

Z' models with less-minimal flavor violationLorenzo Calibbi^{*}*School of Physics, Nankai University, Tianjin 300071, China*Andreas Crivellin,[†] Fiona Kirk,[‡] and Claudio Andrea Manzari[§]
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We study the phenomenology of simplified Z' models with a global $U(2)^3$ flavor symmetry in the quark sector, broken solely by the Standard Model Yukawa couplings. This flavor symmetry, known as less-minimal flavor violation, protects $\Delta F = 2$ processes from dangerously large new physics (NP) effects and at the same time provides a free complex phase in $b \rightarrow s$ transitions, allowing for an explanation of the hints for additional direct CP violation in kaon decays (ϵ'/ϵ) and in hadronic B -decays ($B \rightarrow K\pi$ puzzle). Furthermore, including the couplings of the Z' boson to the leptons, it is possible to address the intriguing hints for NP (above the 5σ level) in $b \rightarrow s\ell^+\ell^-$ transitions. Taking into account all flavor observables in a global fit, we find that our model can (for the first time) provide a common explanation for ϵ'/ϵ , the $B \rightarrow K\pi$ puzzle and $b \rightarrow s\ell^+\ell^-$ data. Sizeable CP violation in $b \rightarrow s\ell^+\ell^-$ observables, in particular A_8 , is predicted, which can be tested in the near future, and an explanation of the $B \rightarrow K\pi$ and ϵ'/ϵ puzzles leads to effects in dijet tails at the LHC that are not far below the current limits. If we require that also $b \rightarrow s\ell^+\ell^-$ anomalies are explained, cancellations in dimuon tails (possibly by a second Z') are needed to satisfy LHC data.

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I. INTRODUCTION

The Standard Model (SM) of particle physics has been very successfully tested with great precision in the last decades. However, it is well known that it cannot be the ultimate theory describing the fundamental constituents and interactions of matter. For example, in order to generate the matter antimatter asymmetry of the Universe, the Sakharov criteria [1] must be satisfied, one of which is the presence of CP violation. Since the amount of CP violation within the SM is far too small to achieve the observed matter antimatter asymmetry [2–7], physics beyond the SM with additional sources of CP violation

is required. New sources of CP violation could also reconcile the theory prediction [8–12]¹ for direct CP violation in kaon decays (ϵ'/ϵ) with the experimental measurements [17–19]. Similarly, the long-standing “ $B \rightarrow K\pi$ puzzle” [20–23], whose tension [24,25] was recently increased by LHCb data [26], can be explained [27].

It has been shown that models with an additional neutral gauge boson, so-called Z' models, not only explain ϵ'/ϵ [28–33], but also provide a promising solution to the $B \rightarrow K\pi$ puzzle [34–40], since they affect electroweak penguin operators [41,42]. Furthermore, the anomalies in $b \rightarrow s\ell^+\ell^-$ data [43–50], which, using a global fit, convincingly point towards NP [51–60], can be explained within Z' models [61–89]. Z' bosons are thus prime candidates for a common explanation of these anomalies and can lead to interesting correlations between $B \rightarrow K\pi$ and $b \rightarrow s\ell^+\ell^-$ [40]. However, a common explanation of ϵ'/ϵ , hadronic B decays and $b \rightarrow s\ell^+\ell^-$ has not been presented in the literature yet.

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¹These predictions are based on lattice and dual QCD. Calculations using chiral perturbation theory [13–16] are consistent with the experimental value but have large errors.

For explaining all three anomalies (ϵ'/ϵ , $B \rightarrow K\pi$ and $b \rightarrow s\ell^+\ell^-$), small flavor changing couplings to quarks are required that respect the bounds from $\Delta F = 2$ processes. In particular, in Z' models the couplings to the first two generations of left-handed quarks must be (nearly) equal, such that the rotations by the Cabibbo-Kobayashi-Maskawa (CKM) matrix do not cause dangerously large effects (in $D - \bar{D}$ and/or $K - \bar{K}$ mixing). Furthermore, as recently shown in Ref. [27], the $d - s$ and $s - b$ couplings of the Z' should, after factoring out CKM elements, be of the same order in a common explanation of ϵ'/ϵ and the $B \rightarrow K\pi$ puzzle. Both the smallness of the flavor changing couplings, as well as the required scaling of $s \rightarrow d$ versus $b \rightarrow s$ transitions (including a free phase in the latter), point towards a $U(2)^3$ flavor symmetry in the quark sector [90–97],² also known as “less-minimal flavor violation.”

In this paper we will examine Z' models in conjunction with a global $U(2)^3$ flavor symmetry. We will work in a simplified framework which only specifies the charges³ of the SM fermions under the new Abelian $U(1)'$ gauge symmetry, but not the symmetry breaking sector. We will not impose anomaly cancellation [102] either, which can be solved at an arbitrary high scale [103–105]. In order to asses the consistency of our model with LHC searches, we consider the bounds on 4-fermion operators (rather than resonant searches), which are model-independent for heavy Z' -bosons, since they only depend on the ratio of coupling over mass. In fact, given the large mass and width of the Z' , we assume the signal of Z' production at the LHC would resemble that of a contact interaction, namely, a modification in the tails of the dijet and dilepton distributions.

The article is structured as follows: In the next section we will establish our setup and discuss the relevant observables in more detail. Then we will derive less minimal flavor violation applied to Z' models in Sec. III, before performing the phenomenological analysis in Sec. IV. Finally, we conclude in Sec. V.

II. SETUP AND OBSERVABLES

Let us first review the relevant observables within a generic Z' model with arbitrary couplings to SM fermions, defined by

$$\mathcal{L} = \sum_{f=u,d,\ell,\nu} \bar{f}_i \gamma^\mu (\Gamma_{ij}^{fL} P_L + \Gamma_{ij}^{fR} P_R) f_j Z'_\mu. \quad (1)$$

We denote the mass of the Z' by $M_{Z'}$. As outlined in the Introduction, we will assume a simplified setup in which the Z' boson originates from a new $U(1)'$ gauge group with

²Similarly, “standard” minimal flavor violation [98–100] (MFV) is based on $U(3)^3$ [101]; however, $U(3)^3$ is strongly broken to $U(2)^3$ by the large third-generation Yukawa couplings.

³We will refer to charges here, but our approach also applies to effective couplings induced e.g., by vectorlike fermions [33].

the gauge coupling g' and charges \mathcal{Q} , but will not specify the corresponding symmetry breaking mechanism, which is very model-dependent.

A. ϵ'/ϵ

For ϵ'/ϵ , we follow the conventions of Ref. [106] and use

$$\mathcal{H}_{\Delta S=1} = -\sum_i \frac{C_i(\mu_{ew})}{(1 \text{ TeV})^2} O_i. \quad (2)$$

In order to achieve a numerically large effect, isospin violation (physics that couples differently to up and down quarks) is necessary [107]. Since the left-handed current respects isospin due to $SU(2)_L$ gauge invariance, only the operators,

$$O_{VLR}^q = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha) (\bar{q}^\beta \gamma^\mu P_R q^\beta), \quad (3)$$

with $q = u, d$ and the color indices α and β , are relevant for Z' models. The matching to our model leads to the Wilson coefficient,

$$C_{VLR}^q = -\Gamma_{21}^{dL} \Gamma_{11}^{qR} \frac{1 \text{ TeV}^2}{M_{Z'}^2}, \quad (4)$$

that contributes to ϵ'/ϵ as follows:

$$\left(\frac{\epsilon'}{\epsilon}\right)_{BSM} \approx 124 \Im[C_{VLR}^d - C_{VLR}^u], \quad (5)$$

for a matching scale of 1 TeV [106].

The experimental average for ϵ'/ϵ of the NA48 [17] and KTeV [18,19] Collaborations,

$$(\epsilon'/\epsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}, \quad (6)$$

lies significantly above the SM prediction,

$$(\epsilon'/\epsilon)_{\text{SM}} \approx (1.5 \pm 5.5) \times 10^{-4}, \quad (7)$$

which is based on lattice QCD results [10,108] and perturbative NLO calculations [9,11].

B. Hadronic B -decays

For hadronic B -decays (HBD) involving $b \rightarrow s$ transitions we use the effective Hamiltonian,

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{q=u,d,s,c} (C_5^q O_5^q + C_6^q O_6^q) + \text{H.c.} \quad (8)$$

At tree-level only the Wilson coefficient,

$$C_5^q = -\frac{\sqrt{2}}{4G_F V_{tb} V_{ts}^*} \Gamma_{23}^{dL} \Gamma_{11}^{qR} \frac{1}{M_{Z'}^2}, \quad (9)$$

of the operator,

$$O_5^q = (\bar{s}\gamma^\mu P_L b)(\bar{q}\gamma_\mu P_R q) \quad (10)$$

(with $q = u, d$) is generated. As in the case of ϵ'/ϵ , the effect from $q = s, c, b, t$ is numerically very small and can thus be neglected.

For the numerical analysis we will rely on the global fit of Ref. [37], recently updated in Ref. [27].

C. $\Delta F = 2$ processes

For concreteness, we give the formula for kaon mixing, following the conventions of Ref. [109],

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \sum_{i=1}^5 C_i Q_i + \sum_{i=1}^3 \tilde{C}_i \tilde{Q}_i. \quad (11)$$

The only nonzero Wilson coefficients are

$$\begin{aligned} C_1(\mu_{Z'}) &= \frac{1}{2M_{Z'}^2} (\Gamma_{12}^{dL})^2 \left(1 + \frac{\alpha_s}{4\pi} \frac{11}{3}\right), \\ C_4(\mu_{Z'}) &= -\frac{\alpha_s}{4\pi} \frac{\Gamma_{12}^{dL} \Gamma_{12}^{dR}}{M_{Z'}^2}, \\ C_5(\mu_{Z'}) &= -\frac{2}{M_{Z'}^2} \Gamma_{12}^{dL} \Gamma_{12}^{dR} \left(1 - \frac{\alpha_s}{4\pi} \frac{1}{6}\right), \end{aligned} \quad (12)$$

associated to the operators,

$$\begin{aligned} Q_1 &= (\bar{d}^\alpha \gamma_\mu P_L s^\alpha)(\bar{d}^\beta \gamma^\mu P_L s^\beta), \\ Q_4 &= (\bar{d}^\alpha P_L s^\alpha)(\bar{d}^\beta P_R s^\beta), \\ Q_5 &= (\bar{d}^\alpha P_L s^\beta)(\bar{d}^\beta P_R s^\alpha), \end{aligned} \quad (13)$$

at the matching scale $\mu_{Z'} \sim M_{Z'}$. The chirality-flipped operator \tilde{Q}_1 , and its corresponding Wilson coefficient \tilde{C}_1 are obtained from Q_1 and C_1 by exchanging L with R . In Eq. (12) we included the matching corrections of Ref. [110], such that the 2-loop renormalization group evolution of Refs. [111,112] can be consistently taken into account. For a Z' -scale of 5 TeV and a low scale of 2 GeV (where the bag factors are calculated [113]), we find

$$\begin{aligned} C_1(\mu_{\text{low}}) &\approx 0.73 C_1(\mu_{Z'}), \\ C_4(\mu_{\text{low}}) &\approx 5.73 C_4(\mu_{Z'}) + 1.66 C_5(\mu_{Z'}), \\ C_5(\mu_{\text{low}}) &\approx 0.23 C_4(\mu_{Z'}) + 0.87 C_5(\mu_{Z'}). \end{aligned} \quad (14)$$

The analogous expressions for $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing are obtained by obvious changes of indices and slight variations of μ_{low} . For the numerical analysis we use the bag factors given in Ref. [114].

Concerning the experimental bounds, for CP violation in kaon mixing (ϵ_K) we use the value given in Ref. [115],

$$0.87 \leq \frac{\epsilon_K^{\text{SM}} + \epsilon_K^{\text{NP}}}{\epsilon_K^{\text{SM}}} \leq 1.39, \quad (95\% \text{ C.L.}), \quad (15)$$

while for $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing we parametrize the two-dimensional fit result of Ref. [115].

D. $b \rightarrow s\ell^+ \ell^-$

Defining the Hamiltonian,

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i O_i + C_i' O_i'), \quad (16)$$

with the operators,

$$\begin{aligned} O_9^{(\ell)} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \\ O_{10}^{(\ell)} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \end{aligned} \quad (17)$$

we get contributions to the Wilson coefficients,

$$\begin{aligned} C_9^{(\ell)} &= -\frac{16\pi^2 \Gamma_{23}^{dL(R)} (\Gamma_{22}^{\ell L} + \Gamma_{22}^{\ell R})}{e^2 4\sqrt{2} G_F M_{Z'}^2 V_{tb} V_{ts}^*}, \\ C_{10}^{(\ell)} &= -\frac{16\pi^2 \Gamma_{23}^{dL(R)} (\Gamma_{22}^{\ell R} - \Gamma_{22}^{\ell L})}{e^2 4\sqrt{2} G_F M_{Z'}^2 V_{tb} V_{ts}^*}, \end{aligned} \quad (18)$$

in the concrete case of $b \rightarrow s\mu^+ \mu^-$ transitions.

In the following numerical analysis, we make use of the global fits in Refs. [51,116]. For example, in the simplest case of C_9 with muons only, one has $-3.04 < C_{9\mu}^{\text{NP}} < -0.76$.

E. $Z - Z'$ mixing

The Z' boson can mix with the SM Z , modifying the couplings of the latter to fermions [103,117–119]. There is no symmetry which can prevent this mixing, and even if it should vanish at a specific scale, it is generated at a different scale via loop effects.

In analogy with Eq. (1), we write the Z couplings as

$$\mathcal{L}_Z = \sum_{f=u,d,\ell,\nu} \bar{f}_i \gamma^\mu (\Delta_{ij}^{fL} P_L + \Delta_{ij}^{fR} P_R) f_j Z_\mu, \quad (19)$$

with

$$\Delta_{ij}^{fL,R} = \sin\theta \Gamma_{ij}^{fL,R} + \cos\theta \Delta_{\text{SM}}^{fL,R} \delta_{ij}, \quad (20)$$

where θ is the $Z - Z'$ mixing angle and $\Delta_{\text{SM}}^{fL,R}$ are the couplings within the SM, given by

$$\begin{aligned}
\Delta_{\text{SM}}^{dL} &= \frac{g_2}{2c_W} \left(1 - \frac{2}{3} s_W^2 \right), & \Delta_{\text{SM}}^{dR} &= -\frac{g_2 s_W^2}{3c_W}, \\
\Delta_{\text{SM}}^{uL} &= \frac{-g_2}{2c_W} \left(1 - \frac{4}{3} s_W^2 \right), & \Delta_{\text{SM}}^{uR} &= \frac{2g_2}{3c_W} s_W^2, \\
\Delta_{\text{SM}}^{\ell L} &= \frac{g_2}{2c_W} (1 - 2s_W^2), & \Delta_{\text{SM}}^{\ell R} &= -\frac{g_2 s_W^2}{c_W}, \\
\Delta_{\text{SM}}^{\nu L} &= \frac{-g_2}{2c_W}. & &
\end{aligned} \tag{21}$$

The contributions to flavor processes are obtained from the expressions in the previous subsections by replacing Γ with Δ and Z' with Z . Note that the contribution of $Z - Z'$ mixing to $\Delta F = 2$ processes is suppressed by $\sin^2 \theta$, while its contribution to other observables involves only $\sin \theta$. Therefore, the effect of $Z - Z'$ mixing in $\Delta F = 2$ processes can be neglected.

Turning to Z couplings to fermions, the best bounds on quark couplings come from $Z \rightarrow b\bar{b}$. Here, due to the forward-backward asymmetry, there is a slight preference for NP effects related to right-handed bottom quarks [120],

$$\begin{aligned}
\Delta_{33}^{dR} - \Delta_{\text{SM}}^{dR} &= 0.012 \pm 0.004, \\
\Delta_{33}^{dL} - \Delta_{\text{SM}}^{dL} &= 0.0015 \pm 0.0007.
\end{aligned} \tag{22}$$

If the Z' couples also to leptons, the bounds from $Z \rightarrow \ell^+ \ell^-$ are very stringent [121]. One can estimate the effect to be at most around 0.2% [122]. More concretely, for vectorial couplings to muons and electrons one has

$$\begin{aligned}
-0.0034 &< \Delta_{22}^{\ell} - \Delta_{\text{SM}}^{\ell} < 0.0031, \\
0.0001 &< \Delta_{11}^{\ell} - \Delta_{\text{SM}}^{\ell} < 0.0016,
\end{aligned} \tag{23}$$

with $\Delta_{ij} = \Delta_{ij}^L + \Delta_{ij}^R$. In addition, there are stringent bounds from $Z \rightarrow \nu\nu$,

$$2.9676 < \sum_{i,j=1}^3 \left| \frac{\Delta_{ij}^{\nu}}{\Delta_{\text{SM}}^{\nu}} \right|^2 < 3.0004; \tag{24}$$

however, since the measurement does not distinguish between the neutrino flavors, this bound can always be avoided by adjusting the charges of the tau leptons.

F. LHC searches

In our phenomenological analysis we will consider a heavy Z' boson, whose width is very large (of the order of its mass). As a consequence, bounds from searches for narrow resonances can not be directly applied. Although the state might be produced on shell, as an effect of the large width, the signal mimics that of a contact interaction, i.e., a change in the tail of dijet and dilepton distributions,

as we checked by means of a simulation. In addition, it is always possible to rescale the mass and the coupling constant by the same factor, leaving the predictions for flavor observables invariant (despite small logarithmic corrections). To a good approximation, one can thus use the bounds on 4-fermion operators from lepton or jet tails which only depend on the ratio of couplings (times charges) squared divided by the mass squared. The current bounds on the Wilson coefficients of 4-quark operators (without any normalization factor in the effective Lagrangian) are between $(0.15/\text{TeV})^2$ and $(0.3/\text{TeV})^2$ [123]. For 2-quark-2-lepton operators the bounds related to muons are between $(0.12/\text{TeV})^2$ and $(0.18/\text{TeV})^2$ [124]. Here both analyses assume quark flavor universality.

G. Landau pole

In presence of sizeable $U(1)'$ charges, the renormalization group (RG) running of the gauge coupling g' may generate a Landau pole at unacceptably low energies. This sets an additional constraint to our model, that we study considering the 1-loop RG equation,

$$\frac{1}{\alpha'}(\mu) = \frac{1}{\alpha'}(\bar{\mu}) - \frac{b}{2\pi} \log(\mu/\bar{\mu}), \tag{25}$$

where $\alpha' \equiv g'^2/4\pi$, $\bar{\mu}$ is a low-energy scale, and b , the coefficient of the β -function, is given in terms of the $U(1)'$ charges of the SM fermions by

$$b = \frac{2}{3} \sum_{i=1}^3 [6Q_{Q_i}^2 + 3(Q_{u_i}^2 + Q_{d_i}^2) + 2Q_{L_i}^2 + Q_{e_i}^2].$$

We define the Landau pole scale μ_{LP} as the scale at which the gauge coupling diverges, which at 1 loop is given by

$$\mu_{\text{LP}} = \bar{\mu} \exp\left(\frac{2\pi}{b\alpha'(\bar{\mu})}\right). \tag{26}$$

III. $U(2)^3$ -FLAVOR

Since only the third-generation-Yukawa couplings are sizeable, the quark sector of the SM Lagrangian possesses an approximate global $U(2)^3 = U(2)_Q \times U(2)_u \times U(2)_d$ flavor symmetry for the first two generations of quarks. Here Q and u and (d) refer to the left-handed quark $SU(2)_L$ doublet and the right-handed up (down) quark $SU(2)_L$ singlet, respectively (see Table I). We assume that this $U(2)^3$ -symmetry is respected by the gauge sector and is only broken by the SM Yukawa couplings [which in turn arise from the unspecified $U(1)'$ -breaking sector]. Therefore, the $U(1)'$ -charges must be equal for the first two generations, leading to the following $U(1)'$ -charge matrices in flavor space (i.e., in the interaction basis):

TABLE I. $U(2)^3$ -representations of the quark fields and spurions in our model.

	$U(2)_Q$	$U(2)_u$	$U(2)_d$
(Q_1, Q_2)	2	1	1
(u_1, u_2)	1	2	1
(d_1, d_2)	1	1	2
Q_3, u_3, d_3	1	1	1
Δ_u	2	$\bar{2}$	1
Δ_d	2	1	$\bar{2}$
X_t	2	1	1
X_b	2	1	1

$$\begin{aligned} Q_Q &= \text{diag}(Q_{Q_{12}}, Q_{Q_{12}}, Q_{Q_3}), \\ Q_u &= \text{diag}(Q_{u_{12}}, Q_{u_{12}}, Q_{u_3}), \\ Q_d &= \text{diag}(Q_{d_{12}}, Q_{d_{12}}, Q_{d_3}). \end{aligned} \quad (27)$$

In order to recover the small quark masses of the first two generation quarks, as well as the suppressed off diagonal elements of the CKM-matrix, the $U(2)^3$ symmetry must be broken. Following the strategy presented in Refs. [90,93,95,96], the Yukawa couplings of the Lagrangian,

$$\mathcal{L}_Y = Q_i Y_{ij}^d d_j H + Q_i Y_{ij}^u u_j \tilde{H}, + \text{H.c.} \quad (28)$$

can be written as

$$\begin{aligned} \frac{Y^u}{y_t} &= \left(\begin{array}{c|c} \Delta_u & X_t \\ \hline 0 & 0 & 1 \end{array} \right), \\ \frac{Y^d}{y_b} &= \left(\begin{array}{c|c} \Delta_d & X_b \\ \hline 0 & 0 & 1 \end{array} \right). \end{aligned} \quad (29)$$

Here $y_{t,b} = \frac{m_{t,b}}{v}$ ($v \approx 174$ GeV) are the Yukawa couplings of the third generation quarks. The minimal spurion sector consisting of $\Delta_{u,d}$ and $X_{t,b}$ is given in Table I. Using $U(2)$ transformations, the spurions $\Delta_{u,d}$ and $X_{t,b}$ can, without loss of generality, be written as

$$\begin{aligned} \Delta_u &= U^u \text{diag}(\lambda_u, \lambda_c), & X_t &= x_t e^{i\phi_t} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \\ \Delta_d &= U^d \text{diag}(\lambda_d, \lambda_s), & X_b &= x_b e^{i\phi_b} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \end{aligned} \quad (30)$$

where U^u and U^d are unitary 2×2 matrices. The parameters,

$$\lambda_u \approx \frac{m_u}{m_t}, \quad \lambda_c \approx \frac{m_c}{m_t}, \quad \lambda_d \approx \frac{m_d}{m_b}, \quad \lambda_s \approx \frac{m_s}{m_b}, \quad (31)$$

are $\mathcal{O}(|V_{cb}| \approx 4 \times 10^{-2})$ and control the $U(2)^3$ -breaking.

In order to arrive at the mass basis, we diagonalize Y^u and Y^d as follows:

$$\begin{aligned} V^{u\dagger} Y^u W^u &= \text{diag}(y_u, y_c, y_t), \\ V^{d\dagger} Y^d W^d &= \text{diag}(y_d, y_s, y_b), \end{aligned} \quad (32)$$

where $V^{u,d}$ ($W^{u,d}$) are unitary the matrices transforming the left- (right-)handed up- and down-type fields. These matrices can be obtained by diagonalizing $Y^q Y^{q\dagger}$ ($Y^{q\dagger} Y^q$) in three steps, such that they take the form,

$$V^d = R_{12}(\theta_{ds}, \phi_{ds}) \times R_{23}(\theta_{sb}, \phi_{sb}) \times R_{13}(\theta_{ab}, \phi_{ab}),$$

(and equivalent for V^u) as a product of three rotations. Here, R_{ij} is the unitary matrix describing the mixing in the ij -sector. R_{12} , for example, is of the form,

$$R_{12}(\theta, \phi) = \begin{pmatrix} \cos(\theta) & e^{i\phi} \sin(\theta) & 0 \\ -e^{-i\phi} \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (33)$$

In order to determine $V^{u,d}$, we first choose an angle $\theta_{ds,uc}$ and a phase $\phi_{ds,uc}$ such that the matrices $U^{u,d}$ in Eq. (29) are eliminated. Subsequently, we perform a perturbatively diagonalization of the 23- and the 13-sector. Keeping only leading-order terms, we obtain

$$\begin{aligned} V^u &= R_{12}(\theta_{uc}, \alpha_u) \times R_{23}(x_t c_{uc}, \phi_t) \\ &\quad \times R_{31}(x_t s_{uc}, -(\alpha_u + \phi_t)), \\ V^d &= R_{12}(\theta_{ds}, \alpha_d) \times R_{23}(x_b c_{ds}, \phi_b) \\ &\quad \times R_{31}(x_b s_{ds}, -(\alpha_d + \phi_b)), \end{aligned} \quad (34)$$

where $c_{ab} = \cos(\theta_{ab})$ and $s_{ab} = \sin(\theta_{ab})$. Explicitly, V^d is given by

$$V^d = \begin{pmatrix} c_{ds} & e^{i\alpha_d} s_{ds} & 0 \\ -e^{-i\alpha_d} s_{ds} & c_{ds} & e^{i\phi_b} x_b \\ e^{-i(\alpha_d + \phi_b)} x_b s_{ds} & -e^{-i\phi_b} x_b c_{ds} & 1 \end{pmatrix}. \quad (35)$$

Despite our minimal choice of spurions, there is still flavor mixing between right-handed fields. However, this effect is suppressed by the parameters λ in Eq. (31) with respect to the mixing of the left-handed fields. Neglecting the first generation couplings $\lambda_{u,d}$, we obtain

$$W^d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda_s \cos(\theta_{ds}) e^{i\phi_b} \\ 0 & -\lambda_s \cos(\theta_{ds}) e^{-i\phi_b} & 1 \end{pmatrix}, \quad (36)$$

and a similar expression for W^u .

Now we can determine the Z' -couplings to quarks appearing in Eq. (1),

$$\begin{aligned}\Gamma^{uL} &\equiv g' V^{u\dagger} \mathcal{Q}_Q V^u, & \Gamma^{uR} &\equiv g' W^{u\dagger} \mathcal{Q}_u W^u, \\ \Gamma^{dL} &\equiv g' V^{d\dagger} \mathcal{Q}_Q V^d, & \Gamma^{dR} &\equiv g' W^{d\dagger} \mathcal{Q}_d W^d.\end{aligned}\quad (37)$$

Making use of the unitarity of the matrices $V^{u,d}$ and $W^{u,d}$ and comparing the results with the elements of the CKM matrix, defined by $V = V^{u\dagger} V^d$, we obtain

$$\begin{aligned}\Gamma_{12}^{dL} &= g' c_K X_Q V_{td}^* V_{ts}, \\ \Gamma_{13}^{dL} &= g' c_B e^{i\alpha_B} X_Q V_{td}^* V_{tb}, \\ \Gamma_{23}^{dL} &= g' c_B e^{i\alpha_B} X_Q V_{ts}^* V_{tb}, \\ \Gamma_{11}^{qR} &= g' \mathcal{Q}_{q_{1,2}}, \quad q = u, d, \\ \Gamma_{23}^{dR} &= -g' X_d \lambda_s x_b e^{i\phi_b} \cos(\theta_{ds}),\end{aligned}\quad (38)$$

at leading order in our perturbative diagonalization. Here, we have introduced the notation,

$$\begin{aligned}X_Q &= (\mathcal{Q}_{Q_3} - \mathcal{Q}_{Q_{1,2}}), \\ X_d &= (\mathcal{Q}_{d_3} - \mathcal{Q}_{d_{1,2}}), \\ X_{ud} &= (\mathcal{Q}_{u_{1,2}} - \mathcal{Q}_{d_{1,2}}),\end{aligned}\quad (39)$$

and the order-one parameters,

$$c_B = \frac{x_b}{|e^{-i\phi_t} x_b - e^{-i\phi_b} x_t|}, \quad c_K = c_B^2, \quad (40)$$

together with the free phase,

$$\alpha_B = \phi_b + \arg(e^{-i\phi_t} x_b - e^{-i\phi_b} x_t). \quad (41)$$

Note that in the limit $x_t, \phi_t \rightarrow 0$ (as in Ref. [65]) $c_B \rightarrow 1$ and $\alpha_B \rightarrow \pi$.

The $U(2)$ flavor symmetry can be extended to the lepton sector, resulting in a global $U(2)^5$ symmetry. However, the $U(2)$ -breaking pattern in the lepton sector cannot be obtained from the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix in the same way as it is obtained from the CKM-matrix in the quark sector; this is due to the probable presence of right-handed neutrinos in the seesaw mechanism. Furthermore, other flavor symmetries [125], such as $L_\mu - L_\tau$ [126–130], can generate the correct structure of the PMNS-matrix. In the phenomenological analysis we will consider two scenarios. In the first scenario the couplings of the leptons respect flavor universality (LFU), which corresponds to a $U(3)^2$ -symmetry in the lepton sector (LFU scenario). In the second scenario leptons violate LFU in the form of a $L_\mu - L_\tau$ symmetry ($L_\mu - L_\tau$ scenario). The first benchmark thus corresponds to the maximally symmetrical situation (resembling the coupling structure of the SM gauge bosons itself), the

second one to a well motivated LFU-violating subgroup of the global SM flavor symmetry. In both cases, the couplings of the Z' to leptons can be generically written as

$$\Gamma_{ij}^{\ell L} = g' \mathcal{Q}_{L_i} \delta_{ij}, \quad \Gamma_{ij}^{\ell R} = g' \mathcal{Q}_{e_i} \delta_{ij}. \quad (42)$$

Note that this flavor structure prevents dangerous Z' -mediated contributions to lepton-flavor-violating processes (cf. [131] for a recent review), and it is automatically achieved in the LFU scenario, while in the case of $L_\mu - L_\tau$, we have to assume that the charged lepton Yukawa matrix is (quasi)diagonal in the interaction basis, a situation that can arise in the presence of an additional, possibly discrete, flavor symmetry.

IV. PHENOMENOLOGICAL ANALYSIS

In a first step we look at the quark sector only. Among the $\Delta F = 2$ processes, we have effects in $K - \bar{K}$, $B_s - \bar{B}_s$ and $B_d - \bar{B}_d$ mixing. Due to the $U(2)^3$ flavor symmetry, the bounds from $D^0 - \bar{D}^0$ are always subleading compared to those from $K - \bar{K}$ mixing, where the phase of the NP contribution is fixed to $\text{Arg}[(V_{ts} V_{td}^*)^2]$ leading to unavoidable effects in ϵ_K . This leads to a maximally allowed value (at 95% C.L.) for the coupling Γ_{12}^{dL} of

$$|g' c_B^2 X_Q| \lesssim 1.1 \frac{M_{Z'}}{5 \text{ TeV}} = \Gamma_{12}^{dL, \text{max}}. \quad (43)$$

Concerning $B_s - \bar{B}_s$ mixing, we note that the bound can always be avoided by an appropriate choice of ϕ_B and s_{b_s} since

$$\langle B_s | \mathcal{H}^{NP} | \bar{B}_s \rangle \sim X_Q + 50 s_{b_s} e^{i(\alpha_B + \phi_b)} X_d / c_B, \quad (44)$$

for natural values of the parameters involved (since s_{b_s} is of order of the V_{cb}). Therefore, we are left with the slightly less stringent bounds from $B_d - \bar{B}_d$ mixing [115] which are (to a good approximation) unaffected by right-handed $Z' ds$ couplings. Here we have

$$|g' c_B X_Q| \lesssim [0.5 - 0.95] = \Gamma_{13}^{dL, \text{max}}(\alpha_B), \quad (45)$$

depending on the specific values of α_B .

Concerning direct CP violation we first include e'/e in our analysis. Here, the bounds from ϵ_K (at 95% C.L.) leads to a minimal charge difference $X_{ud} = \mathcal{Q}(u_{1,2}) - \mathcal{Q}(d_{1,2})$ necessary to get a NP contribution $(e'/e)_{\text{NP}}$ in e'/e ,

$$|g' X_{ud}| \gtrsim 1.26 \times \frac{(e'/e)_{\text{NP}}}{10^{-3}}. \quad (46)$$

Let us turn to CP violation in hadronic B -decays (HBD), in particular in $B_s \rightarrow \rho\phi, K\bar{K}$ and in $B \rightarrow \pi K, \rho K, \pi K^*, \rho K^*$. We find that for $g' X_Q = 0.5$ and $g' X_{ud} = 3$, all HBD can be explained simultaneously by fitting c_B and α_B . This is

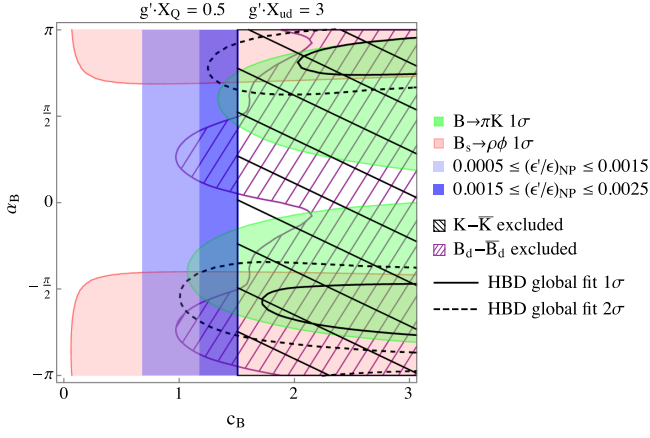


FIG. 1. Preferred regions in the $c_B - \alpha_B$ plane from $B \rightarrow \pi K$ and $B_s \rightarrow \rho\phi$ (1σ) together with regions from the global fit, including all observables on hadronic B -decays (1σ and 2σ) as well as e'/ϵ for $g'X_Q = 0.5$ and $g'X_{ud} = 3$. Here, we marginalized over $Q_{u_1} + Q_{d_1}$.

illustrated in Fig. 1, where we marginalized over $Q_{u_1} + Q_{d_1}$ [27]. It is also possible to address e'/ϵ and the $B \rightarrow K\pi$ puzzle simultaneously without violating bounds from $\Delta F = 2$ processes. The resulting charges lead to a naive estimate of an interaction strength for the 4-quark operators of $\approx 0.15 \text{ TeV}^2$. This is still consistent with LHC searches, but very close to the current exclusion limits.

We move on to the study of $b \rightarrow s\ell^+\ell^-$ transitions. As outlined in the previous section, we consider a scenario with LFU couplings, corresponding to $C_9^{ee} = C_9^{\mu\mu}$, and a scenario with $L_\mu - L_\tau$, corresponding to the $C_9^{\mu\mu}$ only scenario in the global fit. In Fig. 2 (left), we show the

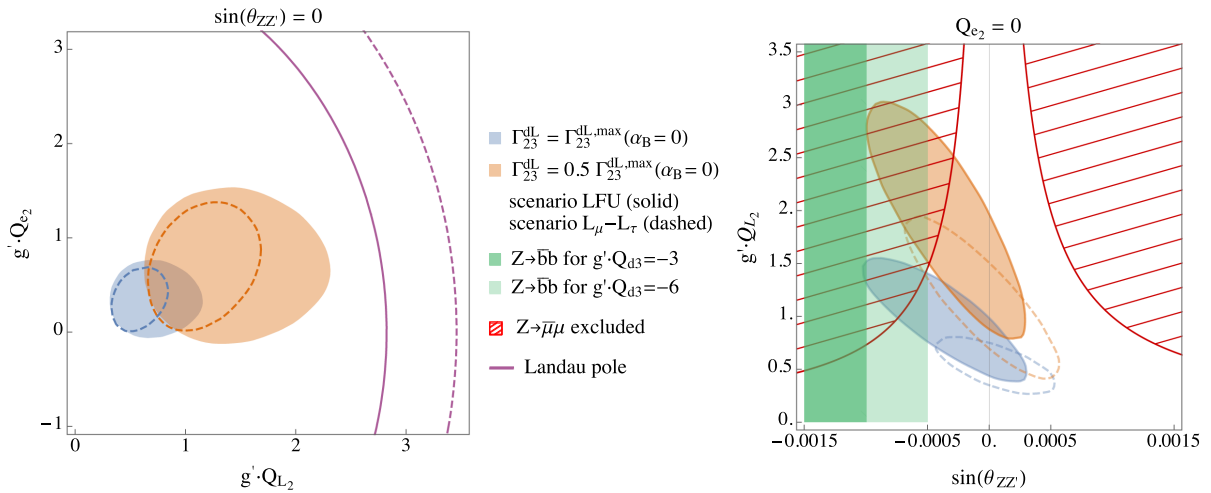


FIG. 2. Left: Preferred regions from $b \rightarrow s\ell^+\ell^-$ data for different values of Γ_{23}^{dL} assuming no $Z - Z'$ mixing for $m_{Z'} = 5 \text{ TeV}$. The filled regions refer to case 1) with LFU while the regions within the dashed curves correspond to the $L_\mu - L_\tau$ scenario. The corresponding regions with a Landau pole above 50 TeV lie to the left of the purple lines. Right: Preferred regions in the $g'Q_{L_2} - \sin(\theta_{ZZ'})$ plane from $b \rightarrow s\ell^+\ell^-$, $Z \rightarrow \bar{b}b$ and $Z \rightarrow \bar{\mu}\mu$ with $Q_{e_2} = 0$ and $m_{Z'} = 5 \text{ TeV}$. Again, solid (dashed) lines correspond to the LFU ($L_\mu - L_\tau$) scenario.

regions preferred by $b \rightarrow s\ell^+\ell^-$ [116] data for different values of Γ_{23}^{dL} , together with the predictions for a Landau pole at 50 TeV. If, in addition, one uses a “minimal” charge assignment that allows the third generation of left-handed quarks to have nonzero charges, Q_{Q_3} , but sets all other quark couplings to zero, LHC bounds are respected [87,88,132–136].

So far, we did not consider the effect of $Z - Z'$ mixing. In the absence of couplings of the Z' -boson to leptons, the most stringent constraints come from $Z \rightarrow \bar{b}b$ [120]. However, once the couplings to the leptons are included, $Z \rightarrow \bar{\mu}\mu$ gives more stringent bounds [137]. Furthermore, $Z - b - s$ couplings induced by $Z - Z'$ mixing have an important impact on the global fit of $b \rightarrow s\ell^+\ell^-$ data [58]. This situation is depicted in the plot at the right-hand side of Fig. 2, where the preferred regions from $b \rightarrow s\ell^+\ell^-$ data (obtained using FLAVIO [138]) and the regions excluded by $Z \rightarrow \bar{\mu}\mu$ are shown in the case of $\alpha_B = 0$, for different values of Γ_{23}^{dL} and $g'Q_{d_3}$. In this figure we also see that the forward-backward asymmetry in $Z \rightarrow \bar{b}b$ [see Eq. (22)] leads to a preference for nonzero mixing. Note that $\sin(\theta_{ZZ'}) \sim -5 \times 10^{-4}$ gives a good fit to data. A value for $\theta_{ZZ'}$ of this order will have an impact on e'/ϵ and hadronic B -decays of the order of 10%, with respect to the Z' contribution.

A. Benchmark scenario

Based on the observations discussed above, we now construct a benchmark scenario (along with our two scenarios concerning the lepton couplings) with the aim of addressing e'/ϵ , hadronic B -decays and $b \rightarrow s\ell^+\ell^-$ data simultaneously. We choose $g' = 0.6$, $M_{Z'} = 6 \text{ TeV}$ and

$$\begin{aligned}
\mathcal{Q}_Q &= (0, 0, 1), & \mathcal{Q}_u &= (2, 2, 1), & \mathcal{Q}_d &= (-4, -4, 0). \\
\mathcal{Q}_L &= (0, -2, 2) \text{ (scenario } L_\mu - L_\tau), \\
\mathcal{Q}_L &= (-2, -2, -2) \text{ (scenario LFU)}, \\
\mathcal{Q}_e &= (0, 0, 0), & \sin(\theta_{ZZ'}) &= 0.001.
\end{aligned} \tag{47}$$

This benchmark point leads to a Landau pole at ~ 50 TeV (~ 60) TeV for the LFU ($L_\mu - L_\tau$) scenario.

The interaction strength of 2-quark-2-muon operators at the benchmark point is $\approx (0.25 \text{ TeV})^2$, which is in conflict with LHC bounds. In order to reconcile the model with LHC data, one could obviously reduce the strength of the Z' couplings to right-handed up and down quarks, which would decrease the effect in ϵ'/ϵ , or one could reduce the strength of the Z' couplings to muons, which would weaken the impact of our model on $b \rightarrow s\ell^+\ell^-$ data. We will pursue another possibility here, which makes use of the sensitivity to interference of the bounds on 4-fermion operators from LHC searches in dilepton or dijet tails. We suppose the existence of a second neutral gauge boson, Z'' . If the product of the $U(1)''$ charges of the right-handed quark and muon has the opposite sign to the product of the $U(1)'$ charges [given in Eq. (47)] of the right-handed quark and muon, the Z' and Z'' bosons interfere destructively in LHC searches. If we further assume that the $U(1)''$ charges of the left-handed quarks respect $U(3)$ flavor symmetry (i.e., that they are equal), only the LHC searches are affected, while the flavor observables are still governed by Z' alone. Note that a destructive interference of about 50% between the Z' and the Z'' contributions would be sufficient for our model to provide a common explanation of ϵ'/ϵ , HBD and $b \rightarrow s\ell^+\ell^-$ data. This is naturally achieved with $M_{Z''} \approx M_{Z'}$, $g'' \approx g'$ and $\mathcal{Q}_Q'' = (0, 0, 0)$, $(-3, -3, -3) < \mathcal{Q}_u'' < (-1, -1, -1)$ and $(2, 2, 2) < \mathcal{Q}_d'' < (6, 6, 6)$, assuming that the Z' and the Z'' couple in the same way to leptons. Finally, note that our model does not feature enhanced couplings to third generations fermions. Therefore, searches based on ditau events are comparatively less sensitive, being penalized by hadronic tau reconstruction efficiencies or leptonic tau branching ratios. Similarly, searches involving bottom quarks can be safely neglected, due to limited bottom content of the proton and b-tagging efficiencies.

Now we proceed to the combined analysis of flavor data. Figure 3 shows the preferred regions of the combined fit to $b \rightarrow s\ell^+\ell^-$, ϵ'/ϵ , ϵ_K and $B_d - \bar{B}_d$ -mixing at 1σ and 2σ , the preferred/excluded regions of each observable separately, as well as the region preferred by hadronic B -decays. We also show the predictions for the $b \rightarrow s\ell^+\ell^-$ observable $\langle A_8(B^0 \rightarrow K^*\mu\mu) \rangle_{[1.1, 6]}$ [46], which is especially sensitive to CP violation. A choice of $\alpha_B \sim [2.5-3]$ and $c_B \sim 1.4$ allows us to explain ϵ'/ϵ , hadronic B -decays and $b \rightarrow s\ell^+\ell^-$ data simultaneously at the 2σ level, and to predict $\langle A_8(B^0 \rightarrow K^*\mu\mu) \rangle_{[1.1, 6]} \sim [0.015 - 0.03]$, which

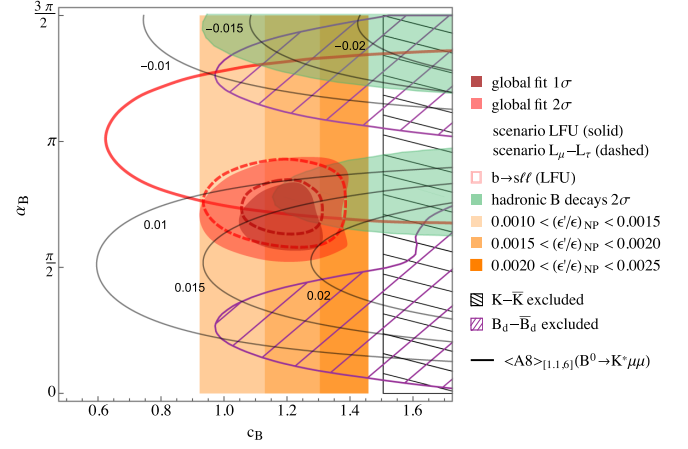


FIG. 3. Preferred regions of the combined fit (red) to ϵ'/ϵ , $b \rightarrow s\ell^+\ell^-$, $K - \bar{K}$ mixing and $B_d - \bar{B}_d$ mixing at 1σ and 2σ for our benchmark point with the two scenarios LFU and $L_\mu - L_\tau$. In addition, the individual regions from hadronic B -decays and $b \rightarrow s\ell^+\ell^-$ data, as well as the regions excluded by $B_d - \bar{B}_d$ mixing and ϵ_K are shown and the contour lines for $A_8(B^0 \rightarrow K^*\mu\mu)$ in the q^2 interval [1.1, 6] are depicted.

is in agreement with the experimental measurements $\langle A_8 \rangle_{[1.1, 6]}^{\text{exp}} = -0.047 \pm 0.058$ [46]. With the expected future improvements [139,140], this prediction will soon be testable.

Finally, let us comment on the preliminary results for $K_L \rightarrow \pi^0 \nu \bar{\nu}$, where three event candidates were observed [141,142]. For the best fit point of our LFU($L_\mu - L_\tau$) scenario we obtain a reduction of $\sim -75\%$ (-30%) with respect to the SM prediction.

V. CONCLUSIONS

Very interesting deviations from the SM predictions have been found in ϵ'/ϵ , hadronic B -decays (HBD) and $b \rightarrow s\ell^+\ell^-$ data. In this article we studied these puzzles in a simplified framework involving a heavy Z' boson, but disregarding the explicit form of the symmetry breaking sector. We derived the flavor structure of such models with a $U(2)^3$ symmetry in the quark sector, finding that it is entirely governed by the known CKM elements, as well as two free parameters, a real order-one factor c_B and a complex phase ϕ_B , which enters $b \rightarrow s(d)$ transitions. Importantly, the phase in $s \rightarrow d$ transitions is fixed by $V_{tb}V_{ts}^*$, and the corresponding real coefficient c_K is to a good approximation equal to c_B^2 , making this setup very predictive.

In the phenomenological part of this article, we first analyzed ϵ'/ϵ and HBD, finding that a common explanation, that respects the bounds from $\Delta_F = 2$ processes, is possible. In particular, within our setup with less-minimal flavor violation, the bounds from $B_s - \bar{B}_s$ mixing can always be avoided. This cancellation is possible for natural values of the $U(2)^3$ breaking parameters, even then a positive effect in ϵ_K is predicted. Furthermore, the large

isospin-violating couplings to quarks, required for a common explanation of direct CP -violating in hadronic kaon and B decays, lead to sizeable effects in dijet tail searches at the LHC, which will be testable at the HL-LHC.

Once $b \rightarrow s\ell^+\ell^-$ data are included in the analysis, the situation becomes even more interesting. Since hadronic $b \rightarrow s$ decays require a large phase ϕ_B , sizeable CP violation in $b \rightarrow s\ell^+\ell^-$ observables, in particular in A_8 , is predicted. We presented a benchmark point, which is capable of providing a common explanation of all anomalies in flavor observables (see Fig. 3). However, the large couplings to up and down quarks required by ϵ'/ϵ and HBD lead to sizable effects in dimuon tails, excluded by current data. This obstacle can be overcome by postulating destructive interference in LHC searches, e.g., by a second Z' boson (Z''), not affecting flavor observables, due to $U(3)_Q$ -symmetric choice of the $U(1)''$ charges.

In summary, we presented a simplified Z' models with less-minimal flavor violation which can (for the first time) explain ϵ'/ϵ , HBD and $b \rightarrow s\ell^+\ell^-$ data simultaneously. Our analysis demonstrates that $U(2)$ -symmetric couplings

in the quark sector significantly reduce the number of free parameters and provide a very good candidate for a flavor structure capable of explaining the anomalies. On the other hand, we showed that more new particles, beyond the Z' , are required, as also suggested by the need for a symmetry breaking sector and the presence of a Landau pole at ≈ 50 TeV, opening up interesting future directions in model building.

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