

An oriented view of flavour physics

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the $5 \div 6 \sigma$ evidence
for the Higgs boson

the mounting success
of the CKM picture

$\lambda_{ij} \psi_i \psi_j h$??

What can be said in absence of a precise enough BSM picture?

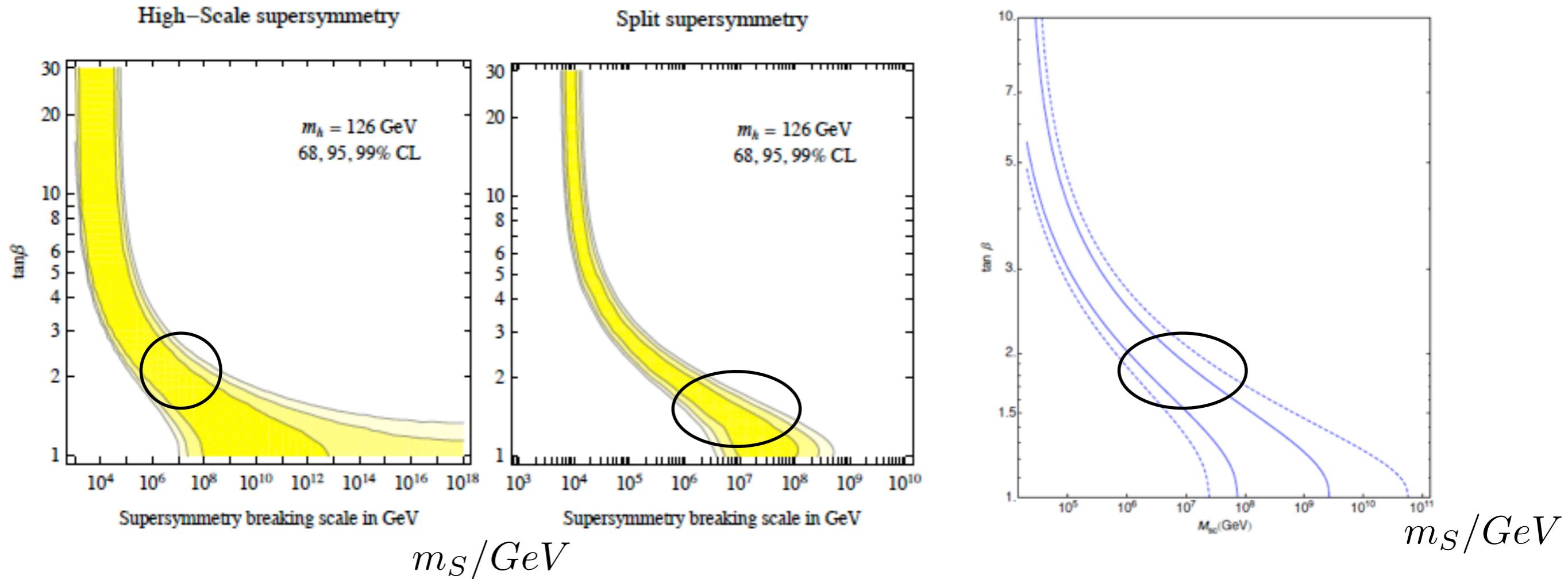
Flavour tests as very high-energy probes

$$\Delta \mathcal{L} = \sum_i \frac{1}{\Lambda_i^2} \mathcal{O}_i \quad (\text{in absence of a flavour structure})$$

| | Lower bounds on Λ_i/TeV | |
|---------------------------|--|---|
| | $\sin \phi = 0$ | $\sin \phi = 1$ |
| $\Delta S = 2$ | $10^3 \div 10^4$ | $2(10^4 \div 10^5)$ |
| $\Delta C = 2$ | $(1 \div 5)10^3$ | $(0.3 \div 1)10^4 \ [(1 \div 5)10^4]^\ast \diamond$ |
| $\Delta B_d = 2$ | $(0.5 \div 2)10^3$ | $(1 \div 3)10^3$ |
| $\Delta B_s = 2$ | $(1 \div 5)10^2$ | $(3 \div 8)10^2 \ [(0.5 \div 2)10^3]^\ast$ |
| $\mu \rightarrow e\gamma$ | $0.5 \cdot 10^3$ | $[5 \cdot 10^3] \ **$ |

- bounds on $\Delta F = 1$ at $10 \div 100$ TeV
- range depends on Lorentz structure of $\mathcal{O} = \bar{f} f \bar{f} f$
- $[]^\ast$ = expected LHCb sensitivity(?)
- \diamond if $(|\frac{p}{q}|_D - 1) \lesssim 10^{-3}$ in the SM defendable (!?)
- $[]^{**}$ = expected from MEG upgrade(?)

A case for a $10^3 \div 10^5$ TeV scale?



Arkani-Hamed, Dimopoulos 2004
 Giudice, Strumia 2011
 Arkani-Hamed et al 2012

[If $m_S < T_R$, not to overclose the universe by a stable LSP, $m_S < 10 \div 100$ TeV]
 Hall et al, 2013

How compelling? Which relation to m_q , V_{CKM} ?

A flavour structure in action 1

Breaking of flavour symmetries embedded in few basic parameters

$$U(3)_Q \times U(3)_u \times U(3)_d \equiv \boxed{U(3)^3}$$

$$Y_u = (3, \bar{3}, 1) \quad Y_d = (3, 1, \bar{3}) \quad (\text{MFV})$$

Chivukula, Georgi 1987 (TC)

Hall, Randall 1990 (SUSY)

D'Ambrosio et al 2002 (general)

$$U(2)_Q \times U(2)_u \times U(2)_d \equiv \boxed{U(2)^3}$$

B, Isidori et al 2011 (general)

Y_u, Y_d split under $U(2)^3$ -representations

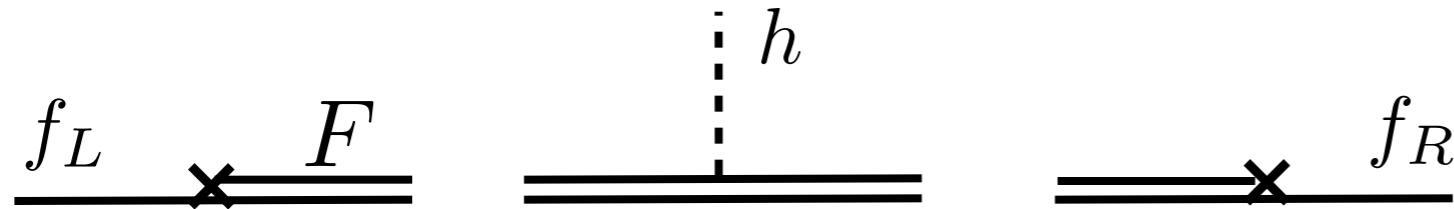
$$Y_u = \lambda_t \begin{pmatrix} \Delta_u & V_Q \\ V_u^T & 1 \end{pmatrix} \quad Y_d = \lambda_b \begin{pmatrix} \Delta_d & V'_Q \\ V_d^T & 1 \end{pmatrix}$$

Requiring a small breaking of $U(2)^3$: $V = V_Q \propto V'_Q$ $\|V\| = O(V_{cb})$
and, by consistency with flavour data, $\|V_u\|, \|V_d\| \ll \|V\|$

$$\left(U(3)^3 \text{ at large } \tan \beta \rightarrow U(2)^3 \begin{array}{l} \text{Feldmann, Mannel 2008} \\ \text{Kagan et al 2009} \end{array} \right)$$

A flavour structure in action 2

“Partial Compositeness”



Kaplan 1991 (TC)

“Anarchy”



Gherghetta, Pomarol 2000 (RS)

“Left/Right compositeness”

$U(3)^3$ or $U(2)^3$ only broken by

Left compositeness:



Right compositeness:



Cacciapaglia et al 2007 (RS, $U(3)^3$)

B, Isidori, Pappadopulo 2009 (general, $U(3)^3$)

Redi, Wyler 2011 (comp Higgs, $U(3)^3$)

The $\Delta F = 2$ case

$U(3)^3$

$$\frac{c_{LL}}{\Lambda^2} \xi_{ij}^2 \frac{1}{2} (\bar{d}_{Li} \gamma_\mu d_{Lj})^2 \quad \xi_{ij} = V_{ti} V_{tj}^* \quad c_{LL}^B = c_{LL}^K \quad (U(3)^3)$$

(cannot fit the “discrepancy”)

$U(2)^3$

$$\frac{c_{LL}^K}{\Lambda^2} \xi_{ds}^2 \frac{1}{2} (\bar{d}_L \gamma_\mu s_L)^2 \quad c_{LL}^B = 0$$

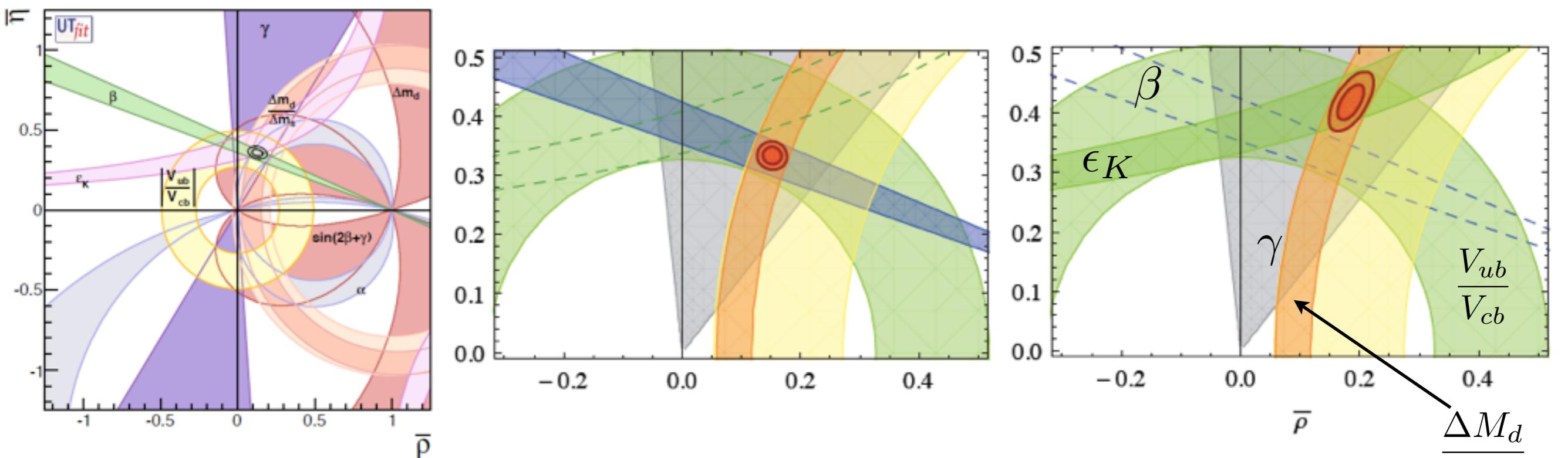
B, Buttazzo et al 2011 (general, $U(2)^3$)

Flavour tests
versus direct searches
(cum grano salis)

for $c = 1 \quad \Lambda \approx 4\pi(m, f)$

E.g. $c \cdot (3 TeV/\Lambda)^2 \approx 0.1$ means $m, f \approx 0.8 TeV$

$\Delta F = 2$ key measurements



$U(2)^3$

$$\epsilon_K = \epsilon_K^{\text{SM}(tt)} (1 + h_K) + \epsilon_K^{\text{SM}(tc+cc)},$$

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

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

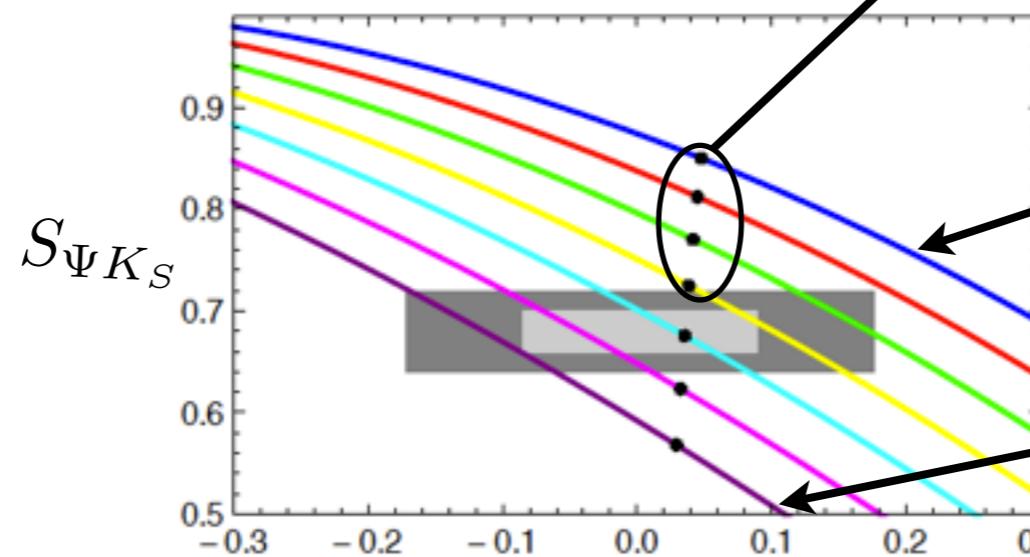
$$\Delta M_d = \Delta M_d^{\text{SM}} |1 + h_B e^{i\phi_B}|,$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{\Delta M_d}{\Delta M_s}|_{SM} = 34.5 \pm 3.0$$

$$\frac{\Delta M_d}{\Delta M_s}|_{exp} = 35.0 \pm 0.3$$

$$\Rightarrow \gamma \approx 70^\circ$$

The key role of
 V_{ub} and $S_{\Psi\phi}$



$$|V_{ub}| = 0.0046$$

$$|V_{ub}| = 0.0028$$

Buras, Girrbach 2012

$\Delta F = 2$ and anarchy

Two physical relevant scales

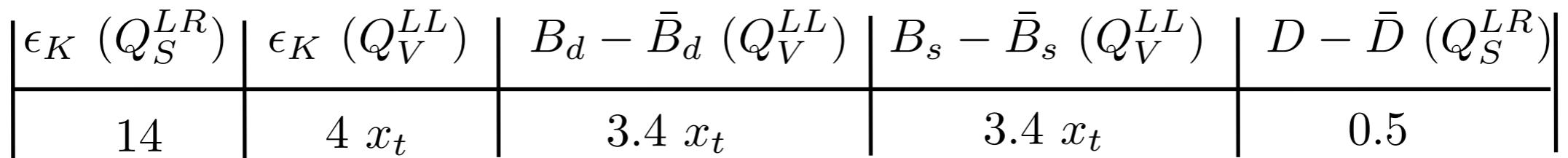
$$m_F = Y f$$

$$\frac{F}{Y}$$

In Higgs-as-PGB models m_F relevant to $pp \rightarrow F\bar{F}$ and to the
 Fine Tuning, since $m_h = C \frac{\sqrt{N_c}}{\pi} m_t Y$ $FT \approx C(\frac{v}{f})^2 \approx \frac{m_h}{125 \text{ GeV}} (\frac{v}{m_F})^2$

$$c_{ij}^{LL} e^{i\phi_{ij}^{LL}} \frac{(x_t y_t)^2}{m_F^2} \xi_{ij}^2 (\bar{d}_L^i \gamma^\mu d_L^j)(\bar{d}_L^i \gamma^\mu d_L^j) \quad c_{ij}^{LR} e^{i\phi_{ij}^{LR}} \frac{y_d^i y_d^j}{m_F^2} (\bar{d}_R^i d_L^j)(\bar{d}_L^i d_R^j)$$

lower bounds on m_F/TeV by taking all $c = 1$



Serious bounds (especially from $\epsilon_K (Q_S^{LR})$)

$$x_t = s_{Lt}/s_{Rt} > y_t/Y$$

but many unknown parameters as well

$\Delta F = 1$ Summary

Chirality breaking
(cromo-)magnetic operators

$$B \rightarrow X_{(s,d)}\gamma$$

$$B \rightarrow K(\pi)\mu\mu$$

$U(3)^3$

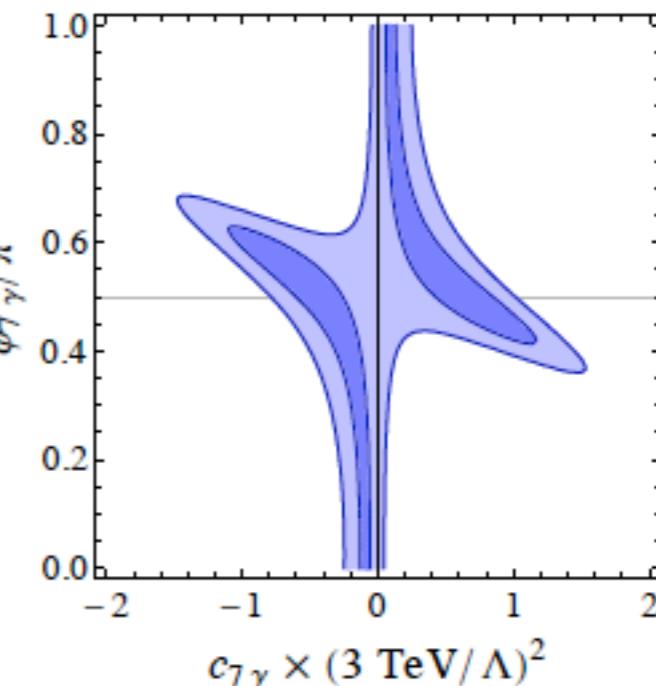
$U(2)^3$

Anarchy

$$\begin{aligned} B &\rightarrow X_{(s,d)}\gamma \\ B &\rightarrow K(\pi)\mu\mu \end{aligned}$$

$$\begin{aligned} \mathcal{A}_{CP}^{direct}(D) \\ \epsilon'/\epsilon \end{aligned}$$

$$f \gtrsim 1 \text{ TeV}$$



Chirality conserving op.s

$$B \rightarrow X_{(s,d)}\gamma$$

$$B \rightarrow K(\pi)\mu\mu$$

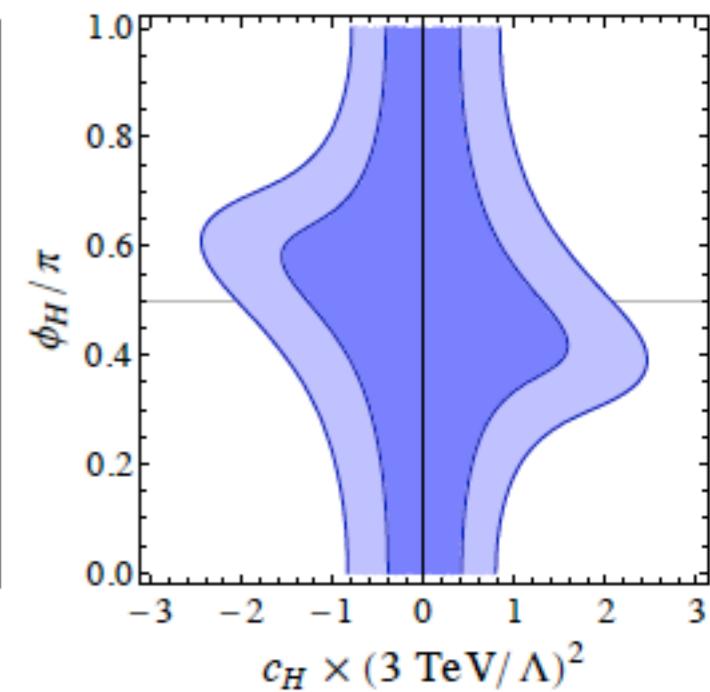
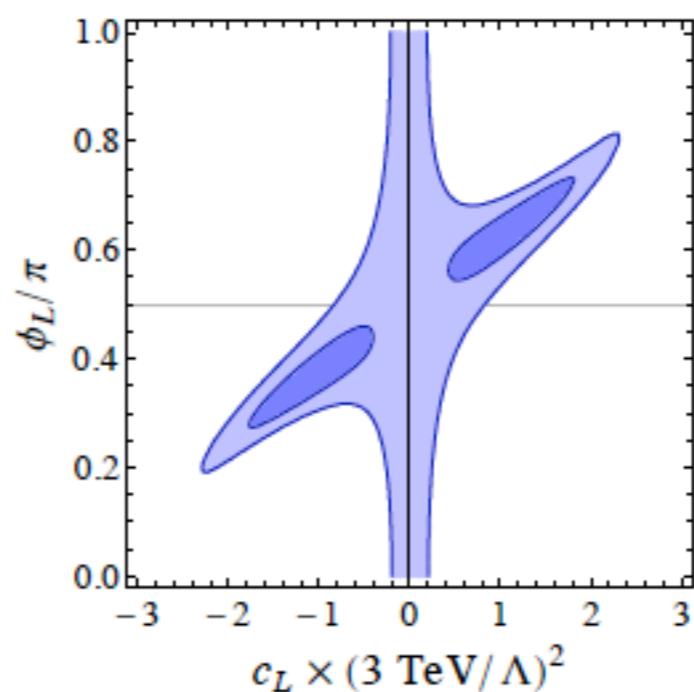
$$B_s \rightarrow \mu\mu$$

$$[K \rightarrow \pi\nu\nu]$$

no phase in $U(3)^3$

$U(2)^3$

} correlated



Overall view

Relevant observables, competitive with current direct searches

| | ϵ_K $\Delta M_{d,s}$ | $\phi_{d,s}$ | $\frac{\Delta M_d}{\Delta M_s}$ $\phi_d - \phi_s$ | ΔM_c \blacktriangledown ϕ_c | $B \rightarrow X_s \gamma$ $B \rightarrow X_s \mu^+ \mu^-$ $B_s \rightarrow \mu^+ \mu^-$ | $K \rightarrow \pi \nu \nu$ | $A_{CP}^{direct}(D)$ |
|-------------------------------------|----------------------------------|--------------|--|---|--|-----------------------------|----------------------|
| $U(2)^3$ | Yes* | Yes | No | No | Yes* | Yes | No |
| Anarchy if $Q_S^{LR} \downarrow$ | Yes, m_F | Yes, m_F | Yes, m_F | No | Yes, f | Yes, $\sqrt{m_F f}$ | Yes, f |

- * Some effects possible in $U(3)^3$ as well
- \blacktriangledown Yes, with flavour breaking at high scale and no flavour structure
- \checkmark If SM under control

Electric Dipole Moments

$$\frac{c_f^\alpha e^{i\phi_f^\alpha}}{\Lambda^2} m_f (\bar{f}_L \sigma_{\mu\nu} f_R) O_\alpha^{\mu\nu}$$

$$O_\alpha^{\mu\nu} = e F^{\mu\nu}, \quad g_S G^{\mu\nu}$$

$U(2)^3$

$U(3)^3$

Anarchy

neutron EDM
 $d_n < 2.9 \cdot 10^{-26} e \text{ cm}$

$$c_{u,d}^\alpha \sin \phi_{u,d}^\alpha (3 \text{ TeV}/\Lambda)^2 \lesssim 3(10^{-2} \div 10^{-3})$$

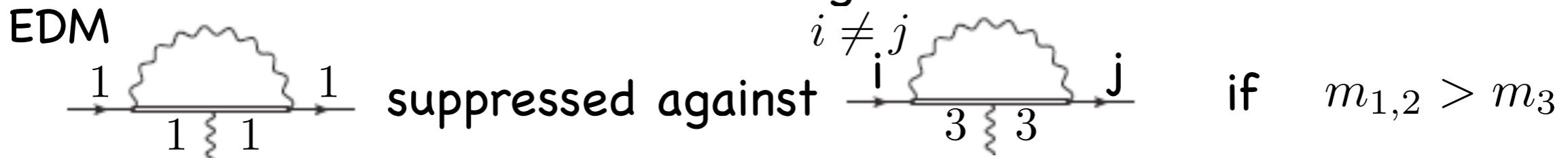
electron EDM
 $d_e < 10^{-27} e \text{ cm}$

$$c_e \sin \phi_e^\gamma (3 \text{ TeV}/\Lambda)^2 \lesssim 3 \cdot 10^{-2}$$

⇒ At face value and for maximal phases: $\Lambda \approx 4\pi(m, f) \gtrsim 20 \div 50 \text{ TeV}$!!

However:

- $U(2)^3$ may suppress first generation effects relative to third generation ones



- $U(2)^3$ or $U(3)^3$ in Left/Right compositeness suppress EDMs, if no phase in the strong sector



Flavour in leptons

Less determined than in quark case

$$Y_u, Y_d \longrightarrow Y_e, Y_\nu, \nu_R M \nu_R$$

Assume Y_ν has no influence on flavour physics at the Fermi scale
(other than giving masses, with M , to ν 's and contributing to V_{PMNS})

$$U(3)_L \times U(3)_e \equiv U(3)^2$$

$Y_e \Rightarrow Y_e^{diag} \Rightarrow$ No new flavour changing phenomena

$$U(2)_L \times U(2)_e \equiv U(2)^2$$

In analogy with quarks

$$Y_e = \lambda_\tau \begin{bmatrix} \Delta & V_L \\ V_e^T & 1 \end{bmatrix}$$

Anarchy:

$$Y_e = s_L Y s_R \quad Y = \mathcal{O}(1)$$

$$\Rightarrow m_i = s_L^i s_R^i Y_{ii} v \quad i = e, \mu, \tau$$

$\Delta L = 1$ chirality breaking op.s

$$\frac{c_{ij}}{\Lambda^2} m_j \zeta_{ij} (\bar{l}_{iL} \sigma_{\mu\nu} l_{jR}) e F_\alpha^{\mu\nu} \quad i, j = e, \mu, \tau$$

current bounds on BR's

| $\mu \rightarrow e\gamma$ | $\tau \rightarrow e\gamma$ | $\tau \rightarrow \mu\gamma$ |
|---------------------------|----------------------------|------------------------------|
| $2.4 \cdot 10^{-12}$ | $3.3 \cdot 10^{-8}$ | $4.3 \cdot 10^{-8}$ |

$$U(2)_L \times U(2)_e \equiv U(2)^2$$

bounds on c_{ij} normalized as $\tilde{c}_{ij} = c_{ij} \times (3 \text{ TeV}/\Lambda)^2 (\zeta_{ij}/V_{ti} V_{tj}^*)$

| $\tilde{c}_{e\mu}$ | $\tilde{c}_{e\tau}$ | $\tilde{c}_{\mu\tau}$ |
|--------------------|---------------------|-----------------------|
| 0.07 | 0.8 | 0.2 |

E.g. from $\tilde{c}_{e\mu} > 0.07 \Rightarrow \Lambda \gtrsim 10 \text{ TeV}$ (or $m \gtrsim 0.8 \text{ TeV}$)

Anarchy:

best case to minimize effects: $\zeta_{ij} \approx \frac{s_L^i}{s_L^j} \approx \frac{s_R^i}{s_R^j} \approx (m_i/m_j)^{1/2} \quad i, j = e, \mu, \tau$

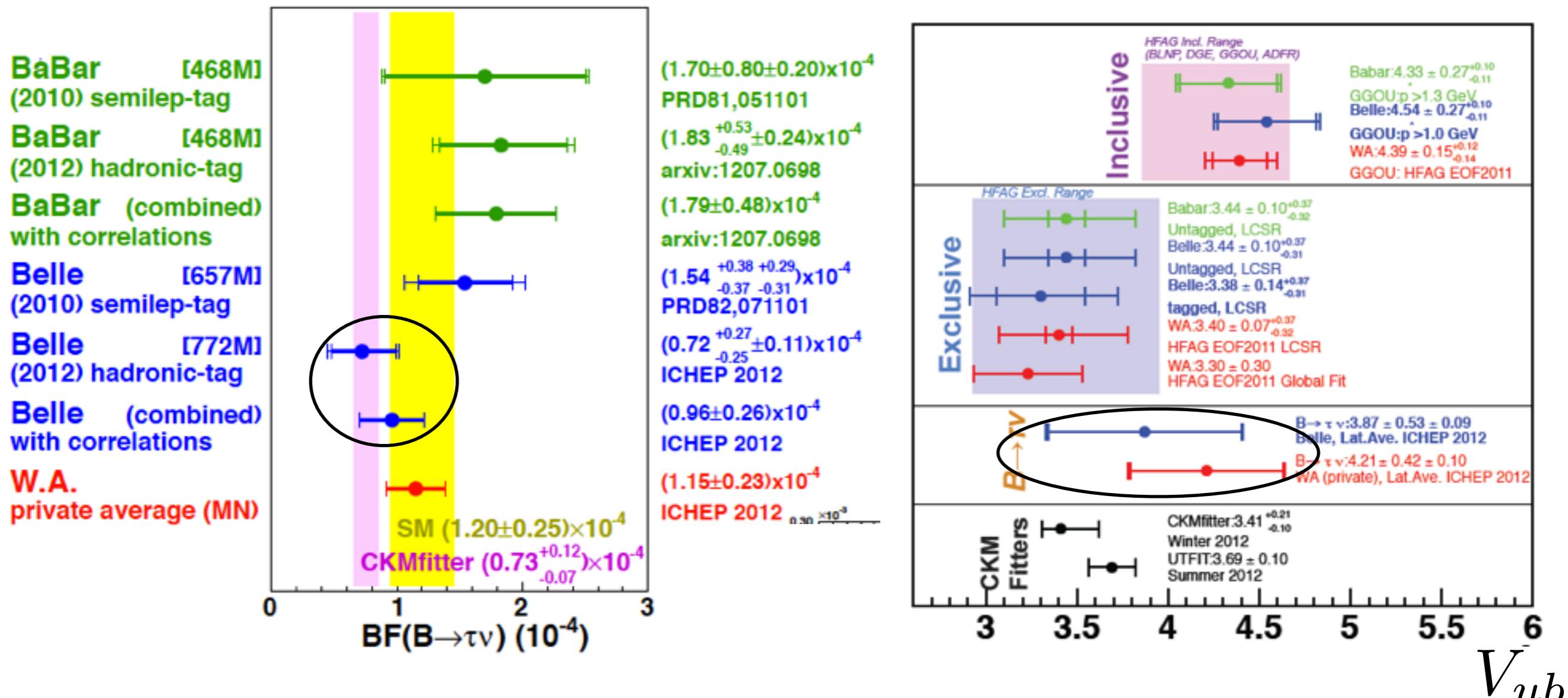
From $\mu \rightarrow e\gamma \Rightarrow f \gtrsim 12 \text{ TeV}$ (or $\Lambda \gtrsim 150 \text{ TeV}$) !!

Summary and conclusions

- ⇒ Flavour Tests as an “unoriented” high energy probe or as an “oriented” search based on a flavour structure
- ⇒ In the quark sector, if $U(2)^3$ or anarchy, Flavour Tests competitive with current new-physics direct searches (and even “stronger” in some “compositeness” cases)
- ⇒ The motivation from “naturalness” still alive
(For how long? Never mind. In view of the point above, only watch theory uncertainties on SM effects (!?))
- ⇒ EDMs a powerful probe (too powerful?). Well known ...
- ⇒ Tests of lepton flavour violations also powerful but intrinsically more uncertain as well
In $U(2)_L \times U(2)_e$ and naive extrapolation from quark mixings $\tau \rightarrow \mu\gamma$ ($4.3 \cdot 10^{-8}$) is below $\mu \rightarrow e\gamma$ ($2.4 \cdot 10^{-12}$) by about a factor of 10

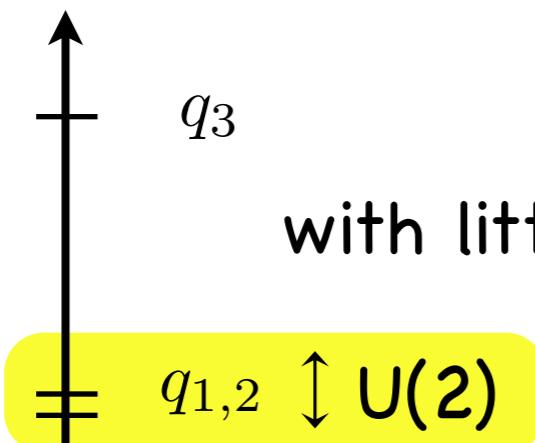
Nakao
Yook
Urquijo

The $B \rightarrow \tau\nu$ “problem”



Better agreement than before ICHEP with CKM fits
(The V_{ub} problem still there)

An approximate flavour symmetry in action



with little communication between q_{1,2} and q₃

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

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

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

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

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

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

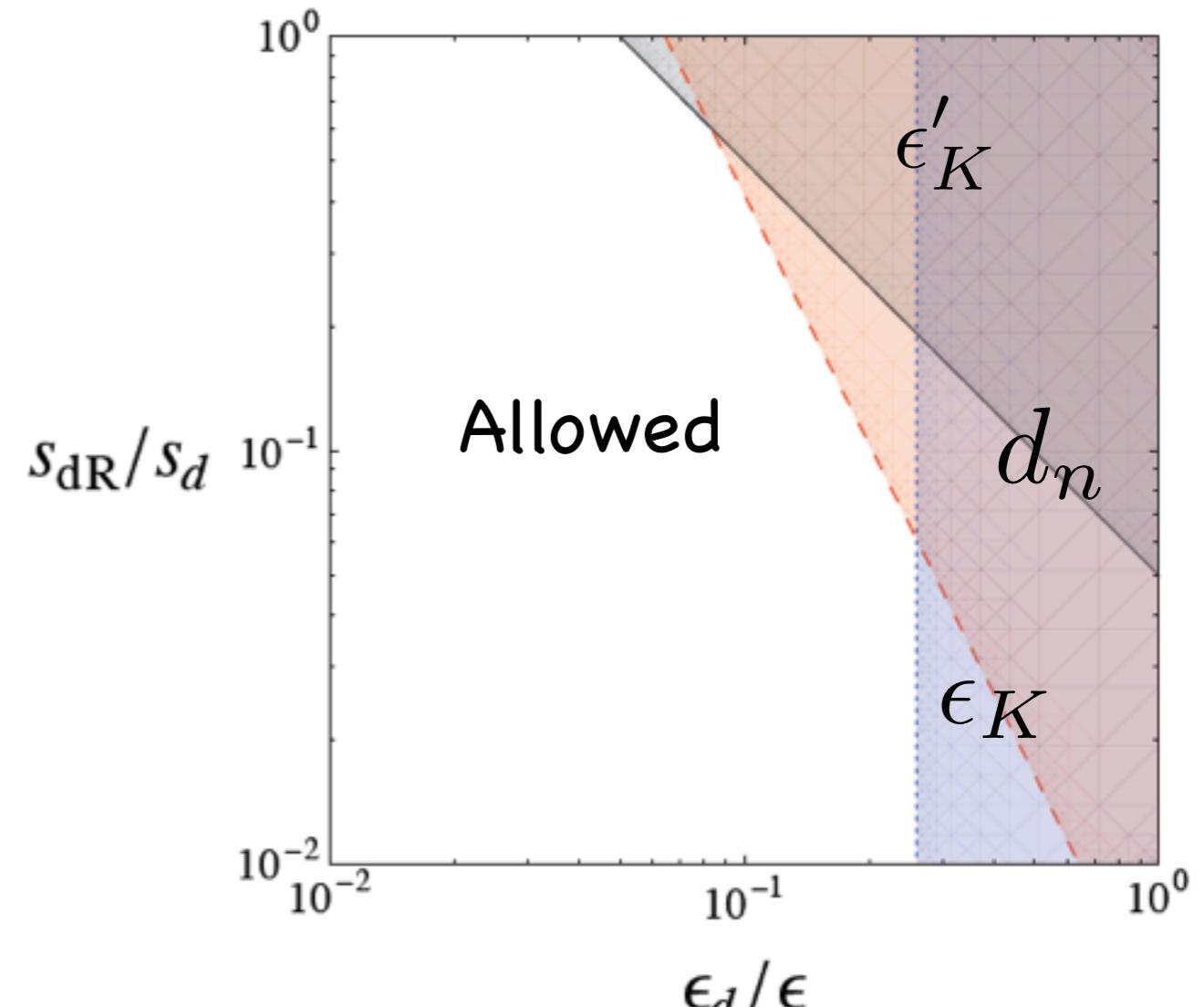
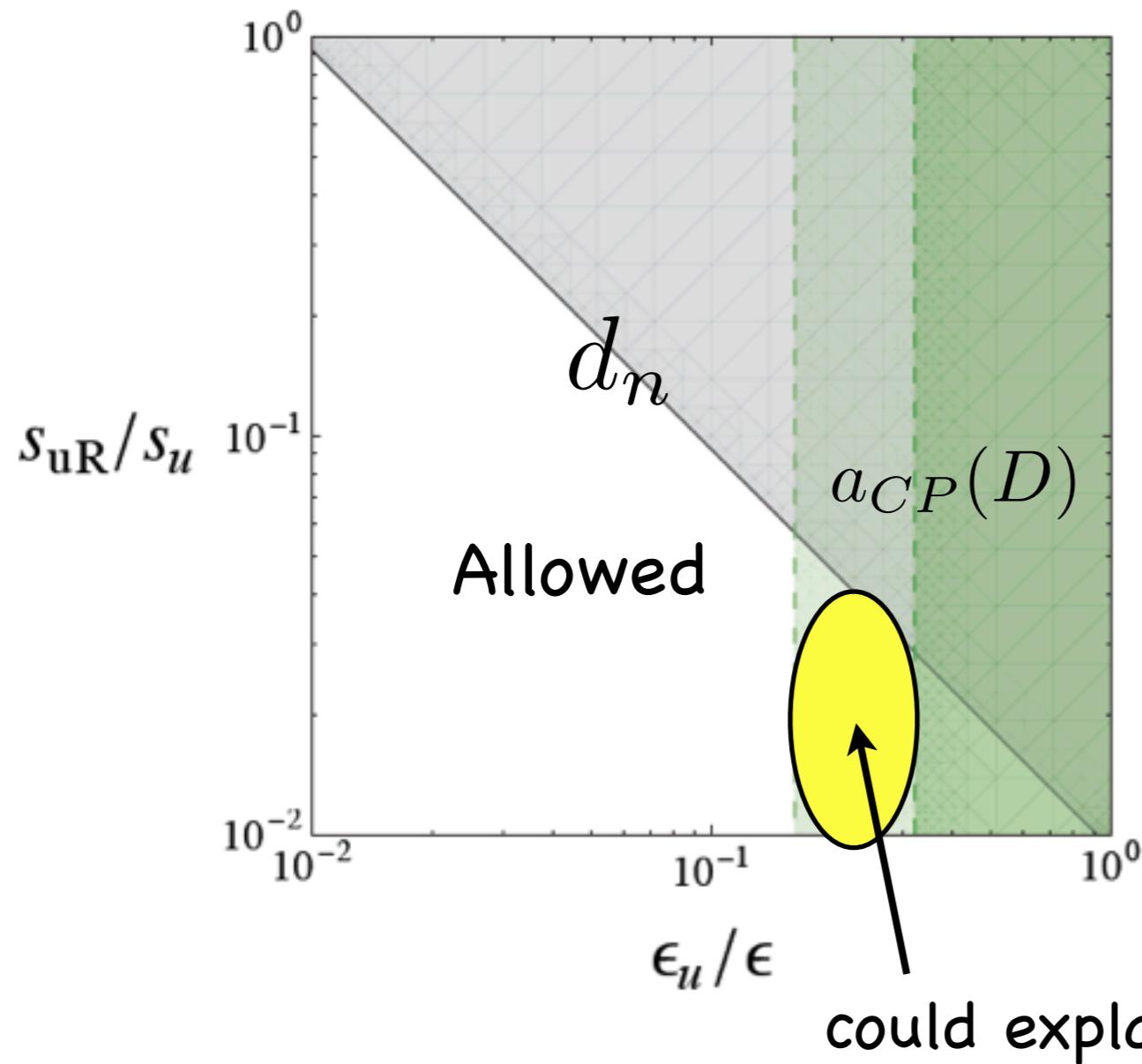
$$\lambda_b (\bar{Q}_L V) b_R$$

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

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

Capital letters = U(2) doublets

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