New flavour phenomena and the Fermi scale

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R. Barbieri
SNS and INFN
UNILHC-EU and MIUR

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

(Directly accessible ≡ 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

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

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

Ideally one would like to have:

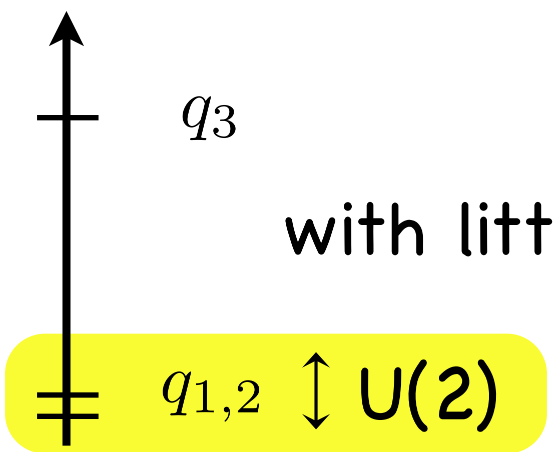
$$\Delta\mathcal{L} = \Sigma_i \frac{c_i}{\Lambda_i^2}\xi_i\mathcal{O}_i$$

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 ~v

An approximate flavour symmetry in action



with little communication between $q_{1,2}$ and q_3

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

$$\boxed{U(2) \rightarrow U(2)_Q \times U(2)_u \times U(2)_d}$$

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

$$\lambda_t(\bar{Q}_L V)t_R \qquad \lambda_t \bar{Q}_L \Delta Y_u U_R \qquad \lambda_t \bar{q}_{3L}(V_u^+ U_R)$$

$$\lambda_b(\bar{Q}_L V)b_R \qquad \lambda_t \bar{Q}_L \Delta Y_d D_R \qquad \lambda_b \bar{q}_{3L}(V_d^+ D_R)$$

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

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

Physical parameters

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

Minimal $U(2)^3$

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

$$\Phi_L = \mathrm{diag}\left(e^{i\phi}, 1\right)$$

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

(MFV)

Generic $U(2)^3$

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

$$\Phi_R^{u,d} = \mathrm{diag}\left(e^{i\phi_1^{u,d}}, e^{i\phi_2^{u,d}}\right)$$

$$\Delta Y_d = \Phi_L L_{12}^d\,\Delta Y_d^{\rm diag}\,\Phi_R^d R_{12}^d$$

$$\boxed{\begin{array}{c} \Rightarrow \epsilon_L, \theta_L^{u,d}, \phi \\ \Rightarrow \epsilon_R^{u,d};\ \theta_R^{u,d};\ \phi_1^{u,d}, \phi_2^{u,d} \end{array}}$$

(LMFV)

The CKM matrix

Since $\mathbf{V}_{u,d} \lesssim \mathbf{V}$, 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 $\quad s = \epsilon_L, \;\; s_{u,d} = \sin\theta_L^{u,d} \qquad s_u c_d - s_d c_u e^{i\phi} = \lambda e^{i\delta}$

and, from a fit of tree level observables:

$$s_u = 0.086 \pm 0.003 \qquad s_d = -0.22 \pm 0.01$$

$$s = 0.0411 \pm 0.0005 \qquad \phi = (-97 \pm 9)^0$$

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

⇒ 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)

$$\Delta\mathcal{L} = \underline{\Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}^{mag}} + \underline{\Delta\mathcal{L}_R^{4f} + \Delta\mathcal{L}_{LR}^{4f}}\,{}^{*}$$

*FV both in L- as in R-current

$\Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}^{mag} \rightarrow$ **Minimal $U(2)^3$**

$\Delta\mathcal{L}_L^{4f} + \Delta\mathcal{L}^{mag},\ \Delta\mathcal{L}_R^{4f} + \Delta\mathcal{L}_{LR}^{4f} \rightarrow$ **Generic $U(2)^3$**

Relevant observables:

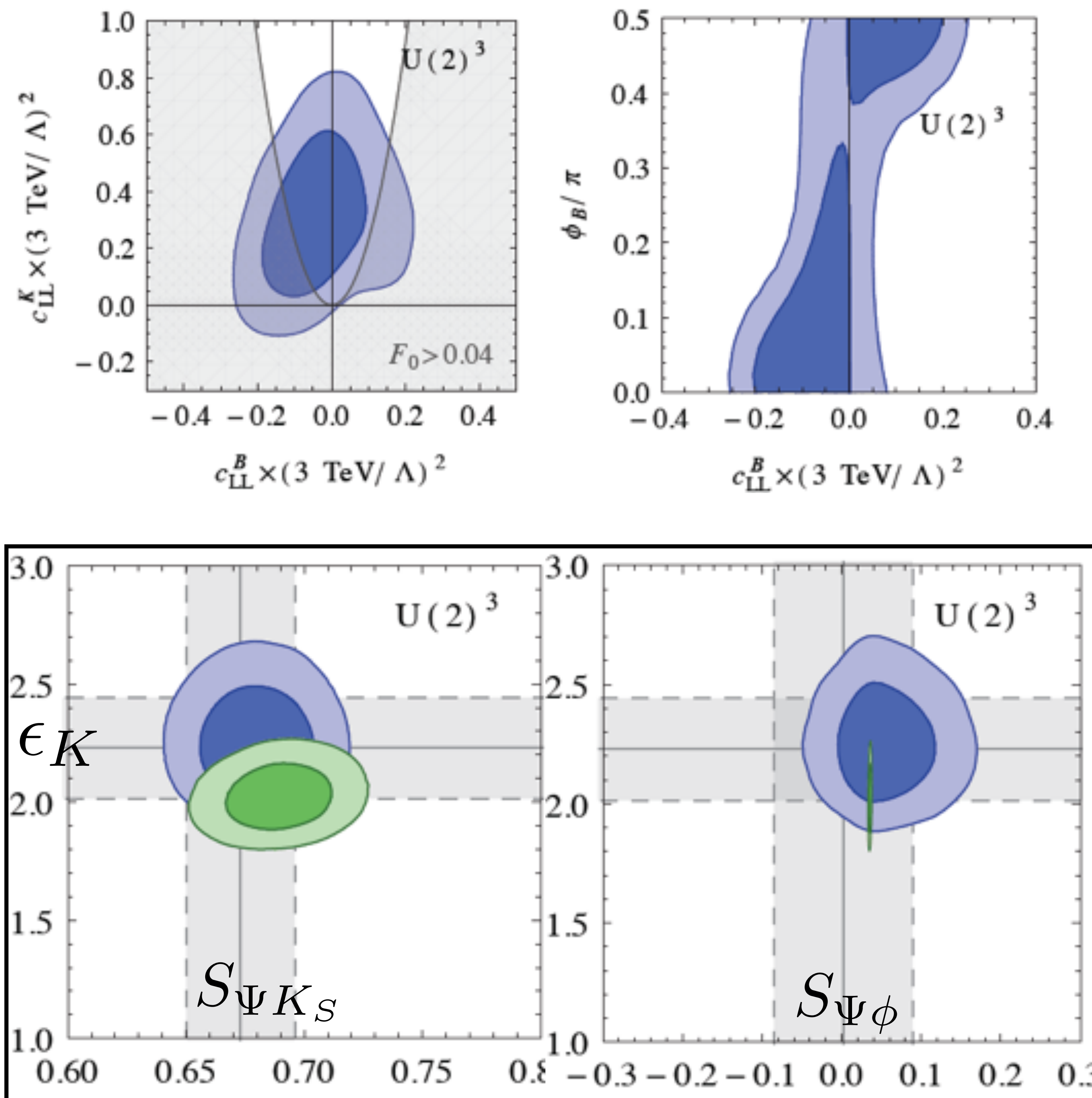
$$\epsilon_K,\, B_d^0 - \bar{B}_d^0,\, B_s^0 - \bar{B}_s^0$$
$$K \to \pi\nu\bar{\nu},\, \epsilon'_K$$
$$b \to s(d)\gamma,\ b \to s(d)l\bar{l},\nu\bar{\nu}$$

Extra relevant observables/effects:

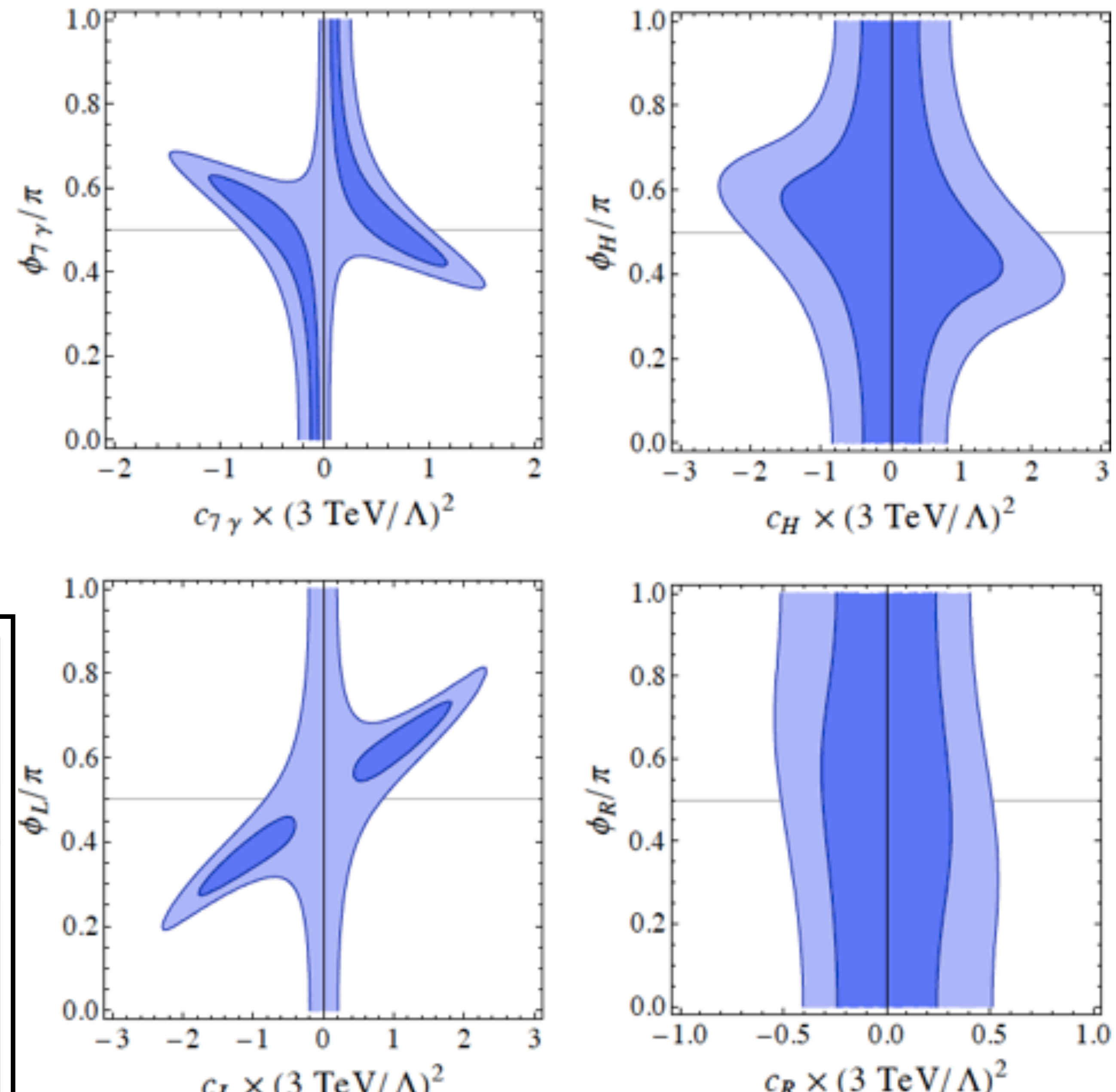
$$D \to \pi\pi, KK$$
$$\Delta\epsilon_K$$
$$d_N$$

A summary of Minimal effects

ΔF = 2



ΔF = 1



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

A digression on ϵ'_K

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

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

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

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

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

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

A significant limit, though still broadly consistent with previous conclusion

Physical parameters

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

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$$\Delta Y_d = \Phi_L L_{12}^d\, \Delta Y_d^{\rm diag}\, \Phi_R^d R_{12}^d$$

$$\boxed{\begin{array}{c} \Rightarrow \epsilon_L \,, \theta_L^{u,d} \,, \phi \\ \Rightarrow \epsilon_R^{u,d};\ \theta_R^{u,d};\ \phi_1^{u,d}, \phi_2^{u,d} \end{array}}$$

what's known about these extra parameters?

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

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

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

2. Cromo-electric up/down dipoles $|d_n| < 2.9 \times 10^{-26} \; e\,\mathrm{cm}$

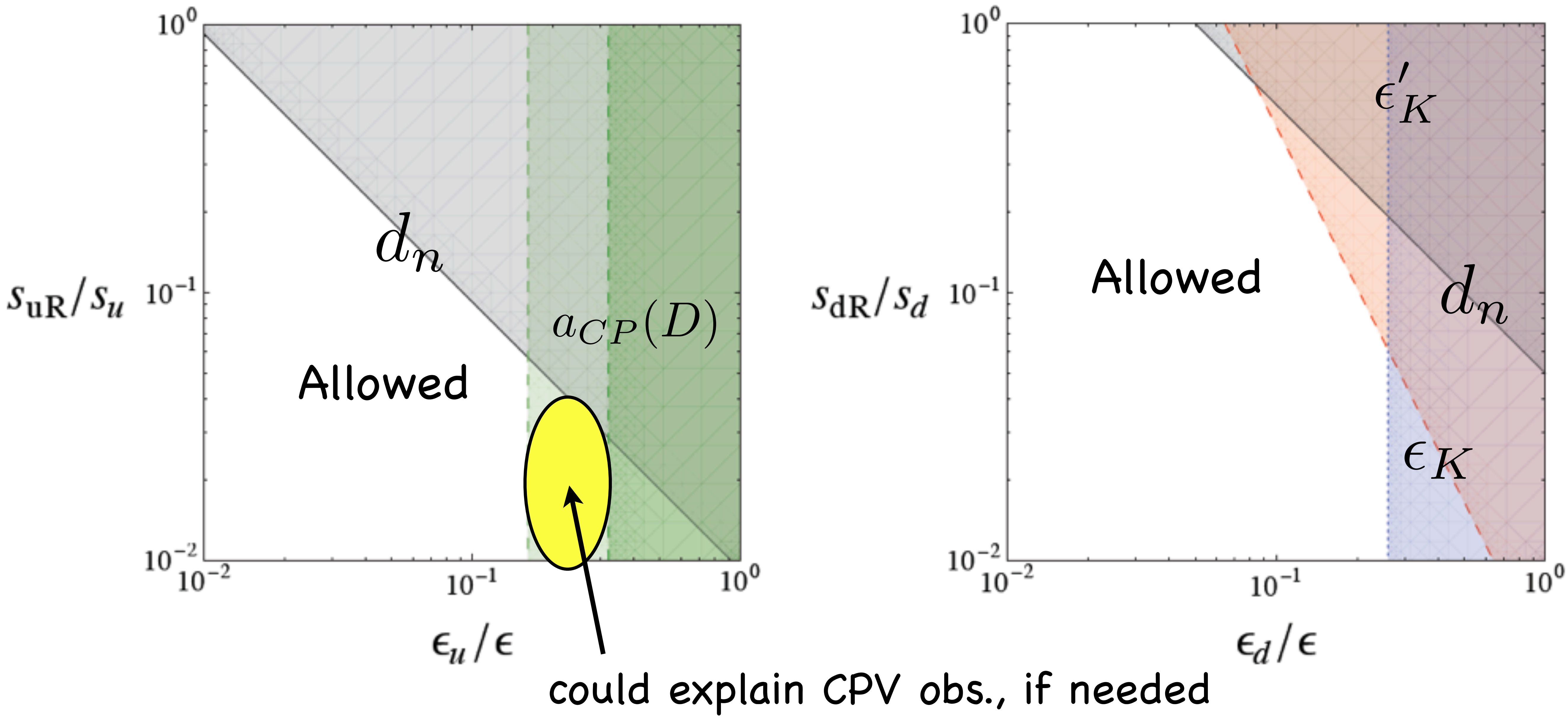
$$c_u^g \, |\sin(\phi_u^g - \phi_1^u)| \frac{s_{uR}}{s_u} \frac{\epsilon_u}{\epsilon} \lesssim 9.2 \times 10^{-3}, \qquad c_d^g \, |\sin(\phi_d^g - \phi_1^d)| \frac{s_{dR}}{s_d} \frac{\epsilon_d}{\epsilon} \lesssim 5.0 \times 10^{-2}$$

3. ΔS=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 Λ = 3 TeV)

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



Λ = 3 TeV

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

O(1) uncertainties all over

Summary and conclusions

⇒ If $U(2)^3$ with Minimal breaking

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

consistent with current data ⇒ Hence the title of the talk

⇒ Several observables to watch:

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

⇒ If $U(2)^3$ with Generic breaking

$\Delta a_{CP}^{exp}(D) = -(0.67 \pm 0.16)\%$ from cromo-electric up⇔charm dipole

if needed, consistently with d_n - bound

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

is s⇔d correlation in b-decays as in the SM

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