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Flavour physics & the special role of the third generation

based on:

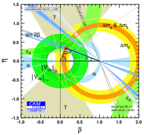
R. Barbieri, G. Isidori, J. Jones-Pérez, P. Lodone, D.M.S., arXiv:1105.2296
R. Barbieri, P. Campli, G. Isidori, F. Sala, D.M.S., arXiv:1108.5125
R. Barbieri, D. Buttazzo, F. Sala, D.M.S., arXiv:1203.4218

17 April, 2012 · LAPTh Seminar · Annecy-le-Vieux

Outline

- The flavour puzzle
  - Recap of Minimal Flavour Violation
- $U(2)^3$ flavour symmetry
  - Generic effective field theory approach
  - Supersymmetry
  - Composite Higgs models
  - Bounds from $\Delta F = 1, 2$ processes
  - Extension to the lepton sector
- Conclusions

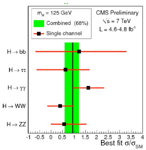
Our understanding of fundamental physics



natural
well-understood

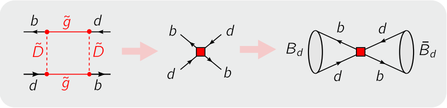
good parametrization
but no explanation

$$\mathscr{L} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \sum_{i,d>4} \frac{O_i^{(d)}}{\Lambda^{4-d}}$$



seems to describe the data
but highly unnatural if Higgs is
fundamental and not SUSY

neutrino masses
dark matter
?



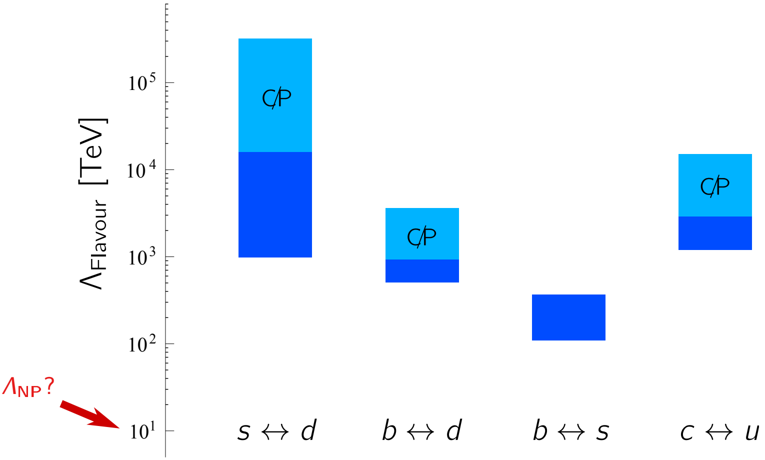
Bounds on new physics from flavour

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_i \frac{O_i^{(d)}}{\Lambda^{4-d}}$$

Operator	Bound on Λ [TeV]		Observables
	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		Δm_{B_s}

[Isidori, Nir, Perez 1002.0900]

The flavour puzzle



TeV scale NP requires weakly broken flavour symmetry

Minimal Flavour Violation

MFV = Maximal flavour symmetry ... [D'Ambrosio et al. (2002)]

$$\mathscr{L}_{\mathrm{SM}} \supset \bar{q}_L(i\not{D})q_L + \bar{u}_R(i\not{D})u_R + \bar{d}_R(i\not{D})d_R - Y_d^{ij}\bar{q}_L^i h d_R^j - Y_u^{ij}\bar{q}_L^i \tilde{h} u_R^j$$

$$U(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R} \to U(1)_B$$

... + minimal symmetry breaking

$$Y_u \sim (3,\bar{3},1) \qquad Y_d \sim (3,1,\bar{3})$$

A convenient basis

$$Y_u = U_{Q_u}^\dagger \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} U_U \qquad Y_d = U_{Q_d}^\dagger \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix} U_D$$

Minimal Flavour Violation

MFV = Maximal flavour symmetry ... [D'Ambrosio et al. (2002)]

$$\mathscr{L}_{\text{SM}} \supset \bar{q}_L(i\not{D})q_L + \bar{u}_R(i\not{D})u_R + \bar{d}_R(i\not{D})d_R - Y_d^{ij}\bar{q}_L^i h d_R^j - Y_u^{ij}\bar{q}_L^i \tilde{h} u_R^j$$

$$U(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R} \to U(1)_B$$

... + minimal symmetry breaking

$$Y_u \sim (3, \bar{3}, 1) \qquad Y_d \sim (3, 1, \bar{3})$$

A convenient basis

$$Y_u = \underbrace{U_{Q_u}^\dagger}_{V_{\text{CKM}}^\dagger} \begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \cancel{U_U} \qquad Y_d = \cancel{U_{Q_d}^\dagger} \begin{pmatrix} y_d & & \\ & y_s & \\ & & y_b \end{pmatrix} \cancel{U_D}$$

Consequences of MFV

All operators have to be formally invariant under the flavour symmetry.

$$\bar{d}_{Li}\gamma_\mu \left[Y_u Y_u^\dagger + Y_d Y_d^\dagger + \dots\right]_{ij} d_{Lj} \sim \bar{d}_{Li}\gamma_\mu \left[y_t^2 V_{ti}^* V_{tj}\right] d_{Lj}$$

$$\left[Y_u Y_u^\dagger\right]^n_{i\neq j} = y_t^{2n} V_{ti}^* V_{tj}$$

$$\|Y_d\| \ll 1$$

$$\bar{d}_{Ri}\sigma_{\mu\nu} \left[Y_d Y_u^\dagger Y_u + \dots\right]_{ij} d_{Lj} \sim \bar{d}_{Ri}\sigma_{\mu\nu} \left[y_{d_i} V_{ti}^* V_{tj}\right] d_{Lj}$$

- same CKM suppression of all amplitudes as in the SM
- no right-handed FCNCs

$$\Rightarrow \text{e.g.} \quad \frac{1}{\Lambda_{\text{NP}}^2}(\bar{d}_{Li}\gamma_\mu \left[y_t^2 V_{ti}^* V_{tj}\right] d_{Lj})^2 \;\rightarrow\; \Lambda_{\text{NP}} \gtrsim 5\,\text{TeV}$$

Example: MFV in supersymmetry

degeneracy & alignment

$$\tilde{m}^2_{Q_L} = \tilde{m}^2 \left(a_1 1 + b_1 Y_U Y_U^\dagger + b_2 Y_D Y_D^\dagger + \dots \right)$$

$$\tilde{m}^2_{U_R} = \tilde{m}^2 \left(a_2 1 + b_5 Y_U^\dagger Y_U + \dots \right)$$

$$\tilde{m}^2_{D_R} = \tilde{m}^2 \left(a_3 1 + b_6 Y_D^\dagger Y_D + \dots \right)$$

$$A_U = A \left(a_4 1 + b_7 Y_D Y_D^\dagger + \dots \right) Y_U$$

$$A_D = A \left(a_5 1 + b_8 Y_U Y_U^\dagger + \dots \right) Y_D$$

can be complex $\to$ EDMs

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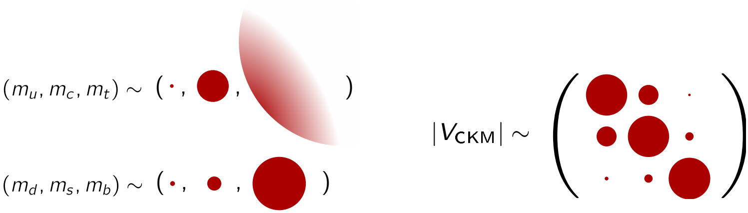
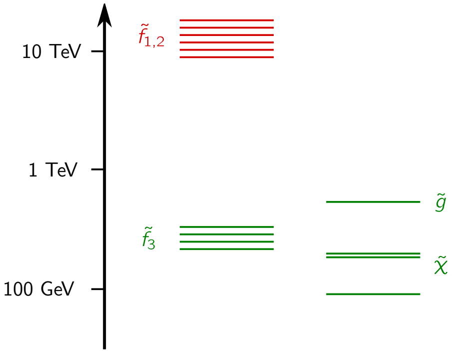
Why $U(2)^3$?



$$U(2)^3 \Rightarrow m_{u,d}^{1,2} = 0,\ V_{i3,3i} = 0$$

Why $U(2)^3$?



$U(2)^3$ and its breaking

~~Maximal~~ flavour symmetry

$$U(2)_{Q_L} \otimes U(2)_{U_R} \otimes U(2)_{D_R}$$

$$\mathbf{q_L} = \begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \sim (2,1,1)$$

$$\mathbf{u_R} = \begin{pmatrix} u_R^1 \\ u_R^2 \end{pmatrix} \sim (1,2,1)$$

$$\mathbf{d_R} = \begin{pmatrix} d_R^1 \\ d_R^2 \end{pmatrix} \sim (1,1,2)$$

$$q_L^3, u_R^3, d_R^3 \sim 1$$

$U(2)^3$ and its breaking

~~Maximal~~ flavour symmetry

$$U(2)_{Q_L} \otimes U(2)_{U_R} \otimes U(2)_{D_R}$$

Resulting Yukawas:

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

$U(2)^3$ and its breaking

~~Maximal~~ flavour symmetry

$$U(2)_{Q_L} \otimes U(2)_{U_R} \otimes U(2)_{D_R} \to U(1)_B$$

Minimal + *weak* breaking

$$\Delta Y_u \sim (2, \bar{2}, 1) \qquad \Delta Y_d \sim (2, 1, \bar{2})$$

$$(y_u, y_c, \theta_u) \qquad (y_d, y_s, \theta_d)$$

Resulting Yukawas:

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

$U(2)^3$ and its breaking

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$$U(2)_{Q_L} \otimes U(2)_{U_R} \otimes U(2)_{D_R} \to U(1)_B$$

Minimal + *weak* breaking

$$\Delta Y_u \sim (2, \bar{2}, 1) \qquad \Delta Y_d \sim (2, 1, \bar{2}) \qquad V \sim (2, 1, 1)$$

$$(y_u, y_c, \theta_u) \qquad (y_d, y_s, \theta_d) \qquad (V_{cb}, V_{ts})$$

Resulting Yukawas:

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

$U(2)^3$ and its breaking

~~Maximal~~ flavour symmetry

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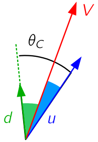
Resulting Yukawas:

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



$$|V_{us}| \sim \theta_u - \theta_d$$
$$|V_{td}/V_{ts}| \sim \theta_d$$
$$|V_{ub}/V_{cb}| \sim \theta_u$$

A convenient basis

$$Y_u = U^\dagger_{Q_u} \begin{pmatrix} y_u & \\ & y_c \end{pmatrix} U_U \qquad Y_d = U^\dagger_{Q_d} \begin{pmatrix} y_d & \\ & y_s \end{pmatrix} U_D \qquad V = U_{Q_V} \begin{pmatrix} 0 \\ \epsilon \end{pmatrix}$$

$U(2)^3$ and its breaking

A convenient basis

$$Y_u = U^\dagger_{Q_u} \begin{pmatrix} y_u & \\ & y_c \end{pmatrix} \cancel{U_u} \qquad Y_d = U^\dagger_{Q_d} \begin{pmatrix} y_d & \\ & y_s \end{pmatrix} \cancel{U_d} \qquad V = \cancel{U_{Q_V}} \begin{pmatrix} 0 \\ \epsilon \end{pmatrix}$$

$$Y^{\text{diag}}_{u,d} = U_{u,dL}\, y_{t,b} \left(\begin{array}{c|c} \Delta Y_{u,d} & x_{t,b}\, V \\ \hline 0 & 1 \end{array}\right) U^\dagger_{u,dR}$$

$$U^*_{uL} U^T_{dL} = V_{\text{CKM}} \qquad\qquad U_{u,dR} = 1 + O(y_c |V_{cb}|)$$

$$U_{u,dL} = \left(\begin{array}{c|c} U_{Q_{u,d}} & 0 \\ \hline 0 & 1 \end{array}\right) \times R_{23}$$

$U(2)^3$: consequences for $\Delta F = 2$

As in MFV, expansion in spurions to obtain operors invariant under the symmetry

$$q_L = \begin{pmatrix} \mathbf{q_L} \\ q_{3L} \end{pmatrix}, \qquad u_R = \begin{pmatrix} \mathbf{u_R} \\ t_R \end{pmatrix}, \qquad d_R = \begin{pmatrix} \mathbf{d_R} \\ b_R \end{pmatrix},$$

e.g. $\bar{q}_{Li}\gamma_\mu X_{ij} q_{Lj} \approx a\, \bar{q}_{3L}\gamma_\mu q_{3L} + b\, \bar{\mathbf{q}}_\mathbf{L}\gamma_\mu \mathbf{q_L}$
$+ c\, \bar{q}_{3L}\gamma_\mu (V^\dagger \mathbf{q_L}) + c^*\, (\bar{\mathbf{q}}_\mathbf{L} V)\gamma_\mu q_{3L} + d\, (\bar{\mathbf{q}}_\mathbf{L} V)\gamma_\mu (V^\dagger \mathbf{q_L}) + \ldots$

Resulting effects in operators relevant for meson mixing:

$c_{LL}^B e^{i\phi_B} (V_{tb} V_{ti}^*)^2 (\bar{d}_{Li}\gamma_\mu b_L)^2$ ⟵ Universal, CPV contribution to $B_{d,s}$ mixing

$c_{LL}^K (V_{tb} V_{ti}^*)^2 (\bar{d}_L\gamma_\mu s_L)^2$ ⟵ Universality with K system broken

(cf. $U(3)^3 : c_{LL}^B = c_{LL}^K, \phi_B = 0$)

$U(2)^3$: consequences for $\Delta F = 2$

$$\epsilon_K = \epsilon_K^{\text{SM}} \times (1 + h_K)$$

$$S_{\psi K_S} = \sin\left[2\beta + \arg\left(1 + h_B e^{i\phi_B}\right)\right]$$

$$S_{\psi\phi} = \sin\left[2|\beta_s| - \arg\left(1 + h_B e^{i\phi_B}\right)\right]$$

$$\frac{\Delta M_d}{\Delta M_s} = \left(\frac{\Delta M_d}{\Delta M_s}\right)^{\text{SM}}$$

CPV in K-$\bar{K}$ mixing

CPV in B_d-$\bar{B}_d$ mixing

CPV in B_s-$\bar{B}_s$ mixing

$$h_{K,B} \approx 1.08\, c_{LL}^{K,B} \left[\frac{3\,\text{TeV}}{\Lambda}\right]^2$$

$U(2)^3$: consequences for $\Delta F = 2$

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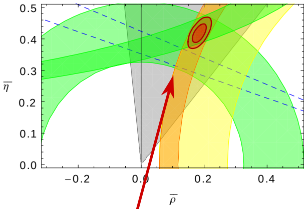
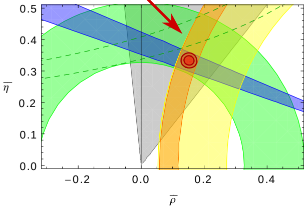
$$\frac{\Delta M_d}{\Delta M_s} = \left(\frac{\Delta M_d}{\Delta M_s}\right)^{\rm SM}$$



Possible tension in CKM fits between $|\epsilon_K|$ and $\sin(2\beta)$ can be solved (in constrast to $U(3)^3$ case)



$$h_{K,B} \approx 1.08\, c_{LL}^{K,B} \left[\frac{3\,\text{TeV}}{\Lambda}\right]^2$$

$U(2)^3$: consequences for $\Delta F = 1$

For $\Delta F = 1$ processes, also chirality breaking bilinears are relevant ($b \to s\gamma$)

$$\bar{q}_{Li} X_{ij} d_{Rj} \approx \lambda_b \left(a_d\, \bar{q}_{3L} b_R + b_d\, (\bar{\mathbf{q}}_\mathbf{L} V) b_R + c_d\, \bar{\mathbf{q}}_\mathbf{L} \Delta Y_d \mathbf{d}_\mathbf{R} \right)$$

Resulting effects in (selected) operators relevant for B and K decays:

$c_{7\gamma} e^{i\phi_{7\gamma}} V_{tb} V_{ti}^* m_b (\bar{d}_{Li} \sigma_{\mu\nu} b_R) e F_{\mu\nu}$ ⟵ Universal, CPV contribution to B decays

$c_L^B e^{i\phi_L} V_{tb} V_{ti}^* (\bar{d}_{Li} \gamma_\mu b_L)(\bar{l}_L \gamma_\mu l_L)$ ⟵ CPV also in chirality conserving operators

$c_L^K V_{ts} V_{td}^* (\bar{d}_L \gamma_\mu s_L)(\bar{\nu}_L \gamma_\mu \nu_L)$ ⟵ Real contribution to K decays

$U(2)^3$: comparison with MFV

	$b_L \leftrightarrow q_L$		$s_L \leftrightarrow d_L$	$b_R \leftrightarrow q_L$
$U(3)^3$	$\mathbb{R}$	$\leftrightarrow$	$\mathbb{R}$	$\mathbb{C}$
$U(2)^3$	$\mathbb{C}$		$\mathbb{R}$	$\mathbb{C}$
Relevant processes	B_q^0-$\bar{B}_q^0$ $b \to s l \bar{l}, \nu\bar{\nu}$		K^0-$\bar{K}^0$ $K \to \pi\nu\bar{\nu}$	$b \to s\gamma$ $b \to s l \bar{l}$

As in MFV

- same CKM suppression of all amplitudes as in the SM
- no right-handed FCNCs
- universality in $b \to s$ vs. $b \to d$

Different from MFV

- correlation between B & K broken
- CP violation also in chirality conserving bilinears

$U(2)^3$ vs. MFV at large $\tan\beta$

(Comments on MFV at large $\tan\beta$

At large $\tan\beta$, the 3rd generation Yukawas effecively break

$$U(3)^3 \stackrel{y_t, y_b}{\rightarrow} U(2)^3$$

[Feldmann, Mannel (2008), ...]

In MFV + large $\tan\beta$, the spurion structure is minimal ($\Delta Y_{u,d} + V$)

$\Rightarrow$ Same structure of FCNCs as in general $U(2)^3$ with minimal breaking

$\Rightarrow$ MFV + large $\tan\beta$ is a special case of general $U(2)^3$

Nomenclature:
"GMFV" = MFV + large $\tan\beta$ + CPV phases outside the spurions
[Kagan, Perez, Volansky, Zupan (2009)]
)

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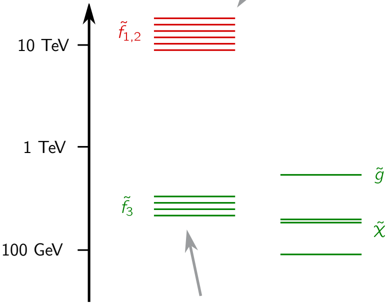
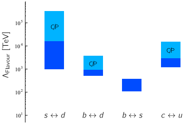
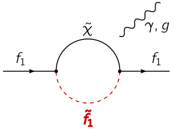
$U(2)^3$ and natural SUSY

1st/2nd generation sfermions heavy

- most strongly constrained by LHC
- CP problem due to 1-loop contributions to EDMs
- strong bound from K mixing on 1-2 transitions



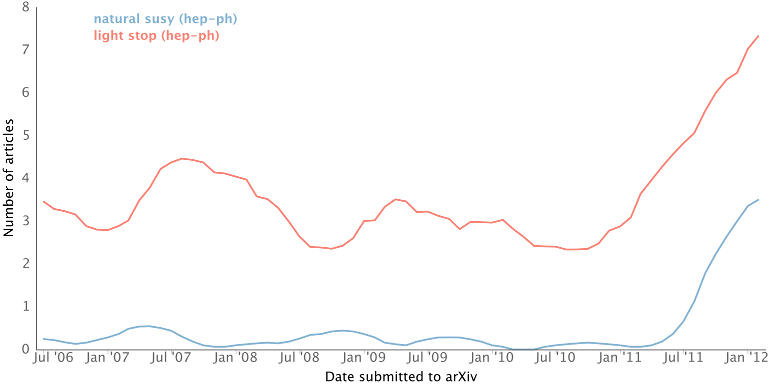




3rd generation sfermions light

- stops and LH sbottom needed to solve the hierarchy problem
- B mixing constraints less stringent

$U(2)^3$ and natural SUSY



http://arxiv.culturomics.org/

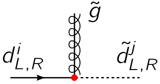
Form of the soft terms:

$$U(2)_{Q_L} \otimes U(2)_{U_R} \otimes U(2)_{D_R} \to U(1)_B$$

$$m^2_{\tilde{Q}} = m^2_{Q_h} \left(\begin{array}{c|c} 1 + c_{Qv} V^* V^T + \ldots & x_Q e^{-i\phi_Q} V^* \\ \hline x_Q e^{i\phi_Q} V^T & m^2_{Q_l}/m^2_{Q_h} \end{array} \right)$$

etc.

Consequence: flavour-violating gaugino vertices



$\propto (W^d_{L,R})_{ij}$

$$W^d_L = \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma_L} \\ -\kappa & c_d & -c_d s_L e^{i\gamma_L} \\ 0 & s_L e^{-i\gamma_L} & 1 \end{pmatrix} \qquad (W^d_R)_{ij} \approx \delta_{ij}$$

$$\epsilon_K = \epsilon_K^{\rm SM} \times (1 + h_K) \qquad h_K = \xi_L^4 F_0$$

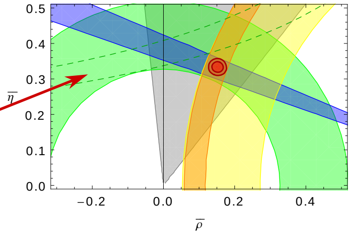
$$S_{\psi K_S} = \sin\left[2\beta + \arg\left(1 + h_B e^{i\phi_B}\right)\right] \qquad h_B = \xi_L^2 F_0$$

$$S_{\psi\phi} = \sin\left[2|\beta_s| - \arg\left(1 + h_B e^{i\phi_B}\right)\right] \qquad \phi_B = -2\gamma_L$$

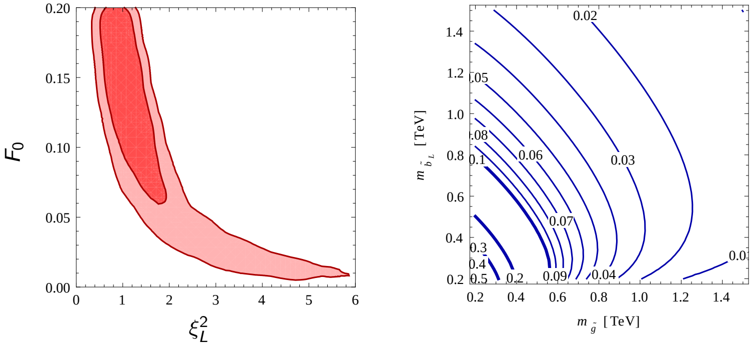
$$\xi_L e^{i\gamma_L} = (W_L^d)^*_{33}(W_L^d)_{23}$$

$$F_0\left(\frac{m^2_{\tilde g}}{m^2_{\tilde b_L}}\right) > 0$$

$\Rightarrow$ $h_K > 0$, i.e. the contribution to ϵ_K has the right sign to fix the possible CKM tension



$U(2)^3$ and SUSY: $\Delta F = 2$



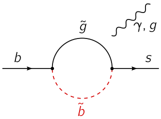
Fit of CKM matrix + F_0, ξ_L: not too heavy sbottom, gluino preferred

[Barbieri, Isidori, Jones-Pérez, Lodone, DMS (2011)]

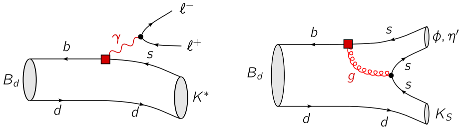
$U(2)^3$ and SUSY: $\Delta F = 1$

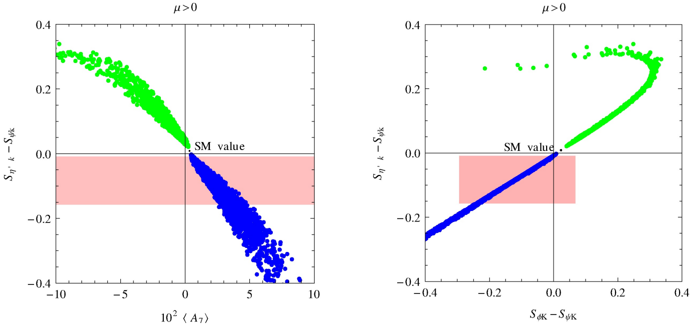
Also: CP violating effects in (chromo-)magnetic penguin operators

[Barbieri, Campli, Isidori, Sala, DMS (2011)]



$$\propto \xi_L e^{i\gamma_L} f\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{b}}^2}\right) \rightarrow$$





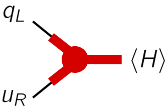
Outline

- The flavour puzzle
  - Recap of Minimal Flavour Violation
- $U(2)^3$ flavour symmetry
  - Generic effective field theory approach
  - Supersymmetry
  - Composite Higgs models
  - Bounds from $\Delta F = 1, 2$ processes
  - Extension to the lepton sector
- Conclusions

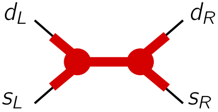
Composite Higgs & Partial compositeness

An alternative solution to the hierarchy problem
+ an interesting approach to the flavour problem

$$\mathscr{L} \supset \epsilon_L \bar{q}_L \mathcal{O}_L + \epsilon_R \bar{u}_R \mathcal{O}_R + m \mathcal{O}_L \mathcal{O}_R$$



$$Y_{ij} \propto \epsilon_L^i (Y_{ij}^*) \epsilon_R^j$$



$$\propto \frac{g_\rho^2}{m_\rho^2} \epsilon_{d_L} \epsilon_{d_R} \epsilon_{s_L} \epsilon_{s_R} \propto \frac{g_\rho^2}{m_\rho^2} m_d m_s$$

$$m_\rho \gtrsim 20\,\text{TeV}$$

[Csaki, Falkowski, Weiler (2008)]

In conflict with naturalness. Flavour symmetry for the strong sector?

Composite MFV

Simplified picture: fermionic partners for all SM fermions

Flavour-invariant strong sector [Redi, Weiler (2011)]
Flavour violation only in composite-elementary mixing

$$\mathscr{L}_{\text{mix}} = m_\rho \left(\bar{U}_L \epsilon_{Ru} u_R + \bar{D}_L \epsilon_{Rd} d_R + \bar{q}_L \epsilon_{Lu} Q_R^u + \bar{q}_L \epsilon_{Ld} Q_R^d \right) + \text{h.c.}$$

Right-handed compositeness

$$U(3)_q \times U(3)_{U+u} \times U(3)_{D+d}$$

$$\epsilon_{Ru} \propto 1$$
$$\epsilon_{Rd} \propto 1$$
$$\epsilon_{Lu} \propto Y_u \sim (3, \bar{3}, 1)$$
$$\epsilon_{Ld} \propto Y_d \sim (3, 1, \bar{3})$$

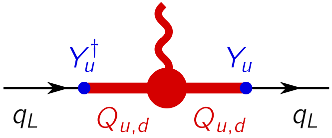
Left-handed compositeness

$$U(3)_{q+U+D} \times U(3)_u \times U(3)_d$$

$$\epsilon_{Ru} \propto Y_u \sim (3, \bar{3}, 1)$$
$$\epsilon_{Rd} \propto Y_d \sim (3, 1, \bar{3})$$
$$\epsilon_{Lu} \propto 1$$
$$\epsilon_{Ld} \propto 1$$

Composite MFV: FCNCs

Tree-level FCNCs: only in right-handed compositeness



$\epsilon_{Ru} \propto 1$

$\epsilon_{Rd} \propto 1$

$\epsilon_{Lu} \propto Y_u \sim (3, \bar{3}, 1)$

$\epsilon_{Ld} \propto Y_d \sim (3, 1, \bar{3})$

$U(3)^3$ EFT vs. CHM

	$b_L \leftrightarrow q_L$		$s_L \leftrightarrow d_L$	$b_R \leftrightarrow q_L$
$U(3)^3$ EFT	$\mathbb{R}$	$\leftrightarrow$	$\mathbb{R}$	$\mathbb{C}$
$U(3)^3$ R-comp.	$\mathbb{R}$	$\leftrightarrow$	$\mathbb{R}$	0
$U(3)^3$ L-comp.	0		0	0
$U(2)^3$ EFT	$\mathbb{C}$		$\mathbb{R}$	$\mathbb{C}$
Relevant processes	B_q^0-$\bar{B}_q^0$ $b \to s l \bar{l}, \nu\bar{\nu}$		K^0-$\bar{K}^0$ $K \to \pi\nu\bar{\nu}$	$b \to s\gamma$ $b \to s l \bar{l}$

Composite MFV

Sizable top Yukawa requires large top compositeness

$$y_t \sim \epsilon_{Lu}^3 \; Y_U \; \epsilon_{Ru}^3$$

Right-handed compositeness

$$\epsilon_{Ru} \propto 1$$

Left-handed compositeness

$$\epsilon_{Lu} \propto 1$$

One chirality of all (1, 2, 3) up quarks has to be strongly composite!
This will soon be probed by dijet searches at LHC.

No problem in $U(2)^3$!

Alternative: $U(3)^2 \times U(2)$ [Redi arXiv:1203.4220]

$U(2)^3$ in Composite Higgs Models

Right-handed compositeness

$$U(2)_q \times U(2)_{U+u} \times U(2)_{D+d}$$

Left-handed compositeness

$$U(2)_{q+U+D} \times U(2)_u \times U(2)_d$$

$$\Delta Y_u \sim (2, \bar{2}, 1) \qquad \Delta Y_d \sim (2, 1, \bar{2}) \qquad V \sim (2, 1, 1)$$

Example: composite-elementary mixing in RH compositeness

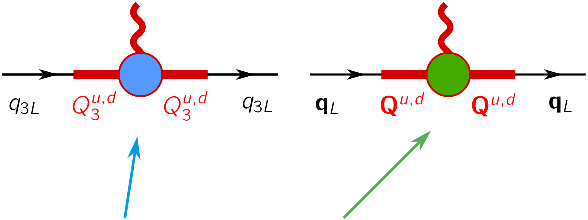
$$\mathscr{L}_{\text{mix}}^{R\text{-comp}}(U(2)^3) \approx m_\rho \times$$
$$\left[\epsilon_{Rd}(A_d\, \bar{B}_L b_R + B_d\, \bar{\mathbf{D}}_\mathbf{L} \mathbf{d}_\mathbf{R}) + \epsilon_{Ld}(a_d\, \bar{q}_{3L} Q^d_{3R} + b_d\, (\bar{\mathbf{q}}_\mathbf{L} V) Q^d_{3R} + c_d\, \bar{\mathbf{q}}_\mathbf{L} \Delta Y_d \mathbf{Q}^\mathbf{d}_\mathbf{R})\right]$$
$$+ \text{h.c.} + (d \to u)$$

$$\epsilon_{Ru,d} \propto \text{diag}(A, A, B)$$

$$\epsilon_{Lu,d} \propto y_{t,b} \left(\begin{array}{c|c} \Delta Y_{u,d} & x_{t,b} V \\ \hline 0 & 1 \end{array} \right)$$

Composite $U(2)^3$: FCNCs

Tree-level FCNCs: this time, also in left-handed compositeness!



Different strong interactions in the two cases lead to flavour violation after rotating to the mass basis for the external quarks

$U(2)^3$ vs. $U(3)^3$ in CHM

	$b_L \leftrightarrow q_L$		$s_L \leftrightarrow d_L$	$b_R \leftrightarrow q_L$
$U(3)^3$ EFT	$\mathbb{R}$	$\leftrightarrow$	$\mathbb{R}$	$\mathbb{C}$
$U(3)^3$ R-comp.	$\mathbb{R}$	$\leftrightarrow$	$\mathbb{R}$	0
$U(3)^3$ L-comp.	0		0	0
$U(2)^3$ EFT	$\mathbb{C}$		$\mathbb{R}$	$\mathbb{C}$
$U(2)^3$ R-comp.	$\mathbb{C}$		$\mathbb{R}$	0
$U(2)^3$ L-comp.	$\mathbb{R}$		$\mathbb{R}$	$\mathbb{C}$
Relevant processes	B_q^0-$\bar{B}_q^0$ $b \to s l \bar{l}, \nu\bar{\nu}$		K^0-$\bar{K}^0$ $K \to \pi\nu\bar{\nu}$	$b \to s\gamma$ $b \to s l \bar{l}$

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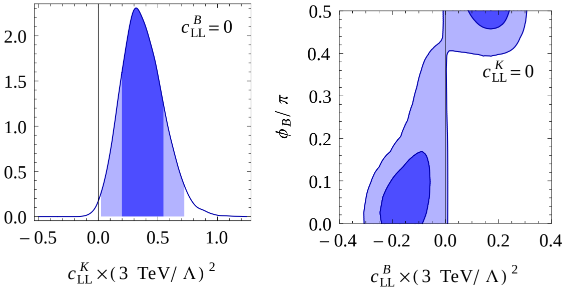
$U(2)^3$: allowed effects in $\Delta F = 2$

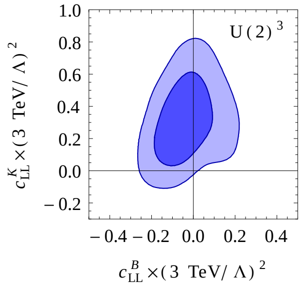
$$\mathcal{H}_{\text{eff}} = \frac{c_{LL}^K}{\Lambda^2}\xi_{ds}^2 \frac{1}{2}\left(\bar{d}_L\gamma_\mu s_L\right)^2 + \sum_{i=d,s}\frac{c_{LL}^B e^{i\phi_B}}{\Lambda^2}\xi_{ib}^2\frac{1}{2}\left(\bar{d}_L^i\gamma_\mu b_L\right)^2 + \text{h.c.}\,,$$

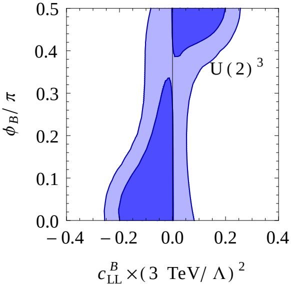


Result of Bayesian fit of CKM Wolfenstein parameters + $c_{LL}^{K,B}$, ϕ_B to all relevant experimental constraints including ϵ_K, $S_{\psi K_S}$, ϕ_s

$U(2)^3$: allowed effects in $\Delta F = 2$

$$\mathcal{H}_{\text{eff}} = \frac{c_{LL}^K}{\Lambda^2}\xi_{ds}^2 \frac{1}{2}\left(\bar{d}_L \gamma_\mu s_L\right)^2 + \sum_{i=d,s} \frac{c_{LL}^B e^{i\phi_B}}{\Lambda^2}\xi_{ib}^2 \frac{1}{2}\left(\bar{d}_L^i \gamma_\mu b_L\right)^2 + \text{h.c.}\,,$$



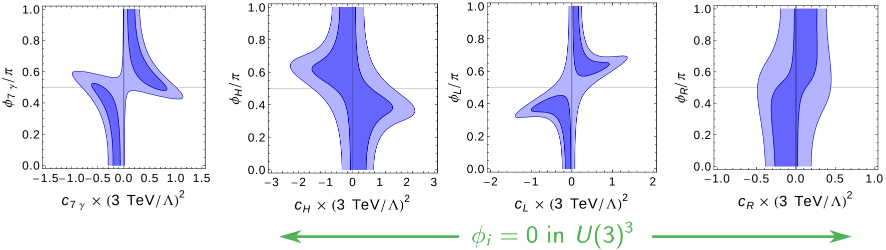


Result of Bayesian fit of CKM Wolfenstein parameters + $c_{LL}^{K,B}$, ϕ_B to all relevant experimental constraints including ϵ_K, $S_{\psi K_S}$, ϕ_s

$U(2)^3$: allowed effects in $\Delta F = 1$

$$\mathscr{H}_{\text{eff}} = \sum_{i=d,s} \xi_{ib} \left[\frac{c_{7\gamma} e^{i\phi_{7\gamma}}}{\Lambda^2} m_b \left(\bar{d}_L^i \sigma_{\mu\nu} b_R\right) e F^{\mu\nu} + \frac{c_{8g} e^{i\phi_{8g}}}{\Lambda^2} m_b \left(\bar{d}_L^i \sigma_{\mu\nu} T^a b_R\right) g_s G^{\mu\nu\, a} \right.$$

$$\left. + \frac{c_L e^{i\phi_L}}{\Lambda^2} \left(\bar{d}_L^i \gamma_\mu b_L\right) (\bar{l}_L \gamma_\mu l_L) + \frac{c_R e^{i\phi_R}}{\Lambda^2} \left(\bar{d}_L^i \gamma_\mu b_L\right) (\bar{e}_R \gamma_\mu e_R) + \frac{c_H e^{i\phi_H}}{\Lambda^2} \frac{v^2}{2} \left(\bar{d}_L^i \gamma_\mu b_L\right) \frac{g}{c_w} Z^\mu \right] + \text{h.c.}\,,$$



- $O(1)$ effects possible for NP scale of 3 TeV $\approx 4\pi v$
- In $\Delta F = 1$, larger effects allowed than in $U(3)^3$ due to additional phases

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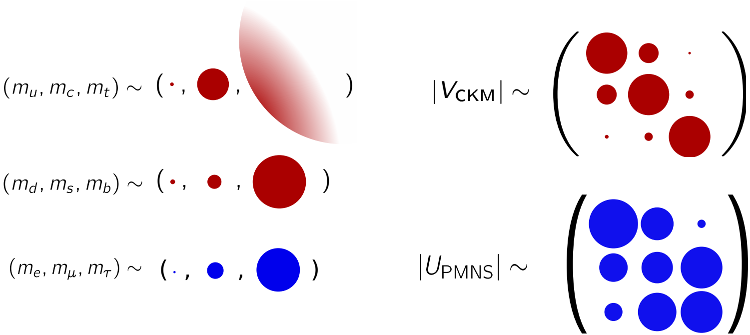


Charged lepton masses fit into $U(2)$ picture — Mixings don't

Extension to the lepton sector

$$U_{uL}^* U_{dL}^T = V_{\text{CKM}} \qquad U_\nu^* U_{eL}^T = V_{\text{PMNS}}$$

$$m_\nu = U_\nu^T \begin{pmatrix} m_{\nu_1} e^{i\phi_1} & & \\ & m_{\nu_2} e^{i\phi_2} & \\ & & m_{\nu_3} \end{pmatrix} U_\nu \qquad Y_e = U_{eL}^\dagger \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix} U_{eR}$$

In the see-saw mechanism, U_ν comes from the diagonalization of the neutrino Majorana mass matrix

$$m_\nu = -\frac{v^2}{2} \frac{Y_\nu^T Y_\nu}{M_{N_R}}$$

U_{eL} comes from the diagonalization of the charged lepton Yukawa

We *assume* that charged leptons (Y_e) behave as quarks and that the large neutrino mixing is caused by Y_ν and/or M_{N_R}

For a more complete model including also neutrino masses, see [Blankenburg, Isidori & Jones-Pérez (2012)]

$U(2)^2$ in the lepton sector

The lepton flavour symmetry

$$U(2)_{L_L} \otimes U(2)_{E_R}$$

is broken minimally by the spurions

$$\Delta Y_e \sim (2, \bar{2}) \qquad V_e \sim (2, 1)$$

Resulting Yukawas

$$Y_e^{\mathbf{diag}} = U_{eL}\, y_\tau \left(\begin{array}{c|c} \Delta Y_e & x_{t,b} V_e \\ \hline 0 & 1 \end{array} \right) U_{eR}^\dagger$$

$$U_\nu^* U_{eL}^T = U_{\mathrm{PMNS}}$$

$U(2)^2$ in the lepton sector

$$Y_e^{\text{diag}} = U_{eL}\, y_\tau \begin{pmatrix} \Delta Y_e & x_{t,b} V_e \\ 0 & 1 \end{pmatrix} U_{eR}^\dagger$$

Chirality breaking, flavour changing bilinears have same spurion structure, but different O(1) coefficients

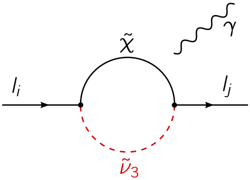
$$\bar{l}_R^T \begin{pmatrix} a\,\Delta Y_e & b\, V_e \\ 0 & c\,1 \end{pmatrix} l_L$$

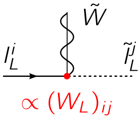
Leads to flavour violation after rotation to the mass basis of external ch. leptons

$$c_\tau\, U_{eL}^{3i*}\, U_{eL}^{3\tau}\, m_\tau\, (\bar{e}_{Li}\sigma_{\mu\nu}\tau_R)\, eF_{\mu\nu}$$
$$c_\mu\, U_{eL}^{3e*}\, U_{eL}^{3\mu}\, m_\mu\, (\bar{e}_{L}\sigma_{\mu\nu}\mu_R)\, eF_{\mu\nu}$$

$U(2)^2$ in the lepton sector: SUSY

Example: LFV in SUSY $U(2)^3$



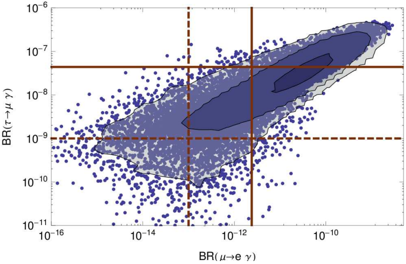


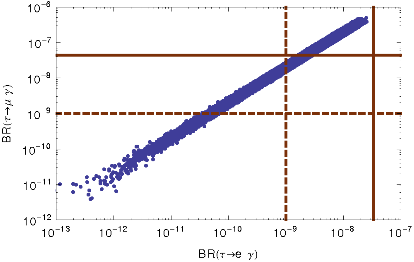
$$\mu \to e\gamma : \quad \frac{|W_L^{23*} W_L^{13}|}{|V_{ts} V_{td}^*|} < 0.6 \times \left[\frac{m_{\tilde{l}_{3L}}}{500\text{ GeV}}\right]^2 \left[\frac{10}{\tan\beta}\right]$$

$$\tau \to e\gamma : \quad \frac{|W_L^{33*} W_L^{13}|}{|V_{tb} V_{td}^*|} < 1.2 \times \left[\frac{m_{\tilde{l}_{3L}}}{500\text{ GeV}}\right]^2 \left[\frac{10}{\tan\beta}\right]$$

$$\tau \to \mu\gamma : \quad \frac{|W_L^{33*} W_L^{23}|}{|V_{tb} V_{ts}^*|} < 0.3 \times \left[\frac{m_{\tilde{l}_{3L}}}{500\text{ GeV}}\right]^2 \left[\frac{10}{\tan\beta}\right]$$

$U(2)^2$ in the lepton sector: SUSY





[Blankenburg, Isidori & Jones-Pérez, arXiv:1204.0688]

Conclusions

A weakly and minimally broken $U(2)^3$ flavour symmetry ...

- provides an effective **protection mechanism** for FCNCs beyond the SM
- could accomodate possible **non-standard CPV** in $\Delta F = 2$
- is compatible with **natural SUSY** (hierarchical sfermions)
- can be implemented in **composite Higgs** models, evading LHC bounds more easily than composite MFV
- can be extended to the lepton sector, predicting potentially **sizable LFV** decays

extra slides

CKM fit: inputs

$\|V_{ud}\|$	$0.97425(22)$	f_K	(155.8 ± 1.7) MeV
$\|V_{us}\|$	$0.2254(13)$	$\hat{B}_K$	0.737 ± 0.020
$\|V_{cb}\|$	$(40.6 \pm 1.3) \times 10^{-3}$	κ_ϵ	0.94 ± 0.02
$\|V_{ub}\|$	$(3.97 \pm 0.45) \times 10^{-3}$	$f_{B_s}\sqrt{\hat{B}_s}$	(288 ± 15) MeV
γ_{CKM}	$(74 \pm 11)^\circ$	ξ	1.237 ± 0.032
$\|\epsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$	η_{tt}	$0.5765(65)$
$S_{\psi K_S}$	0.673 ± 0.023	η_{ct}	$0.496(47)$
ΔM_d	$(0.507 \pm 0.004)\,\text{ps}^{-1}$	η_{cc}	$1.87(76)$
$\Delta M_s/\Delta M_d$	(35.05 ± 0.42)		
ϕ_s	-0.002 ± 0.087		

Conclusions

$U(2)^3$ in Composite Higgs Models