

Flavour physics at the Fermi scale

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⇒ Is it or is it not the SM
up to “any” directly accessible scale?

(Directly accessible \equiv by the LHC at 14 TeV with 100 (1000) fb^{-1})

What flavour has to say on this?

B, Bertuzzo, Buttazzo, Farina, Isidori, Lodone, Sala, Straub

The (scaring) success of the CKM picture

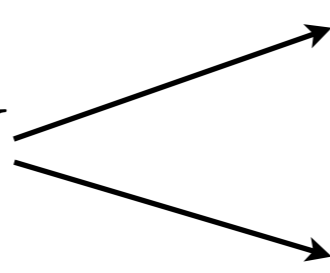
$$\Delta\mathcal{L} = \sum_i \frac{1}{\Lambda_i^2} \mathcal{O}_i$$

In some cases $\Lambda_i \gtrsim 10^3 \div 10^4 TeV$, unless some restriction operative

Ideally one would like to have:

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

with ξ_i controlled by symmetries and, otherwise $c_i = O(1)$

and $\Lambda_i \approx 4\pi v \approx 3 TeV$  strongly interacting EWSB
new weakly int. particle(s) at $\sim v$

An approximate flavour symmetry in action



$$\mathcal{L} \approx \sum_{i=1,2,3} (\bar{q}_L^i \not{D} q_L^i + \bar{u}_R^i \not{D} u_R^i + \bar{d}_R^i \not{D} d_R^i) + \lambda_t H_u \bar{t}_L t_R + \lambda_b H_d \bar{b}_L b_R$$

$$U(2) \rightarrow U(2)_Q \times U(2)_u \times U(2)_d$$

and its possible breaking terms in fermion bilinears (Yukawa couplings)

$$\lambda_t (\bar{Q}_L V) t_R$$

$$\lambda_t \bar{Q}_L \Delta Y_u U_R$$

$$\lambda_t \bar{q}_{3L} (V_u^+ U_R)$$

$$\lambda_b (\bar{Q}_L V) b_R$$

$$\lambda_t \bar{Q}_L \Delta Y_d D_R$$

$$\lambda_b \bar{q}_{3L} (V_d^+ D_R)$$

Capital letters = $U(2)$ doublets

The (high energy?) origin of the breaking terms unknown

Assume:

1. Under $U(2)^3$

$$\mathbf{V} = (2, 1, 1), \quad \mathbf{V}_u = (1, 2, 1), \quad \mathbf{V}_d = (1, 1, 2)$$

$$\Delta Y_u = (2, 2, 1), \quad \Delta Y_d = (2, 1, 2)$$

and all small $\|\mathbf{V}, \Delta Y\| \lesssim O(V_{cb}, m_2/m_3)$

2. No other breaking parameter
in the full (unknown) flavour theory

Examples:

supersymmetry

$$\mathcal{L}_{SB} = m^2 (\mathbf{V}, \Delta Y) \tilde{q}^+ \tilde{q} + A(\mathbf{V}, \Delta Y) \tilde{q}_L \tilde{q}_R h$$

strong EWSB

$$\mathcal{L}_m = M_F \bar{F} F + m \bar{F} f_{L,R} + m (\mathbf{V}, \Delta Y) \bar{F} f_{R,L}$$

Physical parameters

(after suitable $U(2)^3$ transformations)

Minimal $U(2)^3$

$$\mathbf{V} = \begin{pmatrix} 0 \\ \epsilon_L \end{pmatrix} \quad \Delta Y_u = L_{12}^u(\theta_L^u) \Delta Y_u^{\text{diag}} \quad \Delta Y_d = \Phi_L L_{12}^d(\theta_L^d) \Delta Y_d^{\text{diag}}$$

$$\Phi_L = \text{diag}(e^{i\phi}, 1)$$

$$\Rightarrow \epsilon_L, \theta_L^{u,d}, \phi \quad (\text{MFV})$$

Generic $U(2)^3$

$$\mathbf{V} = \begin{pmatrix} 0 \\ \epsilon_L \end{pmatrix} \quad \mathbf{V}_{u,d} = \begin{pmatrix} 0 \\ \epsilon_R^{u,d} \end{pmatrix} \quad \Delta Y_u = L_{12}^u \Delta Y_u^{\text{diag}} \Phi_R^u R_{12}^u$$

$$\Delta Y_d = \Phi_L L_{12}^d \Delta Y_d^{\text{diag}} \Phi_R^d R_{12}^d \quad \Phi_R^{u,d} = \text{diag}(e^{i\phi_1^{u,d}}, e^{i\phi_2^{u,d}})$$

$$\Rightarrow \epsilon_L, \theta_L^{u,d}, \phi$$

$$\Rightarrow \epsilon_R^{u,d}; \theta_R^{u,d}; \phi_1^{u,d}, \phi_2^{u,d} \quad (\text{LMFV})$$

The CKM matrix

Since $V_{u,d} \lesssim V$, as required by data,
either in Minimal or in Generic $U(2)^3$

$$V_{CKM} = \begin{pmatrix} c_u c_d & \lambda & s_u s e^{-i\delta} \\ -\lambda & c_u c_d & c_u s \\ -s_d s e^{i(\delta-\phi)} & -c_d s & 1 \end{pmatrix},$$

where $s = \epsilon_L$, $s_{u,d} = \sin \theta_L^{u,d}$ $s_u c_d - s_d c_u e^{i\phi} = \lambda e^{i\delta}$

and, from a fit of tree level observables:

$$s_u = 0.086 \pm 0.003$$

$$s_d = -0.22 \pm 0.01$$

$$s = 0.0411 \pm 0.0005$$

$$\phi = (-97 \pm 9)^\circ$$

\Rightarrow In Minimal $U(2)^3$ every parameter determined

\Rightarrow In Generic $U(2)^3$ "right-handed" angles still undetermined/unconstrained

Back to the Effective Field Theory

Express any $U(2)^3$ invariant D=6 operator in terms of the physical parameters (up to $O(1)$ coefficients)

$$\Delta\mathcal{L} = \underbrace{\Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}^{mag}}_{\text{Minimal } U(2)^3} + \underbrace{\Delta\mathcal{L}_R^{4f} + \Delta\mathcal{L}_{LR}^{4f}}_{\text{Generic } U(2)^3} *$$

* FV both in L- as in R-current

Minimal $U(2)^3$

Generic $U(2)^3$

Relevant observables:

$$\epsilon_K, B_d^0 - \bar{B}_d^0, B_s^0 - \bar{B}_s^0$$

$$K \rightarrow \pi\nu\bar{\nu}, \epsilon'_K$$

$$b \rightarrow s(d)\gamma, b \rightarrow s(d)l\bar{l}, \nu\bar{\nu}$$

Extra relevant observables/effects:

$$D \rightarrow \pi\pi, KK$$

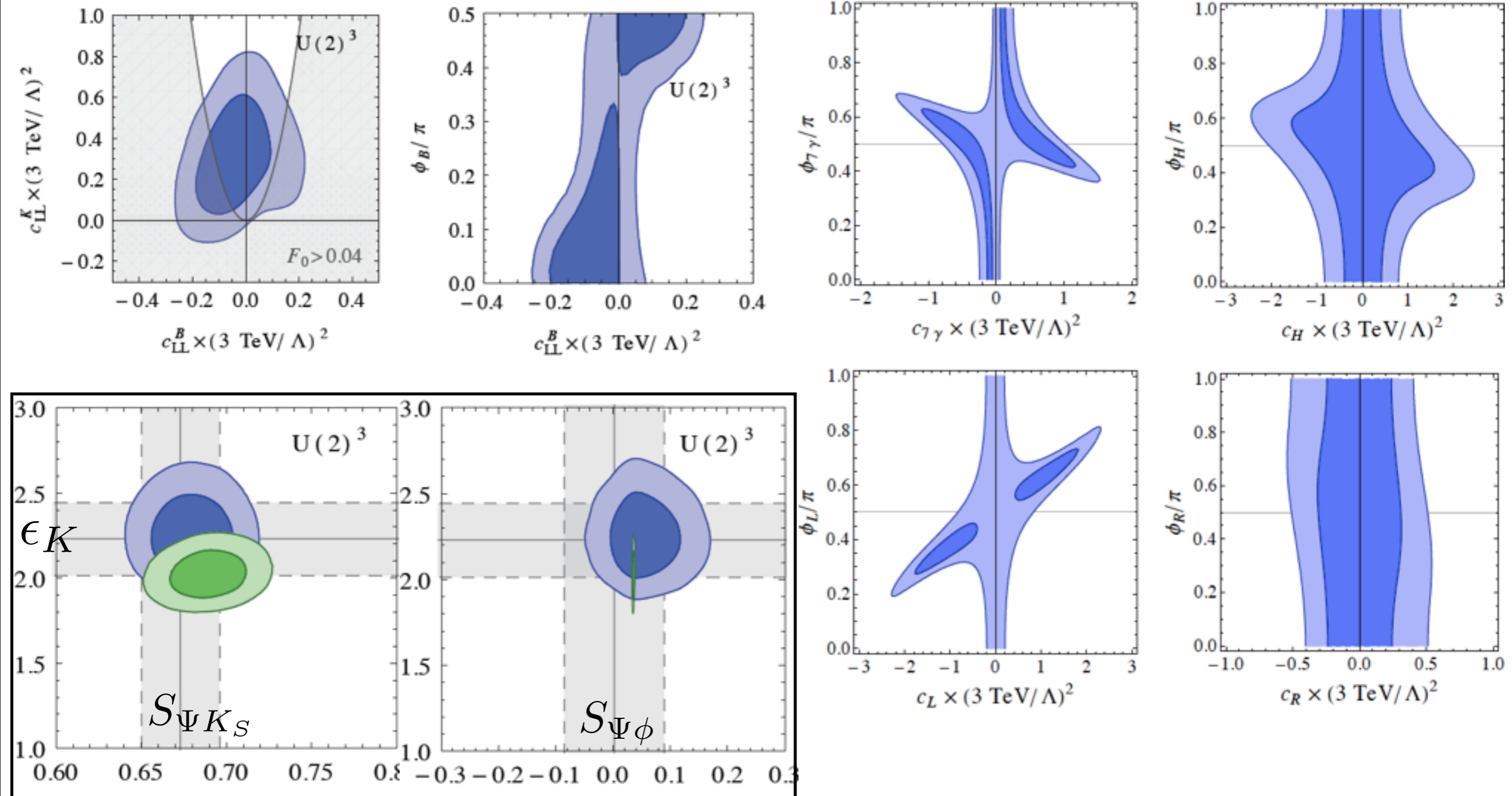
$$\Delta\epsilon_K$$

$$d_N$$

A summary of Minimal effects

$\Delta F = 2$

$\Delta F = 1$



Consistent with $\Delta\mathcal{L} = \sum_i \frac{c_i}{(4\pi v)^2} \xi_i \mathcal{O}_i$ and $|c_i| = 0.2 \div 1$

A digression on ϵ'_K

(relevant to $U(2)^3$ and to $U(3)^3$ as well)

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

1. $\langle (\pi\pi)_{I=2} | Q_{LR}^d | K \rangle = -\langle (\pi\pi)_{I=2} | Q_{LR}^u | K \rangle \propto \left(\frac{m_K}{m_s} \right)^2$

2. $\left| \frac{\epsilon'}{\epsilon} \right| \simeq \frac{|\text{Im}A_2|}{\sqrt{2} |\epsilon| \text{Re}A_0} \quad \omega = \frac{\text{Re}A_2}{\text{Re}A_0} \approx 20$

$$\Rightarrow \left| \frac{\epsilon'}{\epsilon} \right| \simeq 1.3 \cdot 10^{-2} \left(\frac{3 \text{ TeV}}{\Lambda} \right)^2 c_K^{u,d}$$

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

A significant limit, though still broadly consistent with previous conclusion

Physical parameters

(after suitable $U(2)^3$ transformations)

Minimal $U(2)^3$

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$$\Delta Y_d = \Phi_L L_{12}^d \Delta Y_d^{\text{diag}} \Phi_R^d R_{12}^d \quad \Phi_R^{u,d} = \text{diag}(e^{i\phi_1^{u,d}}, e^{i\phi_2^{u,d}})$$

$$\Rightarrow \epsilon_L, \theta_L^{u,d}, \phi$$

$$\Rightarrow \epsilon_R^{u,d}; \theta_R^{u,d}; \phi_1^{u,d}, \phi_2^{u,d}$$

what's known about these extra parameters?

New possible effects/limits on generic $U(2)^3$

1. Chromo-electric up \leftrightarrow charm dipole $\Delta a_{CP}^{exp}(D \rightarrow \pi\pi, KK) = -(0.67 \pm 0.16)\%$

$$c_D^g \frac{\epsilon_u}{\epsilon} \sin(\delta - \phi_2^u + \phi_D^g) \lesssim 0.3 \quad c_D^g \frac{s_{uR}}{s_u} \frac{\epsilon_u}{\epsilon} \sin(\delta + \phi_1^u - \phi_D^g) \lesssim 0.3$$

2. Chromo-electric up/down dipoles $|d_n| < 2.9 \times 10^{-26} e \text{ cm}$

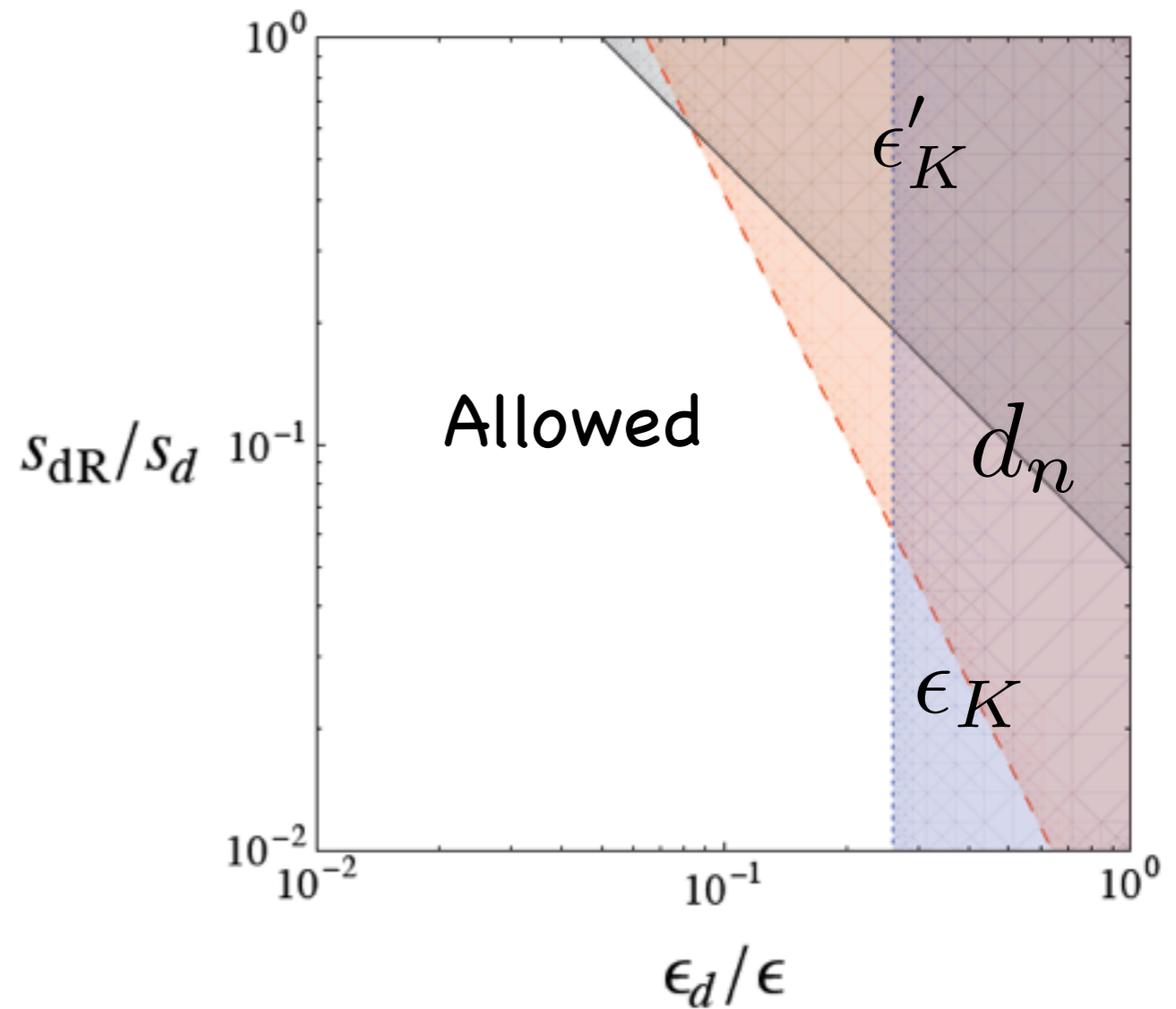
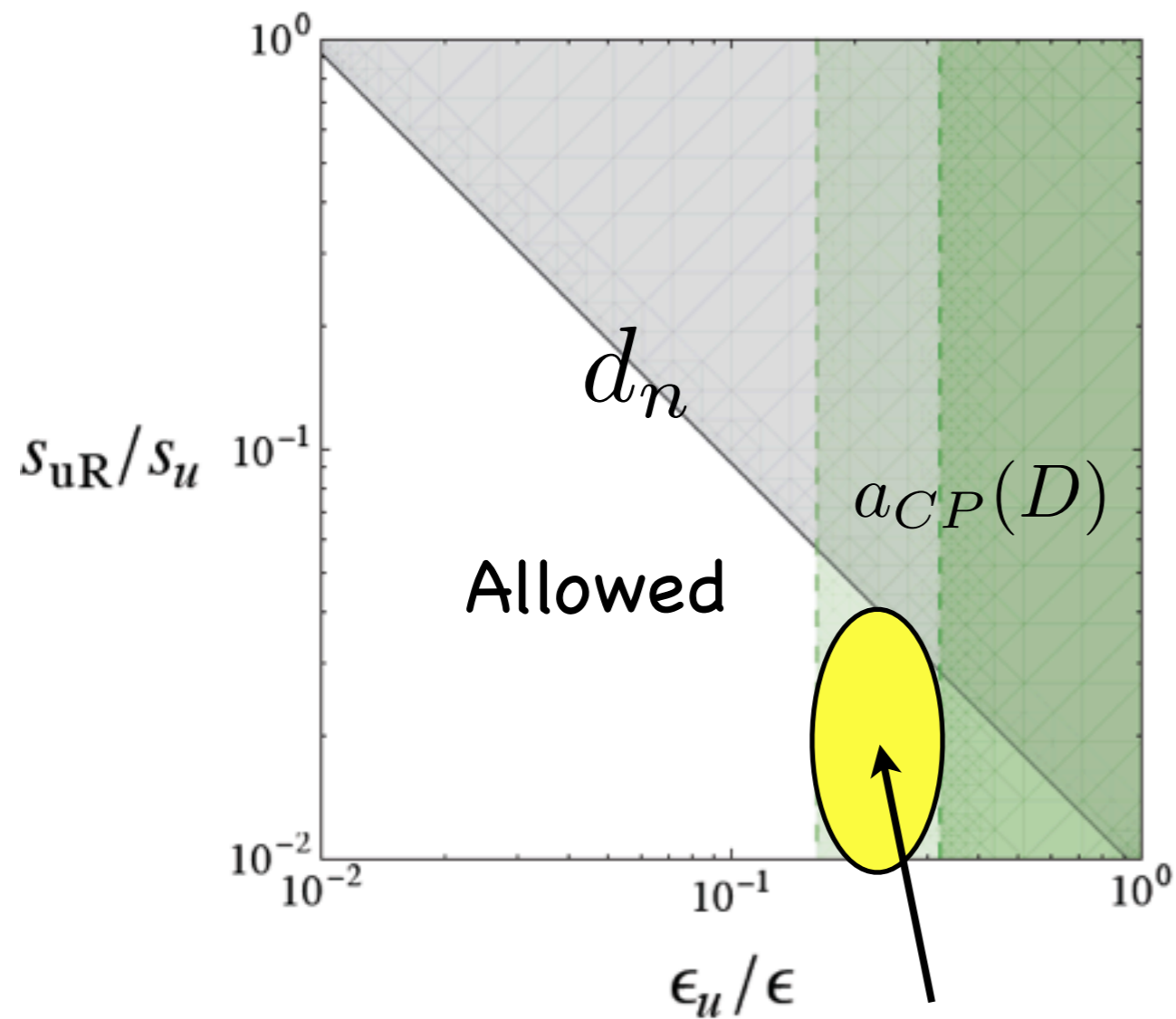
$$c_u^g |\sin(\phi_u^g - \phi_1^u)| \frac{s_{uR}}{s_u} \frac{\epsilon_u}{\epsilon} \lesssim 9.2 \times 10^{-3}, \quad c_d^g |\sin(\phi_d^g - \phi_1^d)| \frac{s_{dR}}{s_d} \frac{\epsilon_d}{\epsilon} \lesssim 5.0 \times 10^{-2}$$

3. $\Delta S=2$ 4-fermion LR interaction $\Delta\epsilon_K$

$$c_K^{VLR} \sin(2\beta + \phi_1^d - \phi_2^d) \frac{s_{dR}}{s_d} \left(\frac{\epsilon_d}{\epsilon}\right)^2 \lesssim 4 \cdot 10^{-3}$$

(all normalized at $\Lambda = 3 \text{ TeV}$)

New possible effects/limits on generic $U(2)^3$



could explain CPV obs., if needed

$$\Lambda = 3 \text{ TeV}$$

$c_i \sin \phi_i = 1$, so that constraints are maximized

$O(1)$ uncertainties all over

If some signals seen, how does one know it is $U(2)^3$?

The best way is $s \Leftrightarrow d$ correlation in b-decays as in the SM

Isn't that a common feature of MFV ($U(3)^3$)?

A synthetic description of qualitative differences:

	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
Minimal $U(2)^3$, $U(3)^3$ large t_β	\mathbb{C}	\mathbb{R}	\mathbb{C}	0
Generic $U(2)^3$	\mathbb{C}	\mathbb{C}	\mathbb{C}	\mathbb{C}

Quantitatively: Definitely smaller effects in MFV at low $\tan\beta$

If MFV with large $\tan\beta$, other tree level effects expected

Summary and conclusions

⇒ If $U(2)^3$ with Minimal breaking

$$\Delta\mathcal{L} = \sum_i \frac{c_i}{(4\pi v)^2} \xi_i \mathcal{O}_i \quad \text{and} \quad |c_i| = 0.2 \div 1$$

consistent with current data ⇒ Hence the title of the talk

⇒ Several observables to watch:

$$S_{\Psi\phi}, \quad b \rightarrow s(d)\gamma, \quad b \rightarrow s(d)l\bar{l}, \nu\bar{\nu}, \quad K \rightarrow \pi\nu\bar{\nu}$$

⇒ If $U(2)^3$ with Generic breaking

$\Delta a_{CP}^{exp}(D) = -(0.67 \pm 0.16)\%$ from chromo-electric $u \leftrightarrow c$ dipole
if needed, consistently with d_n - bound

⇒ If new signals observed, best signature of $U(2)^3$

is $s \leftrightarrow d$ correlation in b-decays as in the SM

(as in MFV, yes, but...)