - \bar{B}_s$ mixing. These requirements only leave a single representation, i.e., IV in the conventions of Ref. [85] whose mass we label M_ϕ.

The couplings to quarks are given by

$$\mathcal{L} = \left(\frac{1}{2}\tilde{\lambda}^L_{ij}(\bar{Q}^{I,\alpha}_i)^c Q^{J,\beta}_j \epsilon_{IJ} + \tilde{\lambda}^R_{ij}\bar{u}^{\alpha c}_i d^\beta_j\right)\phi^\gamma \epsilon_{\alpha\beta\gamma} + \text{H.c.} \qquad (1)$$

Here, α, β, γ are color indices, I, J (i, j) $SU(2)_L$ (flavor) indices and c stands for charge conjugation. Note that $\tilde{\lambda}^L$ can be chosen to be symmetric in flavor space, i.e., $\tilde{\lambda}^L_{ij} = \tilde{\lambda}^L_{ji}$, without loss of generality. After electroweak symmetry breaking, the quark doublets decompose into their $SU(2)_L$ components and in the mass eigenbasis we have

$$\mathcal{L} = \varepsilon_{\alpha\beta\gamma}(\lambda^L_{ij}\bar{u}^{\alpha c}_i P_L d^\beta_j + \lambda^R_{ij}\bar{u}^{\alpha c}_i P_R d^\beta_j)\phi^\gamma + \text{H.c.}, \qquad (2)$$

where we absorbed the rotation matrices into the definition of λ^R and, working in the down basis, defined $V^*_{ii'}\tilde{\lambda}^L_{i'j} = \lambda^L_{ij}$.

Tree-level matching: The Lagrangian

$$\mathcal{L} = -N_{ij}\sum_{X=1}^{10}(C^{ij}_X Q^{ij}_X + C'^{ij}_X Q'^{ij}_X) \qquad (3)$$

with $N_{ij} = 4G_F V_{ib}V^*_{js}/\sqrt{2}$ and the operators

$$\begin{aligned} Q^{ij}_1 &= (\bar{u}^\alpha_i \gamma_\mu P_L b^\beta)(\bar{s}^\beta \gamma^\mu P_L u^\alpha_j), \\ Q^{ij}_2 &= (\bar{u}^\alpha_i \gamma_\mu P_L b^\alpha_L)(\bar{s}^\beta_L \gamma^\mu P_L u^\beta_j), \\ Q^{ij}_7 &= (\bar{u}^\alpha_i P_R b^\beta)(\bar{s}^\beta P_R u^\alpha_j), \\ Q^{ij}_8 &= (\bar{u}^\alpha_i P_R b^\alpha)(\bar{s}^\beta_L P_R u^\beta_j), \\ Q^{ij}_9 &= (\bar{u}^\alpha_i \sigma_{\mu\nu} P_R b^\beta)(\bar{s}^\beta \sigma^{\mu\nu} P_R u^\alpha_j), \\ Q^{ij}_{10} &= (\bar{u}^\alpha_i \sigma_{\mu\nu} P_R b^\alpha)(\bar{s}^\beta_L \sigma^{\mu\nu} P_R u^\beta_j), \end{aligned} \qquad (4)$$

defines the charged current interactions. Our diquark, integrated out at tree level at the electroweak scale, leads to the coefficients

$$C^{ij}_1 = -C^{ij}_2 = -\frac{\lambda^{L*}_{i2}\lambda^L_{j3}}{2N_{ij}M^2_\phi}, \qquad (5)$$

$$C^{ij}_7 = -C^{ij}_8 = -4C^{ij}_9 = 4C^{ij}_{10} = \frac{\lambda^{L*}_{i2}\lambda^R_{j3}}{2N_{ij}M^2_\phi}, \qquad (6)$$

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[2] This field is also known as the S_1 leptoquark when it couples to quarks and leptons instead of two quarks. However, to avoid proton decay, we will assume that it couples only to quarks which can be achieved by, e.g., assuming that lepton number is conserved.

with the primed coefficients obtained by $\lambda^L \leftrightarrow \lambda^R$.[3]

$b \to s\ell^+\ell^-$: The effective Lagrangian governing $b \to s\ell\ell$ transitions is given by

$$\mathcal{L} \supset N_{33}\frac{\alpha}{4\pi}[C_9(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\ell) + C_{10}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma^5\ell)], \tag{7}$$

where the primed operators and coefficients are again obtained by exchanging L and R. The tree-level induced operators $Q_{1,2}^{cc}$ generate via mixing

$$\begin{aligned} C_9(m_b) &= 8.5C_1^{cc}(M_W) + 2.1C_2^{cc}(M_W) \\ &\quad + [3.1C_1^{cc}(M_W) + 0.32C_2^{cc}(M_W)] \times h(q^2), \end{aligned} \tag{8}$$

at the B meson scale (and similarly for C_9') with

$$h(q^2, m_c) = -\frac{4}{9}\left[\ln\frac{m_c^2}{m_b^2} - \frac{2}{3} + (2+z)a(z) - z\right], \tag{9}$$

$a(z) = \sqrt{|z-1|}\arctan\frac{1}{\sqrt{z-1}}$, and $z = 4m_c^2/q^2$. Note that h also includes finite subleading q^2-dependent effects (which we evaluate at $q^2 = 5\ \mathrm{GeV}^2$) [77].

The threshold effects from top quark loops induce at the EW scale

$$\frac{-C_9}{1-4s_W^2} = C_{10} = -\frac{\lambda_{32}^{L*}\lambda_{33}^L}{2e^2 V_{tb}V_{ts}^*} f\left(\frac{m_t^2}{M_\phi^2}\right), \tag{10}$$

with $f(x) = x(x - \log x - 1)/(x-1)^2$ and $C_{9,10}'$ obtained from $C_{9,10}$ by exchanging L and R.

$B \to X_s\gamma$: The relevant effective operators are defined by

$$\mathcal{L} \supset N_{33}C_{7\gamma(8g)}\frac{e(g_s)m_b}{16\pi^2}\bar{s}\sigma^{\mu\nu}(t^a)P_R b F_{\mu\nu}(G_{\mu\nu}^a), \tag{11}$$

with primed operators obtained through $P_R \to P_L$. We have two NP contributions to $C_{7\gamma}$. The mixing of the $\bar{s}b\bar{c}c$ operators into $C_{7\gamma}$ leads to [77,112]

$$\begin{aligned} C_{7\gamma}(m_b) &= 0.02C_1^{cc}(M_W) - 0.19C_2^{cc}(M_W) - 1.0C_7^{cc}(M_W) \\ &\quad - 0.47C_8^{cc}(M_W) + 4.0C_9^{cc}(M_W) + 0.47C_{10}^{cc}(M_W) \\ &\quad - \frac{m_c}{m_b}(2.5C_7^{cc} + 1.3C_8^{cc} - 10C_9^{cc} + 0.89C_{10}^{cc}) \times y, \end{aligned} \tag{12}$$

where, similarly to the case of C_9, we have included subleading q^2 dependent terms via $y = -(1 + 2\log(m_c^2/m_b^2))/6$. The equivalent result for the primed operators is again obtained by an exchange of chiralities.[4]

Second, the direct matching at the new physics scale (to be taken the weak scale) gives direct contributions to $C_{7\gamma,8g}^{(\prime)}(M_W)$. The most important result is the existence of m_t/m_b enhanced terms for both coefficients which are proportional to $\lambda_{22}^L\lambda_{33}^R$, while the full expressions can be found in the Supplemental Material [113]. These coefficients are then evolved to the B meson scale resulting in

$$C_{7\gamma}^{(\prime)}(m_b) = 0.65C_{7\gamma}^{(\prime)}(M_W) + 0.10C_{8g}^{(\prime)}(M_W). \tag{13}$$

The latest SM prediction for the inclusive radiative decay $B \to X_s\gamma$ [114]

$$\mathrm{Br}[B \to X_s\gamma]^{\mathrm{SM}} = (3.40 \pm 0.17)10^{-4}, \tag{14}$$

is in good agreement with the experimental average [115]

$$\mathrm{Br}[B \to X_s\gamma]^{\mathrm{EXP}} = (3.49 \pm 0.19)10^{-4}. \tag{15}$$

This measurement stringently constrains a BSM contribution to $C_{7\gamma}$. In addition, asymmetries in $B \to K^*e^+e^-$ [116] are very sensitive to $C_{7\gamma}'$. We performed a fit to $C_{7\gamma}$ and $C_{7\gamma}'$ using `smelli` [117–119].

$B_s - \bar{B}_s$ mixing: In the SM, EW box diagrams give rise to $B_s - \bar{B}_s$ mixing, which can be measured through observables including ΔM_s, $\Delta\Gamma_s$, and a_{sl}^s that can in principle constrain our NP model.

The mass difference $\Delta M_s = 2|M_{12}^s|$ in the SM is

$$\Delta M_s^{\mathrm{SM}} = (18.2_{-0.8}^{+0.6})\ \mathrm{ps}^{-1}, \tag{16}$$

using the nonperturbative bag parameter combination from Ref. [75] (based on results in Refs. [120–122]), the FLAG 2023 average for f_{B_s} from FLAG 2023 [123] (based on results in Refs. [124–126]), m_t from PDG 2022 [127], and the Spring 2021 CKMfitter collaboration results [128,129],

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[3] It can be seen that C_X^{uc} (which give $b \to u\bar{c}s$ transitions) are enhanced relative to the SM by the large ratio V_{us}/V_{ub}. However, the effects of these operators in meson mixing-related observables is too small [103]. Furthermore, C_X^{cu} (which give $b \to c\bar{u}s$ transitions) have been considered as part of a potential explanation of the discrepancy between the SM prediction with QCD factorization and experiment for $\bar{B}_{(s)}^0 \to D_{(s)}^{*+}\{\pi^-, K^-\}$ [104–111]. However as no analysis has been done with just NP in $\bar{s}b\bar{c}u$, this interesting future direction is beyond the scope of this article.

[4] In principle, there are potential RGE contributions from $\bar{s}b\bar{c}c$ operators in C_{8g} which are however expected to be very small (see appendix of Ref. [77]).

which should be compared to the latest HFLAV average of [115]

$$\Delta M_s^{\rm EXP} = (17.765 \pm 0.006)\ {\rm ps}^{-1}. \tag{17}$$

Our new physics contributes through various 1-loop box diagrams, which generate electroweak scale $\Delta B = 2$ coefficients whose full expressions are given in the Supplemental Material [113].

The width difference for B_s mesons can be calculated as $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos(\arg(-M_{12}^s/\Gamma_{12}^s))$, where the current SM prediction is [130]

$$\Delta\Gamma_s = (0.0895 \pm 0.0131)\ {\rm ps}^{-1}, \tag{18}$$

and the latest HFLAV average[5] is [115]

$$\Delta\Gamma_s = (0.083 \pm 0.005)\ {\rm ps}^{-1}. \tag{19}$$

Our model alters this quantity through the $\bar{s}b\bar{c}c$ operators, where the full NP contributions were calculated in Refs. [77,112].

In addition the semileptonic asymmetry $a_{\rm sl}^s$ receives a large NP contribution since our NP does not suffer the severe GIM cancellation seen in the SM. However, at least orders of magnitude improvement in the experimental precision would be required for this effect to be observable, and so we make no further mention of it here (some more detailed discussion can be found in the Supplemental Material [113]).

$D^0 - \bar{D}^0$ mixing: The $\Delta C = 2$ coefficients which give a short-distance contribution to ΔM_D are

$$C_1 = \frac{1}{64\pi^2 M_\phi^2}[(\lambda^L\lambda^{L\dagger})_{12}]^2, \tag{20}$$

$$C_2 = C_3 = 0, \tag{21}$$

$$C_4 = C_5 = -\frac{1}{32\pi^2 M_\phi^2}(\lambda^L\lambda^{L\dagger})_{12}(\lambda^R\lambda^{R\dagger})_{12}. \tag{22}$$

$C'_{1,2,3}$ are found from $C_{1,2,3}$ by exchanging $\lambda^L \leftrightarrow \lambda^R$.

The SM prediction is currently unclear, as a naive calculation gives a result four or five orders of magnitude too small, while other estimates (albeit not from first principles) suggest the SM alone could give a result $x^{\rm SM} \sim 0.1\%$ [131–137], where

$$x \equiv \frac{2\Delta M_D}{\Gamma_D}, \tag{23}$$

is the commonly reported observable in $D^0 - \bar{D}^0$-mixing. Comparing this to the current HLFAV average [115]

$$x^{\rm EXP} = (0.407 \pm 0.044)\%, \tag{24}$$

we take a conservative approach and allow the short-distance NP contribution to be up to twice the size of the experimental value (i.e. we impose $\Delta M_D^{\rm NP} \leq 2\Delta M_D^{\rm exp}$, allowing in principle for a 100% cancellation between BSM and SM).

B_s/B_d lifetime ratio: The ratio of the B_s to B_d lifetimes was long thought to be a theoretically clean observable, benefiting from many cancellations of uncertainties. However, recent calculations of the SM contribution to the Darwin operator [138–140] has lead to a situation where the theory prediction is unclear, and in addition there is some tension between the different experimental measurements [115] (see the Supplemental Material [113] for further discussion). As such we do not consider this observable further.

Phenomenology. We now turn to the phenomenology of our model. First of all, we set $M_\phi = 500$ GeV which is compatible with the nonresonant paired dijet search of CMS due to the weaker-than-expected limit in this mass region [102]. Note that using a light DQ helps to reduce the relative effect in $\Delta F = 2$ processes since here the DQ contribution is proportional to λ^4/M_ϕ^2 while for all other flavor processes the leading DQ effect has a λ^2/M_ϕ^2 scaling.

The product of $\tilde{\lambda}_{23}^L$ and $\tilde{\lambda}_{22}^L$ is necessary to give the effect in $b \to s\ell^+\ell^-$ via C_9 while the product of $\tilde{\lambda}_{22}^R$ and $\tilde{\lambda}_{23}^R$ (λ_{12}^R) helps to weaken the bound from $B_s - \bar{B}_s$ mixing ($D^0 - \bar{D}^0$). To avoid a chirally enhanced effect in $b \to s\gamma$ $\lambda_{33}^R \approx 0$ is helpful. Furthermore, to avoid bounds from dijet resonance searches [141,142] and Kaon mixing, we assume the left-handed coupling involving the first generation to be approximately zero. Thus we consider the following structure for the DQ quark couplings

$$\tilde{\lambda}^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \tilde{\lambda}_{22}^L & \tilde{\lambda}_{23}^L \\ 0 & \tilde{\lambda}_{23}^L & 0 \end{pmatrix}, \quad \lambda^R = \begin{pmatrix} 0 & \lambda_{12}^R & 0 \\ 0 & \lambda_{22}^R & \lambda_{23}^R \\ 0 & 0 & 0 \end{pmatrix}. \tag{25}$$

Note that we input $\tilde{\lambda}^L$ in the down quark basis (not including CKM rotations).

Since $\tilde{\lambda}_{22}^{L*}\tilde{\lambda}_{23}^L$ must be positive to give the preferred sign in C_9 we set for simplicity $\tilde{\lambda}_{22}^L = \tilde{\lambda}_{23}^L$ and $\lambda_{22}^R = \lambda_{23}^R$, assume real couplings and show the preferred regions of the various observables in Fig. 1. We see that a reasonably sizable LFU C_9, of the order of -0.5, can be generated in our model while still respecting the other experimental constraints. For $D^0 - \bar{D}^0$-mixing, we show the regions compatible with our fine-tuning argument for $\lambda_{12}^R = 0$ and floating it within two different (small) ranges which are compatible with LHC dijet searches. Interestingly, our model predicts $|C'_9| \ll |C_9|$ but with the same sign as (slightly) preferred

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[5] There is some tension between the ATLAS, CMS, and LHCb measurements, such that this HLFAV average applied a scale factor of 1.8 (according to the PDG prescription) to the total uncertainty.

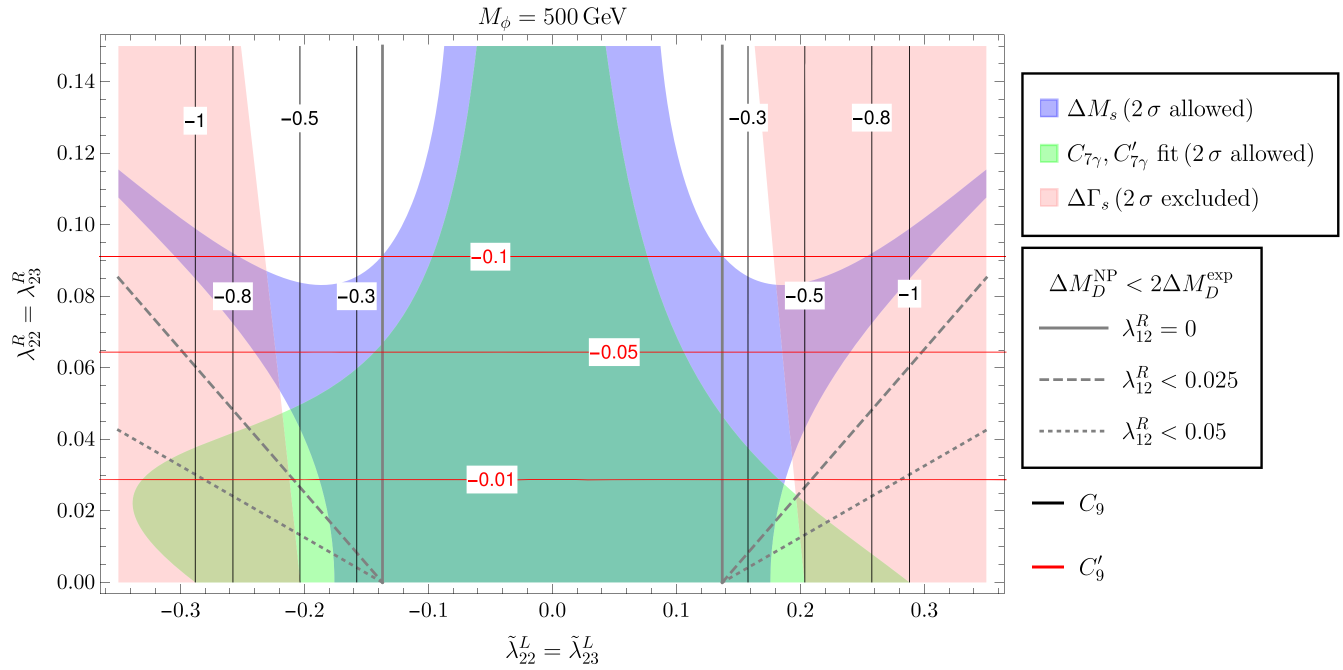

FIG. 1. Experimental constraints given our assumed UV couplings matrices. The black and red vertical and horizontal lines show the generated LFU contributions to C_9 and C'_9, respectively.

by the current global fit [52]. Note that generating the sizeable negative C_9 leads to a positive shift in $\Delta\Gamma_s$. This is more in line with the latest experimental result from CMS, which is in slight tension with LHCb and ATLAS measurements [115].

Conclusions and outlook. There are persistent and significant tensions in $b \to s\ell^+\ell^-$ observables. They are most pronounced in $\mathrm{Br}[B \to K\mu^+\mu^-]$, in the angular observable P'_5 (in $B \to K^*\mu^+\mu^-$) and the total branching ratio as well as angular observables in $B_s \to \phi\mu^+\mu^-$. In combination with the constraints from $R(K^{(*)})$ and $B_s \to \mu^+\mu^-$ they point toward lepton flavor universal NP in C_9 with a significance at the 5σ level. This poses a challenge for model building because heavy NP is generally chiral, while for generating a dominant effect in C_9, a vectorial lepton current is needed. Furthermore, bounds from charged lepton flavor violation require a separation of the electron and muon sectors, which is difficult to achieve in many models.

In this article, we proposed a novel model explaining the $b \to s\ell^+\ell^-$ anomalies: an $SU(3)_c$ triplet scalar DQ with hypercharge $Y = -1/3$. This field can generate a LFU effect in C_9 via the mixing of the $(\bar s\gamma^\mu P_L b)(\bar c\gamma_\mu P_L c)$ operator into O_9. Since only quarks are directly involved in this model, charged lepton flavor violation is automatically respected. Furthermore, due to the weaker-than-expected LHC limit, DQs can still be relatively light, around 500 GeV.

We show that in this setup one can obtain $C_9 \approx -0.5$ while respecting the bounds from $B_s - \bar B_s$ and $D^0 - \bar D^0$ mixing as well as LHC searches. We predict a small negative value of C'_9 as well as a positive shift in $\Delta\Gamma_s$ of around 20% with respect to the SM prediction. For $b \to s\gamma$ our model predicts NP shifts in $|C^{(\prime)}_{7\gamma}| \approx 0.05$. Furthermore, DQs are candidates for sizable effects in hadronic decays of mesons, like ϵ'/ϵ [143,144] and could explain several anomalies in nonleptonic B decays like the longitudinal polarization in $B_q \to K^*\bar K^*$ [145], the $B \to K\pi$ puzzle [146–148], the $B_{(s)} \to D_{(s)}\{K, \pi\}$ [104–110] discrepancy within QCD factorization or the LHC di-dijet excess [100].

Finally, our NP contributions to the $C^{cc}_{1,2}$ coefficients have opposite sign than C^{cc}_1 in the SM. This reduces the theory prediction for the inclusive branching ratio $b \to c\bar cs$ where in the SM we have $\mathrm{Br}[b \to c\bar cs]_{\rm SM} = 23 \pm 2\%$ [149]. However, while the situation for the experimental determination of this fully inclusive quantity is currently quite unclear, and $O(30\%)$ effects in $\mathrm{Br}[b \to c\bar cs]$ are possible, our model prediction is in line with the so-called "missing charm puzzle" [150]. A clarification of the experimental situation would therefore be of great interest.

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[1] Makoto Kobayashi and Toshihide Maskawa, *CP* violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. Abashian *et al.* (Belle Collaboration), The Belle detector, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).

[3] Bernard Aubert *et al.* (*BABAR* Collaboration), The *BABAR* detector, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).

[4] R. Aaij *et al.* (LHCb Collaboration), Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, Phys. Rev. D **108**, 032002 (2023).

[5] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality in $b \to s\ell^+\ell^-$ decays, Phys. Rev. Lett. **131**, 051803 (2023).

[6] Roel Aaij *et al.* (LHCb Collaboration), Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays, Phys. Rev. Lett. **113**, 151601 (2014).

[7] R. Aaij *et al.* (LHCb Collaboration), Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays, J. High Energy Phys. 08 (2017) 055.

[8] Roel Aaij *et al.* (LHCb Collaboration), Test of lepton universality in beauty-quark decays, Nat. Phys. **18**, 277 (2022).

[9] Wolfgang Altmannshofer and Peter Stangl, New physics in rare *B* decays after Moriond 2021, Eur. Phys. J. C **81**, 952 (2021).

[10] Li-Sheng Geng, Benjamín Grinstein, Sebastian Jäger, Shuang-Yi Li, Jorge Martin Camalich, and Rui-Xiang Shi, Implications of new evidence for lepton-universality violation in $b \to s\ell^+\ell^-$ decays, Phys. Rev. D **104**, 035029 (2021).

[11] Marcel Algueró, Bernat Capdevila, Sébastien Descotes-Genon, Joaquim Matias, and Martín Novoa-Brunet, $b \to s\ell^+\ell^-$ global fits after R_{K_S} and $R_{K^{*+}}$, Eur. Phys. J. C **82**, 326 (2022).

[12] T. Hurth, F. Mahmoudi, D. Martinez Santos, and S. Neshatpour, More indications for lepton nonuniversality in $b \to s\ell^+\ell^-$, Phys. Lett. B **824**, 136838 (2022).

[13] Kamila Kowalska, Dinesh Kumar, and Enrico Maria Sessolo, Implications for new physics in $b \to s\mu^+\mu^-$ transitions after recent measurements by Belle and LHCb, Eur. Phys. J. C **79**, 840 (2019).

[14] Marco Ciuchini, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini, and Mauro Valli, Charming penguins and lepton universality violation in $b \to s\ell^+\ell^-$ decays, Eur. Phys. J. C **83**, 64 (2023).

[15] Guido D'Amico, Marco Nardecchia, Paolo Panci, Francesco Sannino, Alessandro Strumia, Riccardo Torre, and Alfredo Urbano, Flavour anomalies after the R_{K^*} measurement, J. High Energy Phys. 09 (2017) 010.

[16] Andreas Crivellin and Martin Hoferichter, Hints of lepton flavor universality violations, Science **374**, 1051 (2021).

[17] Andreas Crivellin and Joaquim Matias, Beyond the standard model with lepton flavor universality violation, in *Proceedings of the 1st Pan-African Astro-Particle and Collider Physics Workshop* (2022), arXiv:2204.12175.

[18] Bernat Capdevila, Andreas Crivellin, and Joaquim Matias, Review of semileptonic *B* anomalies, arXiv:2309.01311.

[19] Sebastien Descotes-Genon, Joaquim Matias, Marc Ramon, and Javier Virto, Implications from clean observables for the binned analysis of $B \to K^*\mu^+\mu^-$ at large recoil, J. High Energy Phys. 01 (2013) 048.

[20] Roel Aaij *et al.* (LHCb Collaboration), Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity, J. High Energy Phys. 02 (2016) 104.

[21] Roel Aaij *et al.* (LHCb Collaboration), Measurement of *CP*-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay, Phys. Rev. Lett. **125**, 011802 (2020).

[22] Roel Aaij *et al.* (LHCb Collaboration), Angular analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ decay, Phys. Rev. Lett. **126**, 161802 (2021).

[23] Roel Aaij *et al.* (LHCb Collaboration), Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$, J. High Energy Phys. 09 (2015) 179.

[24] Roel Aaij *et al.* (LHCb Collaboration), Branching fraction measurements of the rare $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to f_2'(1525)\mu^+\mu^-$- decays, Phys. Rev. Lett. **127**, 151801 (2021).

[25] Roel Aaij *et al.* (LHCb Collaboration), Angular analysis of the rare decay $B_s^0 \to \phi\mu^+\mu^-$, J. High Energy Phys. 11 (2021) 043.

[26] R. Aaij *et al.* (LHCb Collaboration), Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays, J. High Energy Phys. 06 (2014) 133.

[27] Roel Aaij *et al.* (LHCb Collaboration), Measurements of the S-wave fraction in $B^0 \to K^+\pi^-\mu^+\mu^-$ decays and the $B^0 \to K^*(892)^0\mu^+\mu^-$ differential branching fraction, J. High Energy Phys. 11 (2016) 047; 04 (2017) 142(E).

[28] Serguei Chatrchyan *et al.* (CMS Collaboration), Angular analysis and branching fraction measurement of the decay $B^0 \to K^{*0}\mu^+\mu^-$, Phys. Lett. B **727**, 77 (2013).

[29] Vardan Khachatryan *et al.* (CMS Collaboration), Angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ from pp collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B **753**, 424 (2016).

[30] Albert M. Sirunyan *et al.* (CMS Collaboration), Measurement of angular parameters from the decay $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B **781**, 517 (2018).

[31] Morad Aaboud *et al.* (ATLAS Collaboration), Angular analysis of $B_d^0 \to K^*\mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 10 (2018) 047.

[32] Albert M. Sirunyan *et al.* (CMS Collaboration), Angular analysis of the decay $B^+ \to \mathrm{K}^*(892)^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 04 (2021) 124.

[33] Patricia Ball and Roman Zwicky, $B_{d,s} \to \rho, \omega, K^*, \phi$ decay form-factors from light-cone sum rules revisited, Phys. Rev. D **71**, 014029 (2005).

[34] Ronald R. Horgan, Zhaofeng Liu, Stefan Meinel, and Matthew Wingate, Lattice QCD calculation of form factors describing the rare decays $B \to K^*\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$, Phys. Rev. D **89**, 094501 (2014).

[35] Chris Bouchard, G. Peter Lepage, Christopher Monahan, Heechang Na, and Junko Shigemitsu (HPQCD Collaboration), Rare decay $B \to K\ell^+\ell^-$ form factors from lattice QCD, Phys. Rev. D **88**, 054509 (2013); **88**, 079901(E) (2013).

[36] Aoife Bharucha, David M. Straub, and Roman Zwicky, $B \to V\ell^+\ell^-$ in the Standard Model from light-cone sum rules, J. High Energy Phys. 08 (2016) 098.

[37] Nico Gubernari, Ahmet Kokulu, and Danny van Dyk, $B \to P$ and $B \to V$ form factors from B-meson light-cone sum rules beyond leading twist, J. High Energy Phys. 01 (2019) 150.

[38] Bo-Yan Cui, Yong-Kang Huang, Yue-Long Shen, Chao Wang, and Yu-Ming Wang, Precision calculations of $\mathrm{B}_{d,s} \to \pi$, K decay form factors in soft-collinear effective theory, J. High Energy Phys. 03 (2023) 140.

[39] A. Khodjamirian, Th. Mannel, A. A. Pivovarov, and Y. M. Wang, Charm-loop effect in $B \to K^{(*)}\ell^+\ell^-$ and $B \to K^*\gamma$, J. High Energy Phys. 09 (2010) 089.

[40] A. Khodjamirian, Th. Mannel, and Y. M. Wang, $B \to K\ell^+\ell^-$ decay at large hadronic recoil, J. High Energy Phys. 02 (2013) 010.

[41] Nico Gubernari, Danny van Dyk, and Javier Virto, Non-local matrix elements in $B_{(s)} \to \{K^{(*)}, \phi\}\ell^+\ell^-$, J. High Energy Phys. 02 (2021) 088.

[42] W. G. Parrott, C. Bouchard, and C. T. H. Davies (HPQCD Collaboration), Standard Model predictions for $B \to K\ell^+\ell^-$, $B \to K\ell_1^+\ell_2^-$ and $B \to K\nu\nu$ using form factors from $N_f = 2+1+1$ lattice QCD, Phys. Rev. D **107**, 014511 (2023); **107**, 119903(E) (2023).

[43] Joaquim Matias, Federico Mescia, Marc Ramon, and Javier Virto, Complete anatomy of $\bar{B}_d \to \bar{K}^{*0}(\to K\pi)\ell^+\ell^-$ and its angular distribution, J. High Energy Phys. 04 (2012) 104.

[44] Sebastien Descotes-Genon, Tobias Hurth, Joaquim Matias, and Javier Virto, Optimizing the basis of $B \to K^*\ell\ell$ observables in the full kinematic range, J. High Energy Phys. 05 (2013) 137.

[45] Sebastien Descotes-Genon, Joaquim Matias, and Javier Virto, Understanding the $B \to K^*\mu^+\mu^-$ anomaly, Phys. Rev. D **88**, 074002 (2013).

[46] Gino Isidori, Zachary Polonsky, and Arianna Tinari, Semi-inclusive $b \to s\ell^+\ell^-$ transitions at high q^2, arXiv:2305.03076.

[47] Christoph Bobeth, Marcin Chrzaszcz, Danny van Dyk, and Javier Virto, Long-distance effects in $B \to K^*\ell^+\ell^-$ from analyticity, Eur. Phys. J. C **78**, 451 (2018).

[48] Nico Gubernari, Méril Reboud, Danny van Dyk, and Javier Virto, Dispersive analysis of $B \to K^{(*)}$ and $B_s \to \phi$ form factors, arXiv:2305.06301.

[49] Marcel Algueró, Bernat Capdevila, Andreas Crivellin, Sébastien Descotes-Genon, Pere Masjuan, Joaquim Matias, Martín Novoa Brunet, and Javier Virto, Emerging patterns of new physics with and without lepton flavour universal contributions, Eur. Phys. J. C **79**, 714 (2019); **80**, 511(E) (2020).

[50] Nico Gubernari, Méril Reboud, Danny van Dyk, and Javier Virto, Improved theory predictions and global analysis of exclusive $b \to s\mu^+\mu^-$ processes, J. High Energy Phys. 09 (2022) 133.

[51] Marco Ciuchini, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini, and Mauro Valli, Constraints on lepton universality violation from rare B decays, Phys. Rev. D **107**, 055036 (2023).

[52] Marcel Algueró, Aritra Biswas, Bernat Capdevila, Sébastien Descotes-Genon, Joaquim Matias, and Martín Novoa-Brunet, To (b)e or not to (b)e: No electrons at LHCb, Eur. Phys. J. C **83**, 648 (2023).

[53] Qiaoyi Wen and Fanrong Xu, The global fits of new physics in $b \to s$ after $R_{K^{(*)}}$ 2022 release, arXiv:2305.19038.

[54] R. Aaij *et al.* (LHCb Collaboration), Analysis of neutral B-meson decays into two muons, Phys. Rev. Lett. **128**, 041801 (2022).

[55] Roel Aaij *et al.* (LHCb Collaboration), Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays, Phys. Rev. D **105**, 012010 (2022).

[56] Morad Aaboud *et al.* (ATLAS Collaboration), Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector, J. High Energy Phys. 04 (2019) 098.

[57] Armen Tumasyan *et al.* (CMS Collaboration), Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **842**, 137955 (2023).

[58] Gudrun Hiller and Martin Schmaltz, R_K and future $b \to s\ell^+\ell^-$ physics beyond the standard model opportunities, Phys. Rev. D **90**, 054014 (2014).

[59] Rodrigo Alonso, Benjamín Grinstein, and Jorge Martin Camalich, Lepton universality violation and lepton flavor conservation in B-meson decays, J. High Energy Phys. 10 (2015) 184.

[60] Ben Gripaios, M. Nardecchia, and S. A. Renner, Linear flavour violation and anomalies in B physics, J. High Energy Phys. 06 (2016) 083.

[61] Pere Arnan, Lars Hofer, Federico Mescia, and Andreas Crivellin, Loop effects of heavy new scalars and fermions in $b \to s\mu^+\mu^-$, J. High Energy Phys. 04 (2017) 043.

[62] B. Grinstein, S. Pokorski, and G. G. Ross, Lepton non-universality in B decays and fermion mass structure, J. High Energy Phys. 12 (2018) 079.

[63] Pere Arnan, Andreas Crivellin, Marco Fedele, and Federico Mescia, Generic loop effects of new scalars and fermions in $b \to s\ell^+\ell^-$, $(g-2)_\mu$ and a vector-like 4th generation, J. High Energy Phys. 06 (2019) 118.

[64] Andreas Crivellin, Dario Müller, Adrian Signer, and Yannick Ulrich, Correlating lepton flavor universality violation in B decays with $\mu \to e\gamma$ using leptoquarks, Phys. Rev. D **97**, 015019 (2018).

[65] Andreas Crivellin, Benjamin Fuks, and Luc Schnell, Explaining the hints for lepton flavour universality violation with three S_2 leptoquark generations, J. High Energy Phys. 06 (2022) 169.

[66] Andrzej J. Buras and Jennifer Girrbach, Left-handed Z' and Z FCNC quark couplings facing new $b \to s\mu^+\mu^-$ data, J. High Energy Phys. 12 (2013) 009.

[67] Rhorry Gauld, Florian Goertz, and Ulrich Haisch, On minimal Z' explanations of the $B \to K^*\mu^+\mu^-$ anomaly, Phys. Rev. D **89**, 015005 (2014).

[68] Marcel Algueró, Joaquim Matias, Bernat Capdevila, and Andreas Crivellin, Disentangling lepton flavor universal and lepton flavor universality violating effects in $b \to s\ell^+\ell^-$ transitions, Phys. Rev. D **105**, 113007 (2022).

[69] Andreas Crivellin, Christoph Greub, Dario Müller, and Francesco Saturnino, Importance of loop effects in explaining the accumulated evidence for new physics in B decays with a vector leptoquark, Phys. Rev. Lett. **122**, 011805 (2019).

[70] Andreas Crivellin, Dario Müller, and Francesco Saturnino, Flavor phenomenology of the leptoquark singlet-triplet model, J. High Energy Phys. 06 (2020) 020.

[71] Javier Fuentes-Martín, Gino Isidori, Matthias König, and Nudžeim Selimović, Vector leptoquarks beyond tree level, Phys. Rev. D **101**, 035024 (2020).

[72] Marzia Bordone and Mario Fernández Navarro, τ_{B_s}/τ_{B_d} and $\Delta\Gamma_s$ confront new physics in $b \to s\tau^+\tau^-$, Eur. Phys. J. C **83**, 842 (2023).

[73] Mario Fernández Navarro and Stephen F. King, B-anomalies in a twin Pati-Salam theory of flavour including the 2022 LHCb $R_{K^{(*)}}$ analysis, J. High Energy Phys. 02 (2023) 188.

[74] Luca Di Luzio, Matthew Kirk, and Alexander Lenz, Updated B_s-mixing constraints on new physics models for $b \to s\ell^+\ell^-$ anomalies, Phys. Rev. D **97**, 095035 (2018).

[75] Admir Greljo, Jakub Salko, Aleks Smolkovič, and Peter Stangl, Rare b decays meet high-mass Drell-Yan, J. High Energy Phys. 05 (2023) 087.

[76] Jason Aebischer, Gino Isidori, Marko Pesut, Ben A. Stefanek, and Felix Wilsch, Confronting the vector leptoquark hypothesis with new low- and high-energy data, Eur. Phys. J. C **83**, 153 (2023).

[77] Sebastian Jäger, Matthew Kirk, Alexander Lenz, and Kirsten Leslie, Charming new physics in rare B-decays and mixing? Phys. Rev. D **97**, 015021 (2018).

[78] Christoph Bobeth, Ulrich Haisch, Alexander Lenz, Ben Pecjak, and Gilberto Tetlalmatzi-Xolocotzi, On new physics in $\Delta\Gamma_d$, J. High Energy Phys. 06 (2014) 040.

[79] Syuhei Iguro and Yuji Omura, Status of the semileptonic B decays and muon g-2 in general 2HDMs with right-handed neutrinos, J. High Energy Phys. 05 (2018) 173.

[80] Andreas Crivellin, Dario Müller, and Christoph Wiegand, $b \to s\ell^+\ell^-$ transitions in two-Higgs-doublet models, J. High Energy Phys. 06 (2019) 119.

[81] Girish Kumar, Interplay of the charged Higgs boson effects in $R_{D^{(*)}}$, $b \to s\ell^+\ell^-$, and W mass, Phys. Rev. D **107**, 075016 (2023).

[82] Syuhei Iguro, Conclusive probe of the charged Higgs solution of P_5' and $R_{D^{(*)}}$ discrepancies, Phys. Rev. D **107**, 095004 (2023).

[83] J. de Blas, J. C. Criado, M. Perez-Victoria, and J. Santiago, Effective description of general extensions of the standard model: The complete tree-level dictionary, J. High Energy Phys. 03 (2018) 109.

[84] Jason Aebischer, Christoph Bobeth, Andrzej J. Buras, and Jacky Kumar, SMEFT ATLAS of $\Delta F = 2$ transitions, J. High Energy Phys. 12 (2020) 187.

[85] Gian Francesco Giudice, Ben Gripaios, and Raman Sundrum, Flavourful production at hadron colliders, J. High Energy Phys. 08 (2011) 055.

[86] Bruna Pascual-Dias, Pratishruti Saha, and David London, LHC constraints on scalar diquarks, J. High Energy Phys. 07 (2020) 144.

[87] JoAnne L. Hewett and Thomas G. Rizzo, Low-energy phenomenology of superstring inspired $E(6)$ models, Phys. Rep. **183**, 193 (1989).

[88] R. Barbier *et al.*, R-parity violating supersymmetry, Phys. Rep. **420**, 1 (2005).

[89] Ernest Ma, Martti Raidal, and Utpal Sarkar, Probing the exotic particle content beyond the standard model, Eur. Phys. J. C **8**, 301 (1999).

[90] Can Kilic, Takemichi Okui, and Raman Sundrum, Colored resonances at the tevatron: Phenomenology and discovery potential in multijets, J. High Energy Phys. 07 (2008) 038.

[91] Kingman Cheung and Gi-Chol Cho, Hadronic production of light color triplet Higgs bosons: An alternative signature for GUT, Phys. Rev. D **67**, 075003 (2003).

[92] Jonathan M. Arnold, Maxim Pospelov, Michael Trott, and Mark B. Wise, Scalar representations and minimal flavor violation, J. High Energy Phys. 01 (2010) 073.

[93] Jing Shu, Tim M. P. Tait, and Kai Wang, Explorations of the top quark forward-backward asymmetry at the tevatron, Phys. Rev. D **81**, 034012 (2010).

[94] Ilja Dorsner, Svjetlana Fajfer, Jernej F. Kamenik, and Nejc Kosnik, Light colored scalars from grand unification and the forward-backward asymmetry in $t\bar{t}$ production, Phys. Rev. D **81**, 055009 (2010).

[95] Ilja Dorsner, Svjetlana Fajfer, Jernej F. Kamenik, and Nejc Kosnik, Light colored scalar as messenger of up-quark flavor dynamics in grand unified theories, Phys. Rev. D **82**, 094015 (2010).

[96] Moira I. Gresham, Ian-Woo Kim, and Kathryn M. Zurek, Searching for top flavor violating resonances, Phys. Rev. D **84**, 034025 (2011).

[97] Ketan M. Patel and Pankaj Sharma, Forward-backward asymmetry in top quark production from light colored scalars in SO(10) model, J. High Energy Phys. 04 (2011) 085.

[98] Benjamin Grinstein, Alexander L. Kagan, Michael Trott, and Jure Zupan, Forward-backward asymmetry in $t\bar{t}$ production from flavour symmetries, Phys. Rev. Lett. **107**, 012002 (2011).

[99] Zoltan Ligeti, Gustavo Marques Tavares, and Martin Schmaltz, Explaining the $t\bar{t}$ forward-backward asymmetry without dijet or flavor anomalies, J. High Energy Phys. 06 (2011) 109.

[100] Andreas Crivellin, Claudio Andrea Manzari, Bruce Mellado, and Salah-Eddine Dahbi, Consistency and interpretation of the LHC dijet excesses, Phys. Rev. D **107**, 054045 (2023).

[101] Georges Aad *et al.* (ATLAS Collaboration), Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 06 (2021) 145.

[102] Armen Tumasyan *et al.* (CMS Collaboration), Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2023) 161.

[103] Alexander Lenz, Jakob Müller, Maria Laura Piscopo, and Aleksey V. Rusov, Taming new physics in $b \to c\bar{u}d(s)$ with $\tau(B^+)/\tau(B_d)$ and a_{sl}^d, J. High Energy Phys. 09 (2023) 028.

[104] Tobias Huber, Susanne Kränkl, and Xin-Qiang Li, Two-body non-leptonic heavy-to-heavy decays at NNLO in QCD factorization, J. High Energy Phys. 09 (2016) 112.

[105] Marzia Bordone, Nico Gubernari, Tobias Huber, Martin Jung, and Danny van Dyk, A puzzle in $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction, Eur. Phys. J. C **80**, 951 (2020).

[106] Fang-Min Cai, Wei-Jun Deng, Xin-Qiang Li, and Ya-Dong Yang, Probing new physics in class-I B-meson decays into heavy-light final states, J. High Energy Phys. 10 (2021) 235.

[107] Motoi Endo, Syuhei Iguro, and Satoshi Mishima, Revisiting rescattering contributions to $\bar{B}_{(s)} \to D^{(*)}_{(s)}M$ decays, J. High Energy Phys. 01 (2022) 147.

[108] Martin Beneke, Philipp Böer, Gael Finauri, and K. Keri Vos, QED factorization of two-body non-leptonic and semi-leptonic B to charm decays, J. High Energy Phys. 10 (2021) 223.

[109] Robert Fleischer and Eleftheria Malami, Using $B^0_s \to D^\mp_s K^\pm$ decays as a portal to new physics, Phys. Rev. D **106**, 056004 (2022).

[110] Robert Fleischer and Eleftheria Malami, Revealing new physics in $B^0_s \to D^\mp_s K^\pm$ decays, Eur. Phys. J. C **83**, 420 (2023).

[111] Maria Laura Piscopo and Aleksey Rusov, Non-factorisable effects in the decays $\bar{B}^0_s \to D^+_s \pi^-$ and $\bar{B}^0 \to D^+ K^-$ from LCSR, J. High Energy Phys. 10 (2023) 180.

[112] Sebastian Jäger, Matthew Kirk, Alexander Lenz, and Kirsten Leslie, Charming new B-physics, J. High Energy Phys. 03 (2020) 122; 04 (2023) 94.

[113] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevD.108.L111701 for analytic expressions for the Wilson coefficients and details on the lifetime ratio and the semi-leptonic asymmetry for B_s mesons.

[114] M. Misiak, Abdur Rehman, and Matthias Steinhauser, Towards $\bar{B} \to X_s\gamma$ at the NNLO in QCD without interpolation in m$_c$, J. High Energy Phys. 06 (2020) 175.

[115] Yasmine Sara Amhis *et al.* (Heavy Flavor Averaging Group, HFLAV), Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021, Phys. Rev. D **107**, 052008 (2023).

[116] Roel Aaij *et al.* (LHCb Collaboration), Strong constraints on the $b \to s\gamma$ photon polarisation from $B^0 \to K^{*0}e^+e^-$ decays, J. High Energy Phys. 12 (2020) 081.

[117] Peter Stangl, smelli—the SMEFT likelihood, Proc. Sci. TOOLS2020 (**2021**) 035.

[118] Jason Aebischer, Jacky Kumar, Peter Stangl, and David M. Straub, A global likelihood for precision constraints and flavour anomalies, Eur. Phys. J. C **79**, 509 (2019).

[119] David M. Straub, FLAVIO: A Python package for flavour and precision phenomenology in the standard model and beyond, arXiv:1810.08132.

[120] A. Bazavov *et al.* (Fermilab Lattice and MILC Collaborations), $B^0_{(s)}$-mixing matrix elements from lattice QCD for the Standard Model and beyond, Phys. Rev. D **93**, 113016 (2016).

[121] R. J. Dowdall, C. T. H. Davies, R. R. Horgan, G. P. Lepage, C. J. Monahan, J. Shigemitsu, and M. Wingate, Neutral B-meson mixing from full lattice QCD at the physical point, Phys. Rev. D **100**, 094508 (2019).

[122] Daniel King, Alexander Lenz, and Thomas Rauh, B$_s$ mixing observables and —V$_{td}$/V$_{ts}$— from sum rules, J. High Energy Phys. 05 (2019) 034.

[123] Y. Aoki *et al.* (Flavour Lattice Averaging Group (FLAG)), FLAG review 2021, Eur. Phys. J. C **82**, 869 (2022).

[124] R. J. Dowdall, C. T. H. Davies, R. R. Horgan, C. J. Monahan, and J. Shigemitsu (HPQCD Collaboration), B-meson decay constants from improved lattice nonrelativistic QCD with physical u, d, s, and c quarks, Phys. Rev. Lett. **110**, 222003 (2013).

[125] A. Bussone *et al.* (ETM Collaboration), Mass of the b quark and B -meson decay constants from $N_f = 2 + 1 + 1$ twisted-mass lattice QCD, Phys. Rev. D **93**, 114505 (2016).

[126] C. Hughes, C. T. H. Davies, and C. J. Monahan, New methods for B meson decay constants and form factors from lattice NRQCD, Phys. Rev. D **97**, 054509 (2018).

[127] R. L. Workman *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).

[128] J. Charles, Andreas Hocker, H. Lacker, S. Laplace, F. R. Le Diberder, J. Malcles, J. Ocariz, M. Pivk, and L. Roos (CKMfitter Group Collaboration), CP violation and the CKM matrix: Assessing the impact of the asymmetric B factories, Eur. Phys. J. C **41**, 1 (2005).

[129] Spring 2021 results, http://ckmfitter.in2p3.fr/www/results/plots_spring21/ckm_res_spring21.html.

[130] Alexander Lenz, https://indico.cern.ch/event/1166059/contributions/5305525/

[131] Lincoln Wolfenstein, $D^0\bar{D}^0$ mixing, Phys. Lett. **164B**, 170 (1985).

[132] John F. Donoghue, Eugene Golowich, Barry R. Holstein, and Josip Trampetic, Dispersive effects in $D^0\bar{D}^0$ mixing, Phys. Rev. D **33**, 179 (1986).

[133] Adam F. Falk, Yuval Grossman, Zoltan Ligeti, and Alexey A. Petrov, $SU(3)$ breaking and $D^0\bar{D}^0$ mixing, Phys. Rev. D **65**, 054034 (2002).

[134] Adam F. Falk, Yuval Grossman, Zoltan Ligeti, Yosef Nir, and Alexey A. Petrov, $D^0 - D^0$ mass difference from a dispersion relation, Phys. Rev. D **69**, 114021 (2004).

[135] Hai-Yang Cheng and Cheng-Wei Chiang, Long-distance contributions to $D^0 - \bar{D}^0$ mixing parameters, Phys. Rev. D **81**, 114020 (2010).

[136] Hua-Yu Jiang, Fu-Sheng Yu, Qin Qin, Hsiang-nan Li, and Cai-Dian Lü, $D^0 - \bar{D}^0$ mixing parameter y in the factorization-assisted topological-amplitude approach, Chin. Phys. C **42**, 063101 (2018).

[137] Alexander Lenz, Maria Laura Piscopo, and Christos Vlahos, Renormalization scale setting for D-meson mixing, Phys. Rev. D **102**, 093002 (2020).

[138] Alexander Lenz, Maria Laura Piscopo, and Aleksey V. Rusov, Contribution of the Darwin operator to non-leptonic decays of heavy quarks, J. High Energy Phys. 12 (2020) 199.

[139] Thomas Mannel, Daniel Moreno, and Alexei Pivovarov, Heavy quark expansion for heavy hadron lifetimes:

Completing the $1/m_b^3$ corrections, J. High Energy Phys. 08 (2020) 089.

[140] Daniel Moreno, Completing $1/m_b^3$ corrections to non-leptonic bottom-to-up-quark decays, J. High Energy Phys. 01 (2021) 051.

[141] M. Aaboud *et al.* (ATLAS Collaboration), Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. **121**, 081801 (2018).

[142] Marzia Bordone, Admir Greljo, and David Marzocca, Exploiting dijet resonance searches for flavor physics, J. High Energy Phys. 08 (2021) 036.

[143] Jason Aebischer, Christoph Bobeth, and Andrzej J. Buras, ε'/ε in the standard model at the dawn of the 2020s, Eur. Phys. J. C **80**, 705 (2020).

[144] Andrzej J. Buras, The ϵ'/ϵ-Story: 1976-2021, Acta Phys. Pol. B **52**, 7 (2021).

[145] Marcel Algueró, Andreas Crivellin, Sébastien Descotes-Genon, Joaquim Matias, and Martín Novoa-Brunet, A new B-flavour anomaly in $B_{d,s} \to K^{*0}\bar{K}^{*0}$: anatomy and interpretation, J. High Energy Phys. 04 (2021) 066.

[146] Lars Hofer, Dominik Scherer, and Leonardo Vernazza, $B_s \to \phi\rho^0$ and $B_s \to \phi\pi^0$ as a handle on isospin-violating new physics, J. High Energy Phys. 02 (2011) 080.

[147] Robert Fleischer, Ruben Jaarsma, Eleftheria Malami, and K. Keri Vos, Exploring $B \to \pi\pi, \pi K$ decays at the high-precision frontier, Eur. Phys. J. C **78**, 943 (2018).

[148] Andreas Crivellin, Christian Gross, Stefan Pokorski, and Leonardo Vernazza, Correlating ϵ'/ϵ to hadronic B decays via $U(2)^3$ flavour symmetry, Phys. Rev. D **101**, 015022 (2020).

[149] Fabian Krinner, Alexander Lenz, and Thomas Rauh, The inclusive decay $b \to c\bar{c}s$ revisited, Nucl. Phys. **B876**, 31 (2013).

[150] Alexander Lenz, Some comments on the missing charm puzzle, in *Proceedings of the UK Phenomenology Workshop on Heavy Flavor and CP Violation* (2000), arXiv:hep-ph/0011258.