Flavour physics at the Fermi scale

Majorana Lectures
Naples, June 18, 2012

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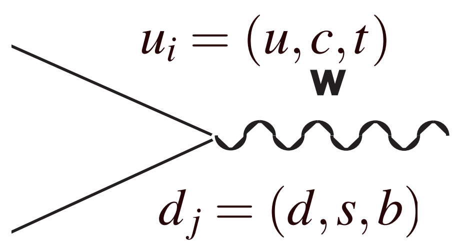
SNS and INFN, Pisa

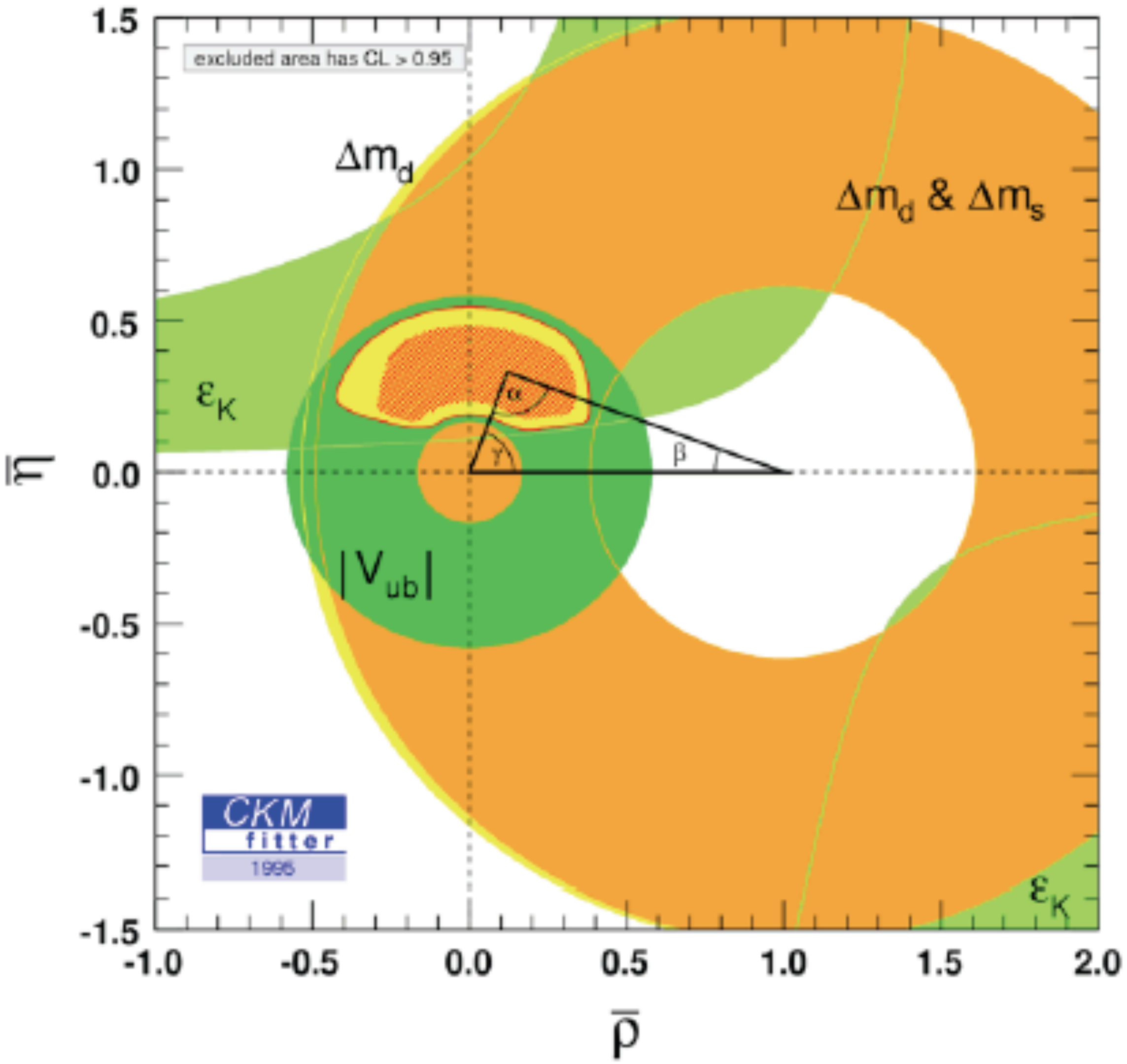
(Bertuzzo, Buttazzo, Farina, Isidori, Lodone, Sala, Straub)

The progress of flavour in a popular figure

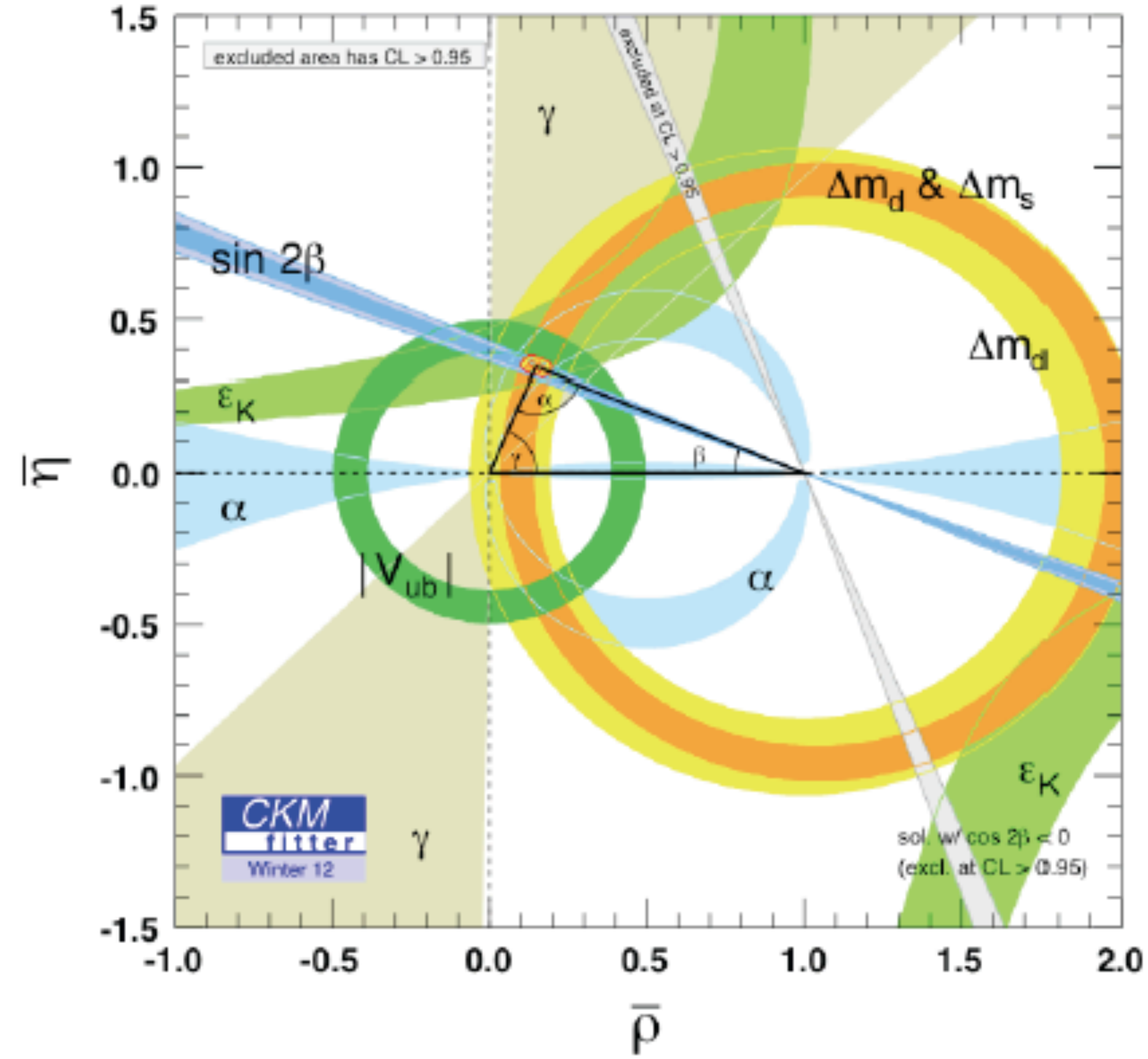


$= V_{ij} A$ with $VV^{+} = \mathbf{1}$

1995



2012



actually a gross underestimate of the real evolution

A different way to represent the flavour constraints

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{NP}$$

$$\mathcal{L}_{eff}^{NP} = \Sigma_i \frac{c_i}{\Lambda_{NP}^2} O_i$$

Operator	Bounds on c_i ($\Lambda = 1$ TeV)		Observables
	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9×10^{-7}	3×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	7×10^{-9}	3×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	6×10^{-7}	1×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6×10^{-8}	1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	3×10^{-6}	1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	6×10^{-7}	2×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	8×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	1×10^{-5}		Δm_{B_s}

Isidori, Nir, Perez 2010

also incomplete

A (very partial) list of recent flavour "problems"

BaBar

$$\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \ell \nu)} = 0.332 \pm 0.030 \qquad \mathcal{R}^{*,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 1.32 \pm 0.12$$

$$\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D \tau \nu)}{\mathcal{B}(B \to D \ell \nu)} = 0.440 \pm 0.072 \qquad \mathcal{R}^{\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{\mathrm{SM}}_{\tau/\ell} = 1.49 \pm 0.26$$

BaBar/Belle

$$\mathcal{R}^{\pi}_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu})} = 1.07 \pm 0.20 \qquad \mathcal{R}^{\pi,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{\pi,\mathrm{SM}}_{\tau/\ell} = 3.45 \pm 0.93$$

Errors of $\mathcal{R}_{\tau/l}$, $\mathcal{R}^*_{\tau/l}$ experimentally dominated

Large deviations from 1 of $\mathcal{R}/\mathcal{R}^{SM}$ in tree level decays

CDF/LHCb

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \qquad \Delta a^{\mathrm{dir}}_{\mathrm{CP}} = a^{\mathrm{dir}}_{\mathrm{CP}}(K^+K^-) - a^{\mathrm{dir}}_{\mathrm{CP}}(\pi^+\pi^-) = (-0.66 \pm 0.16)\ \%$$

A potential penguin effect

In the SM theoretically uncertain, but "normally" expected below 0.1%

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

q_3

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

$q_{1,2}$ ↕ U(2)

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

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

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

(See below)

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 $U(2)^3$

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

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

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

(MFV)

Generic $U(2)^3$

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

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

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

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

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

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

and, from a fit of tree level observables:

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

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

$\Rightarrow$ 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)

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

* FV both in L- as in R-current

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

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

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:

$$D \to \pi\pi, KK$$

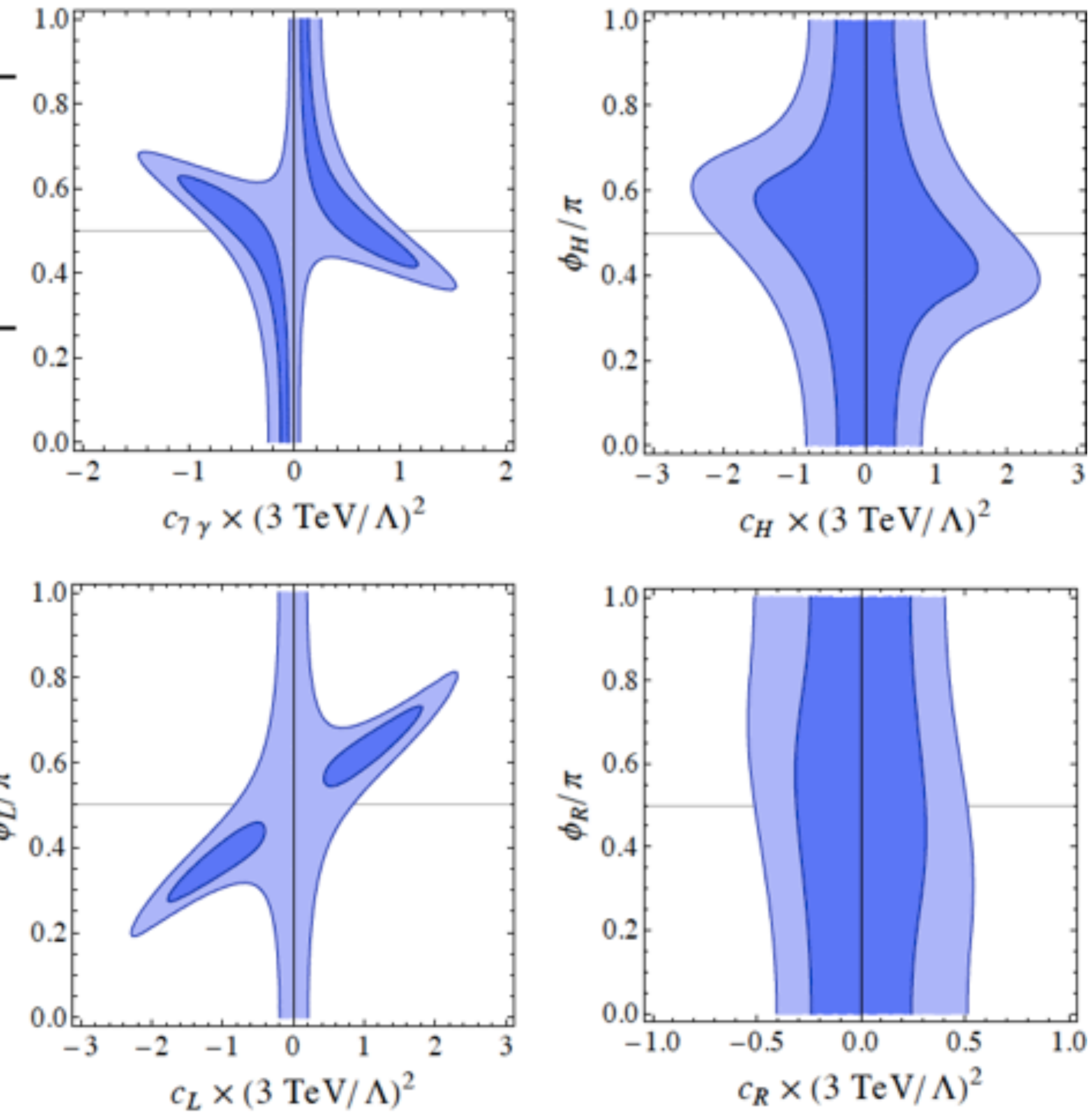
$$\Delta\epsilon_K$$

$$d_N$$

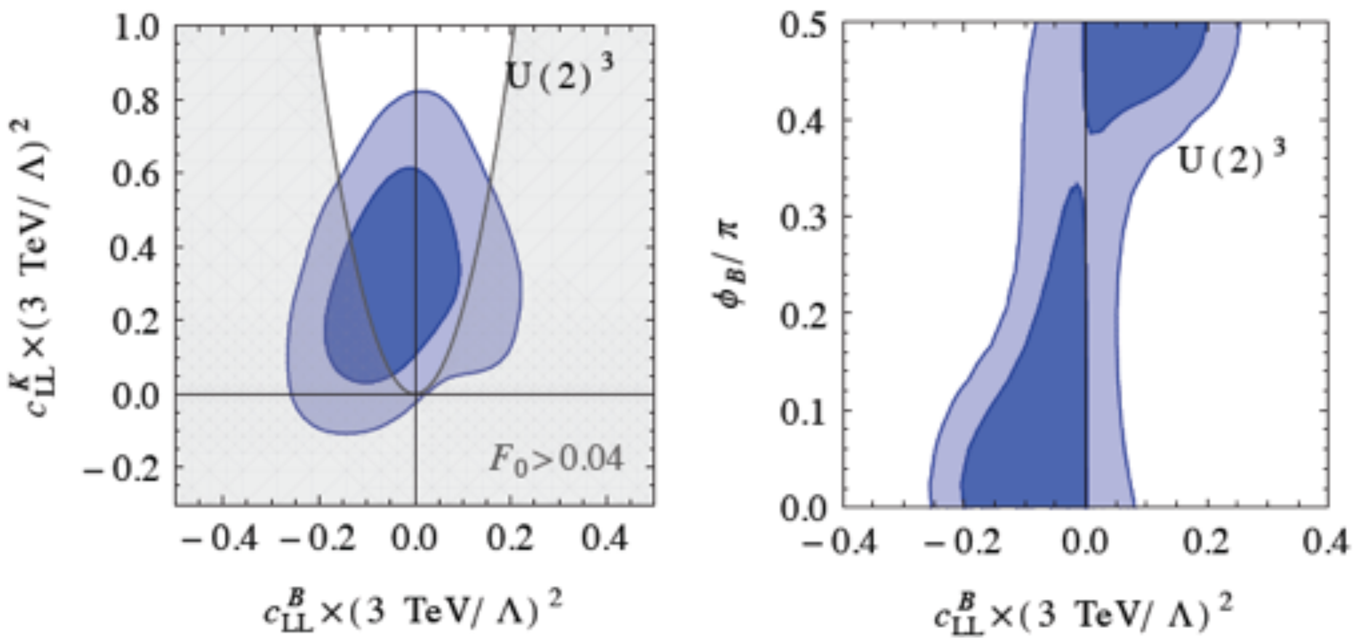
A summary of Minimal effects

B_q^0-$\bar{B}_q^0$	K^0-$\bar{K}^0$	$b \to s\gamma$
$b \to s l \bar{l}, \nu\bar{\nu}$	$K \to \pi\nu\bar{\nu}$	$b \to s l \bar{l}$

ΔF = 1

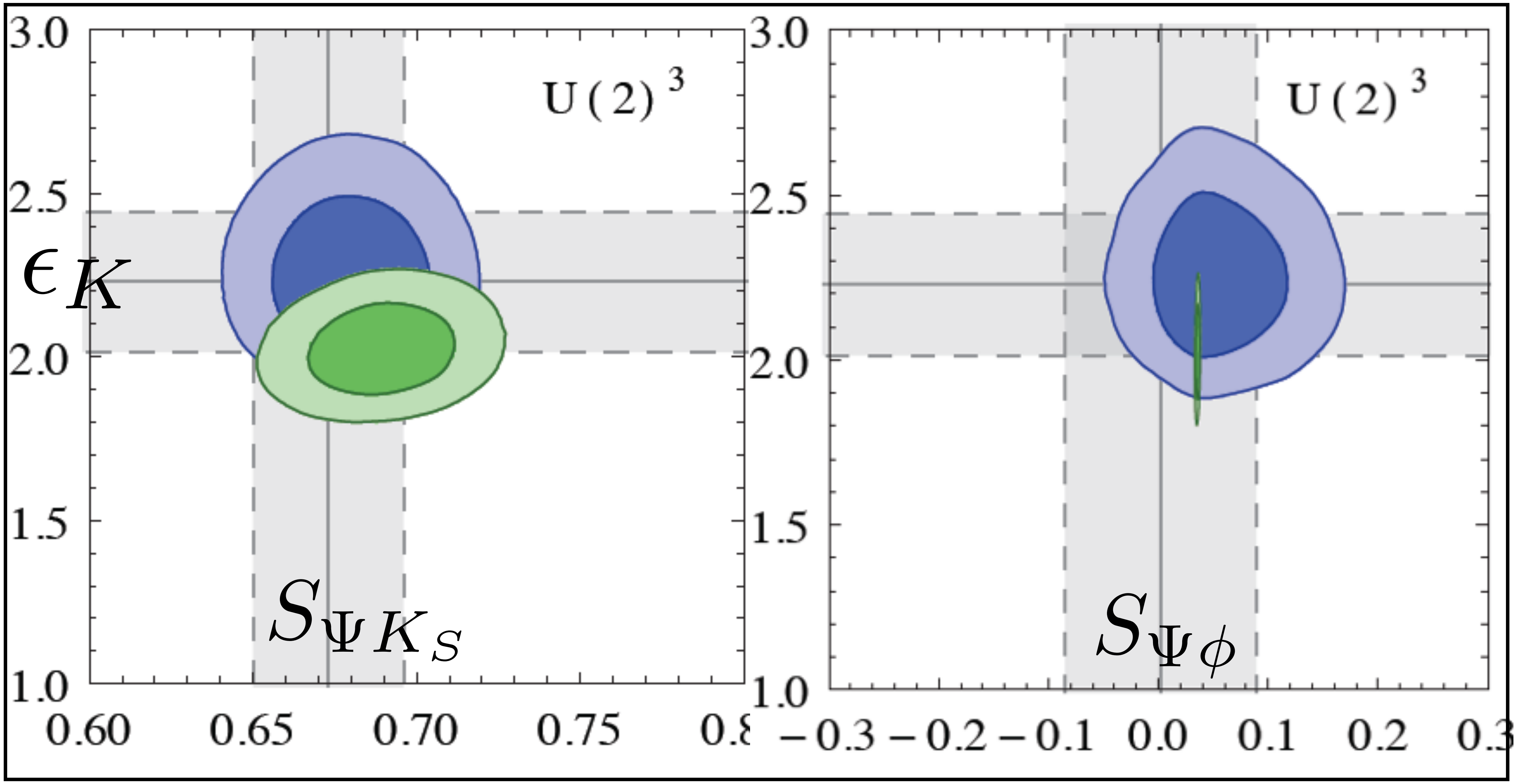


ΔF = 2



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

SM versus $U(2)^3$ fit in ΔF=2



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. $\langle(\pi\pi)_{I=2}|Q^d_{LR}|K\rangle = -\langle(\pi\pi)_{I=2}|Q^u_{LR}|K\rangle \propto (\frac{m_K}{m_s})^2$

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

A significant limit, though still broadly consistent with previous conclusion

Physical parameters

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

Minimal $U(2)^3$

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

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

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

(MFV)

Generic $U(2)^3$

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

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

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

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

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

what's known about these extra parameters?

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

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

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

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

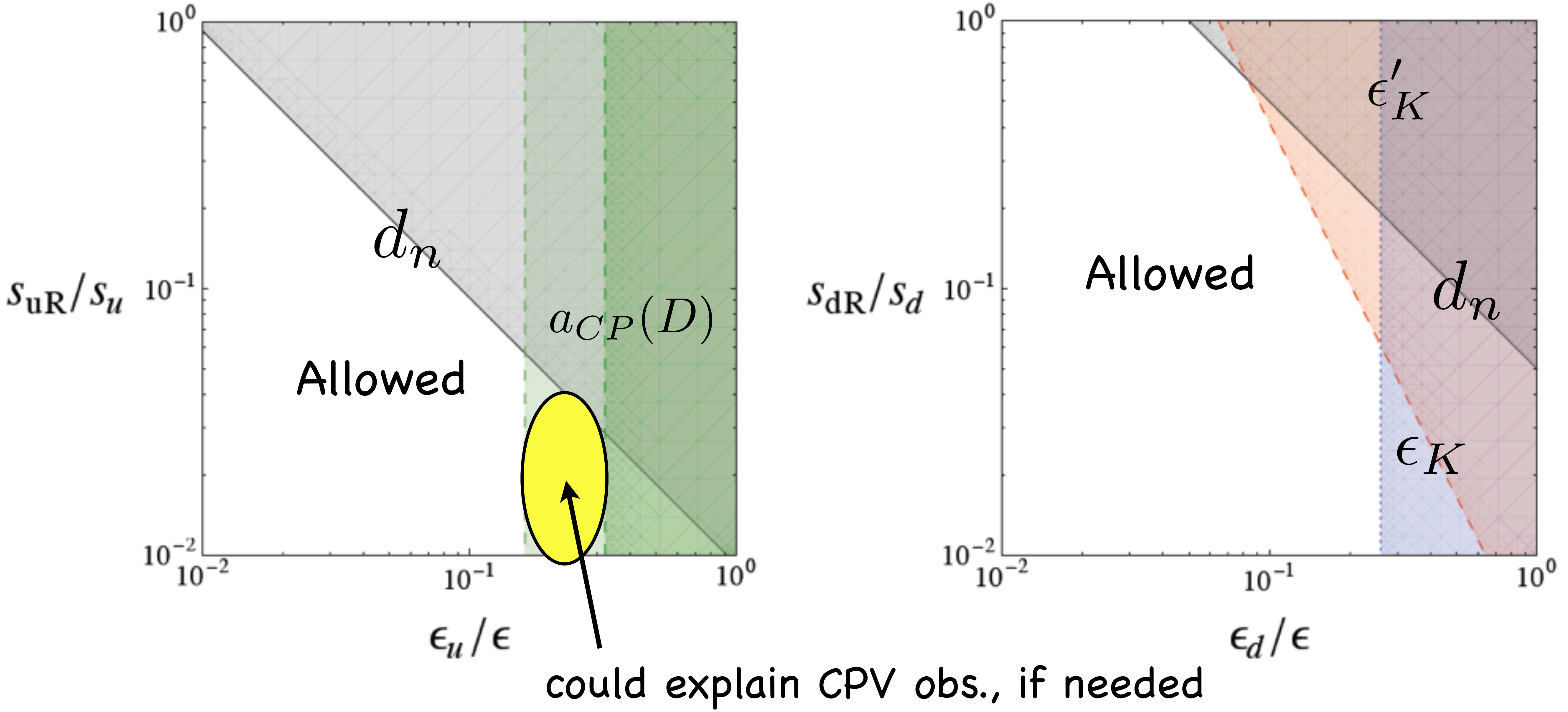
$$c_u^g \,|\sin(\phi_u^g - \phi_1^u)| \frac{s_{uR}}{s_u} \frac{\epsilon_u}{\epsilon} \lesssim 9.2 \times 10^{-3}, \qquad c_d^g \,|\sin(\phi_d^g - \phi_1^d)| \frac{s_{dR}}{s_d} \frac{\epsilon_d}{\epsilon} \lesssim 5.0 \times 10^{-2}$$

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 $U(2)^3$



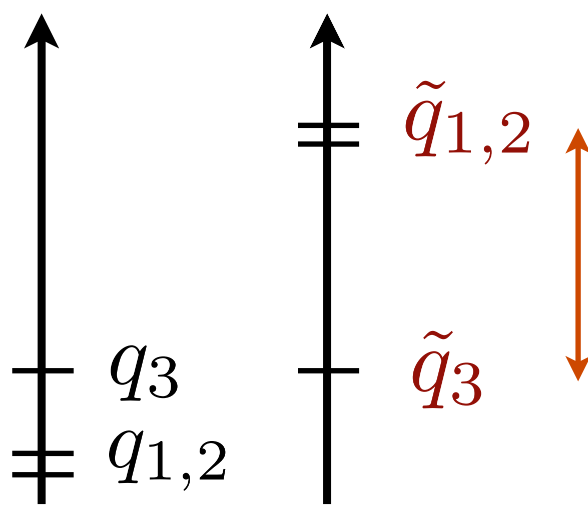
Λ = 3 TeV

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

O(1) uncertainties all over

A relevant example: supersymmetry

Particle spectrum

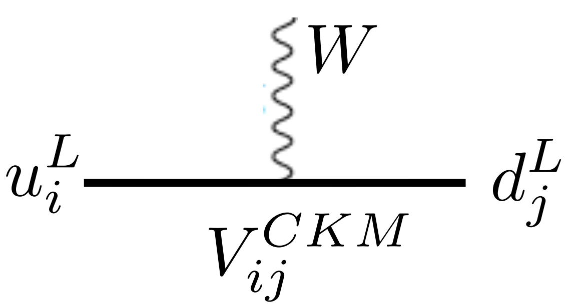


TeV's, not controlled by symmetry breaking
nor by naturalness

(MFV: $\tilde{q}_{1,2,3}$ quasi degenerate)

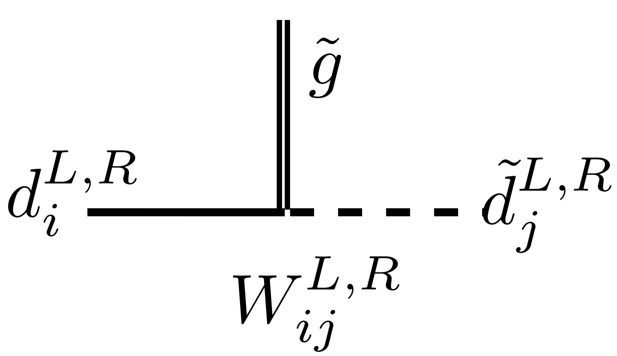
Flavour changing interactions

standard parametrization, in non standard notation



$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & s_u s e^{-i\delta} \\ -\lambda & 1-\lambda^2/2 & c_u s \\ -s_d s\, e^{i(\phi+\delta)} & -s c_d & 1 \end{pmatrix}$$

$$s_u c_d - c_u s_d e^{-i\phi} = \lambda e^{i\delta}$$



$$W^L = \begin{pmatrix} c_d & s_d e^{-i(\delta+\phi)} & -s_d s_L e^{i\gamma} e^{-i(\delta+\phi)} \\ -s_d e^{i(\delta+\phi)} & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

$W^R \approx 1$ 1 new angle s_L and 1 new phase γ

Flavour changing interactions

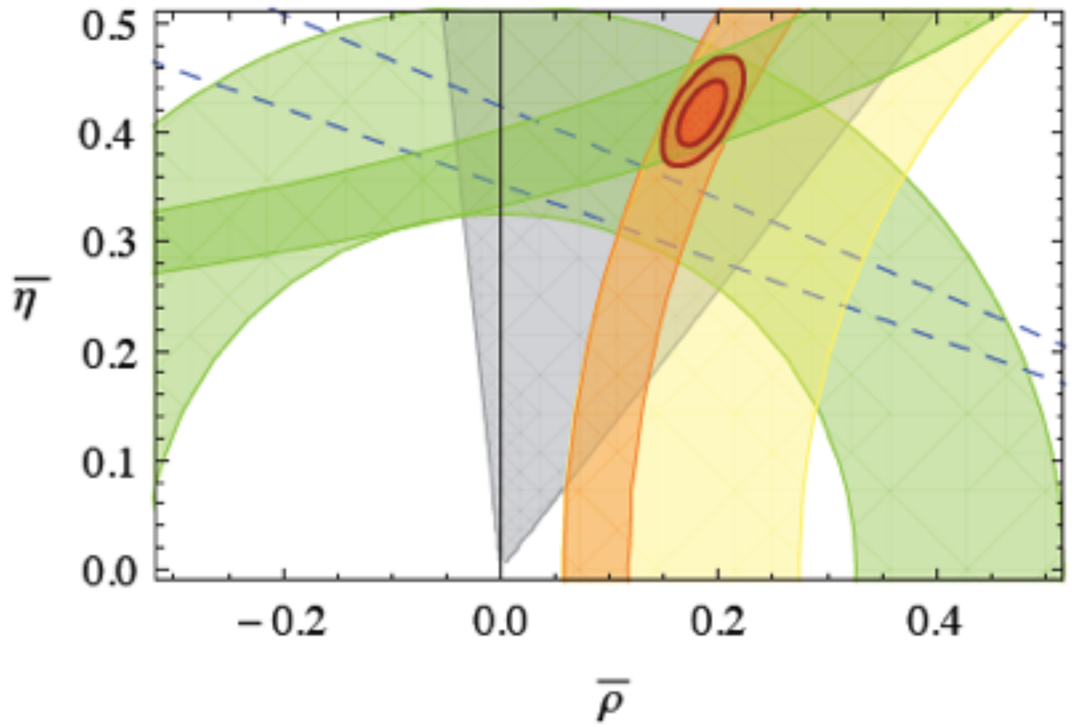
$\Delta F = 2$ – SM fit

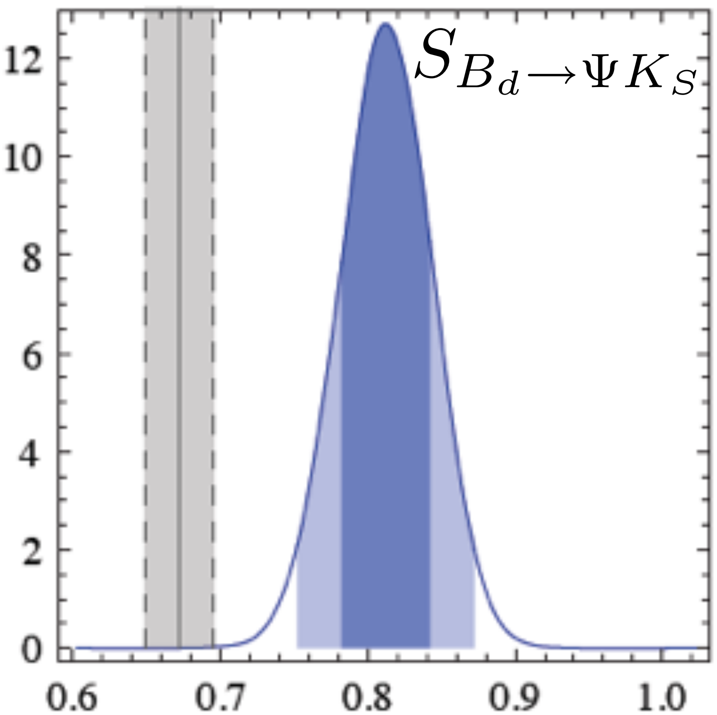
Tree level +

ΔM_d

ΔM_s

ϵ_K



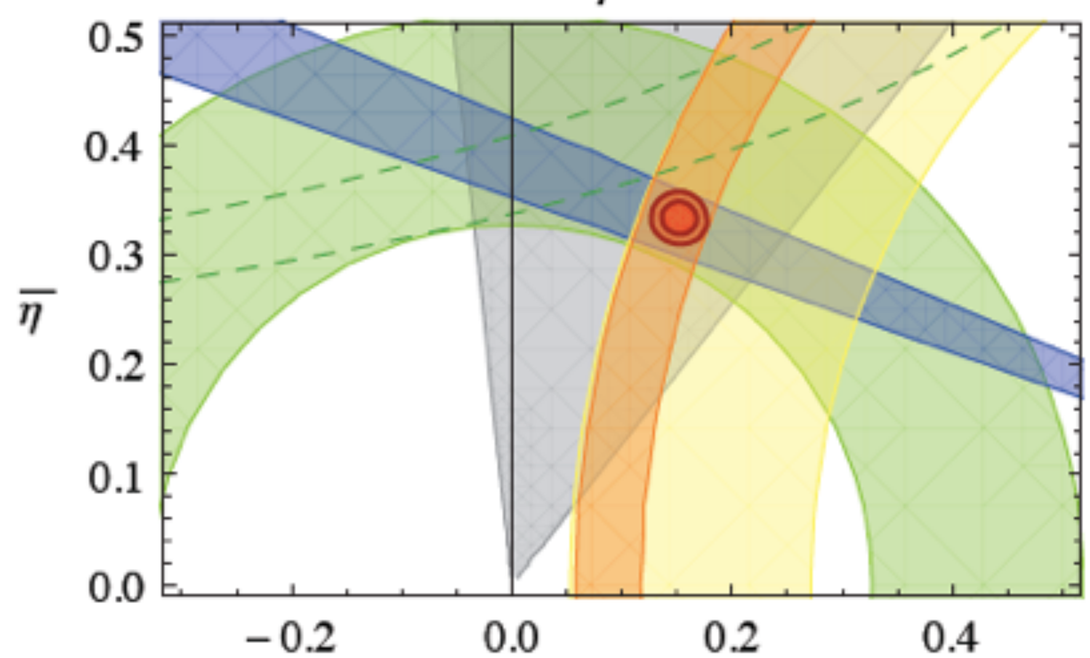


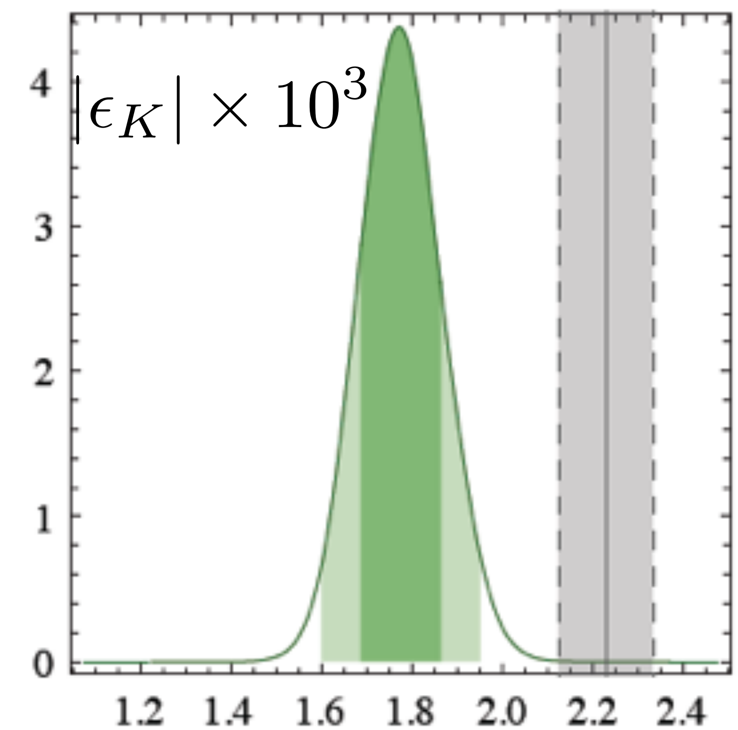
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$





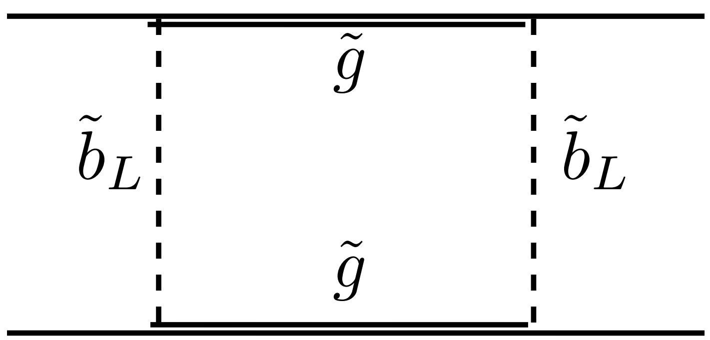
details subject to discussion

a hint of a potential problem for the SM

Lunghi, Soni
Buras, Guadagnoli
UT fit, CKM fit

Supersymmetric flavour fit

including:



$$\epsilon_K = \epsilon_K^{\mathrm{SM(tt)}} \times (1 + x^2 F_0) + \epsilon_K^{\mathrm{SM(tc+cc)}}$$

$$S_{\psi K_S} = \sin\left(2\beta + \arg\left(1 + xF_0 e^{-2i\gamma}\right)\right) \ ,$$

$$\Delta M_d = \Delta M_d^{\mathrm{SM}} \times \left|1 + xF_0 e^{-2i\gamma}\right| \ ,$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{\Delta M_d^{\mathrm{SM}}}{\Delta M_s^{\mathrm{SM}}} \ .$$

where $F_0 = F_0(m_{\tilde{b}_L}, m_{\tilde{g}})$ and $x = \dfrac{s_L^2 c_d^2}{|V_{ts}^2|}$

B, Isidori, Jones-Perez, Lodone, Straub 2011

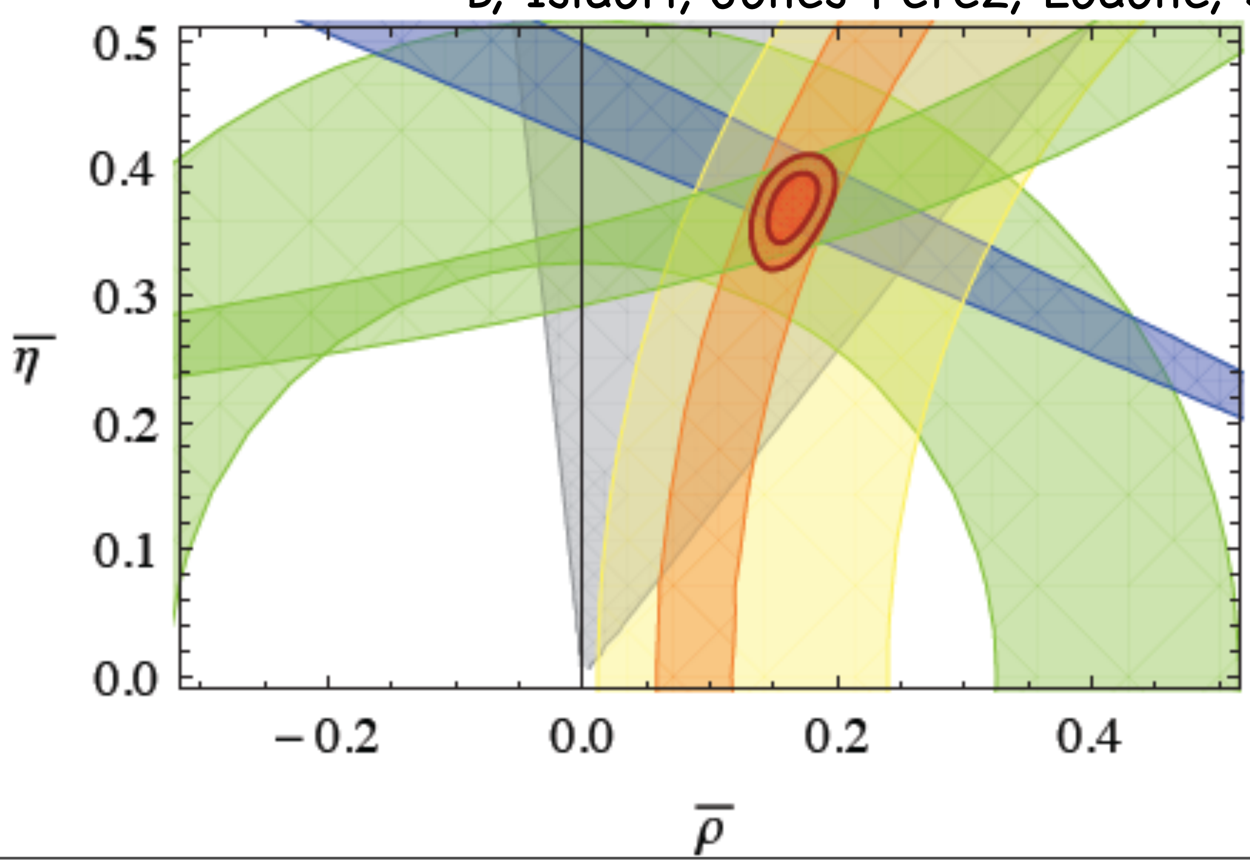
Tree level +

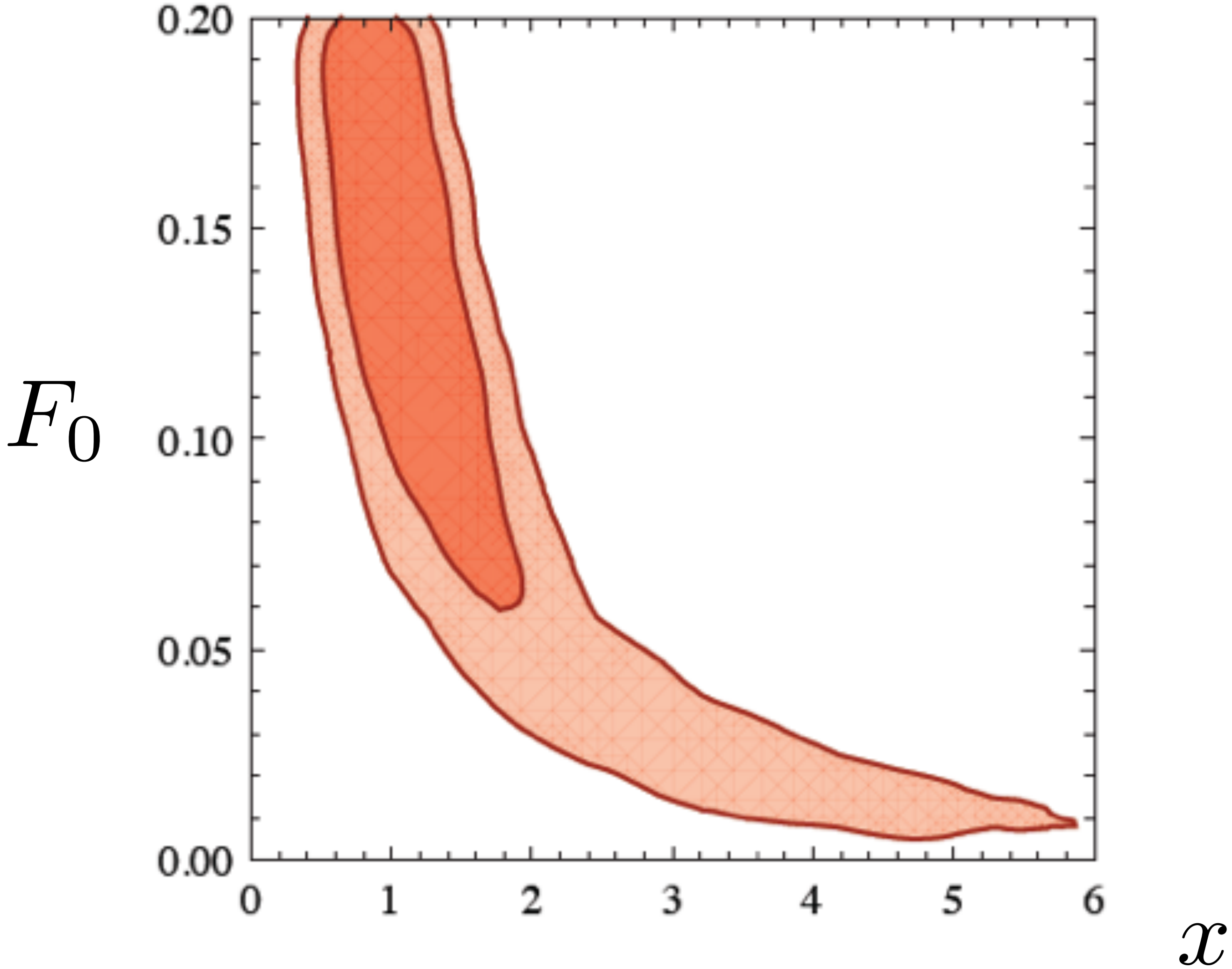
ΔM_d

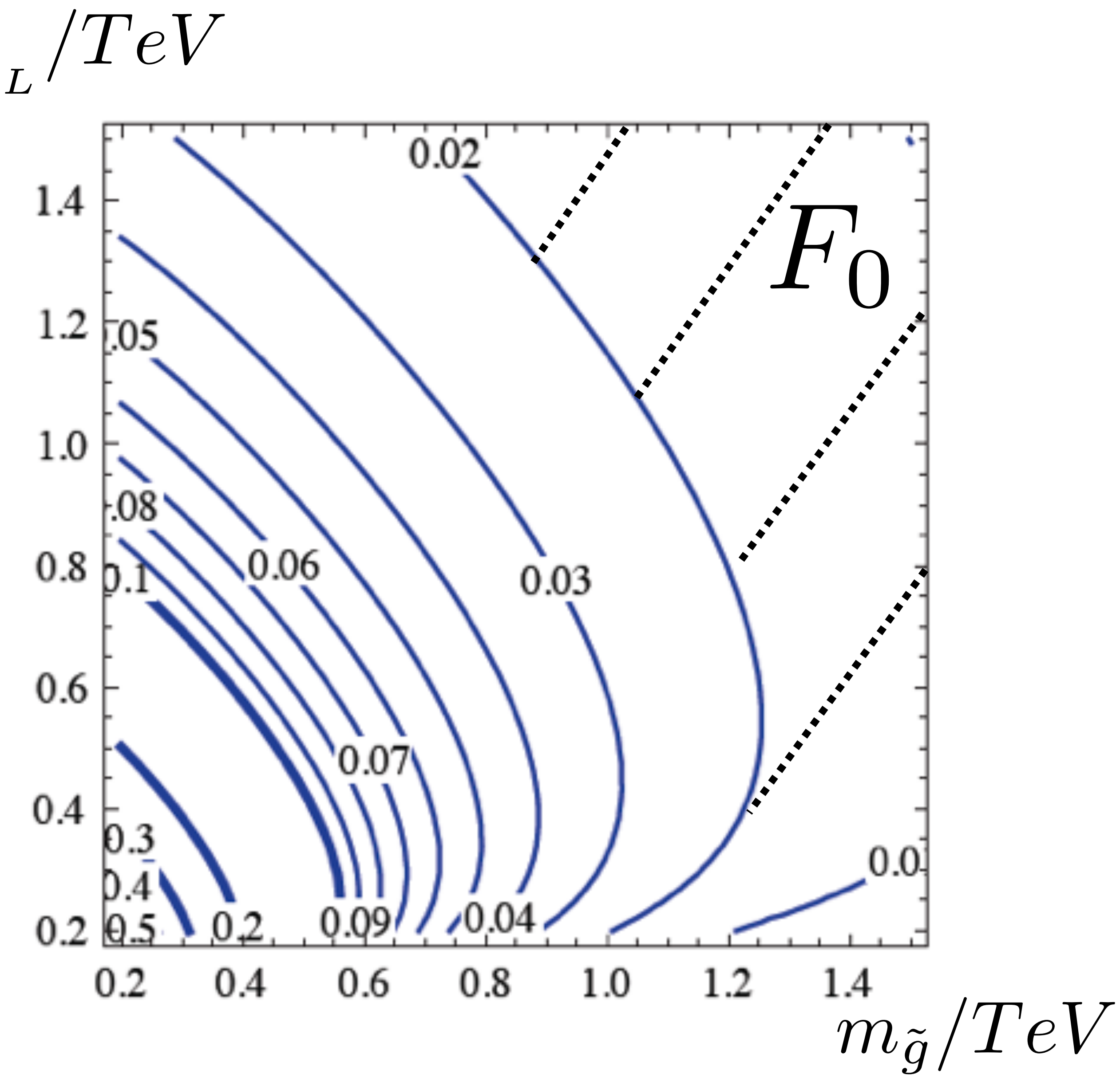
ΔM_s

$S_{B_d \to \Psi K_S}$

ϵ_K





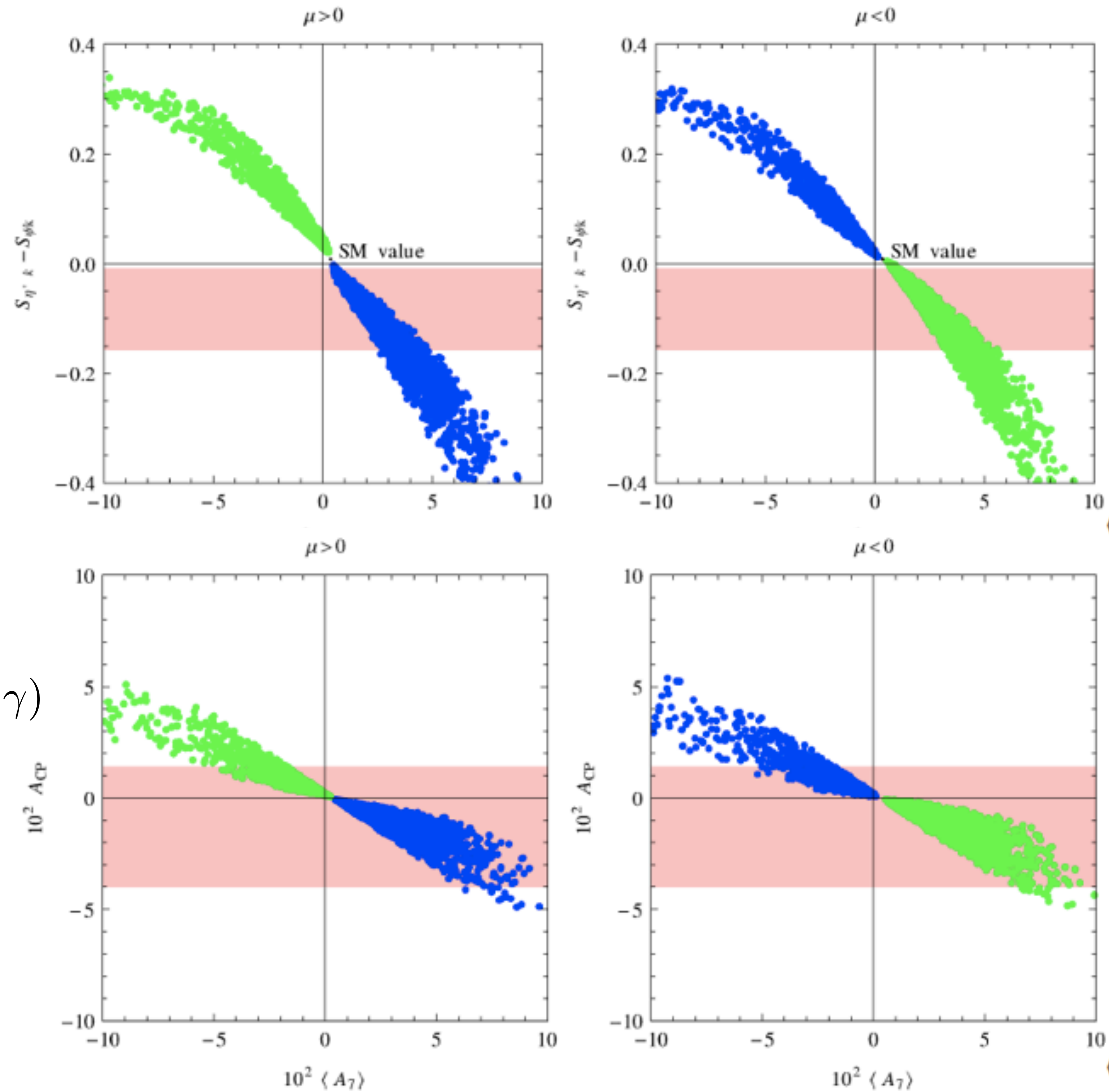


where $F_0 = F_0(m_{\tilde{b}_L}, m_{\tilde{g}})$ and $x = \frac{s_L^2 c_d^2}{|V_{ts}^2|}$

Examples of ΔB=1 corelations

$S_{\eta' K_S} - S_{\psi K_S}$

$A_{CP}(B \to X_s \gamma)$



$\langle A_7(B \to K^* \mu^+ \mu^-) \rangle$

$\langle A_7(B \to K^* \mu^+ \mu^-) \rangle$

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

The best way is s⇔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 tanβ

If MFV with large tanβ, other tree level effects expected

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 lecture

⇒ 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...)