# Scalar leptoquarks from grand unified theories to accommodate the *B*-physics anomalies

Damir Bečirević,[1,*] Ilja Doršner,[2,†] Svjetlana Fajfer,[3,4,‡] Darius A. Faroughy,[4,§] Nejc Košnik,[3,4,¶] and Olcyr Sumensari[5,6,**]

[1]*Laboratoire de Physique Théorique (Bât. 210), Université Paris-Sud and CNRS,*
*F-91405 Orsay-Cedex, France*
[2]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering*
*and Naval Architecture in Split (FESB), Ruđera Boškovića 32, 21 000 Split, Croatia*
[3]*Department of Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia*
[4]*Jožef Stefan Institute, Jamova 39, P.O. Box 3000, 1001 Ljubljana, Slovenia*
[5]*Dipartimento di Fisica e Astronomia "G. Galilei," Università di Padova, I-35131 Padova, Italy*
[6]*Istituto Nazionale Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

We address the *B*-physics anomalies within a two scalar leptoquark model. The low-energy flavor structure of our setup originates from two $SU(5)$ operators that relate Yukawa couplings of the two leptoquarks. The proposed scenario has a UV completion, can accommodate all measured lepton flavor universality ratios in *B*-meson decays, is consistent with related flavor observables, and is compatible with direct searches at the LHC. We provide prospects for future discoveries of the two light leptoquarks at the LHC and predict several yet-to-be-measured flavor observables.

## I. INTRODUCTION

Lepton flavor universality (LFU) ratios appear to be very interesting observables to test the validity of the Standard Model (SM). Several experiments found that LFU ratios $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(B \to D^{(*)}l\bar{\nu}_l)$, $l = e$, $\mu$, are larger than $R_{D^{(*)}}^{\mathrm{SM}}$. The measurements of $R_D$ [1–3] differ by $\sim 2\sigma$ with respect to the SM prediction [4] and by $\sim 3\sigma$ in the case of $R_{D^*}$ [5–7]. Further hints of LFU violation in transitions $b \to c\ell\nu$ ($\ell = \mu, \tau$) were observed in $R_{J/\psi}$ ratio between $B_c \to J/\psi\ell\nu$ decay widths [8]. On the other hand, the LHCb experiment has measured LFU ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$ related to the neutral-current process $b \to sll$ and found them to be systematically lower than expected in the SM. While $R_K$ was measured in a single kinematical region, $q^2 \in [1.1, 6]$ GeV$^2$ [9], $R_{K^*}$ was measured also in the region $q^2 \in [0.045, 1.1]$ GeV$^2$ [10].

The three measured $R_{K^{(*)}}$ deviate from the SM predictions at $\sim 2.5\sigma$ level [11,12].

New physics (NP) explanations of the *B*-physics anomalies suggest a presence of one or more TeV scale mediators which couple to left-handed currents with predominantly third generation fermions [12–16]. Among the most prominent NP candidates are leptoquarks (LQs). It turns out that a single scalar LQ cannot provide solution to the both *B*-physics anomalies. The scalar LQ that can explain $R_{K^*}$ is not suitable for accommodating $R_{D^*}$ and vice versa. By using an effective theory approach, it was shown in Ref. [13] that of all possible single mediators only one particular vector LQ can generate suitable $V - A$ operators for the anomalies and satisfy both low-energy and high-$p_T$ constraints. The construction of ultraviolet (UV) complete models for these scenarios became a challenge that was addressed in Refs. [17–23]. Another possible approach is to consider models with several mediators. The low energy $V - A$ structure can be generated by integrating out two scalar LQs [13,24,25]. Incidentally, one can explore two scalar LQs even when they are known to generate operators with Lorentz structures other than $V - A$ for $R_{D^{(*)}}$.

In this article we propose an UV complete model based on $SU(5)$ grand unified theory (GUT) with two light scalar LQs that can address both anomalies. The LQs in question are $R_2(\mathbf{3}, \mathbf{2}, 7/6)$ and $S_3(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$, where we specify their representation under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. At low energies, $R_2$ generates a combination of scalar and tensor effective operators that accommodate $R_{D^{(*)}}$, while $S_3$ generates a $V - A$ operator which

[*]damir.becirevic@th.u-psud.fr
[†]dorsner@fesb.hr
[‡]svjetlana.fajfer@ijs.si
[§]darius.faroughy@ijs.si
[¶]nejc.kosnik@ijs.si
[**]olcyr.sumensari@pd.infn.it

accommodates $R_{K^{(*)}}$. In our setup, since the Yukawa interactions have a common $SU(5)$ origin, both LQs share one Yukawa matrix. If we take into account all relevant flavor constraints we find that the preferred region in the parameter space is compatible with direct searches at the LHC. Furthermore, if we demand perturbativity of all the couplings to the GUT scale, we find that the mass of $R_2$ needs to be around 1 TeV. In the following we present our setup, outline the UV completion, discuss the low-energy phenomenology and LHC signatures.

## II. SETUP

The interactions of $R_2$ and $S_3$ with the SM fermions are

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}_i' \ell_{Rj}' R_2 + Y_L^{ij} \bar{u}_{Ri} \tilde{R}_2^\dagger L_j' + Y^{ij} \bar{Q}_i'^C i\tau_2 (\tau_k S_3^k) L_j', \quad (1)$$

where $Y_L$, $Y_R$, and $Y$ are Yukawa matrices, $\tau_k$ denote the Pauli matrices, $S_3^k$ are the $SU(2)_L$ triplet components, $\widetilde{R_2} \equiv i\tau_2 R_2^*$, and $i$, $j$, $k = 1$, 2, 3. We omit Hermitian conjugate parts throughout the article. This part of the Lagrangian, in the mass eigenstate basis, reads

$$\begin{aligned}
\mathcal{L} \supset &+ (VY_R E_R^\dagger)^{ij} \bar{u}_{Li} \ell_{Rj} R_2^{\frac{5}{3}} + (Y_R E_R^\dagger)^{ij} \bar{d}_{Li} \ell_{Rj} R_2^{\frac{2}{3}} \\
&+ (U_R Y_L U)^{ij} \bar{u}_{Ri} \nu_{Lj} R_2^{\frac{2}{3}} - (U_R Y_L)^{ij} \bar{u}_{Ri} \ell_{Lj} R_2^{\frac{5}{3}} \\
&- (YU)^{ij} \bar{d}_{Li}^C \nu_{Lj} S_3^{\frac{1}{3}} + 2^{\frac{1}{2}} (V^* YU)^{ij} \bar{u}_{Li}^C \nu_{Lj} S_3^{-\frac{2}{3}} \\
&- 2^{\frac{1}{2}} Y^{ij} \bar{d}_{Li}^C \ell_{Lj} S_3^{\frac{4}{3}} - (V^* Y)^{ij} \bar{u}_{Li}^C \ell_{Lj} S_3^{\frac{1}{3}},
\end{aligned} \quad (2)$$

where $R_2^{(Q)}$ and $S_3^{(Q)}$ are the charge (and mass) eigenstates with charge $Q$. We define the mass eigenstates $u_{L,R} = U_{L,R} u_{L,R}'$, $d_{L,R} = D_{L,R} d_{L,R}'$, $\ell_{L,R} = E_{L,R} \ell_{L,R}'$, and $\nu_L = N_L \nu_L'$, where $U_{L,R}$, $D_{L,R}$, $E_{L,R}$, and $N_L$ are unitary matrices. $V = U_L D_L^\dagger \equiv U_L$ and $U \equiv E_L N_L^\dagger \equiv N_L^\dagger$ are the CKM and PMNS matrices, respectively.

We adopt the following features for the Yukawa matrices:

$$Y_R E_R^\dagger = (Y_R E_R^\dagger)^T, \qquad Y = -Y_L, \quad (3)$$

and assume

$$Y_R E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad U_R Y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}, \quad (4)$$

where $U_R^{22} = \cos\theta \equiv c_\theta$, $U_R^{23} = -\sin\theta \equiv -s_\theta$, and $|U_R^{11}| = 1$. Relevant NP parameters are $m_{R_2}$, $m_{S_3}$, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$, and $\theta$.

*SU(5) embedding.* In the simplest $SU(5)$ scenario that can accommodate light $R_2$ and $S_3$ and (re)produce the associated flavor structure of Eqs. (3) and (4), the scalar sector needs to contain $\underline{\mathbf{45}}$ and $\underline{\mathbf{50}}$ whereas the SM fermions

comprise $\bar{\mathbf{5}}_i$ and $\mathbf{10}_i$, where $i(=1,2,3)$ is a generation index. We omit the $SU(5)$ indices and underline scalar representations throughout this section.

To generate all three operators of Eq. (1) it is sufficient to introduce $a^{ij} \mathbf{10}_i \bar{\mathbf{5}}_j \underline{\mathbf{45}}$, and $b^{ij} \mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}$, where $a$ and $b(=b^T)$ are $3 \times 3$ matrices in generation space. The former contraction couples $R_2 \in \underline{\mathbf{45}}$ ($S_3 \in \underline{\mathbf{45}}$) with the right-handed up-type quarks (quark doublets) and leptonic doublets, while the latter generates couplings of $R_2 \in \underline{\mathbf{50}}$ with the quark doublets and right-handed charged leptons. To break $SU(5)$ down to the SM gauge group we can use $\underline{\mathbf{24}}$ [26] or $\underline{\mathbf{75}}$ [27,28]. This allows us to write either $m\underline{\mathbf{45}}\,\overline{\underline{\mathbf{50}}}\,\underline{\mathbf{24}}$ or $m\underline{\mathbf{45}}\,\overline{\underline{\mathbf{50}}}\,\underline{\mathbf{75}}$, where $m$ is a dimensionful parameter. The two $R_2$'s that reside in $\underline{\mathbf{45}}$ and $\underline{\mathbf{50}}$ mix through either of these two contractions allowing us to end up with two light scalars, i.e., $R_2$ and $S_3$, and one heavy $R_2$ state that completely decouples from the low-energy spectrum for large values of $m$. The relevant Lagrangian after the $SU(5)$ breaking, in the mass eigenstate basis of the two light LQs, is

$$\begin{aligned}
\mathcal{L} \supset &+ s_\phi (V' b E_R'^\dagger)^{ij} \bar{u}_{Li} \ell_{Rj} R_2^{\frac{5}{3}} + s_\phi (b E_R'^\dagger)^{ij} \bar{d}_{Li} \ell_{Rj} R_2^{\frac{2}{3}} \\
&+ c_\phi (U_R' a U')^{ij} \bar{u}_{Ri} \nu_{Lj} R_2^{\frac{2}{3}} - c_\phi (U_R' a)^{ij} \bar{u}_{Ri} \ell_{Lj} R_2^{\frac{5}{3}} \\
&+ 2^{-\frac{1}{2}} (a U')^{ij} \bar{d}_{Li}^C \nu_{Lj} S_3^{\frac{1}{3}} - (V'^* a U')^{ij} \bar{u}_{Li}^C \nu_{Lj} S_3^{-\frac{2}{3}} \\
&+ a^{ij} \bar{d}_{Li}^C \ell_{Lj} S_3^{\frac{4}{3}} + 2^{-\frac{1}{2}} (V'^* a)^{ij} \bar{u}_{Li}^C \ell_{Lj} S_3^{\frac{1}{3}},
\end{aligned} \quad (5)$$

where we define the mixing angle between the two $R_2$'s to be $\phi$. The primed unitary transformations in Eq. (5), i.e., $V'$, $E_R'$, $U_R'$, $U'$, as well as Yukawa matrices $a$ and $b$ are defined at the GUT scale. It is now trivial to compare Eq. (2) with Eq. (5) to obtain the following identification after renormalization group running from the GUT scale down to the electroweak scale: $a \rightarrow -\sqrt{2}Y$, $c_\phi U_R' a \rightarrow U_R Y_L$, $s_\phi b E_R'^\dagger \rightarrow Y_R E_R^\dagger$, $V' \rightarrow V$, and $U' \rightarrow U$. Our particular ansatz given in Eqs. (3) and (4) is consistent with this identification if we take both $R_2$ states to mix maximally, i.e., $s_\phi = c_\phi = 1/\sqrt{2}$. Clearly, the two $SU(5)$ operators proportional to $a$ and $b$ suffice to generate the three operators of Eq. (1) associated with the Yukawa matrices $Y$, $Y_L$, and $Y_R$.

*Perturbativity.* We advocate the case that the low-energy Yukawa couplings have an $SU(5)$ origin. We implement the low-energy Lagrangian of Eq. (1) in SARAH-4.12.3 [29] and obtain one- and two-loop beta function coefficients to accomplish the renormalization group running from the electroweak to the GUT scale which we set at $5 \times 10^{15}$ GeV. The low-energy Yukawas that we use as input are the ones presented in Eq. (4) and we scan over $y_R^{b\tau}$, $y_L^{c\mu}$, and $y_L^{c\tau}$ to identify the region of parameter space for which all Yukawa couplings remain below $\sqrt{4\pi}$ up to the GUT scale. We find, e.g., that the most relevant Yukawa coupling contributions for the running of $y_R^{b\tau}$ are

$$16\pi^2 \frac{d\ln y_R^{b\tau}}{d\ln\mu} = |y_L^{c\mu}|^2 + |y_L^{c\tau}|^2 + \frac{9}{2}|y_R^{b\tau}|^2 + \frac{1}{2}y_t^2 + ...,$$

where $y_t$ is the top Yukawa coupling.

*Proton decay.* LQs are commonly associated with proton decay. It is thus important to address the issue of matter stability. $R_2$ cannot mediate proton decay at tree level either directly or through mixing via one or two Higgs scalars in our setup. It is an innocuous field with regard to the issue of matter stability. It can also be arranged that $S_3$ does not contribute towards proton decay. One prerequisite for this to happen is the absence (or suppression) of the contraction $c^{ij}\mathbf{10}_i\mathbf{10}_j\underline{\mathbf{45}}$ that couples $S_3$ to two quark doublets [30]. The other prerequisite is that $S_3$ does not mix with any other LQ with diquark couplings. Both prerequisites can be simultaneously satisfied in a generic $SU(5)$ framework [31]. It is thus possible to have light $R_2$ and $S_3$ without any conflict with the stringent experimental limits on matter stability.

## III. LOW-ENERGY PHENOMENOLOGY

*Charged-current decays.* The relevant effective Lagrangian for (semi-)leptonic decays is

$$\mathcal{L}_{\text{eff}}^{d\to u\ell\bar{\nu}} = -\frac{4G_F}{\sqrt{2}}V_{ud}[(1 + g_{V_L})(\bar{u}_L\gamma_\mu d_L)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+ g_{S_L}(\mu)(\bar{u}_R d_L)(\bar{\ell}_R\nu_L)$$
$$+ g_T(\mu)(\bar{u}_R\sigma_{\mu\nu}d_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)], \quad (6)$$

where neutrinos are in the flavor basis. The effective Wilson coefficients of $d \to u\ell\bar{\nu}_{\ell'}$ are related to the LQ couplings at the matching scale $\Lambda(\approx 1 \text{ TeV})$ via the expressions

$$g_{S_L}(\Lambda) = 4g_T(\Lambda) = \frac{y_L^{u\ell'}y_R^{d\ell *}}{4\sqrt{2}m_{R_2}^2 G_F V_{ud}},$$

$$g_{V_L} = -\frac{y^{d\ell'}(Vy^*)^{u\ell}}{4\sqrt{2}m_{S_3}^2 G_F V_{ud}}. \quad (7)$$

From the above equations we learn that the only transitions affected by $R_2$ in our scenario are $b \to c\tau\bar{\nu}_\ell$. $S_3$, on the other hand, contributes to processes involving $u$, $c$, $s$, $b$, and $\ell, \ell' = \mu, \tau$, but gives a negligibly small contribution to $R_{D^{(*)}}$.

To compute $R_D$ we employ the $B \to D$ form factors calculated using the lattice QCD [4,32], resulting in prediction $R_D^{\text{SM}} = 0.29(1)$ which is $\approx 2\sigma$ below the experimental average $R_D^{\text{exp}} = 0.41(5)$ [33–35]. On the other hand, the $B \to D^*$ form factors have never been computed on the lattice at nonzero recoil. Thus, for $R_{D^*}$ we consider the leading form factors extracted from the $B \to D^*l\bar{\nu}$ ($l = e, \mu$) spectra [36], which are combined with the ratios $A_0(q^2)/A_1(q^2)$ and $T_{1-3}(q^2)/A_1(q^2)$ computed in Ref. [6].

We obtain the value $R_{D^*}^{\text{SM}} = 0.257(3)$ which is $\approx 3\sigma$ below the experimental average $R_{D^*}^{\text{exp}} = 0.30(2)$ [36]. Moreover, to confront the scalar (tensor) effective coefficients in Eq. (7) with low-energy data, we account for the SM running from the matching scale $\mu = \Lambda$ down to $\mu = m_b$, while the vector coefficient is not renormalized by QCD [37].

We include in the fit several (semi-)leptonic decays which are sensitive to the $S_3$ couplings [38]. Particularly, the LFU ratios $R_{D^{(*)}}^{\mu/e} = \mathcal{B}(B \to D^{(*)}\mu\bar{\nu})/\mathcal{B}(B \to D^{(*)}e\bar{\nu})$ [39,40] impose severe constraints to simultaneous explanations of the $b \to c$ and $b \to s$ anomalies [41]. Furthermore, we consider $\mathcal{B}(B \to \tau\bar{\nu})$ and the kaon LFU ratio $R_{e/\mu}^K = \Gamma(K^- \to e^-\bar{\nu})/\Gamma(K^- \to \mu^-\bar{\nu})$ [42], both in agreement with their SM predictions. See, e.g., Ref. [38] for further discussion.

*Neutral-current decays.* The standard left-handed effective Hamiltonian for the $b \to s$ (semi-)leptonic transition can be written as

$$\mathcal{H}_{\text{eff}}^{b\to sll} = -\frac{4G_F\lambda_t}{\sqrt{2}}\sum_{i=7,9,10}C_i(\mu)\mathcal{O}_i(\mu), \quad (8)$$

where $\lambda_t = V_{tb}V_{ts}^*$. The relevant operators for our discussion are

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{l}\gamma^\mu(\gamma^5)l). \quad (9)$$

In our setup, only $S_3$ contributes at tree level via [38]

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = \frac{\pi v^2}{\lambda_t\alpha_{\text{em}}}\frac{y^{b\mu}(y^{s\mu})^*}{m_{S_3}^2}$$
$$= \frac{\pi v^2}{\lambda_t\alpha_{\text{em}}}\frac{\sin 2\theta(y_L^{c\mu})^2}{2m_{S_3}^2}. \quad (10)$$

In the second line we explicitly write the dependence of $\delta C_9^{\mu\mu}$ on $\sin 2\theta$. This angle allows one to vary $R_{K^{(*)}}$, independently of $R_{D^{(*)}}$. Since we consider a scenario with relatively small Yukawa couplings, it is a very good approximation to neglect loop-induced contributions of $R_2$ (and $S_3$) to this transition. For a different setup, see Ref. [43]. The $1\sigma$ interval $C_9^{\mu\mu} = -C_{10}^{\mu\mu} \in (-0.85, -0.50)$ is obtained by performing a fit to the clean $b \to sll$ observables, namely, $R_K$, $R_{K^*}$, and $\mathcal{B}(B_s \to \mu\mu)$ [44,45].

Contributions to the left-handed current operators in $b \to sll$ transition unavoidably imply contributions to $B \to K^{(*)}\nu\nu$ decays which are well constrained by experiments. These decays are governed by

$$\mathcal{L}_{\text{eff}}^{b\to s\nu\nu} = \frac{\sqrt{2}G_F\alpha_{\text{em}}\lambda_t}{\pi}C_L^{ij}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj}), \quad (11)$$

where $C_L^{ij} = \delta_{ij}C_L^{\text{SM}} + \delta C_L^{ij}$ is the Wilson coefficient which includes the SM contribution $C_L^{\text{SM}} = -6.38(6)$ [46] and the

contribution $\delta C_L^{ij}$ from NP. Similarly as in the $b \to sll$ transition, the only tree-level contribution to $b \to s\nu\bar{\nu}$ comes from the $S_3$ state and reads [38]

$$\delta C_L^{ij} = \frac{\pi v^2}{2\alpha_{\text{em}}\lambda_t} \frac{y^{bj}(y^{si})^*}{m_{S_3}^2}, \qquad i,j = \mu, \tau. \quad (12)$$

These effective coefficients modify the ratios $R_{\nu\nu}^{(*)} = \mathcal{B}(B \to K^{(*)}\nu\nu)/\mathcal{B}(B \to K^{(*)}\nu\nu)^{\text{SM}}$ in the following way:

$$R_{\nu\nu}^{(*)} = \frac{\sum_{ij}|\delta_{ij}C_L^{\text{SM}} + \delta C_L^{ij}|^2}{3|C_L^{\text{SM}}|^2}. \quad (13)$$

In Sec. IV we confront the predictions of $R_{\nu\nu}^{(*)}$ with experimental bounds $R_{\nu\nu} < 3.9$ and $R_{\nu\nu}^* < 2.7$ [47].

*Further flavor constraints.* Our low-energy fit also includes constraints which will be more extensively discussed in a future publication. These are (i) the $B_s - \bar{B}_s$ mixing amplitude, which is shifted by the $S_3$ box diagram, proportional to $\sin^2 2\theta[(y_L^{c\mu})^2 + (y_L^{c\tau})^2]^2/m_{S_3}^2$, (ii) the experimental limits $\mathcal{B}(\tau \to \mu\phi) \sim \cos^4\theta(y_L^{c\mu}y_L^{c\tau})^2/m_{S_3}^4$, bounded to remain below $8.4 \times 10^{-8}$, and $\mathcal{B}(\tau \to \mu\gamma)^{\text{exp}} < 4.4 \times 10^{-8}$ [48], (iii) the muon $g - 2$, which shows $\approx 3.6\sigma$ discrepancy with respect to the SM [49] but receives only small contribution in our setup, and (iv) the $Z$-boson couplings to leptons measured at LEP [50], which are modified at loop level by both $R_2$ and $S_3$. Finally, we have also checked that our model is compatible with measured $D - \bar{D}$ mixing parameters.

## IV. NUMERICAL RESULTS

We perform a fit to the observables listed above by varying the parameters $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and $\theta$, which were introduced in Sec. II. The fit requires $S_3$ to be more massive than $R_2$. The masses $m_{R_2}$ and $m_{S_3}$ are set to the lowest values allowed by projected LHC constraints, namely, $m_{R_2} = 800$ GeV and $m_{S_3} = 2$ TeV, as we discuss later on. Note that in our flavor fit we obtain two solutions corresponding to small ($\theta \sim 0$) and large ($|\theta| \sim \pi/2$) mixing angles. These two solutions successfully suppress the key constraints, such as $R_{K^{(*)}}$ and $\Delta m_s$ since they are proportional to $\sin 2\theta$. Further inclusion of $\mathcal{B}(\tau \to \mu\phi) \propto \cos^4\theta$ in the fit selects the solution with $|\theta| \approx \pi/2$ as the only viable one. The results of our fit in the $g_{S_L}$ complex plane are shown in Fig. 1 to $1\sigma$ and $2\sigma$ accuracies. The SM point is excluded with $3.8\sigma$ significance, while the best fit point provides a perfect agreement with $R_{D^{(*)}}$ and $R_{K^{(*)}}$. Interestingly, a simultaneous explanation of $R_D$ and $R_{D^*}$ requires complex $g_{S_L}$, which is why we consider complex $y_R^{b\tau}$ [51,52]. Note that the phase in $y_R^{b\tau}$ causes no observable *CP* violating effects. The best fit point is consistent with the LHC constraints superimposed on the same plot. A purely imaginary solution is
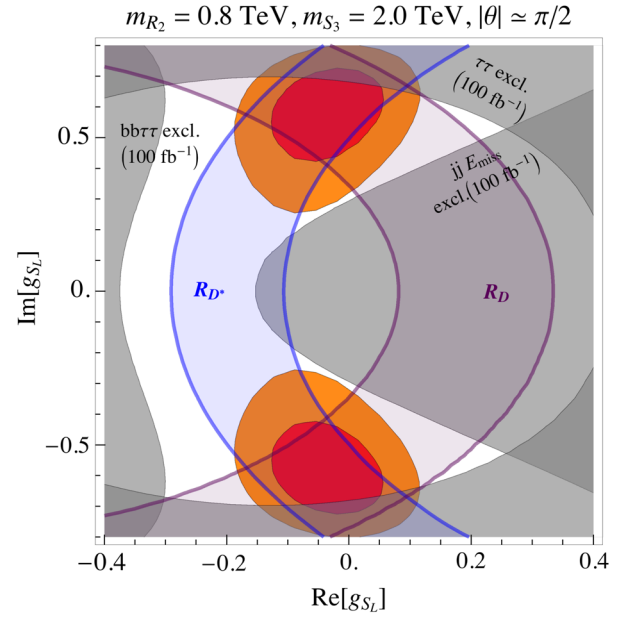


$$m_{R_2} = 0.8 \text{ TeV}, \, m_{S_3} = 2.0 \text{ TeV}, \, |\theta| \simeq \pi/2$$

FIG. 1.   Results of the flavor fit in the $g_{S_L}$ plane, as defined in Eq. (6) for the transition $b \to c\tau\bar{\nu}_\tau$. The allowed $1\sigma(2\sigma)$ regions are rendered in red (orange). Separate constraints from $R_D$ and $R_{D^*}$ to $2\sigma$ accuracy are shown by the blue and purple regions, respectively. The LHC exclusions, as discussed in Sec. V, are depicted by the gray regions.

$$\text{Re}[g_{S_L}] = 0, \qquad |\text{Im}[g_{S_L}]| = 0.59\binom{+0.13}{-0.14}_{1\sigma}\binom{+0.20}{-0.29}_{2\sigma}. \quad (14)$$

An important prediction of our scenario is that $\mathcal{B}(B \to K\mu\tau)$ is bounded from above and below, as illustrated in Fig. 2. At $1\sigma$ we obtain

$$1.1 \times 10^{-7} \lesssim \mathcal{B}(B \to K\mu^\pm\tau^\mp) \lesssim 6.5 \times 10^{-7}. \quad (15)$$

This value is smaller than the current $\mathcal{B}(B \to K\mu\tau)^{\text{exp}} < 4.8 \times 10^{-5}$ [53], which can certainly be improved by LHCb
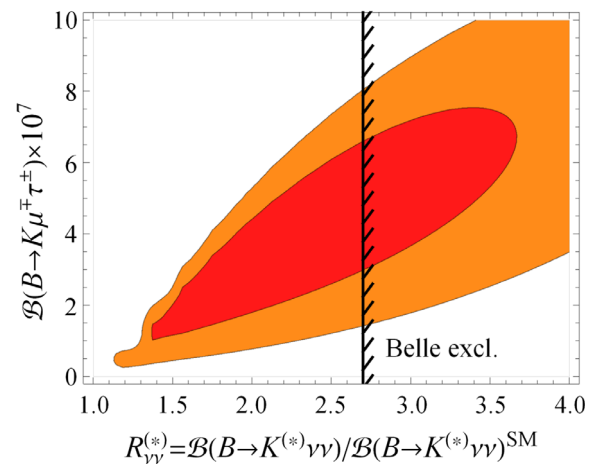


FIG. 2.   $\mathcal{B}(B \to K\mu\tau)$ is plotted against $R_{\nu\nu} = \mathcal{B}(B \to K^{(*)}\nu\bar{\nu})/\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\text{SM}}$ for the $1\sigma$ (red) and $2\sigma$ (orange) regions of Fig. 1. The black line denotes the current experimental limit, $R_{\nu\nu}^* < 2.7$ [47].

and Belle-II. Note that our prediction can easily be translated into similar modes via relations $\mathcal{B}(B \to K^*\mu\tau) \approx 1.9 \times \mathcal{B}(B \to K\mu\tau)$ and $\mathcal{B}(B_s \to \mu\tau) \approx 0.9 \times \mathcal{B}(B \to K\mu\tau)$ [54–56]. Another important prediction of our setup is a $\gtrsim 50\%$ enhancement of $\mathcal{B}(B \to K^{(*)}\nu\nu)$, which can be tested in the near future at Belle-II. Remarkably, these two observables are highly correlated as depicted in Fig. 2. Furthermore, we predict a lower bound on $\mathcal{B}(\tau \to \mu\gamma)$, which lies just below the current experimental limit,

$$\mathcal{B}(\tau \to \mu\gamma) \gtrsim 1.5 \times 10^{-8}. \qquad (16)$$

Finally, our description of the $B$-physics anomalies, and most particularly $R_{D^{(*)}}$, strongly depends on the assumption that the LQ states are not too far from the TeV scale. Thus, these particles are necessarily accessible at the LHC, yielding also predictions for the direct searches which we discuss next.

## V. LHC PHENOMENOLOGY

Direct searches at the LHC can play an important role in constraining LQ model(s) aiming to explain the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies. In the following we show that the benchmark masses $m_{R_2} = 800$ GeV and $m_{S_3} = 2$ TeV are currently allowed by the high-$p_T$ and direct search experiments at the LHC and present exclusion limits for a projected LHC luminosity of 100 fb$^{-1}$ of data.

*High-$p_T$ di-tau tails.* The dominant NP contributions to $q\bar{q} \to \tau\tau$ production, in view of the flavor structure of Eq. (4), come from the $t$-channel exchange of $R_2^{\frac{5}{3}}$ and $R_2^{\frac{2}{3}}$ states in charm and bottom annihilation, respectively. Similar contributions from $S_3$ depend on the value of the mixing angle $\theta$. As discussed in Sec. IV, the low-energy fit prefers $|\theta| \approx \pi/2$. In this case an almost exact flavor alignment takes place between $\tau$ and the third quark generation, meaning that only the exchange of $S_3^{-\frac{1}{3}}$ from initial $b\bar{b}$ collisions contributes to $\tau\tau$ production. Following Ref. [57], we confront this scenario with data by recasting the most recent search by ATLAS [58] at 13 TeV and 36.1 fb$^{-1}$ for a $Z' \to \tau_{\text{had}}\bar{\tau}_{\text{had}}$ heavy resonance in the high-mass tails. Our results for the 95% C.L. limits in the $y_L^{c\tau}$–$(y_R^{b\tau}/i)$ plane are given by the red exclusion region in Fig. 3 for the two benchmark masses, $|\theta| \approx \pi/2$, and the LHC luminosity of 100 fb$^{-1}$.

*Leptoquark pair production.*—For the benchmark masses, bounds from pair-produced LQs can only be derived for $R_2$. The dominant decay channels for each charged eigenstate are $R_2^{\frac{2}{3}} \to \tau b, \nu c$ and $R_2^{\frac{5}{3}} \to \tau t, \tau c$ with the corresponding branching fractions fixed by the squared ratio of Yukawa couplings $y_L^{c\tau}/y_R^{b\tau}$. To set limits on $gg \to (R_2^{\frac{2}{3}})^* R_2^{\frac{2}{3}}$, we use CMS results from the search [59] for $b\bar{b}\tau\bar{\tau}$ final states and the multijet plus missing energy search [60] for $c\bar{c}\nu\bar{\nu}$ final states, i.e., $jj$ plus missing energy signature. The 95% C.L.
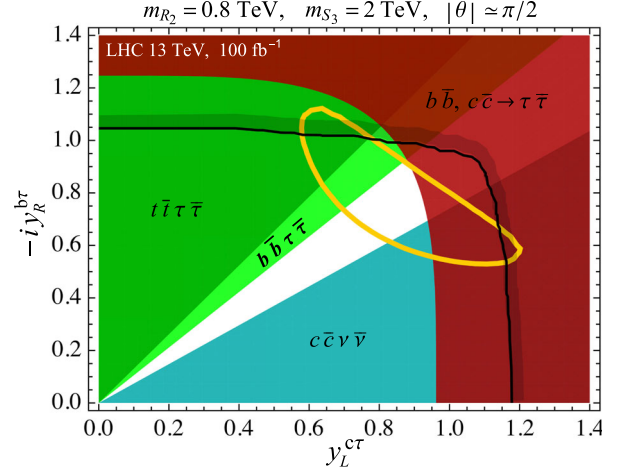


FIG. 3. Summary of the LHC limits for each LQ process at a projected luminosity of 100 fb$^{-1}$ for $m_{R_2} = 800$ GeV, $m_{S_3} = 2$ TeV, and $|\theta| \approx \pi/2$. The red region corresponds to the exclusion limit from the high-$p_T$ di-tau search by ATLAS [58], while the green and turquoise exclusion regions come from LQ pair production searches by CMS [59–61]. The region above the solid black contour represents values of the couplings that become nonperturbative at the GUT scale. The region inside the yellow contour corresponds to the $1\sigma$ fit to the low-energy observables.

exclusion limits are given by the light green and turquoise regions in Fig. 3 for a luminosity of 100 fb$^{-1}$. As for the pair production of $R_2^{\frac{5}{3}}$ states, we employ the search by CMS [61] targeting $t\bar{t}\tau\bar{\tau}$ final states. Results from this search are given by the dark green exclusion region in Fig. 3.

## VI. CONCLUSIONS

We propose a two scalar LQ extension of the SM that can accommodate all measured LFU ratios in $B$-meson decays and related flavor observables, while being compatible with direct search constraints at the LHC. The extension has an $SU(5)$ origin that relates Yukawa couplings of the two LQs through a mixing angle and all Yukawas remain perturbative up to the unification scale. We provide prospects for future discoveries of the two light LQs at the LHC and spell out predictions for several yet-to-be-measured flavor observables. In particular, we predict and correlate $\mathcal{B}(B \to K\mu\tau)$ with $\mathcal{B}(B \to K^{(*)}\nu\nu)$. We also predict a lower bound for $\mathcal{B}(\tau \to \mu\gamma)$ which is just below the current experimental limit.

[1] J. P. Lees *et al.* (*BABAR* Collaboration), Measurement of an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons, Phys. Rev. D **88,** 072012 (2013).

[2] S. Hirose *et al.* (Belle Collaboration), Measurement of the $\tau$ Lepton Polarization and $R(D^*)$ in the Decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$, Phys. Rev. Lett. **118,** 211801 (2017).

[3] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$, Phys. Rev. Lett. **115,** 111803 (2015); Erratum, Phys. Rev. Lett. **115,** 159901 (2015).

[4] J. A. Bailey *et al.* (MILC Collaboration), $B \to Dl\nu$ form factors at nonzero recoil and $|V_{cb}|$ from $2+1$-flavor lattice QCD, Phys. Rev. D **92,** 034506 (2015).

[5] S. Fajfer, J. F. Kamenik, and I. Nisandzic, $B \to D^*\tau\bar{\nu}_\tau$ sensitivity to new physics, Phys. Rev. D **85,** 094025 (2012).

[6] F. U. Bernlochner, Z. Ligeti, M. Papucci, and D. J. Robinson, Combined analysis of semileptonic $B$ decays to $D$ and $D^*$: $R(D^{(*)})$, $|V_{cb}|$, and new physics, Phys. Rev. D **95,** 115008 (2017); Erratum, Phys. Rev. D **97,** 059902 (2018).

[7] D. Bigi, P. Gambino, and S. Schacht, A fresh look at the determination of $|V_{cb}|$ from $B \to D^*\ell\nu$, Phys. Lett. B **769,** 441 (2017).

[8] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Ratio of Branching Fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, Phys. Rev. Lett. **120,** 121801 (2018).

[9] R. Aaij *et al.* (LHCb Collaboration), Test of Lepton Universality Using $B^+ \to K^+\ell^+\ell^-$ Decays, Phys. Rev. Lett. **113,** 151601 (2014).

[10] 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.

[11] G. Hiller and F. Kruger, More model-independent analysis of $b \to s$ processes, Phys. Rev. D **69,** 074020 (2004).

[12] M. Bordone, G. Isidori, and A. Pattori, On the Standard Model predictions for $R_K$ and $R_{K^*}$, Eur. Phys. J. C **76,** 440 (2016).

[13] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, B-physics anomalies: A guide to combined explanations, J. High Energy Phys. 11 (2017) 044.

[14] B. Bhattacharya, A. Datta, D. London, and S. Shivashankara, Simultaneous explanation of the $R_K$ and $R(D^{(*)})$ puzzles, Phys. Lett. B **742,** 370 (2015).

[15] F. Feruglio, P. Paradisi, and A. Pattori, Revisiting Lepton Flavor Universality in B Decays, Phys. Rev. Lett. **118,** 011801 (2017).

[16] G. Hiller and M. Schmaltz, $R_K$ and future $b \to s\ell\ell$ physics beyond the standard model opportunities, Phys. Rev. D **90,** 054014 (2014).

[17] N. Assad, B. Fornal, and B. Grinstein, Baryon number and lepton universality violation in leptoquark and diquark models, Phys. Lett. B **777,** 324 (2018).

[18] M. Bordone, C. Cornella, J. Fuentes-Martín, and G. Isidori, Low-energy signatures of the $PS^3$ model: From B-physics anomalies to LFV, arXiv:1805.09328.

[19] M. Bordone, C. Cornella, J. Fuentes-Martin, and G. Isidori, A three-site gauge model for flavor hierarchies and flavor anomalies, Phys. Lett. B **779,** 317 (2018).

[20] A. Greljo and B. A. Stefanek, Third family quark–lepton unification at the TeV scale, Phys. Lett. B **782,** 131 (2018).

[21] L. Di Luzio, A. Greljo, and M. Nardecchia, Gauge leptoquark as the origin of B-physics anomalies, Phys. Rev. D **96,** 115011 (2017).

[22] M. Blanke and A. Crivellin, $B$ meson Anomalies in a Pati-Salam Model within the Randall-Sundrum Background, Phys. Rev. Lett. **121,** 011801 (2018).

[23] L. Calibbi, A. Crivellin, and T. Li, A model of vector leptoquarks in view of the $B$-physics anomalies, arXiv:1709.00692.

[24] A. Crivellin, D. Müller, and T. Ota, Simultaneous explanation of $R(D^{(*)})$ and $b \to s\mu^+\mu^-$: the last scalar leptoquarks standing, J. High Energy Phys. 09 (2017) 040.

[25] D. Marzocca, Addressing the B-physics anomalies in a fundamental composite Higgs model, J. High Energy Phys. 07 (2018) 121.

[26] H. Georgi and S. L. Glashow, Unity of All Elementary Particle Forces, Phys. Rev. Lett. **32,** 438 (1974).

[27] T. Hubsch and S. Pallua, Symmetry breaking mechanism in an alternative Su(5) model, Phys. Lett. **138B,** 279 (1984).

[28] T. Hubsch, S. Meljanac, and S. Pallua, A nonminimal Su(5) model, Phys. Rev. D **31,** 2958 (1985).

[29] F. Staub, SARAH 4: A tool for (not only SUSY) model builders, Comput. Phys. Commun. **185,** 1773 (2014).

[30] I. Doršner, S. Fajfer, and N. Košnik, Heavy and light scalar leptoquarks in proton decay, Phys. Rev. D **86,** 015013 (2012).

[31] I. Doršner, S. Fajfer, and N. Košnik, Leptoquark mechanism of neutrino masses within the grand unification framework, Eur. Phys. J. C **77,** 417 (2017).

[32] H. Na, C. M. Bouchard, G. P. Lepage, C. Monahan, and J. Shigemitsu (HPQCD Collaboration), $B \to Dl\nu$ form factors at nonzero recoil and extraction of $|V_{cb}|$, Phys. Rev. D **92,** 054510 (2015); Erratum, Phys. Rev. D **93,** 119906 (2016).

[33] J. P. Lees *et al.* (*BABAR* Collaboration), Evidence for an Excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays, Phys. Rev. Lett. **109,** 101802 (2012).

[34] M. Huschle *et al.* (Belle Collaboration), Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle, Phys. Rev. D **92,** 072014 (2015).

[35] R. Aaij *et al.* (LHCb Collaboration), Test of lepton flavor universality by the measurement of the $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong $\tau$ decays, Phys. Rev. D **97,** 072013 (2018).

[36] Y. Amhis *et al.* (HFLAV Collaboration), Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2016, Eur. Phys. J. C **77,** n895 (2017).

[37] M. González-Alonso, J. Martin Camalich, and K. Mimouni, Renormalization-group evolution of new physics contributions to (semi)leptonic meson decays, Phys. Lett. B **772,** 777 (2017).

[38] I. Doršner, S. Fajfer, D. A. Faroughy, and N. Košnik, The role of the $S_3$ GUT leptoquark in flavor universality and collider searches, J. High Energy Phys. 10 (2017) 188.

[39] R. Glattauer *et al.* (Belle Collaboration), Measurement of the decay $B \to D\ell\nu_\ell$ in fully reconstructed events and determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$, Phys. Rev. D **93,** 032006 (2016).

[40] A. Abdesselam *et al.* (Belle Collaboration), Precise determination of the CKM matrix element $|V_{cb}|$ with $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle, arXiv:1702.01521.

[41] D. Bečirević, N. Košnik, O. Sumensari, and R. Zukanovich Funchal, Palatable leptoquark scenarios for lepton flavor violation in exclusive $b \to s\ell_1\ell_2$ modes, J. High Energy Phys. 11 (2016) 035.

[42] V. Cirigliano and I. Rosell, Two-Loop Effective Theory Analysis of $\pi(K) \to e\bar{\nu}_e[\gamma]$ Branching Ratios, Phys. Rev. Lett. **99,** 231801 (2007).

[43] D. Bečirević and O. Sumensari, A leptoquark model to accommodate $R_K^{\text{exp}} < R_K^{\text{SM}}$ and $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$, J. High Energy Phys. 08 (2017) 104.

[44] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, and A. Urbano, Flavour anomalies after the $R_{K^*}$ measurement, J. High Energy Phys. 09 (2017) 010.

[45] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, Patterns of New Physics in $b \to s\ell^+\ell^-$ transitions in the light of recent data, J. High Energy Phys. 01 (2018) 093.

[46] W. Altmannshofer, A. J. Buras, D. M. Straub, and M. Wick, New strategies for New Physics search in $B \to K^*\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$ and $B \to X_s\nu\bar{\nu}$ decays, J. High Energy Phys. 04 (2009) 022.

[47] J. Grygier *et al.* (Belle Collaboration), Search for $\boldsymbol{B \to h\nu\bar{\nu}}$ decays with semileptonic tagging at Belle, Phys. Rev. D **96,** 091101 (2017); Publisher s Note: Search for $\boldsymbol{B \to h\nu\bar{\nu}}$ decays with semileptonic tagging at Belle, Phys. Rev. D **97,** 099902 (2018).

[48] C. Patrignani *et al.* (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C **40,** 100001 (2016).

[49] J. Beringer *et al.* (Particle Data Group Collaboration), Review of particle physics (RPP), Phys. Rev. D **86,** 010001 (2012).

[50] S. Schael *et al.* (The ALEPH Collaboration, The DELPHI Collaboration, The L3 Collaboration, The OPAL Collaboration, The SLD Collaboration, The LEP Electroweak Working Group, The SLD Electroweak, and Heavy Flavour Groups), Precision electroweak measurements on the $Z$ resonance, Phys. Rep. **427,** 257 (2006).

[51] Y. Sakaki, M. Tanaka, A. Tayduganov, and R. Watanabe, Probing New Physics with $q^2$ distributions in $\bar{B} \to D^{(*)}\tau\bar{\nu}$, Phys. Rev. D **91,** 114028 (2015).

[52] D. Bečirević, B. Panes, O. Sumensari, and R. Zukanovich Funchal, Seeking leptoquarks in IceCube, J. High Energy Phys. 06 (2018) 032.

[53] J. P. Lees *et al.* (*BABAR* Collaboration), A search for the decay modes $B^{+-} \to h^{+-}\tau^{+-}l$, Phys. Rev. D **86,** 012004 (2012).

[54] D. Bečirević, O. Sumensari, and R. Zukanovich Funchal, Lepton flavor violation in exclusive $b \to s$ decays, Eur. Phys. J. C **76,** 134 (2016).

[55] S. L. Glashow, D. Guadagnoli, and K. Lane, Lepton Flavor Violation in $B$ Decays?, Phys. Rev. Lett. **114,** 091801 (2015).

[56] D. Guadagnoli and K. Lane, Charged-lepton mixing and lepton flavor violation, Phys. Lett. B **751,** 54 (2015).

[57] D. A. Faroughy, A. Greljo, and J. F. Kamenik, Confronting lepton flavor universality violation in B decays with high-$p_T$ tau lepton searches at LHC, Phys. Lett. B **764,** 126 (2017).

[58] M. Aaboud *et al.* (ATLAS Collaboration), Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in $36 \times \text{fb}^{-1}$ of pp collisions at $\sqrt{S} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 01 (2018) 055.

[59] A. M. Sirunyan *et al.* (CMS Collaboration), Search for third-generation scalar leptoquarks and heavy right-handed neutrinos in final states with two tau leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2017) 121.

[60] CMS Collaboration, Search for new physics in the all-hadronic final state with the MT2 variable, Report No. CMS-PAS-SUS-16-036, http://cds.cern.ch/record/2256872.

[61] A. M. Sirunyan *et al.* (CMS Collaboration), Search for third-generation scalar leptoquarks decaying to a top quark and a $\tau$ lepton at $\sqrt{s} = 13$ TeV, arXiv:1803.02864.