Flavour physics from an approximate $U(2)^3$ symmetry

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based on:
Barbieri,Isidori,Jones-Perez,Lodone,Straub arXiv:1105.2296
Barbieri,Campli,Isidori,S,Straub arXiv:1108.5125
Barbieri,Buttazzo,S,Straub arXiv:1203.4218 and 1206.1327

Why is CKM so good?

Flavour: excellent agreement between data and CKM picture

In other words: $\Delta\mathcal{L} = \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i \quad \Rightarrow \quad \boxed{\Lambda_i \gtrsim 10^3 \div 10^4\,\mathrm{TeV}}$

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Possible way out: $\Delta\mathcal{L} = \sum_i \xi_i \frac{c_i}{\Lambda_i^2}\mathcal{O}_i$

with $c_i \sim O(1)$ and ξ_i small due to some **flavour symmetry**

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Minimal Flavour Violation paradigm

[D'Ambrosio, Giudice, Isidori, Strumia 2002]

$$U(3)^3 = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$$

$Y_u \sim (3, \bar{3}, 1)$, $Y_d \sim (3, 1, \bar{3})$ so that SM is formally invariant

Assumption: BSM also formally invariant, only with Y_u, Y_d

✓ $\xi \sim V_{CKM}^{2\div4} \quad \Rightarrow \quad \Lambda \sim$ a few TeV is OK with flavour bounds

Beyond MFV: a way to proceed

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Reduce symmetry, round 1

From $U(3)^3$ to $U(2)$ [Pomarol,Tommasini 1995 and Barbieri,Dvali,Hall 1995]

✓ Exhibited by quark spectrum

× Too large flavour-violating effects in the RH sector [Barbieri,Hall,Romanino 1997]

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Reduce symmetry, round 2

$$U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$$

$$\begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \quad \begin{pmatrix} u_R \\ c_R \end{pmatrix} \quad \begin{pmatrix} d_R \\ s_R \end{pmatrix}$$

$$q_L^3 \quad t_R \quad b_R$$

Breaking $U(2)^3$

Exact $U(2)^3 \quad \longrightarrow \quad m_u = m_d = m_s = m_c = 0,\ V_{CKM} = 1$

$$Y_u = y_t \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array} \right) \qquad Y_d = y_b \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array} \right)$$

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- $\Delta Y_u \sim (2, \bar{2}, 1),\ \Delta Y_d \sim (2, 1, \bar{2})$ to explain quark masses

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- $\Delta Y_u \sim (2, \bar{2}, 1)$, $\Delta Y_d \sim (2, 1, \bar{2})$ to explain quark masses
- Minimal $U(2)^3$: only 1 doublet $V \sim (2, 1, 1)$ to explain CKM

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & s_L^u s e^{-i\delta} \\ -\lambda & 1-\lambda^2/2 & c_L^u s \\ -s_L^d s\, e^{i\beta} & -s c_L^d & 1 \end{pmatrix}, \qquad \begin{array}{c} (\bar{u}_L \gamma_\mu V_{CKM} d_L)\, W_\mu \\ s_L^u c_L^d - s_L^d c_L^u e^{i(\delta-\beta)} = \lambda e^{i\delta} \end{array}$$

All Minimal $U(2)^3$ **4** physical parameters from tree level observables

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$$Y_u = y_t \left(\begin{array}{c|c} \Delta Y_u & x_t V \\ \hline x_u V_u^\dagger & 1 \end{array} \right) \qquad Y_d = y_b \left(\begin{array}{c|c} \Delta Y_d & x_b V \\ \hline x_d V_d^\dagger & 1 \end{array} \right)$$

- $\Delta Y_u \sim (2, \bar{2}, 1)$, $\Delta Y_d \sim (2, 1, \bar{2})$ to explain quark masses
- Minimal $U(2)^3$: only 1 doublet $V \sim (2, 1, 1)$ to explain CKM
- Generic $U(2)^3$: 2 extra doublets $V_u \sim (1, 2, 1)$, $V_d \sim (1, 1, 2)$

$$V_{\rm CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & s_L^u s e^{-i\delta} \\ -\lambda & 1 - \lambda^2/2 & c_L^u s \\ -s_L^d s\, e^{i\beta} & -s c_L^d & 1 \end{pmatrix}, \qquad \begin{array}{c} (\bar{u}_L \gamma_\mu V_{CKM} d_L) W_\mu \\ \\ s_L^u c_L^d - s_L^d c_L^u e^{i(\delta - \beta)} = \lambda e^{i\delta} \end{array}$$

All Minimal $U(2)^3$ **4** physical parameters from tree level observables

$U(2)^3$: effective theory

Assume: all FV controlled by the spurions, i.e. $\Delta\mathcal{L}$ built with the bilinears:

$$\bar{\mathbf{q}}_{\mathbf{L}} V V^{\dagger} \mathbf{q}_{\mathbf{L}}, \quad \bar{\mathbf{q}}_{\mathbf{L}} V q_{3L}, \quad \bar{\mathbf{q}}_{\mathbf{L}} V t_R, \quad \lambda_b \bar{\mathbf{q}}_{\mathbf{L}} V b_R, \quad \bar{\mathbf{q}}_{\mathbf{L}} \Delta Y_u \mathbf{u}_{\mathbf{R}}, \quad \lambda_b \bar{\mathbf{q}}_{\mathbf{L}} \Delta Y_d \mathbf{d}_{\mathbf{R}}$$

$$\Rightarrow \ \Delta\mathcal{L} = \Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}_{\text{mag}}$$

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$$\Rightarrow \; \Delta\mathcal{L} = \Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}_{\text{mag}}$$

FV controlled by $\mathbf{V_{CKM}}$ (like $U(3)^3$) (but $c_L^B = c_L^K$ and $\phi_B = 0$ in $U(3)^3$)

Selected operators and relevant observables $(1/\Lambda^2$ understood)

$\Delta\mathcal{L}_L^{4f} \supset c_L^B e^{i\phi_B} (\mathbf{V_{tb}} \mathbf{V_{ti}^*})^2 (\bar{d}_L^i \gamma_\mu b_L)^2, \quad i = d, s$	$B_{d,s}^0 - \bar{B}_{d,s}^0$
$c_L^K (\mathbf{V_{ts}} \mathbf{V_{td}^*})^2 (\bar{d}_L \gamma_\mu s_L)^2,$	ϵ_K
$\Delta\mathcal{L}_{\text{mag}} \supset c_{7\gamma} e^{i\phi_{7\gamma}} m_b \mathbf{V_{tb}} \mathbf{V_{ti}^*} (\bar{d}_L^i \sigma_{\mu\nu} b_R) e F_{\mu\nu}$	$b \to s(d)\gamma$

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$$\Rightarrow \ \Delta\mathcal{L} = \Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}_{\text{mag}} + \Delta\mathcal{L}_R^{4f} + \Delta\mathcal{L}_{LR}^{4f}$$

FV both in L and R currents

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$$c_L^K (\mathbf{V_{ts}} \mathbf{V_{td}^*})^2 (\bar{d}_L \gamma_\mu s_L)^2, \qquad \epsilon_K$$

$$\Delta\mathcal{L}_{\text{mag}} \supset c_{7\gamma} e^{i\phi_{7\gamma}} m_b \mathbf{V_{tb}} \mathbf{V_{ti}^*} (\bar{d}_L^i \sigma_{\mu\nu} b_R) e F_{\mu\nu} \qquad b \to s(d)\gamma$$

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$$\Rightarrow \Delta\mathcal{L} = \Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}_{\text{mag}} + \Delta\mathcal{L}_R^{4f} + \Delta\mathcal{L}_{LR}^{4f}$$ FV both in L and R currents

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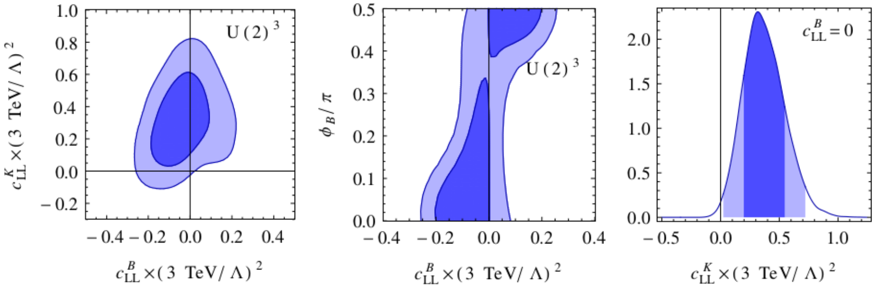
$$c_D e^{i\phi_D} m_t \frac{\epsilon_R^u}{\epsilon_L} \mathbf{V_{ub}} \mathbf{V_{cb}^*} (\bar{u}_L \sigma_{\mu\nu} T^a c_R) g_s G^a_{\mu\nu} \qquad \Delta A_{CP}^D$$

$$\Delta\mathcal{L}_{LR}^{4f} \supset c_R^K e^{i\phi_R^K} \frac{s_R^d}{s_L^d} \left(\frac{\epsilon_R^d}{\epsilon_L^d}\right)^2 (\mathbf{V_{ts}} \mathbf{V_{td}^*})^2 (\bar{d}_L \gamma_\mu s_L)(\bar{d}_R \gamma_\mu s_R) \qquad \epsilon_K$$

Minimal $U(2)^3$: bounds and new effects

$\Delta F = 2$

Can solve CKM fit tensions!



Messages

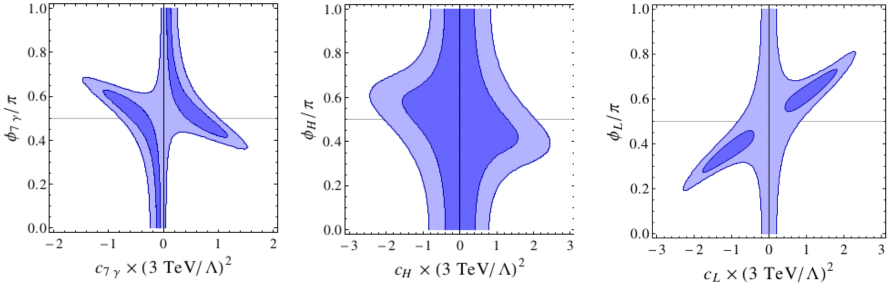
- Data consistent with $\Delta\mathcal{L} = \sum_i \xi_i \frac{c_i}{\Lambda_i^2}\mathcal{O}_i$ and $|c_i| = 0.2 \div 1$
- Larger effects than $U(3)^3$ allowed see also [Buras, Girrbach 2012]

$\Lambda_i \simeq 4\pi v \simeq 3\,\mathrm{TeV}$ (compos. scale/new weakly int. particles of mass $\sim v$)

Minimal $U(2)^3$: bounds and new effects

$\Delta F = 1$

$b \to s(d)\ell\bar{\ell},\ b \to s(d)\nu\bar{\nu}$



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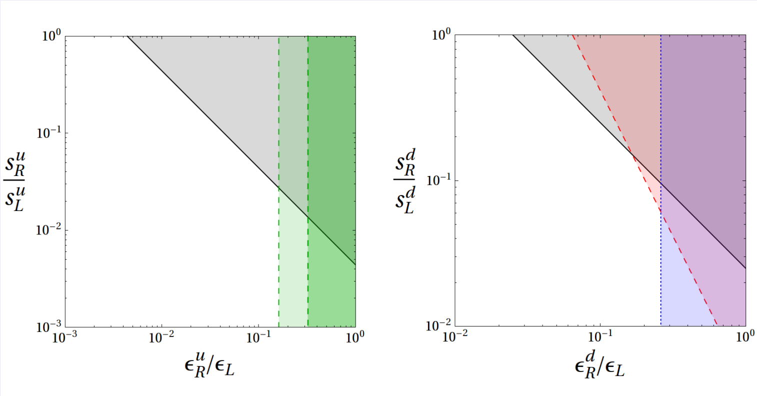
Generic $U(2)^3$: bounds and new effects

$$\Delta Y_{u,d} = L(s_L^{u,d}) \cdot \Delta Y_{u,d}^{\text{diag}} \cdot R(s_R^{u,d}), \quad V = (0, \epsilon_L), \quad V_{u,d} = (0, \epsilon_R^{u,d})$$

$s_L^{u,d}$, ϵ_L fixed from tree level observables, $s_R^{u,d}$, $\epsilon_R^{u,d}$ bounded from above



$\Lambda = 3\,\mathrm{TeV}$ and $c_i \sin\phi_i = 1$ ($\rightarrow$ constraints are maximized)

Legend: black = d_n, green = ΔA_{CP}^D, red = ϵ_K, blue = ϵ'_K

Up sector within $U(2)^3$

Minimal $U(2)^3$: prediction of no detectable effects in

- Top FCNC [$\mathrm{BR}(t \to c\gamma, cZ)$]: below future LHC sensitivity
- CPV in $D - \bar{D}$ mixing [ϕ_{12}]: below future LHCb sensitivity
- Direct CPV in D decay [$A^D_{CP}(\pi\pi, KK)$]: below per mille level

What if $A^D_{CP}(\pi\pi) - A^D_{CP}(KK) = -0.67 \pm 0.16\%$ is new physics?

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Generic $U(2)^3$

- could explain ΔA^{exp}_{CP}
- respecting all current flavour and EDMs bounds
- keeping the same null predictions for $BR(t \to c\gamma, cZ)$ and ϕ_{12}

How to know it is $U(2)^3$? (if some new physics signal seen)

$s - d$ correlation in B decays (same as in SM)

Then: how to know it is not $U(3)^3$?

Qualitative picture:

	Chirality conserving		Chirality breaking	
	$\Delta B = 1,2$	$\Delta S = 1,2$	$\Delta B = 1$	$\Delta C = 1$
$U(3)^3$ moderate t_β	$\mathbb{R}$	$\mathbb{R}$	$\mathbb{C}$	0
M$U(2)^3$, $U(3)^3$ large t_β	$\mathbb{C}$	$\mathbb{R}$	$\mathbb{C}$	0
G$U(2)^3$	$\mathbb{C}$	$\mathbb{C}$	$\mathbb{C}$	$\mathbb{C}$

Legend: $\mathbb{C}$ = new effect, $\mathbb{R}$ = new effect aligned with SM, 0 = negligible new effect

Quantitavely: smaller effects in MFV at moderate $\tan\beta$

$U(3)^3$ at large $\tan\beta$: other tree level effects expected
[Feldmann, Mannel 2008 and Kagan et al. 2009]

Where I am?

- Motivations
- Breaking $U(2)^3$
- Phenomenology
- $U(2)^3$ in Supersymmetry and in Composite Higgs Models
- Conclusions

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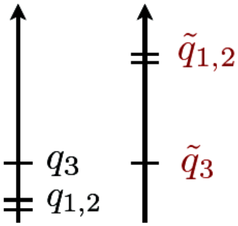
SUSY realisation of Minimal $U(2)^3$



SUSY with heavy 1, 2 generations

✓ Flavour blind CP violation (EDMs)

(Natural and ok with collider bounds)

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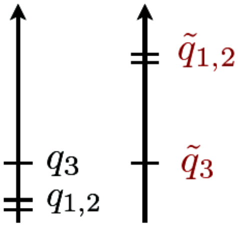

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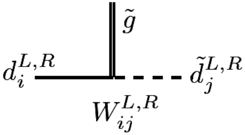
(Natural and ok with collider bounds)

$$\mathcal{L}_{F-breaking} \sim \ \tilde{q}^\dagger \, \tilde{m}^2(\Delta Y, V) \, \tilde{q}$$

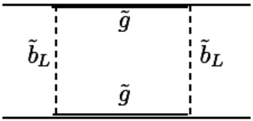
$$W^L = \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma} \\ -\kappa & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$



$$W^R = \ 1 \qquad\qquad \kappa = s_d e^{i\beta}$$

- One new angle s_L and 1 new CP-violating phase γ
- Minimal breaking leads to flavour alignment

SUSY $\Delta F = 2$: K and B mixings

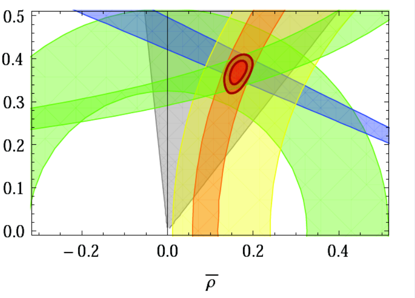


$$\epsilon_K = \epsilon_K^{\mathrm{SM},tt}\left(1+|\xi_L|^4 F_0\right) + \epsilon_K^{\mathrm{SM},tc+cc}$$

$$S_{\psi K_S} = \sin\left(2\beta + \phi_\Delta\right), \quad M^{B_{d,s}} = M^{B_{d,s}}_{\mathrm{SM}}\left(1 + \xi_L^2 F_0\right)$$

$$\xi_L = \frac{c_d s_L}{|V_{ts}|} e^{i\gamma}, \quad F_0(m_{\tilde{b}}, m_{\tilde{g}}) > 0, \quad \phi_\Delta = \arg\left(1 + \xi_L{}^2 F_0\right)$$

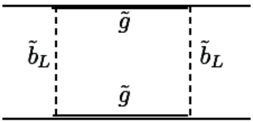
New parameters by solving CKM fit tensions



$|\xi_L| \in [0.8, 2.1]$, $\phi_\Delta \in [-9^\circ, -1^\circ]$,

$\gamma \in [-86^\circ, -25^\circ]$ or $[94^\circ, 155^\circ]$

SUSY $\Delta F = 2$: K and B mixings



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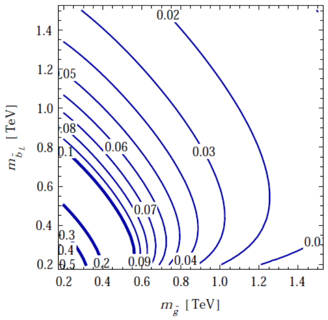


$|\xi_L| \in [0.8, 2.1]$, $\phi_\Delta \in [-9°, -1°]$,

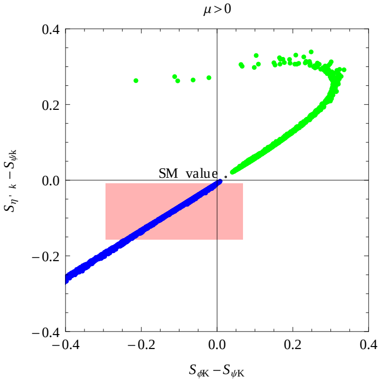
$\gamma \in [-86°, -25°]$ or $[94°, 155°]$

Prediction: $m_{\tilde{b}}, m_{\tilde{g}} \lesssim 1.5$ TeV

SUSY $\Delta F = 1$: selected B decays

CP asymmetries in $B \to \phi K_S,\ \eta' K_S,$ $\boxed{S_{\phi K_S},\ S_{\eta' K_S}}$

$S_f = \sin(2\beta + \phi_\Delta + \delta_f)$, $\delta_f(\xi_L, \gamma, m_{\tilde{b}}, m_{\tilde{g}}, \mu \tan\beta - A_b)$



Blue: $\gamma > 0$, Green: $\gamma < 0$,
Red: $1\ \sigma$ experimental bound

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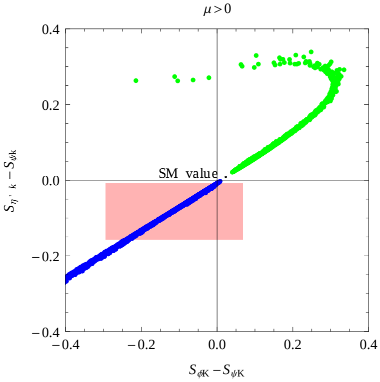

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Relevant for:

- Future improvement in sensitivity: a $5 \div 10$ factor!
- Sizeable effects with negligible flavour blind phases

Similar clean correlations also for $A_{CP}(B \to K^* \mu^+ \mu^-, B \to X_s \gamma)$

Message

Peculiar phenomenological pattern of interest for LHC

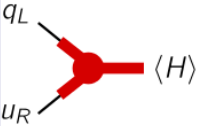
CHM realisation of Minimal $U(2)^3$

Flavour symmetric strong sector as an alternative to "RS-GIM" mechanism

$$\mathcal{L}_s = \lambda_U \bar{Q}_L^u H U_R + \lambda_D \bar{Q}_L^d \tilde{H} D_R + M_Q^u \bar{Q}_L^u Q_R^u + M_Q^d \bar{Q}_L^d Q_R^d + M_U \bar{U}_L U_R + M_D \bar{D}_L D_R$$

Flavour violation only in composite-elementary mixings:

$U(3)^3$ [Redi, Weiler 2011]



$$\mathcal{L}_{\text{mix}}^{R\text{-comp}} = \bar{U}_L m_U u_R + \bar{D}_L m_D d_R + \bar{q}_L \hat{m}_u Q_R^u + \bar{q}_L \hat{m}_d Q_R^d$$

$$\mathcal{L}_{\text{mix}}^{L\text{-comp}} = \bar{q}_L m_U Q_R^u + \bar{q}_L m_U Q_R^d + \bar{U}_L \hat{m}_u u_R + \bar{D}_L \hat{m}_d d_R, \qquad \hat{m}_{u,d} \propto Y_{u,d}$$

Flavour symmetric strong sector as an alternative to "RS-GIM" mechanism

$$\mathcal{L}_s = \lambda_U \bar{Q}_L^u H U_R + \lambda_D \bar{Q}_L^d \tilde{H} D_R + M_Q^u \bar{Q}_L^u Q_R^u + M_Q^d \bar{Q}_L^d Q_R^d + M_U \bar{U}_L U_R + M_D \bar{D}_L D_R$$

Flavour violation only in composite-elementary mixings:

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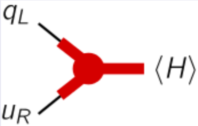

$$\mathcal{L}_{\text{mix}}^{R\text{-comp}} = \bar{U}_L m_U u_R + \bar{D}_L m_D d_R + \bar{q}_L \hat{m}_u(V, \Delta Y_u) Q_R^u + \bar{q}_L \hat{m}_d(V, \Delta Y_u) Q_R^d$$

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✓ distinguishing generations ⇒ light quarks can be mostly elementary

⇒ easier to satisfy precision and collider constraints!

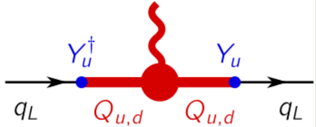
see also $U(3)^2 \times U(2)$, [Redi 2012]

CHM flavour phenomenology

Example: chirality conserving, $U(3)^3$

L-comp.
$\bar{U}_L \hat{m}_u u_R$, $\bar{D}_L \hat{m}_d d_R$
No tree level FV!

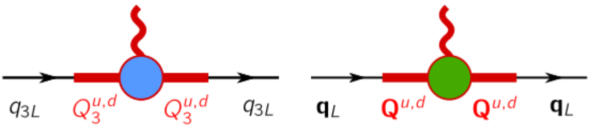
R-comp.
$\bar{q}_L \hat{m}_u Q_R^u$, $\bar{q}_L \hat{m}_d Q_R^d$



Tree level FCNCs:	Chir. conserving		Chir. breaking
	$\Delta B = 1,2$	$\Delta S = 1,2$	$\Delta B = 1$
$U(3)^3$ moderate t_β	$\mathbb{R}$	$\mathbb{R}$	$\mathbb{C}$
$U(3)^3$ **R-comp.**	$\mathbb{R}$	$\mathbb{R}$	0
$U(3)^3$ **L-comp.**	0	0	0

Example: chirality conserving, $U(2)^3$, **L-comp.**

$\bar{U}_L \hat{m}_u(V, \Delta Y_u) u_R$
$\bar{D}_L \hat{m}_d(V, \Delta Y_d) d_R$



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M$U(2)^3$, $U(3)^3$ large t_β	$\mathbb{C}$	$\mathbb{R}$	$\mathbb{C}$
M$U(2)^3$ **R-comp.**	$\mathbb{C}$	$\mathbb{R}$	0
M$U(2)^3$ **L-comp.**	$\mathbb{R}$	$\mathbb{R}$	$\mathbb{C}$

Summary of $U(2)^3$ phenomenology

$\Delta F = 2$

- new phase ϕ_B in $B - \bar{B}$ mixing
- M^{B_d}/M^{B_s} SM-like
- no new phase in K mixing

$\Delta B = 1$

- effects *can* be large

Up

- effects cannot be large (ΔA^D_{CP} in Generic $U(2)^3$ *can*)

Observables to watch: $S_{\psi\phi}$, $S_{\phi K}$, $b \to s(d)\ell\bar{\ell}, \nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, ...

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$\Delta B = 1$

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- clean correlations between observables — SUSY

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Observables to watch: $S_{\psi\phi}$, $S_{\phi K}$, $b \to s(d)\ell\bar{\ell}, \nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, ...

Summary of $U(2)^3$ phenomenology

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$\Delta B = 1$

- effects *can* be large
- clean correlations between observables — SUSY

Up

- effects cannot be large (ΔA_{CP}^D in Generic $U(2)^3$ *can*)

Some effects cannot be large (implementation dependent) — CHM

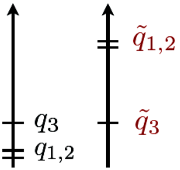
Observables to watch: $S_{\psi\phi}$, $S_{\phi K}$, $b \to s(d)\ell\bar{\ell}, \nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, ...

Conclusions

$U(2)^3$ is in the data

Naturally safe with flavour bounds

Large effects *allowed*



SUSY Natural and ok with collider bounds

Small EDMs

CHM Collider and precision constraints easier to satisfy than $U(3)^3$

Conclusions

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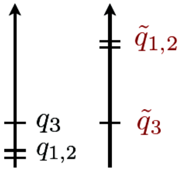

SUSY Natural and ok with collider bounds

Small EDMs

CHM Collider and precision constraints easier to satisfy than $U(3)^3$

Thank you for your attention!

Back up

$\Delta F = 1$: ϵ'_K

A significant limit for both $U(2)^3$ and $U(3)^3$

$$\mathcal{H}_{\text{eff}}^{\Delta S=1} = \frac{1}{\Lambda^2}\xi_{ds}\left(\bar{d}_L^\alpha \gamma_\mu s_L^\beta\right)\left[c_K^d\left(\bar{d}_R^\beta \gamma_\mu d_R^\alpha\right) + c_K^u\left(\bar{u}_R^\beta \gamma_\mu u_R^\alpha\right)\right]$$

$$\left|\frac{\epsilon'}{\epsilon}\right| \simeq \frac{|\text{Im}A_2|}{\sqrt{2}\,|\epsilon|\,\text{Re}A_0}, \qquad \langle(\pi\pi)_{I=2}|Q_{LR}^u + Q_{LR}^d|K\rangle = 0$$

$$c_K^{u,d} \lesssim 0.1 \div 0.2\left(\frac{3\,\text{TeV}}{\Lambda^2}\right)$$

Still roughly consistent with previous discussion of bounds

$U(2)^3$+ SUSY solves the "problem"!

- box diagrams are suppressed by heavy $\tilde{u}$, $\tilde{d}$