

A $U(2)^3$ flavour symmetry in Supersymmetry

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A $U(2)^3$ flavour symmetry acting on the first two generations of quarks partially explains the hierarchies of the yukawa couplings, and provides a natural embedding for Supersymmetry with heavier first two generations, where collider constraints are not in conflict with the requirement of naturalness and the SUSY CP problem is solved. Within this context a specific pattern of flavour symmetry breaking is considered. The K , B_d and B_s mixing amplitudes show a definite correlation that can resolve existing tensions in the CKM fit, pointing in this way to sbottom and gluino masses below about 1.5 TeV. Potentially sizeable contributions to both indirect and direct CP violation in B decays are allowed, even in the absence of flavour-blind phases. In case some effects are observed, the peculiar pattern in $\Delta F = 2$ and $\Delta B = 1$ observables may allow to distinguish between this and other models.

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[†]Based on [1, 2].

1. Introduction and motivations

The Standard Model (SM) description of flavour and CP violation, encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix, has shown an excellent agreement with data so far. If one wants to allow for New Physics (NP) near the Fermi scale, as required by naturalness, one then has to explain why no large deviations from the above flavour picture show up in experiments.

A possible approach to solve this issue is assuming that beyond the SM physics respects some flavour symmetry. The most popular attempt in this direction is the Minimal Flavour Violation (MFV) paradigm [3, 4, 5]: NP is formally invariant under a $U(3)^3 = U(3)_{qL} \times U(3)_{uR} \times U(3)_{dR}$ symmetry, broken only by the SM Yukawas, which are promoted to spurion fields transforming as $Y_u \sim (3, \bar{3}, 1)$ and $Y_d \sim (3, 1, \bar{3})$. While this makes possible, on general model independent grounds, to lower the scale of NP to a few TeV [6], it lacks of an explanation of (i) the smallness of the measured electric dipole moments, which would be generated by flavour-blind CP phases, (ii) the hierarchy of the fermion masses and the specific pattern of mixing angles.

The first issue can be accomodated e.g. in Supersymmetry with heavier first two generation sfermions [7, 8, 9, 10]. This scenario is favoured by current LHC sparticle searches if one wants to preserve the Supersymmetric solution to the hierarchy problem [11]. On the other hand, an attempt in the direction of explaining the hierarchies of the fermions is reducing the $U(3)^3$ symmetry to a $U(2)$ acting on the first two generations of quarks, irrespective of their chirality [12, 13]. However it turns out that this symmetry is not enough to suppress right-handed currents contribution to the ϵ_K parameter [14, 1]. The above considerations motivate us to study the consequences of a $U(2)^3 = U(2)_{qL} \times U(2)_{uR} \times U(2)_{dR}$ flavour symmetry in the context of Supersymmetry with hierarchical squark masses.

2. The $U(2)^3$ framework within Supersymmetry

In the limit of exact $U(2)^3$ the up, down, strange and charm quark masses are zero and the CKM matrix V_{CKM} is the identity. Our choice for the breaking of this symmetry is dictated by minimality: we introduce two spurions $\Delta Y_u \sim (2, \bar{2}, 1)$ and $\Delta Y_d \sim (2, 1, \bar{2})$ to generate the masses and mixings of the first two generation quarks, and a spurion $V \sim (2, 1, 1)$ to let the first two generations communicate with the third one. By sole $U(2)^3$ transformations the spurions can be set to the form

$$V^T = (0, \varepsilon), \quad \Delta Y_u = R_{12}^u \cdot \Delta Y_u^{diag}, \quad \Delta Y_d = \Phi \cdot R_{12}^d \cdot \Delta Y_d^{diag}, \quad (2.1)$$

where ε is a parameter of the order of $|V_{cb}|$, $R_{12}^{u,d}$ are rotations in the 12 sectors, $\Phi = \text{diag}(e^{-i\varphi}, 1)$, with φ giving rise to the CKM matrix phase. At first order in the spurions the Yukawa matrices read

$$Y_u = y_t \left(\begin{array}{c|c} \Delta Y_u & x_t V \\ \hline 0 & 1 \end{array} \right), \quad Y_d = y_b \left(\begin{array}{c|c} \Delta Y_d & x_b V \\ \hline 0 & 1 \end{array} \right), \quad (2.2)$$

so that they are formally invariant under $U(2)^3$. Analogously, we assume the flavour symmetry breaking in the soft squark masses and A terms to be controlled by the same spurions¹. After

¹This spurion structure is effectively realized in MFV at large $\tan\beta$ [15, 16]. A $U(2)^3$ symmetry, broken only by the A terms and without this specific spurion structure, has also been considered in the context of radiative flavour violation in the MSSM in [17, 18].

rotating to the mass basis for both the quarks and their superpartners, V_{CKM} and the supersymmetric mixing matrices appearing in the vertices $(\tilde{d}_{L,R} W^{L,R} \tilde{d}_{L,R}) \tilde{g}$ take the correlated forms

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & s_u s e^{-i\delta} \\ -\lambda & 1 - \lambda^2/2 & c_u s \\ -s_d s e^{i(\varphi+\delta)} & -s c_d & 1 \end{pmatrix}, \quad W^L = \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma} \\ -\kappa & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}, \quad W^R = \mathbb{1}, \quad (2.3)$$

where $\kappa = s_d e^{i(\delta+\varphi)}$, the phases δ and φ are related to each other and to the other parameters via $s_u c_d - c_u s_d e^{-i\varphi} = \lambda e^{i\delta}$, the new parameter $s_L > 0$ is of order $\lambda^2 \sim \varepsilon$, like s , and γ is an independent CP violating phase, which is zero if we do not allow for phases outside the spurions. W_R is equal to the identity to an accuracy which is sufficient to avoid a too large contribution to ε_K^2 .

3. Phenomenology of $\Delta F = 2$ and $\Delta B = 1$ observables

The mixing amplitudes in the kaon and $B_{d,s}$ systems, including SM and gluino-mediated contributions, read:

$$M_{12}^K = (M_{12}^K)^{\text{SM, tt}} (1 + |\xi_L|^4 F_0) + (M_{12}^K)^{\text{SM, tc + cc}}, \quad M_{12}^{B_{d,s}} = (M_{12}^{B_{d,s}})^{\text{SM}} (1 + \xi_L^2 F_0), \quad (3.1)$$

where $\xi_L = (c_d s_L / |V_{ts}|) e^{i\gamma}$ and $F_0(m_{\tilde{b}}, m_{\tilde{g}})$ is a positive function of the sbottom and gluino masses. In this way one obtains correlated expressions for the indirect CP violating parameter ε_K and the mixing-induced CP asymmetries in $B^0 \rightarrow \psi K_S$ and $B^0 \rightarrow \psi \phi$ decays:

$$\begin{aligned} \varepsilon_K &= \varepsilon_K^{\text{SM, tt}} (1 + |\xi_L|^4 F_0) + \varepsilon_K^{\text{SM, tc + cc}}, \\ S_{\psi K_S} &= \sin(2\beta + \phi_\Delta), \\ S_{\psi \phi} &= \sin(2|\beta_s| - \phi_\Delta), \end{aligned} \quad (3.2)$$

where β and β_s are the SM mixing phases and $\phi_\Delta = \arg(1 + \xi_L^2 F_0)$.

The above effects are interesting in light of the tension in the CKM description of flavour and CP violation, namely among ε_K , $S_{\psi K_S}$ and $\Delta M_d / \Delta M_s$ [19, 20, 21, 22, 23]. This tension can be solved in our framework by the new contributions we obtain to the first two observables. Note that a specific prediction of the model (with the assumption of gluino dominance) is a definite sign of the correction to ε_K , which is the one needed in order to solve the CKM tension.

We then perform a global fit varying the SUSY parameters ξ_L , F_0 and γ together with the four parameters of the CKM matrix, using all the observables listed in Table 1 of [1] as constraints. This leads, at the 90% C.L., to the preferred intervals

$$|\xi_L| \in [0.8, 2.1], \quad \phi_\Delta \in [-9^\circ, -1^\circ], \quad \gamma \in [-86^\circ, -25^\circ] \text{ or } \gamma \in [94^\circ, 155^\circ], \quad (3.3)$$

and to the predictions $S_{\psi \phi} \in [0.05, 0.20]$ and $m_{\tilde{g}}, m_{\tilde{b}} \lesssim 1.5$ TeV (the latter due to $F_0 \neq 0$). The favoured value for $S_{\psi \phi}$ is within the 1σ interval of the recent LHCb result [25].

It should be noted that some of the predictions we make are independent of the specific model under

²Note that a non-minimal breaking pattern (e.g. with $V_u \sim (1, \bar{2}, 1)$ and $V_d \sim (1, 1, \bar{2})$ instead of V) would in general spoil this feature. For a recent discussion of the inclusion of these two spurions *in addition to* V see [26].

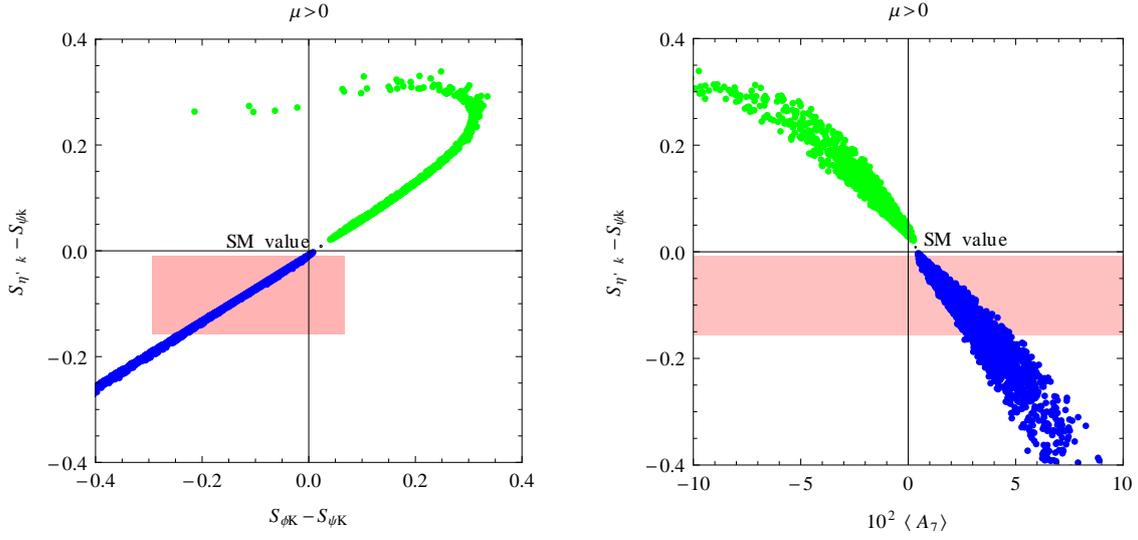


Figure 1: Left: correlation between $S_{\phi K_S} - S_{\psi K_S}$ and $S_{\eta' K} - S_{\psi K}$. Right: correlation between $\langle A_7 \rangle$ and $S_{\eta' K} - S_{\psi K}$. Points with $\gamma > 0$ ($\gamma < 0$) are shown in blue (green). The red shaded regions show the 1σ experimental range. The plots where the supersymmetric parameter μ is chosen to be negative do not show qualitative differences, apart from the inversion of the $\gamma > 0$ and $\gamma < 0$ points

consideration (Supersymmetry with hierarchical squark masses), namely (i) the absence of a new phase in M_{12}^K , (ii) the presence of a new phase in $B_{s,d}$ mixing and (iii) the universality $M_{12}^{B_d} = M_{12}^{B_s}$.

The presence of the phase γ leads to sizeable contributions to CP asymmetries in B decays. So, in [2], we study them in the case of negligible flavour-blind phases, in order to isolate the genuine $U(2)^3$ effect and make the link with the $\Delta F = 2$ observables evident (for this reason we also assume gluino-mediated amplitudes to dominate).

More specifically, we study the angular CP asymmetries in $B \rightarrow K^* \mu^+ \mu^-$, $\langle A_7 \rangle$ and $\langle A_8 \rangle$ [27], and the CP asymmetries in $B \rightarrow \eta' K_S$ and $B \rightarrow \phi K_S$ decays, $S_{\eta' K_S}$ and $S_{\phi K_S}$. The former turn out to be strictly correlated, $\langle A_8 \rangle \simeq -0.56 \langle A_7 \rangle$, confirming the result of [10]. The latter take the form $S_f = \sin(2\beta + \Phi_\Delta + \delta_f)$, where δ_f is a parameter encoding the direct CP violation contributions. In order to effectively ignore the modified B mixing phase, we show in figure 1 their correlation after subtraction of $S_{\psi K_S}$. The plots shown are obtained scanning the gluino mass between 0.5 and 1 TeV, the sbottom mass, the μ and the A term between 0.2 and 0.5 TeV and $\tan\beta$ between 2 and 10. The new flavour parameters $|\xi_L|$ and γ are required to lie in the region where the CKM fit tension is reduced (i.e. we impose (3.3)); the most effective constraint from other observables comes from $\text{BR}(B \rightarrow X_s \gamma)$. We also study the direct CP asymmetry $A_{CP}(B \rightarrow X_s \gamma)$, the contribution we find is sizeable and shows a specific correlations with the other direct CP violating observables. However the sensitivity of this observable to NP is spoiled by non-perturbative SM effects, which can saturate the future expected experimental sensitivity [29].

It is interesting to note that the above correlations between the $\Delta B = 1$ observables are very similar to those obtained in MFV [28, 21] or in effective MFV [10] with flavour-blind phases, while in our setup flavour-blind phases were assumed to be zero. Another important difference is that in our case we expect new CP violating effects in K and B mixing, which are instead absent in (effective)

MFV.

4. Summary and outlook

A suitably broken $U(2)^3$ flavour symmetry is considered as an alternative to MFV. A model independent consequence is a universal shift in B_s and B_d mixings, which can be complex, and a non standard real contribution to ϵ_K . The phenomenological consequences of this symmetry are explored in the context of Supersymmetry with hierarchical squark masses. The contributions to $\Delta F = 2$ observables are required to ameliorate tensions in the CKM fit, in this way one obtains for the sbottom and gluino masses the preferred region $m_{\tilde{b}}, m_{\tilde{g}} \lesssim 1.5$ TeV. Even if flavour-blind phases are negligible, one finds potentially sizeable contributions to both indirect and direct CP violation in B decays (the processes studied are $B \rightarrow \psi\phi$, $B \rightarrow \eta' K_S$, $B \rightarrow \phi K_S$, $B \rightarrow K^* \mu^+ \mu^-$ and $B \rightarrow X_s \gamma$). These effects, while being consistent with data so far, can be in the region to be probed by LHCb and the next generation B factories, and display a peculiar pattern in $\Delta F = 2$ and $\Delta B = 1$ observables that may help in distinguishing other models from the one presented here, in case some signal is observed.

The interest in studying this flavour symmetry goes beyond the specific case of Supersymmetry, see [30] for a recent treatment of $U(2)^3$, both in a model independent way and in composite Higgs models, and for a possible extension to the lepton sector.

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References

- [1] R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone and D. M. Straub, *$U(2)$ and Minimal Flavour Violation in Supersymmetry*, Eur. Phys. J. C **71** (2011) 1725 [arXiv:1105.2296 [hep-ph]].
- [2] R. Barbieri, P. Campli, G. Isidori, F. Sala and D. M. Straub, *B -decay CP-asymmetries in SUSY with a $U(2)^3$ flavour symmetry*, Eur. Phys. J. C **71** (2011) 1812 [arXiv:1108.5125 [hep-ph]].
- [3] R. S. Chivukula and H. Georgi, *Composite Technicolor Standard Model*, Phys. Lett. B **188** (1987) 99.
- [4] L. J. Hall and L. Randall, *Weak scale effective supersymmetry*, Phys. Rev. Lett. **65** (1990) 2939.
- [5] G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, *Minimal flavor violation: An Effective field theory approach*, Nucl. Phys. B **645** (2002) 155 [hep-ph/0207036].
- [6] G. Isidori, Y. Nir and G. Perez, *Flavor Physics Constraints for Physics Beyond the Standard Model*, Ann. Rev. Nucl. Part. Sci. **60** (2010) 355 [arXiv:1002.0900 [hep-ph]].
- [7] A. G. Cohen, D. B. Kaplan and A. E. Nelson, *The More minimal supersymmetric standard model*, Phys. Lett. B **388** (1996) 588 [hep-ph/9607394].
- [8] R. Barbieri, E. Bertuzzo, M. Farina, P. Lodone and D. Pappadopulo, *A Non Standard Supersymmetric Spectrum*, JHEP **1008** (2010) 024 [arXiv:1004.2256 [hep-ph]].

- [9] R. Barbieri, E. Bertuzzo, M. Farina, P. Lodone and D. Zhuridov, *Minimal Flavour Violation with hierarchical squark masses* JHEP **1012** (2010) 070 [Erratum-ibid. **1102** (2011) 044] [arXiv:1011.0730 [hep-ph]].
- [10] R. Barbieri, P. Lodone and D. M. Straub, *CP Violation in Supersymmetry with Effective Minimal Flavour Violation*, JHEP **1105** (2011) 049 [arXiv:1102.0726 [hep-ph]].
- [11] M. Papucci, J. T. Ruderman and A. Weiler, *Natural SUSY Endures*, arXiv:1110.6926 [hep-ph].
- [12] A. Pomarol and D. Tommasini, *Horizontal symmetries for the supersymmetric flavor problem*, Nucl. Phys. B **466** (1996) 3 [hep-ph/9507462].
- [13] R. Barbieri, G. R. Dvali and L. J. Hall, *Predictions from a $U(2)$ flavor symmetry in supersymmetric theories*, Phys. Lett. B **377** (1996) 76 [hep-ph/9512388].
- [14] R. Barbieri, L. J. Hall and A. Romanino, *Consequences of a $U(2)$ flavor symmetry*, Phys. Lett. B **401** (1997) 47 [hep-ph/9702315].
- [15] T. Feldmann and T. Mannel, *Large Top Mass and Non-Linear Representation of Flavour Symmetry*, Phys. Rev. Lett. **100** (2008) 171601 [arXiv:0801.1802 [hep-ph]].
- [16] A. L. Kagan, G. Perez, T. Volansky and J. Zupan, *General Minimal Flavor Violation*, Phys. Rev. D **80** (2009) 076002 [arXiv:0903.1794 [hep-ph]].
- [17] A. Crivellin and U. Nierste, *Supersymmetric renormalisation of the CKM matrix and new constraints on the squark mass matrices*, Phys. Rev. D **79** (2009) 035018 [arXiv:0810.1613 [hep-ph]].
- [18] A. Crivellin, L. Hofer, U. Nierste and D. Scherer, *Phenomenological consequences of radiative flavor violation in the MSSM*, Phys. Rev. D **84** (2011) 035030 [arXiv:1105.2818 [hep-ph]].
- [19] E. Lunghi and A. Soni, *Possible Indications of New Physics in $B(d)$ -mixing and in $\sin(2\beta)$ Determinations*, Phys. Lett. B **666** (2008) 162 [arXiv:0803.4340 [hep-ph]].
- [20] A. J. Buras and D. Guadagnoli, Phys. Rev. D **78** (2008) 033005 [arXiv:0805.3887 [hep-ph]].
- [21] W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi and D. M. Straub, *Anatomy and Phenomenology of FCNC and CPV Effects in SUSY Theories*, Nucl. Phys. B **830** (2010) 17 [arXiv:0909.1333 [hep-ph]].
- [22] E. Lunghi and A. Soni, *Possible evidence for the breakdown of the CKM-paradigm of CP-violation*, Phys. Lett. B **697** (2011) 323 [arXiv:1010.6069 [hep-ph]].
- [23] A. J. Bevan *et al.* [UTfit Collaboration], PoS **ICHEP2010** (2010) 270 [arXiv:1010.5089 [hep-ph]].
- [24] D. M. Straub, *$U(2)$ and MFV in Supersymmetry*, arXiv:1110.6391 [hep-ph].
- [25] The LHCb collaboration, *Tagged time-dependent angular analysis of $B_s \rightarrow J/\psi\phi$ decays at LHCb* LHCb-CONF-2012-002.
- [26] R. Barbieri, D. Buttazzo, F. Sala and D. M. Straub, *Less Minimal Flavour Violation*, arXiv:1206.1327 [hep-ph].
- [27] W. Altmannshofer, P. Ball, A. Bharucha, A. J. Buras, D. M. Straub and M. Wick, *Symmetries and Asymmetries of $B \rightarrow K^* \mu^+ \mu^-$ Decays in the Standard Model and Beyond*, JHEP **0901** (2009) 019 [arXiv:0811.1214 [hep-ph]].
- [28] W. Altmannshofer, A. J. Buras and P. Paradisi, *Low Energy Probes of CP Violation in a Flavor Blind MSSM*, Phys. Lett. B **669** (2008) 239 [arXiv:0808.0707 [hep-ph]].
- [29] M. Benzke, S. J. Lee, M. Neubert and G. Paz, *Long-Distance Dominance of the CP Asymmetry in $B^- \rightarrow X_{s,d} + \text{gamma}$ Decays*, Phys. Rev. Lett. **106** (2011) 141801 [arXiv:1012.3167 [hep-ph]].

- [30] R. Barbieri, D. Buttazzo, F. Sala and D. M. Straub, *Flavour physics from an approximate $U(2)^3$ symmetry*, arXiv:1203.4218 [hep-ph].