Combined Explanation of the $Z \to b\bar{b}$ Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, and $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ Data

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(Received 29 October 2020; accepted 1 June 2021; published 2 July 2021)

In this Letter, we propose a simple model that can provide a combined explanation of the $Z \to b\bar{b}$ forward-backward asymmetry, the Cabibbo angle anomaly (CAA), $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ data. This model is obtained by extending the standard model (SM) by two heavy vectorlike quarks (an $SU(2)_L$ doublet (singlet) with hypercharge $-5/6$ $(-1/3)$, two new scalars (a neutral and a singly charged one), and a gauged $L_\mu - L_\tau$ symmetry. The mixing of the new quarks with the SM ones, after electroweak symmetry breaking, does not only explain $Z \to b\bar{b}$ data, but also generates a lepton flavor universal contribution to $b \to s\ell^+\ell^-$ transitions. Together with the lepton flavor universality violating effect, generated by loop-induced Z' penguins involving the charged scalar and the heavy quarks, it gives an excellent fit to data (6.1σ better than the SM). Furthermore, the charged scalar (neutral vector) gives a necessarily constructive tree-level (loop) effect in $\mu \to e\nu\nu$ $(\tau \to \mu\nu\nu)$, which can naturally account for the CAA ($\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\tau \to e\nu\nu]$ and $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\mu \to e\nu\nu]$).

DOI: 10.1103/PhysRevLett.127.011801

Introduction.—The standard model (SM) of particle physics has been very successfully tested with great precision in the last decades. Nonetheless, and despite the fact that the LHC has not observed any additional particles directly, it is clear that the SM cannot be the ultimate fundamental theory of physics. In particular, it has to be extended to account for dark matter and neutrino masses, but neither the scale nor the concrete nature of the additional particles is unambiguously established. Fortunately, in the flavor sector we obtained intriguing (indirect) hints for physics beyond the SM at the (multi-)TeV scale.

In particular, global fits [1–11] to $b \to s\ell^+\ell^-$ data [12–19] point convincingly toward new physics (NP), and several simple model-independent scenarios are significantly preferred over the SM hypothesis (by more then 5σ). Furthermore, many NP models were proposed that give rise to these scenarios, including Z' models [20–59], leptoquarks [60–77] or loop effects involving top quarks [78,79] or new scalars and fermions [80–83]. While the large majority of these models generate simple patterns, which are mostly purely lepton flavor universality (LFU) violating, it has been shown in Refs. [9,84] that slightly more elaborated patterns with both LFU and LFU violating effects can describe data even better.

Furthermore, the anomaly in $b \to s\ell^+\ell^-$ data is accompanied by additional hints for the violation of LFU that are very interesting, even though they are statistically less significant: (i) $R(D^{(*)})$ [85–90] points toward $\tau - \mu$ LFU violation with a significance of $> 3\sigma$ [91–95], (ii) the anomalous magnetic moment of the muon a_μ [96] prefers NP coupling to muons by 3.7σ [97], (iii) $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\tau \to e\nu\nu]$ and $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\mu \to e\nu\nu]$ are indications for LFU violation with a significance of $\approx 2\sigma$, and (iv) the deficit in first row Cabibbo-Kobayashi-Maskawa (CKM) unitarity, known as the Cabibbo angle anomaly (CAA), is at the ≈ 2–4σ level [98–100] and can possibly be interpreted as a sign of LFU violation [101–106].

Interestingly, it has been shown that NP models can provide combined explanations of these anomalies together with $b \to s\ell^+\ell^-$ data. For example, common solutions of the $b \to s\ell^+\ell^-$ anomalies together with a_μ [107–112] and/or $b \to c\tau\nu$ data [64,113–123] were studied, mostly within leptoquark models, and also the CAA was correlated to $b \to s\ell^+\ell^-$ data using a heavy vector boson in the adjoint representations of $\mathrm{SU}(2)_L$ [124].

In addition to the anomalies i–iv, related to $b \to s\ell^+\ell^-$ in the context of LFU violation, there is also the long-standing discrepancy between the SM prediction and the large electron-positron collider measurement of the $Z \to b\bar{b}$ forward-backward asymmetry [125]. Here, the global fit to Zbb couplings reveals a tension of $\approx 2\sigma$ both in the left- and right-handed coupling with a strong correlation [126,127]. Interestingly, even though this observable could obviously be related to $b \to s\ell^+\ell^-$ transitions via NP coupling to the bottom quark, models providing such a connection have received surprisingly little attention in the literature so far.

In this Letter, we want to fill this gap by presenting a model that can not only provide a common explanation of $b \to s\ell^+\ell^-$ data and the $Z \to b\bar{b}$ forward-backward asymmetry but also account for $\tau \to \mu\nu\nu$ and the Cabibbo angle anomaly. Notice that a quite large effect in $Z \to b\bar{b}$ with respect to the SM is necessary (in particular, in the right-handed Zbb coupling), such that loop effects are, in general, too small to account for it. Therefore, two possibilities remain to construct a viable model: the mixing of the SM Z with a neutral Z' boson coupling to $b\bar{b}$ or vectorlike quarks (VLQs) mixing with the SM ones after electroweak (EW) symmetry breaking. While the former case can in fact account for $Z \to b\bar{b}$, it is difficult to explain simultaneously $b \to s\ell^+\ell^-$ data since the effect in $Z\mu\mu$ would be too large [128]. Concerning vectorlike quarks, there is only one representation each that gives the appropriate effect in the left- or right-handed coupling [129]. Clearly, if these vectorlike quarks mix with the strange quark as well, a modified Zsb coupling is generated. While such modified Z couplings can improve the fit in $b \to s\ell^+\ell^-$, they cannot explain the hints for LFU violation in $R(K^{(*)})$ and additional ingredients are required to fully account for all data. Therefore, we will add two new scalars (one charged and one neutral) to our particle content and extend the gauge group by a $L_\mu - L_\tau$ symmetry to obtain a LFU violating effect. Interestingly, the charged scalar turns out to have just the right quantum numbers to explain at the same time the Cabibbo angle anomaly via an effect in the determination of the Fermi constant from muon decay, while the Z' of the gauged $L_\mu - L_\tau$ symmetry improves the agreement with data in $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\tau \to e\nu\nu]$ and $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\mu \to e\nu\nu]$.

The model.—Our starting point is $Z \to b\bar{b}$, which, as outlined in the Introduction, can only be explained by adding two new heavy quarks to the SM particle content, an $\mathrm{SU}(2)_L$ doublet with hypercharge $-5/6$ (Q) and an $\mathrm{SU}(2)_L$ singlet with hypercharge $-1/3$ (D). They couple to right-handed down-type quarks and left-handed quark doublets, respectively, via the SM Higgs doublet (H) and therefore can mix with b quarks after EW symmetry breaking. Because of the stringent LHC bounds on new quarks, their mass must be larger than ≈ 1 TeV [131,132]. Therefore, the new quarks must be vectorlike under the SM gauge group such that their masses are not confined to the EW scale. However, we assume them to be chiral under a new $\mathrm{U}(1)'$ gauge group (with coupling constant g') such that they cannot be arbitrarily heavy but have masses of the order of the $\mathrm{U}(1)'$ breaking scale. In fact, we charge Q_R and D_L under $\mathrm{U}(1)'$, while Q_L and D_R are neutral. This does not only allow for the desired mixing with the SM down-type quarks but also turns out to be crucial for generating a $Z'bs$ coupling later on. All SM particles are neutral under the gauged $\mathrm{U}(1)'$ except for leptons, for which we assume an $L_\mu - L_\tau$ symmetry [133–135]. This symmetry can not only naturally generate the observed pattern from the Pontecorvo–Maki–Nakagawa–Sakata matrix [136–138], but also avoids stringent large electron-positron collider bounds on four-lepton contact interactions [139]. In addition, we introduce two $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L$ singlet scalars with $L_\mu - L_\tau$ charge of -1: one electrically neutral (S) and the other with charge $+1$ (ϕ^+). In summary, our particle content is given in Table I.

This allows for the following Yukawa-type interactions involving quarks:

$$
\begin{aligned}
-\mathcal{L}_Y^Q = {} & (Y_f^d \delta_{fi} \bar{q}_{Lf} d_{Ri} + \lambda_f^D \bar{q}_{Lf} D_R) H + \kappa_f \bar{q}_{Lf} Q_R \phi^+ \\
& + (\kappa_{RL} \bar{Q}_R D_L + \kappa_{LR} \bar{Q}_L D_R + \lambda_i^Q \bar{Q}_L d_{Ri}) \tilde{H} \\
& + (\eta_D \bar{D}_L D_R + \eta_Q \bar{Q}_R Q_L) S^\dagger + Y_{fi}^u \bar{q}_{Lf} u_{Ri} \tilde{H} + \mathrm{H.c.},
\end{aligned}
\tag{1}
$$

where $\tilde{H} = i\sigma_2 H^*$ is the complex conjugate of the SM Higgs doublet and f and i are flavor indices [140]. Here we choose to work in the down basis where Y^d is diagonal and

TABLE I. SM particle content and the scalar and fermion fields added to it in our model, together with their representations under the gauge group $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)'$. Here the bracket $(0, 1, -1)$ in the columns for left- and right-handed leptons means that we assume a $L_\mu - L_\tau$ flavor symmetry.

	q_L	d_R	u_R	H	ℓ_L	e_R	Q_L	Q_R	D_L	D_R	ϕ^+	S
$SU(3)_c$	3	3	3	1	1	1	3	3	3	3	1	1
$SU(2)_L$	2	1	1	2	2	1	2	2	1	1	1	1
$U(1)_Y$	1/6	−1/3	2/3	1/2	−1/2	−1	−5/6	−5/6	−1/3	−1/3	1	0
$U(1)'$	0	0	0	0	(0, 1, −1)	0	1	1	0	−1	−1	

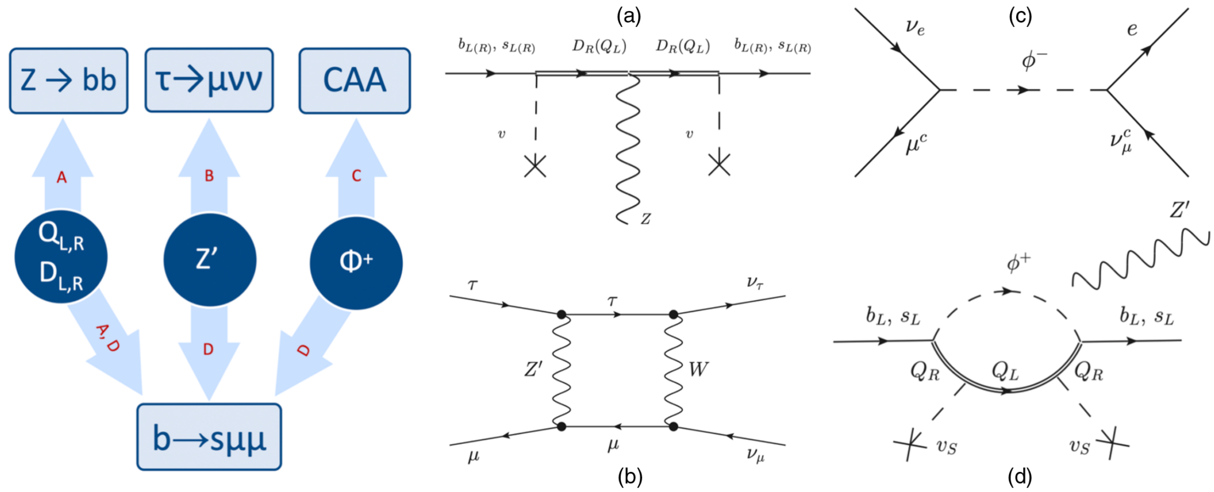

FIG. 1. Diagrammatic representation of how the Feynman diagrams (a)–(d) within our model contribute to $Z \to \bar{b}b(\bar{s}s)$, muon decay, $\tau \to \mu\nu\nu$, and $b \to s\ell\ell$ and explain the associated anomalies.

the CKM matrix originates from the up sector. In addition, there is only one possible coupling of the charged scalar to leptons allowed by our charge assignment $-\mathcal{L}_Y^{L\phi^+} = \xi \bar{L}_2^c \times L_1 \phi^+ + \mathrm{H.c.}$, where $\times$ stands for a contraction in $\mathrm{SU}(2)_L$ space via the antisymmetry tensor.

The vacuum expectation value $\langle S \rangle = v_S/\sqrt{2}$ generates masses for the Z' boson ($m_{Z'} = g' v_S$) and the VLQs ($m_Q = v_S/\sqrt{2}\eta_Q$, $m_D = v_S/\sqrt{2}\eta_D$), as well as the mass of the charged and neutral singlet [$m_\phi = \mathcal{O}(v_S)$, $m_S = \mathcal{O}(v_S)$]. After EW symmetry breaking, the quark doublet is decomposed into its components and CKM rotations generate $V_{fj}\kappa_j^\phi \bar{u}_{Lf}\phi^+ Q_R$ couplings, which will later be relevant for $D^0 - \bar{D}^0$ mixing.

Explaining the anomalies.—Let us now discuss how our model can explain the anomalies and which observables are relevant in constraining it, starting with $Zb\bar{b}$.

$Zb\bar{b}$: The mixing of the heavy quarks with the SM ones leads to desired modifications of the Zbb couplings via Fig. 1(a). Using the publicly available HEPFIT code [141], we updated the fit of Refs. [126,127], finding

$$|\lambda_b^Q|^2 = (1.12 \pm 0.46)\frac{M_Q}{\mathrm{TeV}}, \quad |\lambda_b^D|^2 = (0.18 \pm 0.09)\frac{M_Q}{\mathrm{TeV}}. \tag{2}$$

Note that this combination of couplings is not significantly constrained from other observables so that we can fully account for the anomaly.

Cabibbo angle anomaly: The Cabibbo angle anomaly originates from an (apparent) deficit in first row CKM unitarity. Equivalently, it manifests itself in a disagreement between the determinations of V_{us} from kaon and tau decays vs V_{us} from superallowed beta decays (assuming CKM unitarity). Following Ref. [103], we have

$$V_{us}^\beta = 0.2281(7), \qquad V_{us}^\beta|_{\mathrm{NNC}} = 0.2280(14), \tag{3}$$

where the latter value contains the "new nuclear corrections" (NNCs) proposed in Refs. [142,143]. Since at the moment the issue of the NNCs is not settled, we will perform our fit for both determinations. The value of V_{us}^β has to be compared to V_{us} from kaon [144] and tau decays [145]

$$V_{us}^{K_{\mu3}} = 0.22345(67), \qquad V_{us}^{K_{e3}} = 0.22320(61),$$
$$V_{us}^{K_{\mu2}} = 0.22534(42), \qquad V_{us}^{\tau} = 0.2195(19), \tag{4}$$

which are significantly lower.

The Feynman diagram [Fig. 1(c)] generates a necessarily constructive effect with respect to the SM in $\mu \to e\nu\nu$ and modifies the determination of the Fermi constant (G_F) from muon decays. While the V_{us} determination from kaon and tau decays is mostly independent of the Fermi constant, V_{us} from superallowed beta decays even has a sensitivity enhanced by V_{ud}^2/V_{us}^2 [102]. This means that the "real" Lagrangian value of V_{us} of the unitary CKM matrix in terms of the one measured from beta decays is given by

$$V_{us} = V_{us}^\beta \left(1 - \left|\frac{V_{ud}^2}{V_{us}^2}\right| \left|\frac{\xi^2}{g_2^2}\right| \frac{m_W^2}{m_\phi^2}\right). \tag{5}$$

As a modification of G_F also affects the EW sector, we included the determinations of V_{us} in Eqs. (3) and (4) into HEPFIT and performed a global fit finding

$$V_{us}^\beta : |\xi|^2 = (0.043 \pm 0.010)\frac{m_\phi^2}{\mathrm{TeV}^2},$$
$$V_{us}^\beta|_{\mathrm{NNC}} : |\xi|^2 = (0.021 \pm 0.013)\frac{m_\phi^2}{\mathrm{TeV}^2}. \tag{6}$$

Note that this range for ξ brings V_{us} from beta decays into agreement with V_{us} from $K\to\mu\nu/\pi\to\mu\nu$ [146]. Therefore, also with respect to the CAA, we improve by $\approx 2\sigma$ with respect to the SM, depending on the value of V_{us}^{β} considered.

$\tau\to\mu\nu\nu$: Let us now study the effect of the Z' in $\tau\to\mu\nu\nu$, which is modified by Fig. 1(b), resulting in [23]

$$\frac{\mathrm{Br}(\tau\to\mu\nu\bar{\nu})}{\mathrm{Br}(\tau\to e\nu\bar{\nu})_{\mathrm{SM}}}=\frac{\mathrm{Br}(\tau\to\mu\nu\bar{\nu})}{\mathrm{Br}(\mu\to e\nu\bar{\nu})_{\mathrm{SM}}}\simeq 1+\Delta, \quad (7)$$

with

$$\Delta=\frac{3(g')^2}{4\pi^2}\frac{\log(m_W^2/m_{Z'}^2)}{1-m_{Z'}^2/m_W^2}=(4.7\pm 2.3)\times 10^{-3}. \quad (8)$$

The experimental value is obtained by averaging the measurements of both ratios, including the correlation of 0.48 [145]. In particular, for $m_{Z'}=1$ TeV, we find

$$(g')^2=(1.9\pm 0.9)\frac{m_{Z'}}{\mathrm{TeV}}, \quad (9)$$

neglecting logarithmic effects. Notice that the Z' only affects the numerator of these ratios, while $\mu\to e\nu\nu$ is affected by tree-level ϕ^+ exchange as discussed above. However, the latter effect is stringently bounded by V_{us} and the EW fit such that its impact on Eq. (7) is negligible.

The Z' also contributes to neutrino trident production (NTP) [147–150] and gives rise to the loop corrections of Z couplings to charged leptons and neutrinos [23,151]. However, neither these effects nor NTP are in conflict with the preferred region from $\tau\to\mu\nu\nu/\tau\to e\nu\nu$ and $\tau\to\mu\nu\nu/\mu\to e\nu\nu$. Therefore, we can obtain the best fit point for $\mathrm{Br}[\tau\to\mu\nu\nu]/\mathrm{Br}[\tau\to e\nu\nu]$ and $\mathrm{Br}[\tau\to\mu\nu\nu]/\mathrm{Br}[\mu\to e\nu\nu]$ and thus improve on the SM by more than 2σ.

$b\to s\ell^+\ell^-$: Here we want to explain $b\to s\ell^+\ell^-$ data with a combination of a LFU effect from modified Zsb coupling [Fig. 1(d)] and a LFU violating one originating from the Z' [Fig. 1(a)]. The former one is generated at tree level via the mixing of the vectorlike quark with SM quarks and it is given by

$$\frac{C_{9^{(\prime)}}^U}{1-4s_w^2}=-C_{10^{(\prime)}}^U=\frac{2\pi^2}{e^2M_Q^2}\frac{\lambda_s^{Q(D*)}\lambda_b^{Q*(D)}}{\sqrt{2}G_FV_{tb}V_{ts}^*}, \quad (10)$$

in the conventions of Ref. [84]. For the latter one, the $Z'sb$ coupling is generated at the loop level through diagrams like the one shown in Fig. 1. We parametrize the effective Z' coupling to down quarks generically as

$$\mathcal{L}=\bar{d}_f\gamma^\mu(\Delta_{fi}^{\prime dL}P_L+\Delta_{fi}^{\prime dR}P_R)Z'_\mu d_i \quad (11)$$

and obtain

$$\Delta_{fi}^{\prime dL}=g'\frac{\kappa_f^\phi\kappa_i^{\phi*}}{16\pi^2}\frac{-x+x\log(x)+1}{(x-1)^2}, \quad (12)$$

with $x=m_\phi^2/M_Q^2$. This results in the purely LFU violating effects

$$C_{9\mu}^V=-\frac{16\pi^2}{e^2}\frac{\Delta_{23}^{\prime dL}(\Delta_{22}^{\prime\ell R}+\Delta_{22}^{\prime\ell L})}{4\sqrt{2}G_FM_{Z'}^2V_{tb}V_{ts}^*}. \quad (13)$$

Performing a global fit within this scenario [152] we find a pull of 6.1σ with respect to the SM and a p value of 47.5%. The best fit points and 1σ C.L. intervals for the Wilson coefficients are

$$C_{9\mu}^V=-1.06\pm 0.16,$$
$$C_{10'}^U=-0.24\pm 0.17,\qquad C_{10}^U=0.18\pm 0.19. \quad (14)$$

However, $b\to s\ell^+\ell^-$ cannot be explained without affecting $\Delta F=2$ processes. While tree-level Z and Z' effects turn out to be negligible (due to the tiny sb couplings), ϕ^+ box contributions generate

$$C_1^{\phi^+}=\frac{(\kappa_s^\phi\kappa_b^{\phi*})^2}{128\pi^2}\frac{m_\phi^4-2m_\phi^2m_Q^2\log\frac{m_\phi^2}{m_Q^2}-m_Q^4}{(m_\phi^2-m_Q^2)^3}, \quad (15)$$

following the conventions in Ref. [153]. Including the two-loop renormalization group equation of Ref. [154,155] and the bag factor of Ref. [144], we find at the B_s meson scale

$$\frac{\Delta m_{B_s}}{\Delta m_{B_s}^{\mathrm{SM}}}=1+1.1C_1^{\phi^+}\times 10^{10}\ \mathrm{GeV}^2=1.11\pm 0.09, \quad (16)$$

for real NP contributions according to the global fit of Ref. [156]. Similarly, we get a bound from CP violation in the $D^0-\bar{D}^0$ system [157,158]

$$2.3|\mathrm{Im}[C_1^{D^0-\bar{D}^0}]|\times 10^{12}\ \mathrm{GeV}^2<0.033, \quad (17)$$

with $C_1^{D^0-\bar{D}^0}$ obtained from Eq. (15) by replacing $\kappa_s^\phi\kappa_b^{\phi*}$ with $V_{us}\kappa_s^\phi(V_{cs}^*\kappa_s^{\phi*}+V_{cb}^*\kappa_b^{\phi*})$. For the experimental limit, we assumed that the SM contribution to CP violation in $D^0-\bar{D}^0$ mixing is negligible.

Turning to the phenomenological analysis, notice that we can generate $C_{10^{(\prime)}}^U$ from the modified Zbs couplings without generating a relevant effect in $B_s-\bar{B}_s$ mixing. Therefore, we can account for the full range of values for $C_{10^{(\prime)}}^U$ preferred by the fit to $b\to s\ell^+\ell^-$ data. Similarly, note that generating $C_{9\mu}^V$ from the Z' penguins also gives rise to an effect in $D^0-\bar{D}^0$ mixing due to CKM rotations. However, the resulting constraint is subleading for $\kappa_b>\kappa_s$. Therefore, we find the results shown in Fig. 2, from which it is clear that we can reach the best fit point for

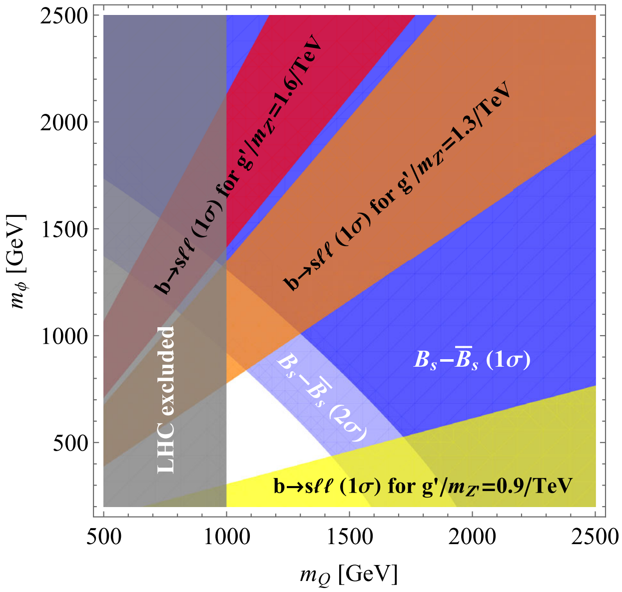

FIG. 2. Preferred and excluded regions in the $m_Q - m_\phi$ plane for $\kappa_s \kappa_s^* = -0.3$ and $m_Q = m_D$. Note that for $m_Q m_\phi > 1.5$ TeV^2 one can account for $b \to s\ell^+\ell^-$ data while being in agreement with $B_s - \bar{B}_s$ mixing at the 1σ level.

$b \to s\ell^+\ell^-$ without being in conflict with $B_s - \bar{B}_s$ mixing while choosing $g'/m_{Z'}$ as preferred by $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\tau \to e\nu\nu]$ and $\mathrm{Br}[\tau \to \mu\nu\nu]/\mathrm{Br}[\mu \to e\nu\nu]$. Note that LHC bounds are not important here due to the small couplings to quarks. Therefore, we can improve the fit compared to the SM by 6.1σ in the $b \to s\ell^+\ell^-$ alone [159].

Conclusions and outlook.—In this Letter, we proposed a simple model obtained from the SM by adding (i) two heavy quarks that are vectorlike (Q and D) under the SM gauge group, (ii) a gauged $L_\mu - L_\tau$ symmetry resulting in a Z' boson, and (iii) a neutral and a singly charged scalar, singlet under color and weak isospin, (S and ϕ^+) with $L_\mu - L_\tau$ charge -1. This model can explain (1) the $Z \to b\bar{b}$ forward-backward asymmetry via the mixing of the vectorlike quarks with the SM bottom quark, (2) the Cabibbo angle anomaly via a positive definite shift in G_F induced by the singly charged scalar, and (3) $\tau \to \mu\nu\nu/\tau \to e\nu\nu$ and $\tau \to \mu\nu\nu/\mu \to e\nu\nu$ via the box contributions involving the Z', and (4) it accounts for $b \to s\ell^+\ell^-$ data through a modified Z coupling and a loop-induced Z' effect without being in conflict with $B_s - \bar{B}_s$ mixing. This is illustrated in Fig. 1.

Therefore, our model describes data significantly better than the SM and constitutes the first unified explanation of all four anomalies. With new particles at the TeV scale, it provides interesting discovery potential for the (high-energy) LHC [161] and the Future Circular Collider (FCC)-hh [162], but could also be indirectly verified through Z pole observables by the FCC-ee [163], International Linear Collider [164], Circular Electron Positron Collider [165], or Compact Linear Collider [166]. Also BELLE II is sensitive to the $Z \to b\bar{b}$ asymmetry via $e^+e^- \to b\bar{b}$ measurements with polarized electron beams [167]. Furthermore, precision measurements of τ decays at BELLE II [168] and of course the pattern predicted in $b \to s\ell^+\ell^-$ at the (high-luminosity) LHC [169] and BELLE II [168] could test our model.

In this Letter, we presented the minimal model capable of providing an explanation of the hints for NP. As it possesses gauge anomalies, it is interesting to look for extensions that are free of this obstacle (see, e.g., Refs. [57,170] for accounts in the context of $b \to s\ell\ell$). For example, by adding two more heavy quarks $Q'_{L,R}$ and $D'_{L,R}$ with the same representation under $\mathrm{SU}(3) \times \mathrm{SU}(2)_L$ as $Q_{L,R}$ and $D_{L,R}$, but with opposite $\mathrm{U}(1)_Y$ and $\mathrm{U}(1)'$ charge, this can be easily achieved without any significant effect on the phenomenology. In general, embedding our model into a more unified framework would be very interesting and opens up novel avenues for model building.

The work of A. C. is supported by a Professorship Grant (No. PP00P2_176884) of the Swiss National Science Foundation. J. M. gratefully acknowledges the financial support by ICREA under the ICREA Academia Programme. J. M. and M. A. received financial support from Spanish Ministry of Science, Innovation and Universities (Project No. FPA2017-86989-P) and from the Research Grant Agency of the Government of Catalonia (Project No. SGR 1069).

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[1] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, J. High Energy Phys. 01 (2018) 093.

[2] W. Altmannshofer, P. Stangl, and D. M. Straub, Phys. Rev. D **96**, 055008 (2017).

[3] G. D'Amico, M. Nardecchia, P. Panci, F. Sannino, A. Strumia, R. Torre, and A. Urbano, J. High Energy Phys. 09 (2017) 010.

[4] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, Eur. Phys. J. C **77**, 688 (2017).

[5] G. Hiller and I. Nisandzic, Phys. Rev. D **96**, 035003 (2017).

[6] L.-S. Geng, B. Grinstein, S. Jäger, J. Martin Camalich, X.-L. Ren, and R.-X. Shi, Phys. Rev. D **96**, 093006 (2017).

[7] T. Hurth, F. Mahmoudi, D. Martinez Santos, and S. Neshatpour, Phys. Rev. D **96**, 095034 (2017).

[8] A. K. Alok, B. Bhattacharya, A. Datta, D. Kumar, J. Kumar, and D. London, Phys. Rev. D **96**, 095009 (2017).

[9] M. Algueró, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias, M. Novoa Brunet, and J. Virto, Eur. Phys. J. C **79**, 714 (2019); **80**, 511(A) (2020).

[10] J. Aebischer, W. Altmannshofer, D. Guadagnoli, M. Reboud, P. Stangl, and D. M. Straub, Eur. Phys. J. C **80**, 252 (2020).

[11] M. Ciuchini, A. M. Coutinho, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, Eur. Phys. J. C **79**, 719 (2019).

[12] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 06 (2014) 133.

[13] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **113**, 151601 (2014).

[14] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 09 (2015) 179.

[15] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 02 (2016) 104.

[16] V. Khachatryan *et al.* (CMS Collaboration), Phys. Lett. B **753**, 424 (2016).

[17] ATLAS Collaboration, Report No. ATLAS-CONF-2017-023, 2017.

[18] CMS Collaboration, Report No. CMS-PAS-BPH-15-008, 2017.

[19] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 08 (2017) 055.

[20] A. J. Buras and J. Girrbach, J. High Energy Phys. 12 (2013) 009.

[21] R. Gauld, F. Goertz, and U. Haisch, Phys. Rev. D **89**, 015005 (2014).

[22] R. Gauld, F. Goertz, and U. Haisch, J. High Energy Phys. 01 (2014) 069.

[23] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. D **89**, 095033 (2014).

[24] A. Crivellin, G. D'Ambrosio, and J. Heeck, Phys. Rev. Lett. **114**, 151801 (2015).

[25] A. Crivellin, G. D'Ambrosio, and J. Heeck, Phys. Rev. D **91**, 075006 (2015).

[26] C. Niehoff, P. Stangl, and D. M. Straub, Phys. Lett. B **747**, 182 (2015).

[27] A. Carmona and F. Goertz, Phys. Rev. Lett. **116**, 251801 (2016).

[28] A. Falkowski, M. Nardecchia, and R. Ziegler, J. High Energy Phys. 11 (2015) 173.

[29] A. Celis, W.-Z. Feng, and D. Lüst, J. High Energy Phys. 02 (2016) 007.

[30] A. Celis, J. Fuentes-Martin, M. Jung, and H. Serodio, Phys. Rev. D **92**, 015007 (2015).

[31] A. Crivellin, L. Hofer, J. Matias, U. Nierste, S. Pokorski, and J. Rosiek, Phys. Rev. D **92**, 054013 (2015).

[32] C.-W. Chiang, X.-G. He, and G. Valencia, Phys. Rev. D **93**, 074003 (2016).

[33] A. Crivellin, J. Fuentes-Martin, A. Greljo, and G. Isidori, Phys. Lett. B **766**, 77 (2017).

[34] I. Garcia Garcia, J. High Energy Phys. 03 (2017) 040.

[35] W. Altmannshofer, M. Carena, and A. Crivellin, Phys. Rev. D **94**, 095026 (2016).

[36] G. Faisel and J. Tandean, J. High Energy Phys. 02 (2018) 074.

[37] S. F. King, J. High Energy Phys. 08 (2017) 019.

[38] C.-W. Chiang, X.-G. He, J. Tandean, and X.-B. Yuan, Phys. Rev. D **96**, 115022 (2017).

[39] S. Di Chiara, A. Fowlie, S. Fraser, C. Marzo, L. Marzola, M. Raidal, and C. Spethmann, Nucl. Phys. **B923**, 245 (2017).

[40] P. Ko, Y. Omura, Y. Shigekami, and C. Yu, Phys. Rev. D **95**, 115040 (2017).

[41] F. Sannino, P. Stangl, D. M. Straub, and A. E. Thomsen, Phys. Rev. D **97**, 115046 (2018).

[42] A. Falkowski, S. F. King, E. Perdomo, and M. Pierre, J. High Energy Phys. 08 (2018) 061.

[43] R. H. Benavides, L. Muñoz, W. A. Ponce, O. Rodriguez, and E. Rojas, J. Phys. G **47**, 075003 (2020).

[44] P. Maji, P. Nayek, and S. Sahoo, Prog. Theor. Exp. Phys. **2019**, 033B06 (2019).

[45] S. Singirala, S. Sahoo, and R. Mohanta, Phys. Rev. D **99**, 035042 (2019).

[46] D. Guadagnoli, M. Reboud, and O. Sumensari, J. High Energy Phys. 11 (2018) 163.

[47] B. Allanach and J. Davighi, J. High Energy Phys. 12 (2018) 075.

[48] G. H. Duan, X. Fan, M. Frank, C. Han, and J. M. Yang, Phys. Lett. B **789**, 54 (2019).

[49] S. F. King, J. High Energy Phys. 09 (2018) 069.

[50] M. Kohda, T. Modak, and A. Soffer, Phys. Rev. D **97**, 115019 (2018).

[51] S. Dwivedi, D. Kumar Ghosh, A. Falkowski, and N. Ghosh, Eur. Phys. J. C **80**, 263 (2020).

[52] P. Foldenauer, Ph.D. thesis, University Heidelberg (main), 2019.

[53] P. Ko, T. Nomura, and C. Yu, J. High Energy Phys. 04 (2019) 102.

[54] B. Allanach and J. Davighi, Eur. Phys. J. C **79**, 908 (2019).

[55] W. Altmannshofer, J. Davighi, and M. Nardecchia, Phys. Rev. D **101**, 015004 (2020).

[56] L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari, and L. Vernazza, Phys. Rev. D **101**, 095003 (2020).

[57] J. Aebischer, A. J. Buras, M. Cerdà-Sevilla, and F. De Fazio, J. High Energy Phys. 02 (2020) 183.

[58] F. J. De Anda and S. F. King, J. High Energy Phys. 03 (2021) 078.

[59] J. Kawamura, S. Raby, and A. Trautner, Phys. Rev. D **100**, 055030 (2019).

[60] G. Hiller, D. Loose, and K. Schönwald, J. High Energy Phys. 12 (2016) 027.

[61] R. Barbieri, G. Isidori, A. Pattori, and F. Senia, Eur. Phys. J. C **76**, 67 (2016).

[62] R. Barbieri, C. W. Murphy, and F. Senia, Eur. Phys. J. C **77**, 8 (2017).

[63] A. Crivellin, D. Müller, A. Signer, and Y. Ulrich, Phys. Rev. D **97**, 015019 (2018).

[64] A. Crivellin, C. Greub, F. Saturnino, and D. Müller, Phys. Rev. Lett. **122**, 011805 (2019).

[65] M. Bordone, C. Cornella, and J. Fuentes-Martín, and G. Isidori, J. High Energy Phys. 10 (2018) 148.

[66] A. Crivellin and F. Saturnino, Proc. Sci. DIS2019 (**2019**) 163 [arXiv:1906.01222].

[67] M. Bordone, O. Catà, and T. Feldmann, J. High Energy Phys. 01 (2020) 067.

[68] J. Bernigaud, I. de Medeiros Varzielas, and J. Talbert, J. High Energy Phys. 01 (2020) 194.

[69] J. Aebischer, A. Crivellin, and C. Greub, Phys. Rev. D **99**, 055002 (2019).

[70] J. Fuentes-Martin, G. Isidori, M. König, and N. Selimović, Phys. Rev. D **101**, 035024 (2020).

[71] S. Fajfer and N. Košnik, Phys. Lett. B **755**, 270 (2016).

[72] I. de Medeiros Varzielas and J. Talbert, Eur. Phys. J. C **79**, 536 (2019).
[73] I. de Medeiros Varzielas and G. Hiller, J. High Energy Phys. 06 (2015) 072.
[74] S. Saad, Phys. Rev. D **102**, 015019 (2020).
[75] S. Saad and A. Thapa, Phys. Rev. D **102**, 015014 (2020).
[76] V. Gherardi, D. Marzocca, and E. Venturini, J. High Energy Phys. 01 (2021) 138.
[77] M. Bordone, O. Cata, T. Feldmann, and R. Mandal, J. High Energy Phys. 03 (2021) 122.
[78] J. Aebischer, A. Crivellin, M. Fael, and C. Greub, J. High Energy Phys. 05 (2016) 037.
[79] J. F. Kamenik, Y. Soreq, and J. Zupan, Phys. Rev. D **97**, 035002 (2018).
[80] B. Gripaios, M. Nardecchia, and S. Renner, J. High Energy Phys. 06 (2016) 083.
[81] P. Arnan, L. Hofer, F. Mescia, and A. Crivellin, J. High Energy Phys. 04 (2017) 043.
[82] B. Grinstein, S. Pokorski, and G. Ross, J. High Energy Phys. 12 (2018) 079.
[83] P. Arnan, A. Crivellin, M. Fedele, and F. Mescia, J. High Energy Phys. 06 (2019) 118.
[84] M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, and J. Matias, Phys. Rev. D **99**, 075017 (2019).
[85] J. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **109**, 101802 (2012).
[86] J. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **88**, 072012 (2013).
[87] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 111803 (2015); **115**, 159901(E) (2015).
[88] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **97**, 072013 (2018).
[89] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **120**, 171802 (2018).
[90] A. Abdesselam *et al.* (Belle Collaboration), arXiv:1904.08794.
[91] Y. Amhis *et al.* (HFLAV Collaboration), Eur. Phys. J. C **77**, 895 (2017).
[92] C. Murgui, A. Peñuelas, M. Jung, and A. Pich, J. High Energy Phys. 09 (2019) 103.
[93] R.-X. Shi, L.-S. Geng, B. Grinstein, S. Jäger, and J. Martin Camalich, J. High Energy Phys. 12 (2019) 065.
[94] M. Blanke, A. Crivellin, T. Kitahara, M. Moscati, U. Nierste, and I. Nišandžić, Phys. Rev. D **100**, 035035(A) (2019).
[95] S. Kumbhakar, A. K. Alok, D. Kumar, and S. U. Sankar, Proc. Sci. EPS-HEP2019 (**2020**) 272 [arXiv:1909.02840].
[96] G. Bennett *et al.* (Muon g-2 Collaboration), Phys. Rev. D **73**, 072003 (2006).
[97] T. Aoyama *et al.*, Phys. Rep. **887**, 1 (2020).
[98] B. Belfatto, R. Beradze, and Z. Berezhiani, Eur. Phys. J. C **80**, 149 (2020).
[99] Y. Grossman, E. Passemar, and S. Schacht, J. High Energy Phys. 07 (2020) 068.
[100] C.-Y. Seng, X. Feng, M. Gorchtein, and L.-C. Jin, Phys. Rev. D **101**, 111301(R) (2020).
[101] A. M. Coutinho, A. Crivellin, and C. A. Manzari, Phys. Rev. Lett. **125**, 071802 (2020).
[102] A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **125**, 111801 (2020).
[103] A. Crivellin, F. Kirk, C. A. Manzari, and M. Montull, J. High Energy Phys. 12 (2020) 166.
[104] C. A. Manzari, A. M. Coutinho, and A. Crivellin, Proc. Sci. LHCP2020 (**2021**) 242 [arXiv:2009.03877].
[105] M. Kirk, Phys. Rev. D **103**, 035004 (2021).
[106] A. K. Alok, A. Dighe, S. Gangal, and J. Kumar, arXiv:2010.12009.
[107] M. Bauer and M. Neubert, Phys. Rev. Lett. **116**, 141802 (2016).
[108] G. Bélanger, C. Delaunay, and S. Westhoff, Phys. Rev. D **92**, 055021 (2015).
[109] A. Crivellin, D. Müller, and C. Wiegand, J. High Energy Phys. 06 (2019) 119.
[110] A. Crivellin, D. Müller, and F. Saturnino, J. High Energy Phys. 06 (2020) 020.
[111] W. Altmannshofer, P. S. Bhupal Dev, A. Soni, and Y. Sui, Phys. Rev. D **102**, 015031 (2020).
[112] D. Huang, A. P. Morais, and R. Santos, Phys. Rev. D **102**, 075009 (2020).
[113] R. Alonso, B. Grinstein, and J. Martin Camalich, J. High Energy Phys. 10 (2015) 184.
[114] B. Bhattacharya, A. Datta, D. London, and S. Shivashankara, Phys. Lett. B **742**, 370 (2015).
[115] L. Calibbi, A. Crivellin, and T. Ota, Phys. Rev. Lett. **115**, 181801 (2015).
[116] B. Bhattacharya, A. Datta, J.-P. Guévin, D. London, and R. Watanabe, J. High Energy Phys. 01 (2017) 015.
[117] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, J. High Energy Phys. 11 (2017) 044.
[118] L. Di Luzio, A. Greljo, and M. Nardecchia, Phys. Rev. D **96**, 115011 (2017).
[119] L. Calibbi, A. Crivellin, and T. Li, Phys. Rev. D **98**, 115002 (2018).
[120] M. Blanke and A. Crivellin, Phys. Rev. Lett. **121**, 011801 (2018).
[121] J. Kumar, D. London, and R. Watanabe, Phys. Rev. D **99**, 015007 (2019).
[122] C. Cornella, J. Fuentes-Martin, and G. Isidori, J. High Energy Phys. 07 (2019) 168.
[123] K. Babu, P. B. Dev, S. Jana, and A. Thapa, J. High Energy Phys. 03 (2021) 179.
[124] B. Capdevila, A. Crivellin, C. A. Manzari, and M. Montull, Phys. Rev. D **103**, 015032 (2021).
[125] J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **40**, 1 (2005).
[126] J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, and L. Silvestrini, J. High Energy Phys. 12 (2016) 135.
[127] J. de Blas, M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, and L. Silvestrini, Proc. Sci. ICHEP2016 (**2017**) 690 [arXiv:1611.05354].
[128] L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari, and L. Vernazza, Phys. Rev. D **101**, 095003 (2020).
[129] There is a second $SU(2)_L$ doublet VLQ which contributes with opposite sign to the right-handed $Zb\bar{b}$ couplings. This VLQ could only account for the anomaly via an overcompensation in the fit, which is in conflict with other EW data and $b \to s\gamma$ [130].
[130] B. Batell, S. Gori, and L.-T. Wang, J. High Energy Phys. 01 (2013) 139.

[131] M. Aaboud *et al.* (ATLAS Collaboration), Phys. Rev. D **98**, 112010 (2018).

[132] CMS Collaboration, Report No. CMS-PAS-B2G-17-018, 2018.

[133] X. G. He, G. C. Joshi, H. Lew, and R. R. Volkas, Phys. Rev. D **43**, 22(R) (1991).

[134] R. Foot, Mod. Phys. Lett. A **06**, 527 (1991).

[135] X.-G. He, G. C. Joshi, H. Lew, and R. R. Volkas, Phys. Rev. D **44**, 2118 (1991).

[136] P. Binetruy, S. Lavignac, S. T. Petcov, and P. Ramond, Nucl. Phys. **B496**, 3 (1997).

[137] N. F. Bell and R. R. Volkas, Phys. Rev. D **63**, 013006 (2000).

[138] S. Choubey and W. Rodejohann, Eur. Phys. J. C **40**, 259 (2005).

[139] S. Schael *et al.* (ALEPH, DELPHI, L3, OPAL, LEP Electroweak Collaborations), Phys. Rep. **532**, 119 (2013).

[140] Note that, in addition to the terms in Eq. (1), one could have a term $\lambda_i^S \bar{D}_L d_i S^\dagger$, which, however, without loss of generality, can be removed by rotations of d_i, D_R, and an appropriate redefinition of the couplings.

[141] J. De Blas *et al.*, Eur. Phys. J. C **80**, 456 (2020).

[142] C. Y. Seng, M. Gorchtein, and M. J. Ramsey-Musolf, Phys. Rev. D **100**, 013001 (2019).

[143] M. Gorchtein, Phys. Rev. Lett. **123**, 042503 (2019).

[144] S. Aoki *et al.* (Flavour Lattice Averaging Group Collaboration), Eur. Phys. J. C **80**, 113 (2020).

[145] Y. S. Amhis *et al.* (HFLAV Collaboration), Eur. Phys. J. C **81**, 226 (2021).

[146] There is a small correlation between the NP effect in G_F and $Z \to b\bar{b}$ such that for the central value of ξ/m_ϕ only a smaller NP effect in left-handed Zbb coupling is needed.

[147] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, Phys. Rev. Lett. **113**, 091801 (2014).

[148] D. Geiregat *et al.* (CHARM-II Collaboration), Phys. Lett. B **245**, 271 (1990).

[149] S. Mishra *et al.* (CCFR Collaboration), Phys. Rev. Lett. **66**, 3117 (1991).

[150] T. Adams *et al.* (NuTeV Collaboration), in *Proceedings of the 29th International Conference on High-Energy Physics* (1998), pp. 631–634.

[151] U. Haisch and S. Westhoff, J. High Energy Phys. 08 (2011) 088.

[152] Note that in the simpler case with only the VLQ Q (but not D) we would obtain to a good approximation scenario 11 of Ref. [9] with a pull of 6.3σ.

[153] M. Ciuchini *et al.*, J. High Energy Phys. 10 (1998) 008.

[154] M. Ciuchini, E. Franco, V. Lubicz, G. Martinelli, I. Scimemi, and L. Silvestrini, Nucl. Phys. **B523**, 501 (1998).

[155] A. J. Buras, M. Misiak, and J. Urban, Nucl. Phys. **B586**, 397 (2000).

[156] M. Bona *et al.* (UTfit Collaboration), J. High Energy Phys. 03 (2008) 049.

[157] A. Bevan *et al.* (UTfit Collaboration), J. High Energy Phys. 03 (2014) 123.

[158] A. Bazavov *et al.*, Phys. Rev. D **98**, 074512 (2018).

[159] Note that recasting the ATLAS analysis [160] for our Z' we find that bounds are not constraining since the couplings to quarks are not only loop induced and therefore small, but also the production cross section is reduced by the small bottom parton distribution function.

[160] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **796**, 68 (2019).

[161] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. Special Topics **228**, 1109 (2019).

[162] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. Special Topics **228**, 755 (2019).

[163] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. Special Topics **228**, 261 (2019).

[164] H. Baer *et al.*, The International Linear Collider Technical Design Report—Volume **2**: Physics, arXiv:1306.6352.

[165] F. An *et al.*, Chin. Phys. C **43**, 043002 (2019).

[166] A Multi-TeV Linear Collider Based on CLIC Technology: CLIC Conceptual Design Report (2012).

[167] J. M. Roney, Proc. Sci. LeptonPhoton2019 (**2019**) 109 [arXiv:1907.03503].

[168] W. Altmannshofer *et al.* (Belle-II Collaboration), Prog. Theor. Exp. Phys. **2019**, 123C01 (2019); **2020**, 029201(E) (2020).

[169] A. Cerri *et al.*, CERN Yellow Rep. Monogr. **7**, 867 (2019).

[170] J. Ellis, M. Fairbairn, and P. Tunney, Eur. Phys. J. C **78**, 238 (2018).