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Yukawa textures, new physics, and nondecoupling

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We point out that new physics can play an important role in rescuing some of the Yukawa texture-zero *Ansätze* which would otherwise be eliminated by the recent, more precise measurements of $V_{\rm CKM}$. As an example, a detailed analysis of a four texture-zero *Ansatz* is presented, showing how the presence of an isosinglet vectorlike quark, which mixes with standard quarks, can render viable this Yukawa texture. The crucial point is the nondecoupling of the effects of the isosinglet quark, even for arbitrary large values of its mass.

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I. INTRODUCTION

The increasingly higher precision in the determination of the elements of the fermion mixing matrices, both in the quark and lepton sectors, is clearly one of the most significant recent developments in particle physics and provides a great challenge to flavor models.

In most of the attempts at understanding the observed pattern of fermion masses and mixing, one assumes the existence of family symmetries either Abelian or non-Abelian, leading to special flavor structures in the Yukawa matrices, often involving texture zeros and/or a Froggatt-Nielsen type [1] power structure of the matrix elements, in terms of a small expansion parameter. In the search for the allowed texture zeros, one may take a bottom-up approach, where one uses the input data on fermion masses and mixing to derive the Yukawa textures which are allowed by experiment. Some years ago, Ramond, Roberts, and Ross (RRR) [2], in a pioneering work, followed this bottom-up approach and made a systematic search for allowed quark Yukawa structures. Assuming symmetric or Hermitian Yukawa matrices and using the experimental data available at the time, RRR found a total of five possible solutions in a survey of all six and five texture-zero *Ansätze*. Meanwhile, with the impressive improvement in the experimental determination of the $V_{\rm CKM}$ matrix, all the texture-zero structures found in [2] have great difficulty in reproducing the data. One of the greatest challenges to these models arises from the precise determination of the rephasing invariant angle $\beta \equiv \arg(-V_{cd}V_{cb}^*V_{td}^*V_{tb})$. Indeed, it has been pointed out [3] that in a large class of texture-zero models which include all those considered by RRR, one cannot have a sufficiently large value of $\sin(2\beta)$, to conform to the present experimental value $\sin(2\beta) = 0.687 \pm 0.032$ [4]

Another important constraint arises from the experimental value of B_d^0-$\bar{B}_d^0$ mixing, combined with the recent measurement of B_s^0-$\bar{B}_s^0$ mixing by D0 [5] and CDF [6], which leads to the extraction of the ratio $|V_{td}|/|V_{ts}|$ with relatively small errors. Very recently, the rephasing invariant phase $\gamma \equiv \arg(-V_{ud}V_{ub}^*V_{cd}^*V_{cb})$ has been measured by Belle [7–9] and *BABAR* [10], leading to the value $\gamma = (63^{+15}_{-12})^\circ$ [4]. In spite of the large experimental errors, the measurement of γ is of crucial importance due to the fact that its extraction from input data is essentially not affected by the presence of new physics (NP) contributions to B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ mixings.

In the study of the impact of NP on the test of Yukawa textures, one has to specify what the assumptions are on the nature of NP. In most of the NP scenarios considered in the literature, one usually assumes that NP does not contribute significantly to the tree level decays of strange and B mesons. This implies that NP does not affect the extraction of $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, and γ, from experimental data. With these four inputs, one can reconstruct the full $V_{\rm CKM}$ matrix and, in particular, the reference unitarity triangle [11–13]. However, we may assume that there may be significant contributions from NP to B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ mixing, thus affecting the extraction of $|V_{td}|$, $|V_{ts}|$ as well as β from the experiment. Apart from these effects, we may assume in these scenarios that NP decouples from low energy physics. This assumption holds in a large class of models beyond the SM and, in particular, in most of the supersymmetric extensions of the standard model (SM). Let us now consider the implications for the tests of Yukawa textures. If a particular texture predicts a value of β and/or of $|V_{td}|$ in disagreement with the experiment, it may be rescued by the presence of NP contributions to B_d^0-$\bar{B}_d^0$ mixing. However, this class of NP cannot rescue a texture which predicts a value $|V_{ub}|/|V_{cb}|$ and/or γ in disagreement with the experiment. This question is especially relevant, due to the fact that some of the most attractive Yukawa textures do have difficulty in conforming to the measured values of $|V_{ub}|/|V_{cb}|$ and γ.

In this paper we will show that there is a class of NP which can solve the above conflict and thus render viable those Yukawa textures. At this stage, it is worth recalling

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that in most proposals for family symmetries which could shed some light on the flavor puzzle, there is the underlying assumption that, even if the family symmetry is embedded in a grand unified theory, the heavy particles decouple and do not affect low energy physics, in particular, the masses and mixing observable at low energies. In this paper, we will consider a scenario with heavy fermions where the decoupling does not occur and in particular heavy fermions do affect the effective standard fermion mass matrices at low energies. We will show that the influence of heavy vectorlike quarks is such that they may render viable some of the texture-zero structures which would otherwise be eliminated by the more precise data presently available on the $V_{\rm CKM}$ matrix. The embedding of a family structure into a larger framework where heavy fermions are included has the following interesting feature. Let us consider a flavor model based on $SU(3)_c \times SU(2)_L \times U(1) \times F$ where F denotes a family symmetry responsible for the presence of a set of texture zeros in the three by three quark mass matrices M_u and M_d. This symmetry can be trivially embedded into a larger framework with isosinglet vectorlike heavy quarks Q by assuming that the SM fields keep their transformation properties under F and allowing for F to be softly broken by $SU(3)_c \times SU(2)_L \times U(1)$ invariant mass terms connecting Q to standard quarks. The striking feature of the example we will consider, with one singlet down-type vectorlike quark, is that its effect in the low energy standard fermion masses and mixing can be sizeable even in the limit where heavy quark masses are very large and deviations from unitarity of the $V_{\rm CKM}$ matrix are arbitrarily suppressed.

The paper is organized as follows. In the next section, we analyze in detail a four texture-zero Hermitian *Ansatz* and illustrate its difficulties in accommodating the present data on $V_{\rm CKM}$. In Sec. III, we present an example of the nondecoupling of NP and analyze in an analytical qualitative way how the presence of vectorlike quarks can render the four texture-zero *Ansatz* compatible with our present knowledge on $V_{\rm CKM}$. In Sec. IV, we provide an explicit example which is solved numerically, confirming our analysis of Sec. III. Finally, we present our conclusions in Sec. V.

II. A FOUR TEXTURE-ZERO HERMITIAN ANSATZ

Several Hermitian *Ansätze* with texture zeros have been studied in the literature. These Ansätze lead in general to predictions which usually consist of simple relations for the mixing angles expressed in terms of quark mass ratios. It is worth emphasizing that Hermiticity is as important as the existence of texture zeros, in order to obtain predictive *Ansätze*. Indeed, it has been shown [14] that if one drops the requirement of Hermiticity, most of the texture-zero *Ansätze* can be obtained, starting from arbitrary quark mass matrices M_u, M_d, by simply making weak-basis transformations. This shows that without the requirement of Hermiticity those texture zeros have no physical implications.

For definiteness, we consider an especially interesting four-zero *Ansatz* which has been analyzed in detail in the literature [15–17]. The quark mass matrices M_u, M_d are assumed to have the form:

$$M_u = \lambda_u K_u^\dagger \begin{bmatrix} 0 & a_u & 0 \\ a_u & b_u & c_u \\ 0 & c_u & 1-b_u \end{bmatrix} K_u; \qquad M_d = \lambda_d \begin{bmatrix} 0 & a_d & 0 \\ a_d & b_d & c_d \\ 0 & c_d & 1-b_d \end{bmatrix}, \tag{1}$$

where $K_u = \mathrm{diag}(e^{i\phi_1}, 1, e^{i\phi_3})$ and all other parameters are real.

It is clear from Eq. (1) that the trace of each matrix was factored out so that one has, by construction,

$$\mathrm{Tr}\,(M_u) = \lambda_u; \qquad \mathrm{Tr}(M_d) = \lambda_d. \tag{2}$$

The convention of phases adopted in K_u corresponds to the factoring out of all phases in M_u and M_d and the elimination of the maximum number of nonphysical ones. It is clear that no nonfactorizable phases remain in this *Ansatz* due to the existence of one zero off-diagonal entry in both M_u and M_d. It was shown in Ref. [3] that the absence of nonfactorizable phases leads to important restrictions on $\sin 2\beta$.

The presence of several zeros in this Hermitian *Ansatz* renders the analytical diagonalization of the mass matrices quite simple. The column vectors of the unitary matrices U^u, U^d which diagonalize M_u, M_d can be determined, in each case, via the vector product of the first and third rows, with the inclusion of the mass eigenvalues. Each one of the three columns can be expressed as

$$(-m_i', a, 0) \times (0, c, 1-b-m_i') \qquad \frac{1}{N_i}, \tag{3}$$

where we have omitted the u, d, subindices, N_i is a normalization factor, and m_i' denotes the ith mass eigenvalue divided by the sum of the three mass eigenvalues. The mass eigenvalues do not depend on K_u and thus both in the up and down quark sectors, the four parameters a, b, c, λ, can be expressed in terms of quark masses, leaving only one free parameter in each sector, which we may choose to be $b_{(u,d)}$. This allows one to write each of the unitary matrices U^u, U^d in terms of quark mass ratios, a single free parameter, and the phases ϕ_1, ϕ_3 which have been factored out.

In this way one obtains the well-known texture-zero relations [2,17–19] valid to leading order:

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \sqrt{\frac{m_u}{m_c}}, \qquad \left|\frac{V_{td}}{V_{ts}}\right| = \sqrt{\frac{m_d}{m_s}},$$
$$|V_{us}| = \left|\sqrt{\frac{m_d}{m_s}}e^{i\phi_1} - \sqrt{\frac{m_u}{m_c}}\right|, \tag{4}$$

which are verified by a wide class of models [18]. Furthermore, as pointed out in the introduction, it has been shown [3] that texture-zero *Ansätze* with no nonfactorizable phases, such as this one, cannot reach values of $\sin(2\beta)$ as high as the present central value [4]:

$$\sin(2\beta) = 0.687 \pm 0.032. \tag{5}$$

It was already pointed out in Ref. [17] that the relation obtained for $|\frac{V_{ub}}{V_{cb}}|$ was problematic, and strongly disfavored this *Ansatz*, due to the smallness of the ratio $\sqrt{\frac{m_u}{m_c}}$. At present the constraint has become even more severe, since the new experimental average for $|V_{ub}|$ went up significantly. The current experimental values for these two $V_{\rm CKM}$ entries are [4]

$$|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3},$$
$$|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}, \tag{6}$$

while the values of the quark mass matrices are taken as [4]

$$m_u = 1.5\text{–}3.0\ (\text{Mev}), \qquad m_c = 1250 \pm 0.090\ (\text{Mev}),$$
$$m_t \simeq 300\ (\text{Gev}), \qquad m_d = 3\text{–}7\ (\text{Mev}),$$
$$m_s = 95 \pm 25\ (\text{Mev}), \qquad m_b = 4.2 \pm 0.07\ (\text{Gev}),$$
$$m_u/m_d = 0.3\text{–}0.7, \qquad m_s/m_d = 17\text{–}22. \tag{7}$$

The new theoretically clean and significantly improved constraint on $|V_{td}|/|V_{ts}|$ is [4]

$$|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.006}. \tag{8}$$

Taking into account the small experimental error, this result deviates significantly from the value predicted by the *Ansatz*, $|V_{td}|/|V_{ts}| = \sqrt{\frac{m_d}{m_s}}$ which leads to the range

$$0.213 < |V_{td}|/|V_{ts}| < 0.243, \tag{9}$$

where we took into account the experimental constraint on m_s/m_d given above.

Next we briefly describe how the value of γ, ($\gamma \equiv \arg(-V_{ud}V_{ub}^*V_{cd}^*V_{cb})$) for this *Ansatz* can be derived analytically. It is clear from Eq. (1) that in our parametrization $\arg V_{ud} = \phi_1$, to an excellent approximation. The phase ϕ_1 is fixed by the experimental value of $|V_{us}|$, given by Eq. (4). Using the central values for the quark mass ratios:

$$\sqrt{\frac{m_d}{m_s}} = \sqrt{\frac{1}{20}} = 0.224; \qquad \sqrt{\frac{m_u}{m_c}} = 0.042 \tag{10}$$

together with [4] $|V_{us}| = 0.2257 \pm 0.0021$, one obtains

$$\phi_1 = -87°. \tag{11}$$

Now, to leading order, one has $V_{ub}/V_{cb} = -\sqrt{\frac{m_u}{m_c}}$, implying $\arg(V_{ub}^*V_{cb}) \simeq \pi$ and one obtains in good approximation

$$\gamma \simeq \arg(V_{ud}V_{cd}^*). \tag{12}$$

Using the fact that in leading order in our parametrization

$$V_{cd} = -\sqrt{\frac{m_d}{m_s}} + \sqrt{\frac{m_u}{m_c}}e^{i\phi_1} \tag{13}$$

and taking central values for the quark mass ratios, one obtains

$$\arg(V_{cd}^*) = 169°, \tag{14}$$

which finally leads to

$$\gamma = \arg V_{ud} + \arg V_{cd}^* = (-87° + 169°) = 82°. \tag{15}$$

It is clear that in the framework of this *Ansatz*, the value of γ is very constrained, even allowing for one σ deviations from central values of the experimental parameters. At present, the current experimental value [4] $\gamma = (63^{+15}_{-12})°$ has large errors and therefore it is not possible to exclude the *Ansatz* only on the grounds of the γ constraint. However, it is clear that the *Ansatz* tends to give values for γ larger than the central experimental value.

Concerning β, it was shown in a previous work [3] that only $\arg(V_{cd})$ contributes significantly, so that in this framework we have

$$\beta \simeq -\arg V_{cd} \simeq 180° - 169° = 11°. \tag{16}$$

In summary, the four texture-zero *Ansatz* of Eq. (1) has serious difficulties in accommodating the recent, more precise, experimental data on $V_{\rm CKM}$. It is useful to separate these difficulties of the *Ansatz* in two classes:

(i) The *Ansatz* predicts too small of a value for β and too large of a value for $|V_{td}|/|V_{ts}|$.

(ii) The *Ansatz* predicts too small of a value for $|V_{ub}|/|V_{cb}|$ and too large of a value for γ.

The important point we wish to emphasize is that, while difficulties of class (i) can be avoided by assuming NP contributions to B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ mixings, those of class (ii) remain a challenge to the *Ansatz* even in the presence of NP contributions to mixing. It is useful to parametrize NP contributions to mixing in the following way:

$$M_{12}^{(q)} = (M_{12}^{(q)})^{\rm SM} r_q^2 e^{-2i\phi_q}, \qquad q = d, s. \tag{17}$$

The SM corresponds to $r_q = 1$, $\phi_q = 0$. In the presence of NP, instead of β one measures $\beta - \phi_d$ and $\Delta M_{B_q} = (\Delta M_{B_q})^{\rm SM} r_q^2$. It is clear that even a small contribution of ϕ_d (i.e. $\phi_d = -11°$) together with a small deviation of r_d/r_s from unity can rescue the *Ansatz* from discrepancies of class (i). On the contrary, the extraction of $|V_{ub}|/|V_{cb}|$ and γ from the experiment is unaffected by the presence of NP in the mixing. At this stage it should be noted that in most of the extensions of the SM, including the supersymmetric ones, there are NP contributions to the mixing [20–26].

An alternative way of checking that this interesting *Ansatz* is in conflict with the experiment is through the use of the following exact unitarity relation [27]:

$$\frac{\sin\beta}{\sin(\gamma+\beta)} = \frac{|V_{ub}|}{|V_{cb}|}\frac{|V_{ud}|}{|V_{cd}|} \tag{18}$$

as well as another unitarity relation, that holds to an excellent approximation [27]:

$$\frac{\sin\gamma}{\sin(\gamma+\beta)} \simeq \frac{|V_{td}|/|V_{ts}|}{|V_{us}|}. \tag{19}$$

Replacing in Eq. (18) the values obtained in this *Ansatz* for $|V_{ud}| \simeq 1$, $|V_{cd}|$ and the ratio $|V_{ub}|/|V_{cb}|$ we obtain the prediction $\sin\beta/\sin(\gamma+\beta) \simeq 0.19$. This is to be compared to the value computed with experimental central values $[\sin\beta/\sin(\gamma+\beta)]_{\text{exp}} \simeq 0.37$. Likewise for the relation given by Eq. (19), where in this case the *Ansatz* predicts $\sin\gamma/\sin(\gamma+\beta) \simeq 0.99$, while the value computed with the experimental central values is 0.89. We have also used the unitarity relations of Eqs. (18) and (19) to verify the validity of our approximate analytical evaluation of the elements of V_{CKM}, predicted by the *Ansatz*.

Given the difficulties of this *Ansatz* in conforming to the experimental data, one may wonder whether the *Ansatz* may be "saved" if implemented in a larger framework. In the next section, we show that this is indeed the case. We describe a scenario where the presence of NP can fully rescue the four texture-zero *Ansatz* by embedding it into a minimal extension of the SM with one additional down vectorial isosinglet quark. This framework could result from a family symmetry of the Lagrangian leading to the existing texture zeros, which is softly broken by mass terms involving the additional heavy quark.

III. AN EXAMPLE OF NONDECOUPLING

Let us consider a model with only one $Q = -1/3$ isosinglet vectorlike quark. Vectorlike quarks arise in a variety of extensions of the SM, in particular, within the framework of grand unified theories based on E_6. Another motivation for introducing vectorlike quarks arises if one requires spontaneous CP violation [28–31] in the context of supersymmetric extensions of the SM [32,33]. Vectorlike quarks are essential in order to generate a complex V_{CKM} from vacuum phases [34].

It can be easily shown that, without loss of generality, one may choose a weak basis where M_u, the up quark mass matrix, is real and diagonal, and the down quark matrix $\mathcal{M}_d$ can be cast in the form

$$\mathcal{M}_d = \left(\begin{array}{ccc|c} & & & 0 \\ & m_d & & 0 \\ & & & 0 \\ - & - & - & - \\ & M_D & & H \end{array}\right) \tag{20}$$

with m_d a Hermitian 3×3 matrix, M_D a 1×3 matrix, and H a single entry. The matrix $\mathcal{M}_d$ is diagonalized by the usual bi-unitary transformation

$$U_L^\dagger \mathcal{M}_d U_R = \begin{pmatrix} \bar{m} & 0 \\ 0 & \bar{M} \end{pmatrix}, \tag{21}$$

where $\bar{m} = \text{diag}(m_d, m_s, m_b)$ and $\bar{M}$ is the heavy quark mass. One can write U_L in block form,

$$U_L = \begin{pmatrix} K & R \\ S & T \end{pmatrix}, \tag{22}$$

where K is the usual 3×3 V_{CKM} matrix. U_L is the matrix that diagonalizes $\mathcal{M}_d\mathcal{M}_d^\dagger$, and the following relations can be readily derived [35] in the limit $M_D, H \gg \mathcal{O}(m_d)$

$$\bar{M}^2 \simeq (M_D {M_D}^\dagger + H^2) \equiv M^2, \tag{23}$$

$$\bar{m}^2 \simeq K^\dagger m_{\text{eff}} m_{\text{eff}}^\dagger K, \tag{24}$$

with

$$m_{\text{eff}} m_{\text{eff}}^\dagger \simeq m_d {m_d}^\dagger - \frac{(m_d {M_D}^\dagger M_D {m_d}^\dagger)}{M^2}. \tag{25}$$

Note that K is the mixing matrix connecting standard quarks and has small deviations from unitarity given by $K^\dagger K = 1 - S^\dagger S$, with

$$S \simeq -\frac{M_D m_d^\dagger K}{M^2}\left(1 + \frac{\bar{m}^2}{M^2}\right). \tag{26}$$

At this stage, it should be noted that the mass terms M_D, H are $SU(2)\times U(1)$ invariant and thus they can be much larger than the electroweak scale. If one makes the natural assumption that $M_D M_D^\dagger$ and H^2 are of the same order of magnitude it is clear that in Eq. (25), the second term contributing to $m_{\text{eff}} m_{\text{eff}}^\dagger$, has a magnitude comparable to that of $m_d {m_d}^\dagger$. This is the crucial point which makes it possible to rescue the four texture *Ansatz* considered in the previous section, through the introduction of a vectorlike isosinglet quark. Let us assume that there is a family symmetry which leads to the four texture-zero *Ansatz*, in the 3×3 quark mass matrices involving standard quarks. The $SU(2)\times U(1)$ invariant mass terms M_D, H may break softly the family symmetry. It is clear that the presence of the second term contributing to $m_{\text{eff}} m_{\text{eff}}^\dagger$ in Eq. (25), does affect the predictions of the *Ansatz*, allowing for it to be in agreement with the present experimental data. In what follows, we explain how this is possible, first through a qualitative analysis and then in the next section through an exact numerical example.

At this stage the following comment is in order. It is well known that in models with isosinglet quarks there are Z mediated flavor changing neutral currents (ZFCNC) [36,37], with strength proportional to deviations of 3×3 unitarity of the $V_{\rm CKM}$ matrix. From Eq. (26) it is clear that deviations of unitarity are proportional to $\frac{m_d^2}{M^2}$ [35,38], and therefore are naturally suppressed. As a result, choosing both M_D and H much larger than m_d strongly suppresses ZFCNC. This in turn implies that for sufficiently large M the extraction of β and of $|V_{td}|/|V_{ts}|$ are not significantly changed from the one based on SM physics.

Let us consider the following structure for $\mathcal{M}_d$, with the previous texture-zero Hermitian *Ansatz* embedded in the new four by four down mass matrix:

$$\mathcal{M}_d = \left(\begin{array}{ccc|c} & M_d & & \begin{matrix}0\\0\\0\end{matrix} \\ - & - & - & - \\ & M_D & & H \end{array}\right) = \begin{pmatrix} 0 & A & 0 & 0 \\ A & B & C & 0 \\ 0 & C & D & 0 \\ 0 & f & g & H \end{pmatrix}. \tag{27}$$

It is now possible to compute $m_{\rm eff} m_{\rm eff}^\dagger$, to a good approximation, using Eq. (25). We are now interested in combining this larger *Ansatz* for $\mathcal{M}_d$ with M_u following the previous pattern of Hermiticity and texture zeros.

It is known [17,39] that the present experimental data can be well reproduced from the following Froggatt-Nielsen pattern for $m_{\rm eff}$:

$$m_{\rm eff} \sim m_b \begin{pmatrix} 0 & \bar{\varepsilon}^3 & \bar{\varepsilon}^4 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^4 & \bar{\varepsilon}^2 & 1 \end{pmatrix}, \tag{28}$$

with $\bar{\varepsilon} \simeq 0.2$ together with a similar pattern for the up sector in terms of a smaller parameter ε with a value close to 0.06.

The required structure for $m_{\rm eff} m_{\rm eff}^\dagger$ is

$$m_{\rm eff} m_{\rm eff}^\dagger \sim m_b^2 \begin{pmatrix} \bar{\varepsilon}^6 & \bar{\varepsilon}^5 & \bar{\varepsilon}^4 \\ \bar{\varepsilon}^5 & \bar{\varepsilon}^4 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^4 & \bar{\varepsilon}^2 & 1 \end{pmatrix}. \tag{29}$$

Using Eqs. (25) and (27) it can be verified that, starting from a Froggatt-Nielsen pattern for M_d given by

$$|M_d| \sim m_b \begin{pmatrix} 0 & \bar{\varepsilon}^3 & 0 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ 0 & \bar{\varepsilon}^2 & 1 \end{pmatrix}, \tag{30}$$

in the context of the previous four texture *Ansatz*, implemented in the above extension of the SM, it is possible to obtain a matrix $m_{\rm eff} m_{\rm eff}^\dagger$ with the structure given by Eq. (29), by assuming: $\frac{|fg|}{H^2} \sim \bar{\varepsilon}$, in Eq. (27).

This implies that the extension of the SM through the inclusion of one down vectorlike isosinglet quark can save the *Ansatz* discussed in the previous section. Since no additional quarks were introduced in the up sector, the matrix M_u remains unchanged. However, due to the different hierarchies of the quark masses in the up and down sector, the sensitivity of the $V_{\rm CKM}$ matrix is much higher to changes in the down sector than to changes in the up sector.

IV. A NUMERICAL EXAMPLE

In this section we give an explicit example which illustrates the above described framework.

Let us consider the following mass matrices in Gev units:

$$\mathcal{M}_d = \begin{pmatrix} 0 & 0.0258 & 0 & 0 \\ 0.0258 & 0.12 & 0.24 & 0 \\ 0 & 0.24 & 4.97 & 0 \\ 0 & 350 & 370i & 500 \end{pmatrix}; \qquad M_u = K_u^\dagger \begin{bmatrix} 0 & 0.056 & 0 \\ 0.056 & 1.3 & 2.8 \\ 0 & 2.8 & 300 \end{bmatrix} K_u, \tag{31}$$

where $K_u = {\rm diag}(e^{i\phi_1}, 1, e^{i\phi_3})$ with $\phi_1 = -98.1°$ and $\phi_3 = 0.0°$. It can be readily verified that $\mathcal{M}_d$ and M_u lead to the following masses and mixing:

$$(m_u, m_c, m_t) = (0.00246, 1.28, 300.0)\ \text{in GeV};$$

$$(m_d, m_s, m_b, M_4) = (0.0058, 0.0935, 4.3, 718.7)\ \text{in GeV};$$

$$V_{\rm CKM}(3 \times 4) = \begin{pmatrix} 0.9743 & 0.2252 & 0.0036 & 0.000013 \\ 0.2251 & 0.9735 & 0.0410 & 0.00016 \\ 0.0084 & 0.0402 & 0.9991 & 0.0036 \end{pmatrix}. \tag{32}$$

The fourth column corresponds to matrix R in Eq. (22). An interesting feature of this example is the extreme smallness of the deviations from unitarity of the 3×3 $V_{\rm CKM}$ matrix as confirmed by the smallness of all the entries in R.

The corresponding values for $\sin(2\beta)$ and γ are

$$\sin(2\beta) = 0.707, \qquad \gamma = 66.1°, \tag{33}$$

which are in good agreement with the present experimental bounds. The ratio $|V_{ub}|/|V_{cb}|$ in this example is equal to 0.088 and therefore is significantly larger than $\sqrt{m_u/m_c}$. The fact that $|V_{ub}|$ in our example does not exactly agree with the new experimental constraint of Eq. (6) should not come as a surprise since in our analysis we are constrained by unitarity. It can be easily checked that the present experimental central values deviate from the unitarity relation of Eq. (18), although verifying Eq. (19). Note that, as emphasized in Ref. [4], the new experimental average for $|V_{ub}|$ is somewhat above the range favored by the measurement of $\sin(2\beta)$.

The fact that physics at a high energy scale can save a low energy texture that, by itself, was already ruled out by experiment, is perhaps unexpected. More surprising even is the fact that a similar effect could be obtained with a much heavier vectorial quark. It was shown in a recent paper [40] that down-type vectorial isosinglet quarks can also play an important role in generating sufficient *CP* violation in models with universal strength of Yukawa couplings [41,42].

V. CONCLUSIONS

We have studied the impact of new physics on tests of Yukawa texture-zero *Ansätze*, emphasizing that the greatest challenge for these textures arises from the measured values of $|V_{ub}|/|V_{cb}|$ and the rephasing invariant angle γ. This stems from the fact that while the presence of new physics contributions to B_d^0-$\bar{B}_d^0$ and/or B_s^0-$\bar{B}_s^0$ mixings can solve eventual discrepancies in the predictions for β, $|V_{td}|$, $|V_{ts}|$, the extracted values of $|V_{ub}|/|V_{cb}|$ and γ are unaffected by the presence of new physics contributions to mixing. We then show that the presence of new physics which does not decouple at low energies can save some of the most interesting *Ansätze* which would otherwise be in conflict with the experiment. We illustrate these effects through a specific four texture-zero *Ansatz* which is studied in the context of a minimal extension of the SM with an isosinglet vectorlike heavy quark which mixes with the standard quarks. We show that the presence of the heavy quark is sufficient to render viable the *Ansatz* which would otherwise be eliminated by the recent measurements of $|V_{ub}|/|V_{cb}|$ and γ. The crucial point is the nondecoupling of the effects of the heavy quark, even in the limit where its mass is arbitrarily large. It is clear that analogous considerations may in principle be applied to other texture-zero *Ansätze* which, without the input of new physics, would be ruled out by experiment. It should be emphasized that the violation of the four-zero ansatz only means that there is no experimentally viable additional family symmetry in the quark sector of the standard model, leading to this texture and, of course, it does not invalidate any of the general predictions of the standard model.

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