Flavour physics and flavour symmetries

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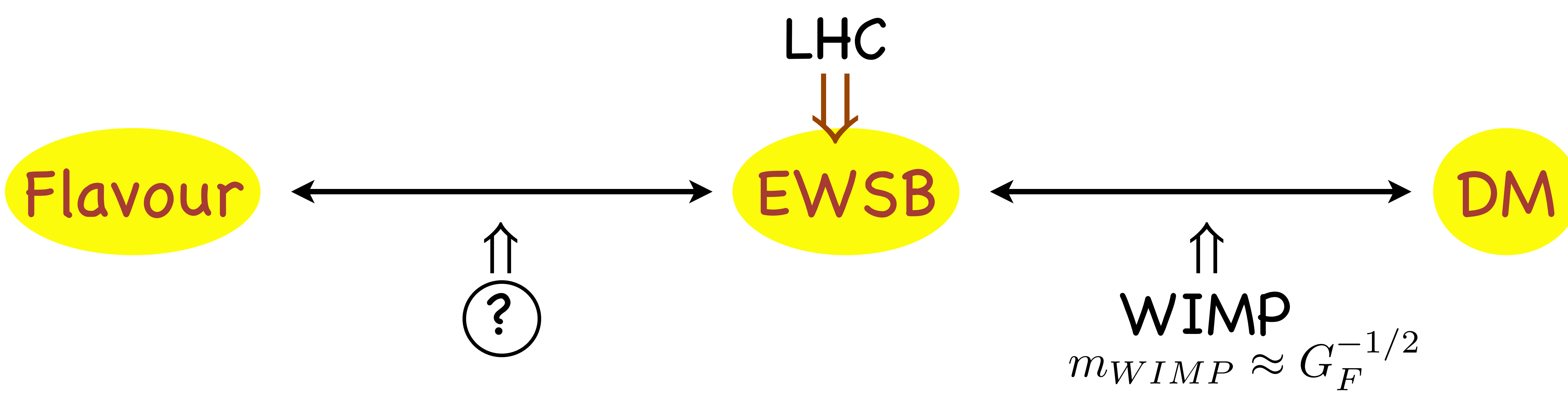
B, Lodone, Isidori, Jones-Perez, Straub
Campli, Sala

(Some of) The problems of particle physics

EWSB: Which physical origin for the Fermi scale?

Flavour: How to explain masses and mixings of SM matter?

Dark Matter: What makes a major part of the universe?



Flavour $\longleftrightarrow$ EWSB

$\Uparrow$

?

1999: "the LEP Paradox"

2001: "the little hierarchy" problem

B, Strumia

While all indirect tests (EWPT, flavour) indicate no new scale below several TeV's, the Higgs boson mass is apparently around the corner and is normally sensitive to any such scale

$$m_h \approx 115\ GeV\left(\frac{\Lambda_{cutoff}}{400\ GeV}\right) \qquad \Lambda_{NP} \gtrsim ?\ TeV$$

$$\Lambda_{NP} \overset{?}{\approx} \Lambda_{cutoff}$$

2011: the problem still there, more than ever

Current flavour constraints

2000÷2010: The CKM picture quantitatively successful

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

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

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

A problem and an opportunity

Some (approximate) flavour symmetry must be operative

Tomassini, Pomarol 1996
B, Dvali, Hall 1996

q_3

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

$q_{1,2}$ $\updownarrow$ U(2)

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

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

only weakly broken along specific minimal directions

$V = (2,1,1)$ $\quad \Gamma_u = (2,\bar{2},1)$ $\quad \Gamma_d = (2,1,\bar{2})$ $\quad$ all $\lesssim \mathcal{O}(\lambda^2)$

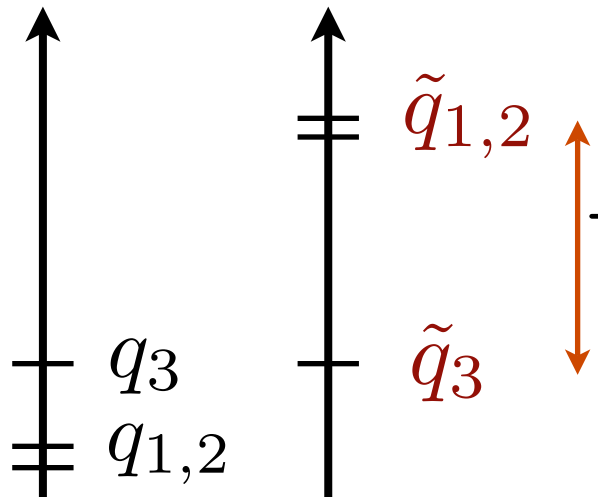
with $\lambda = 0.2254$

(as opposed to MFV: $U(3)_Q \times U(3)_u \times U(3)_d$)

$\Gamma_u = (3,\bar{3},1)$ $\quad \Gamma_d = (3,1,\bar{3})$

A relevant example: supersymmetry

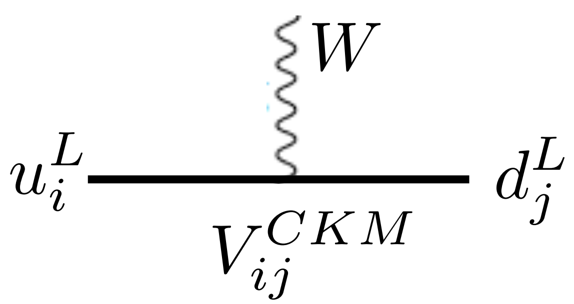
Particle spectrum



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

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

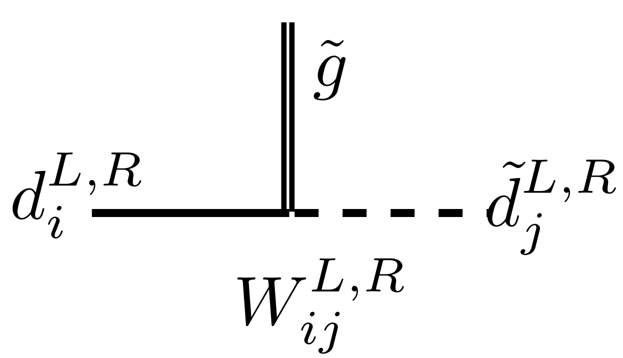
Flavour changing interactions



standard parametrization, in non standard notation

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

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



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

$$W^R \approx \mathbf{1}$$

1 new angle s_L and 1 new phase γ

ΔF = 2 - Our own SM fit

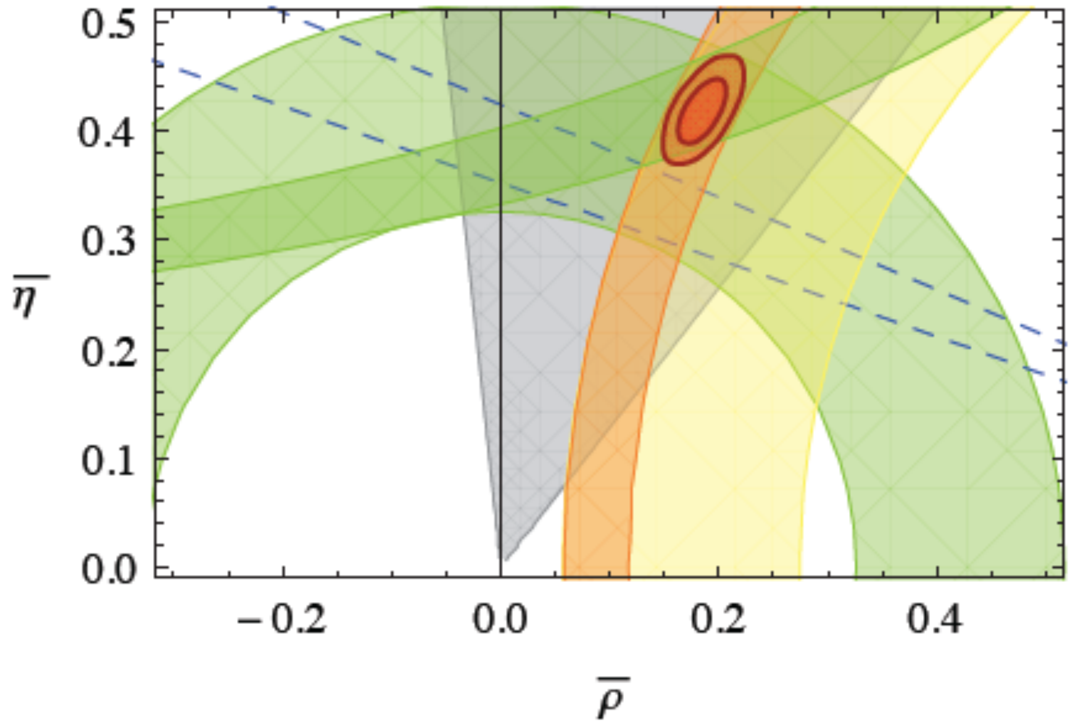
No B_s-input

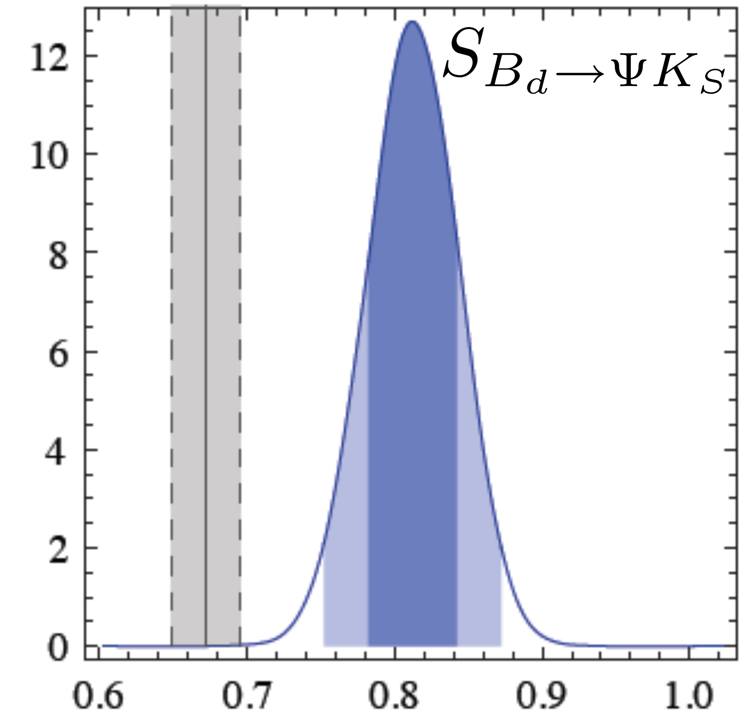
Tree level +

ΔM_d

ΔM_s

ϵ_K



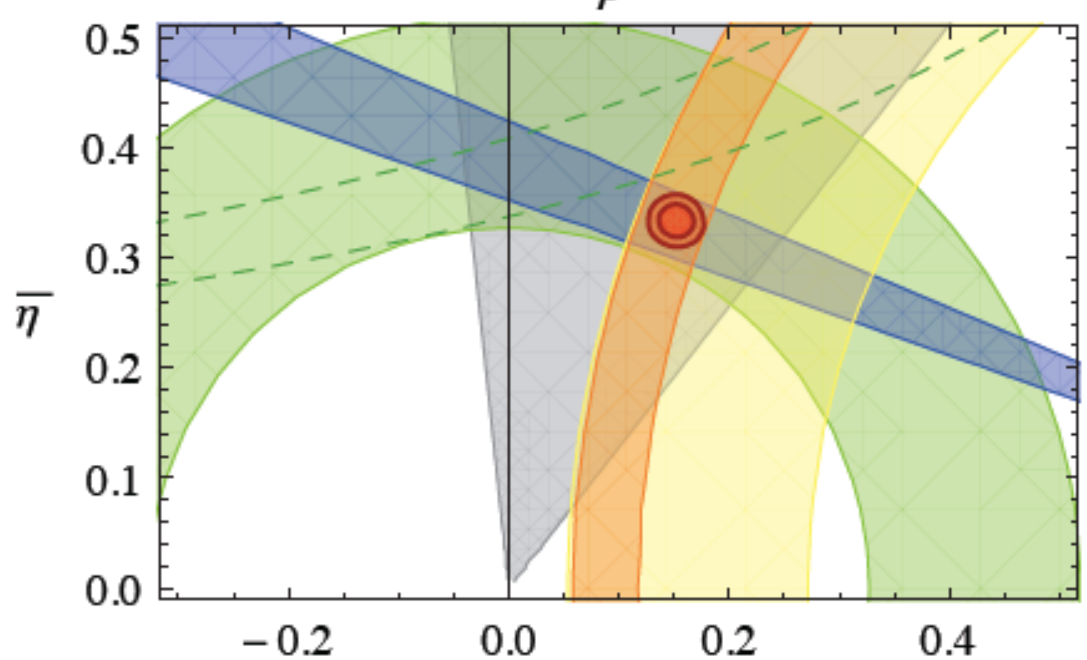


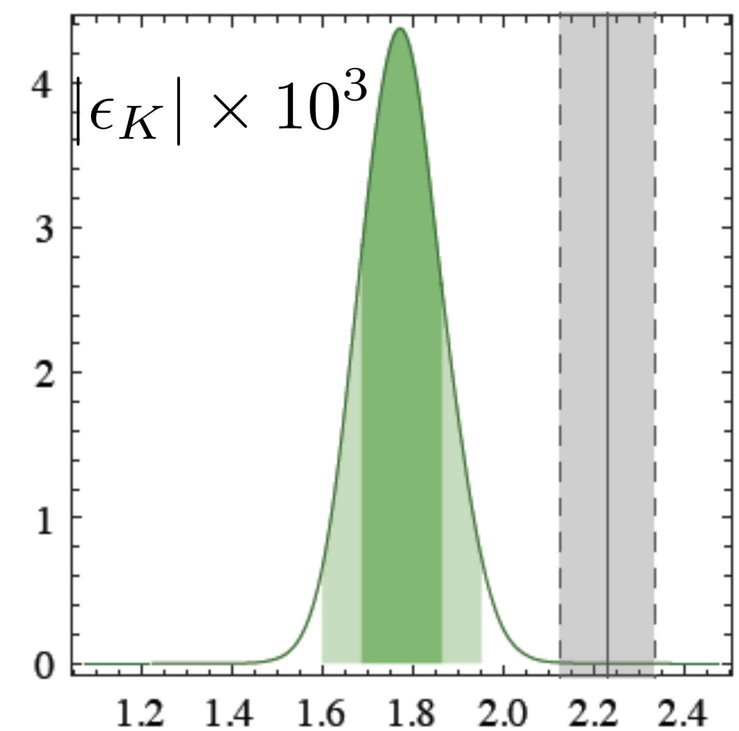
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$



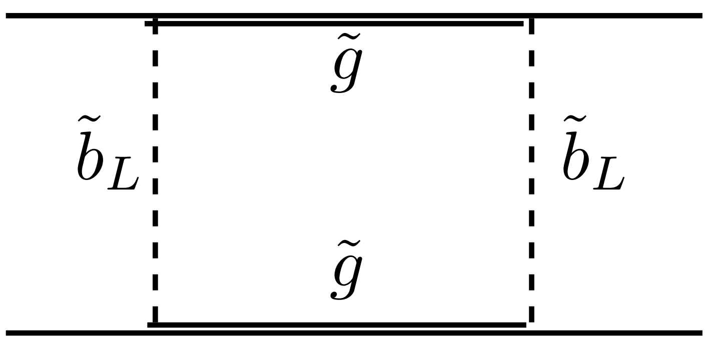


details subject to discussion

a hint of a potential problem for the SM

Supersymmetric fit

including:



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

$$S_{\psi K_S} = \sin\left(2\beta + \arg\left(1 + x F_0 e^{-2i\gamma}\right)\right) \;,$$

$$\Delta M_d = \Delta M_d^{\mathrm{SM}} \times \left|1 + x F_0 e^{-2i\gamma}\right| \;,$$

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

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

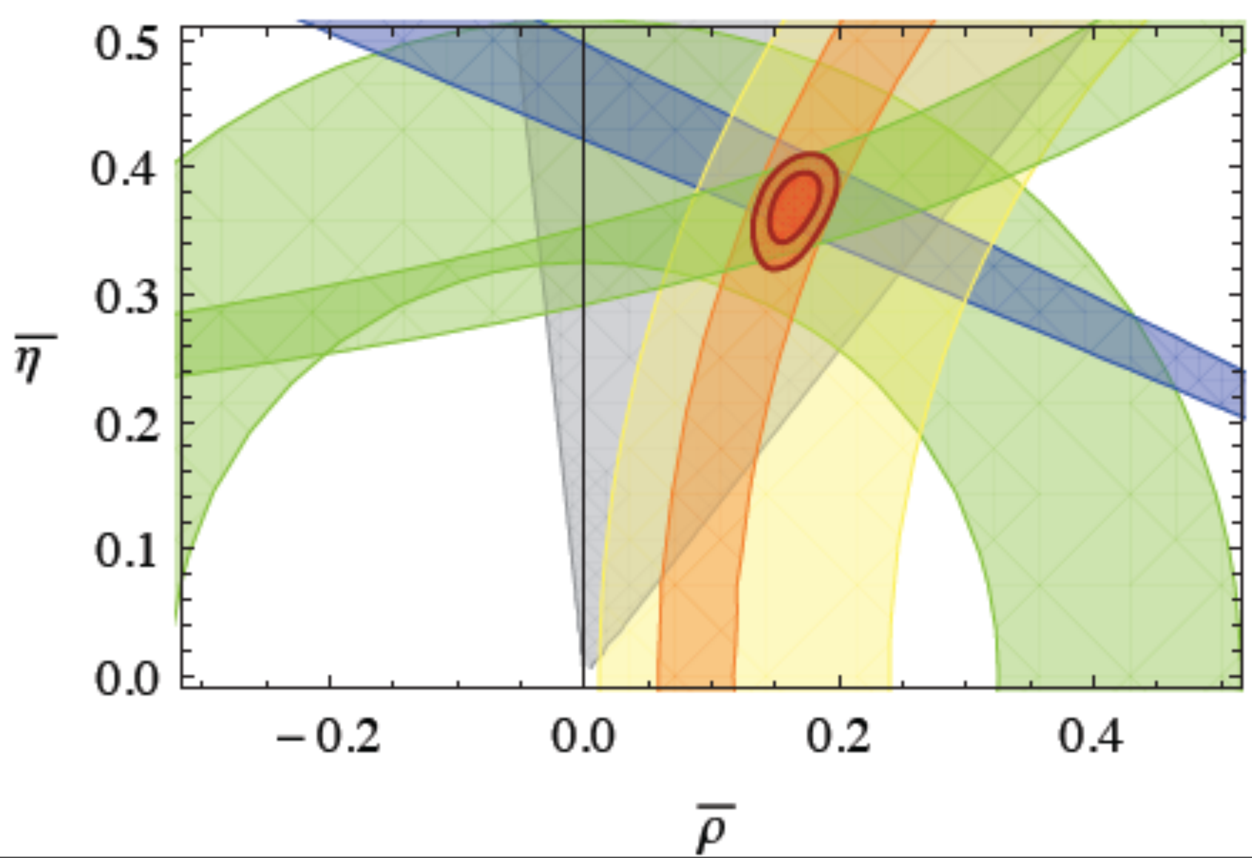
Tree level +

ΔM_d

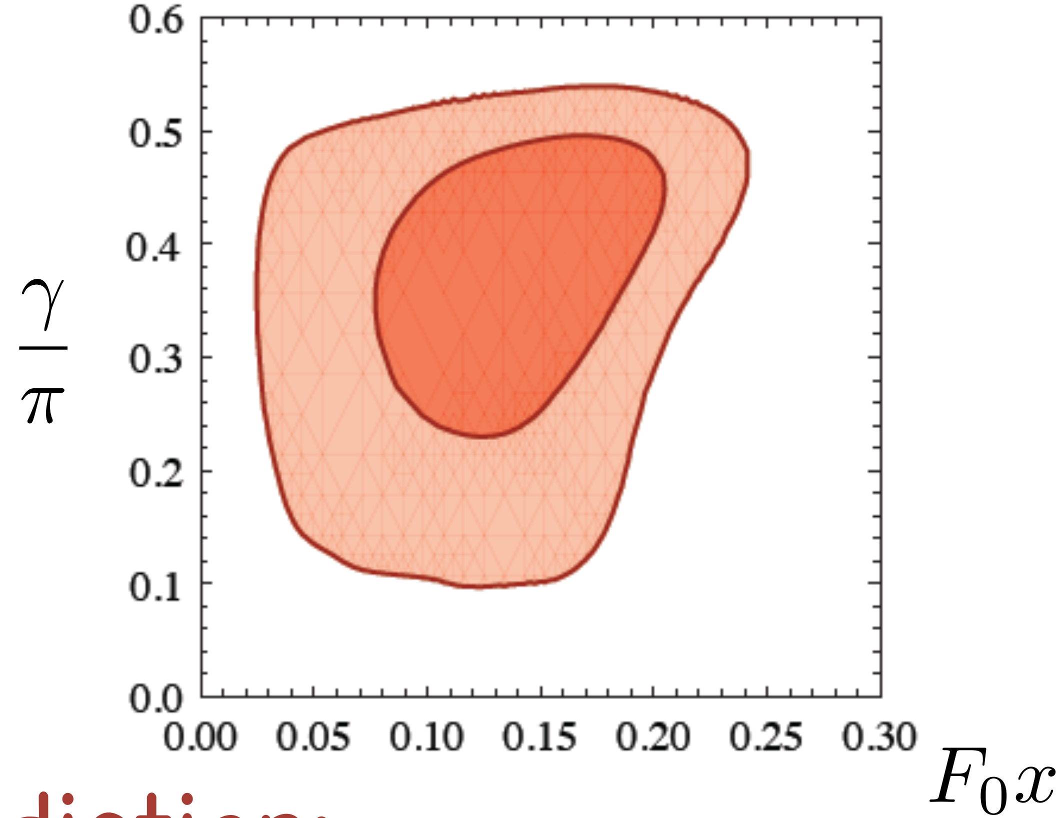
ΔM_s

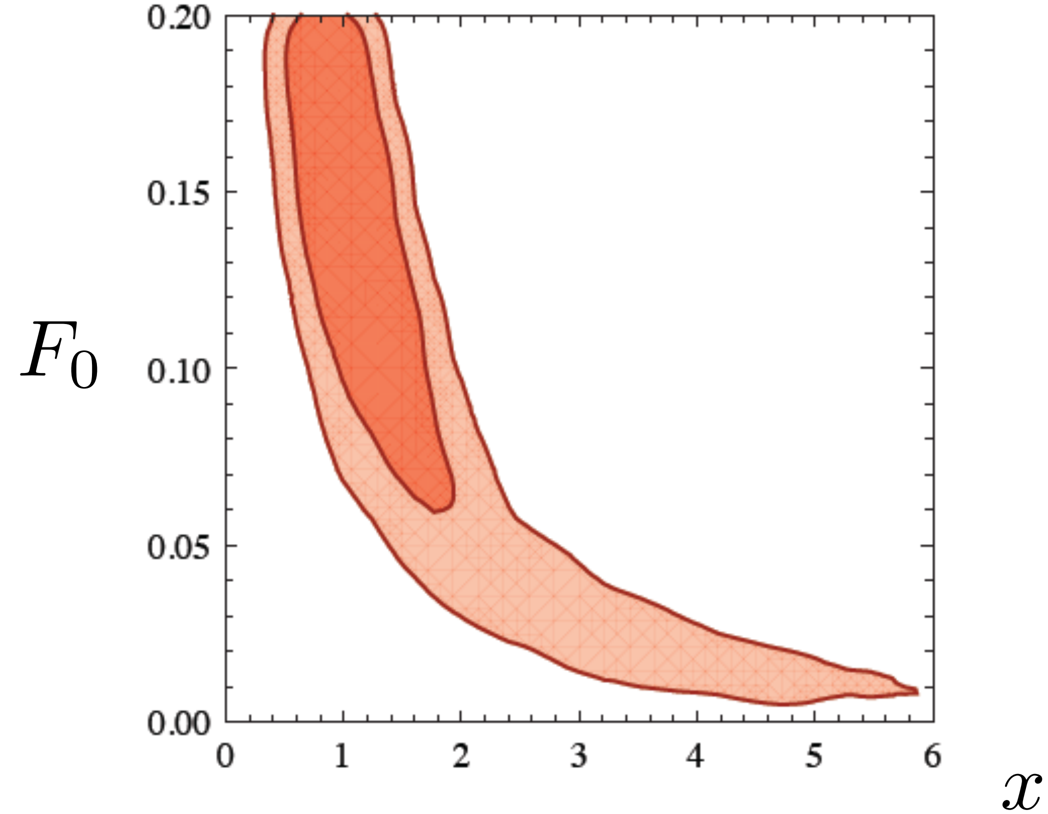
$S_{B_d \to \Psi K_S}$

ϵ_K

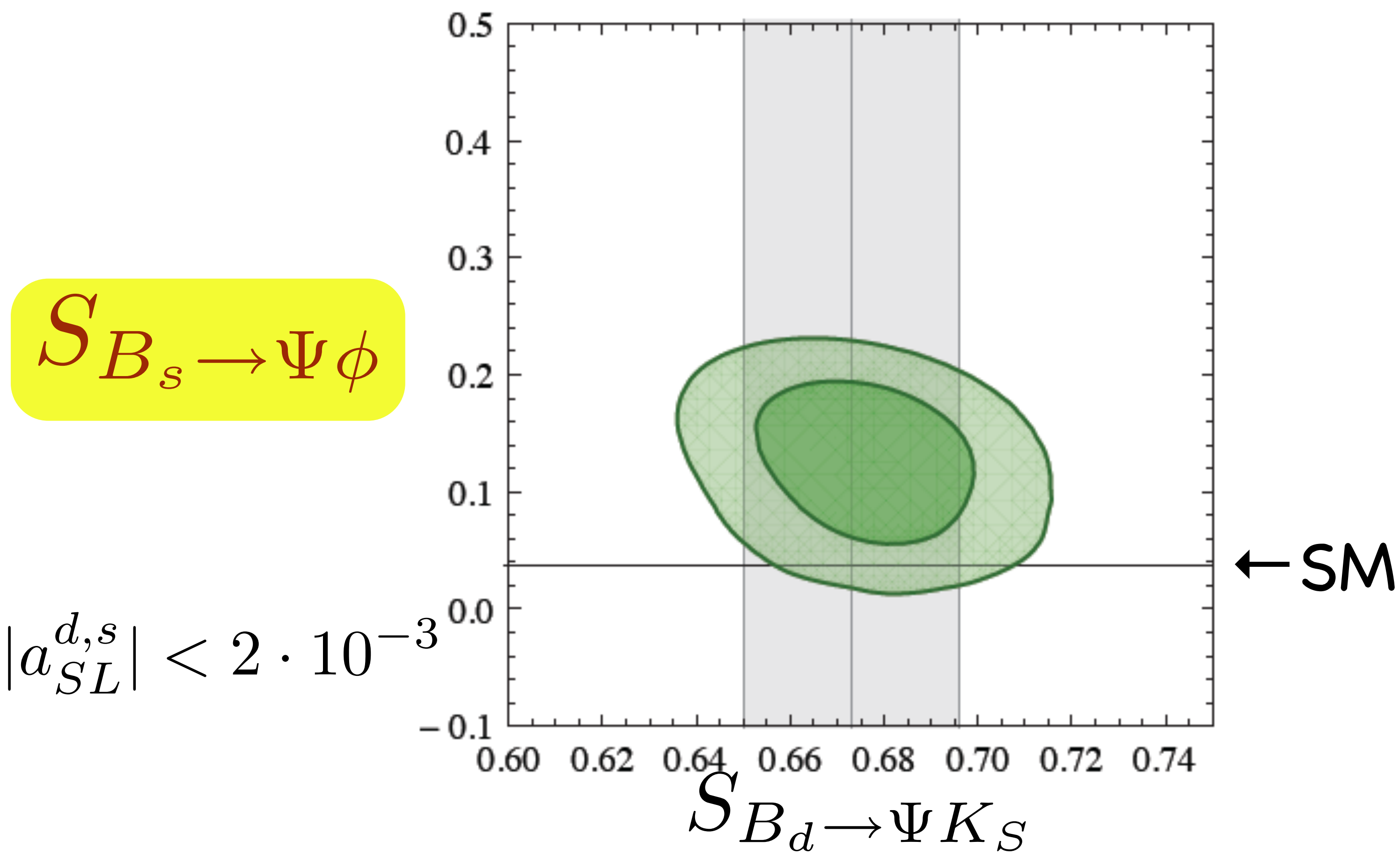


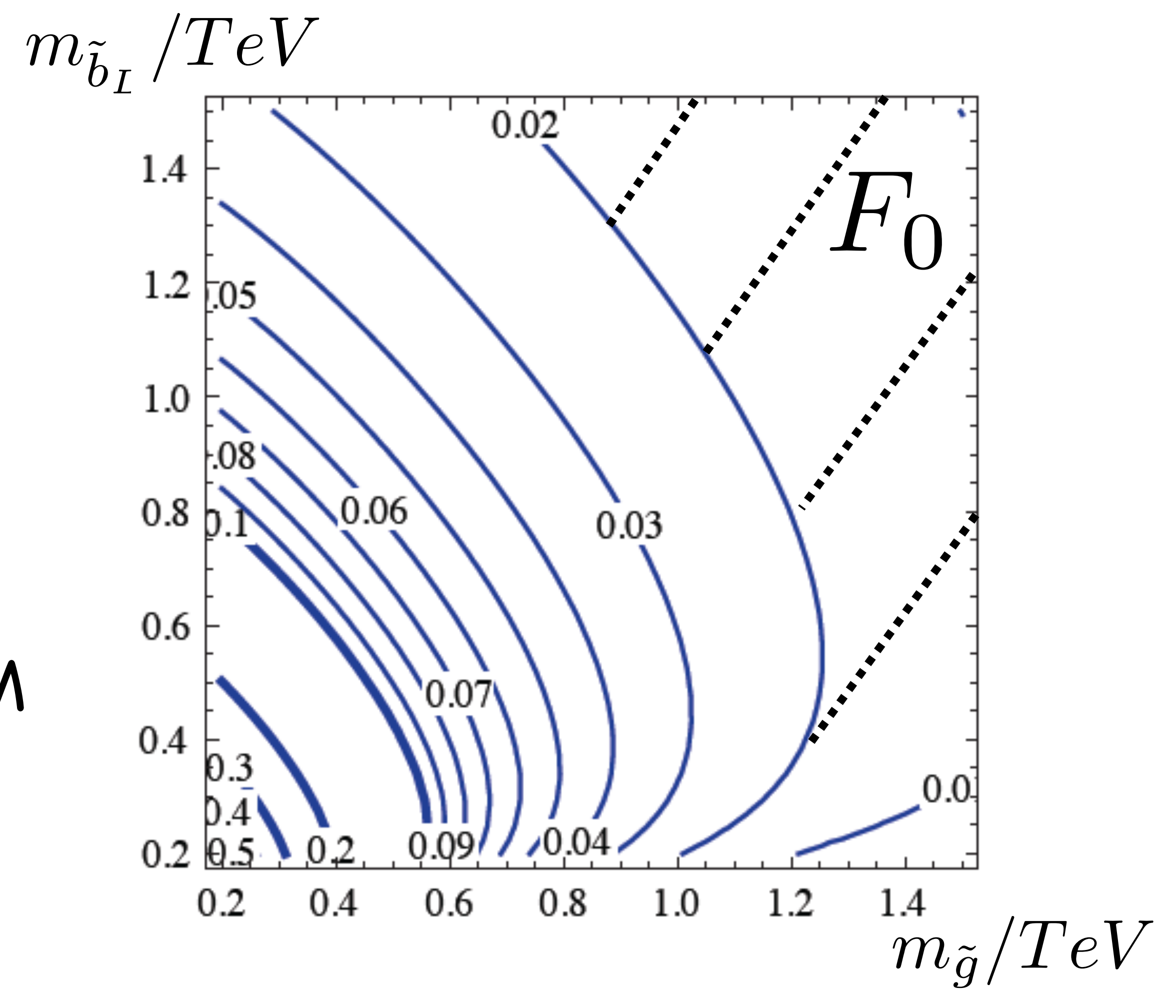
Constraints on extra parameters:





Prediction:



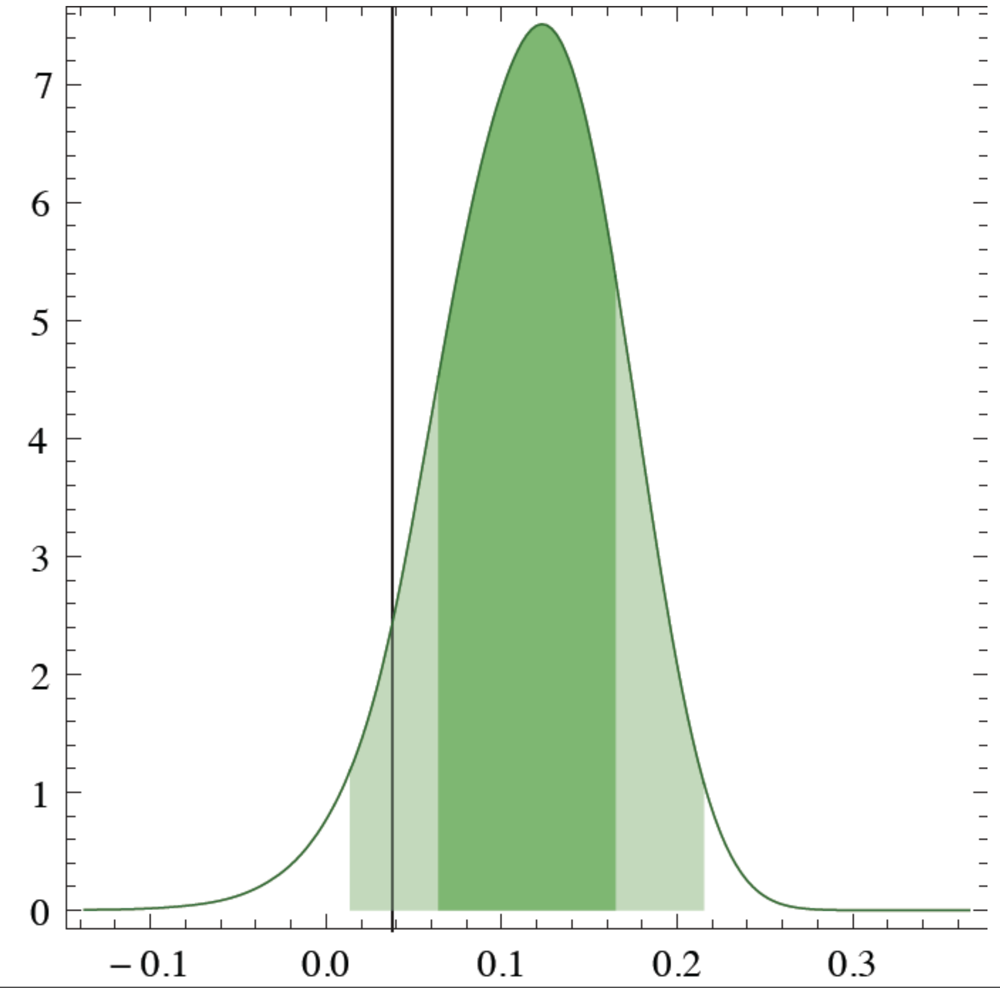


Input data

$\lvert V_{ud}\rvert$	$0.97425(22)$	[14]	f_K	(155.8 ± 1.7) MeV	[15]
$\lvert V_{us}\rvert$	$0.2254(13)$	[16]	$\hat{B}_K$	0.724 ± 0.030	[17]
$\lvert V_{cb}\rvert$	$(40.89 \pm 0.70) \times 10^{-3}$	[13]	κ_ϵ	0.94 ± 0.02	[18]
$\lvert V_{ub}\rvert$	$(3.97 \pm 0.45) \times 10^{-3}$	[19]	$f_{B_s}\sqrt{\hat{B}_s}$	(291 ± 16) MeV	[20]
γ_{CKM}	$(74 \pm 11)^\circ$	[11]	ξ	1.23 ± 0.04	[20]
$\lvert\epsilon_K\rvert$	$(2.229 \pm 0.010) \times 10^{-3}$	[21]			
$S_{\psi K_S}$	0.673 ± 0.023	[22]			
ΔM_d	$(0.507 \pm 0.004)\,\text{ps}^{-1}$	[22]			
ΔM_s	$(17.77 \pm 0.12)\,\text{ps}^{-1}$	[23]			

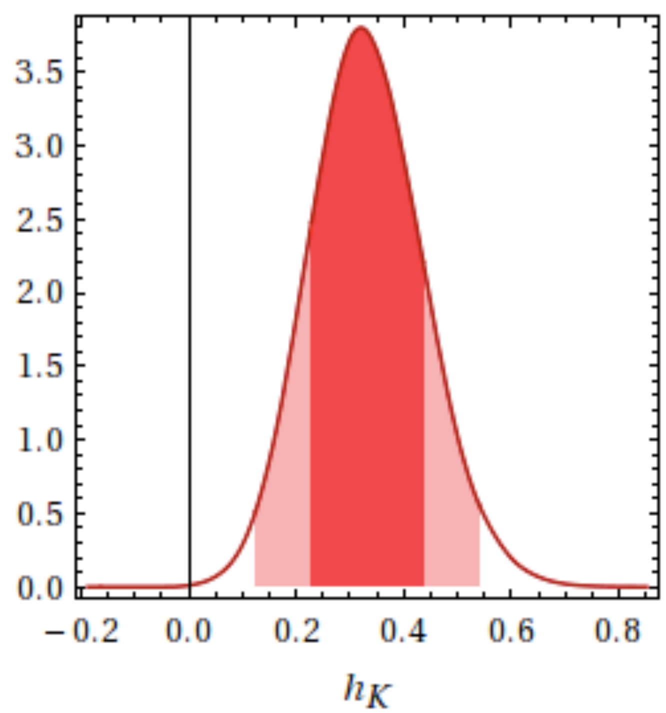
$U(2)^3$ prediction

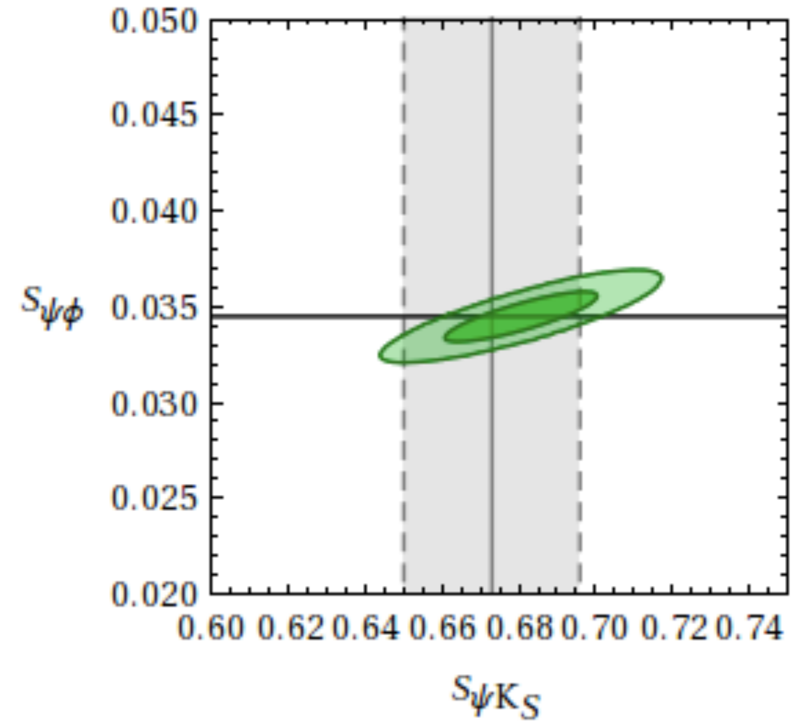
$$S_{B_s \to \Psi\phi} = 0.12 \pm 0.5$$



general $U(2)^3$

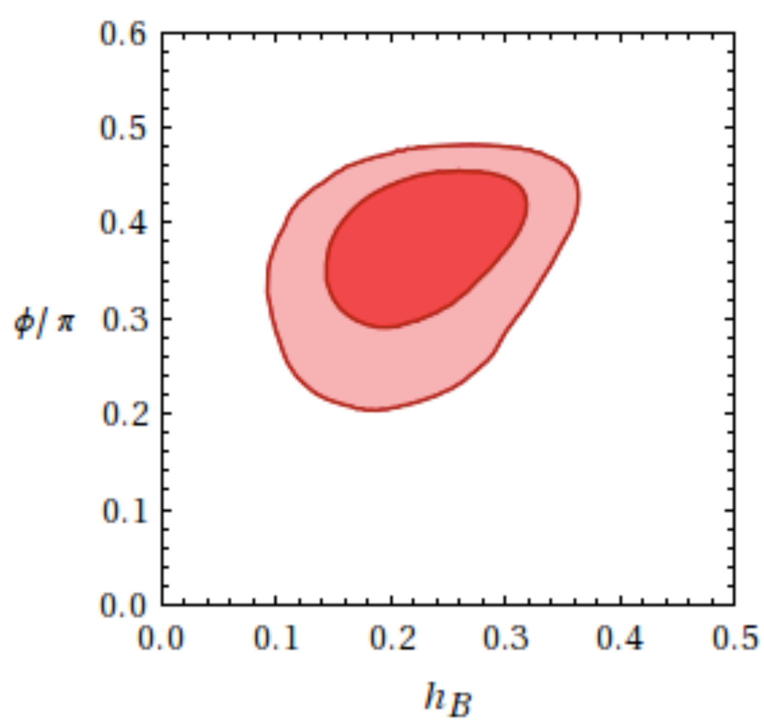
$$\mathcal{M}(K^0 \to \bar{K}^0) = \mathcal{M}^{SM}(K^0 \to \bar{K}^0)(1 + h_K)$$

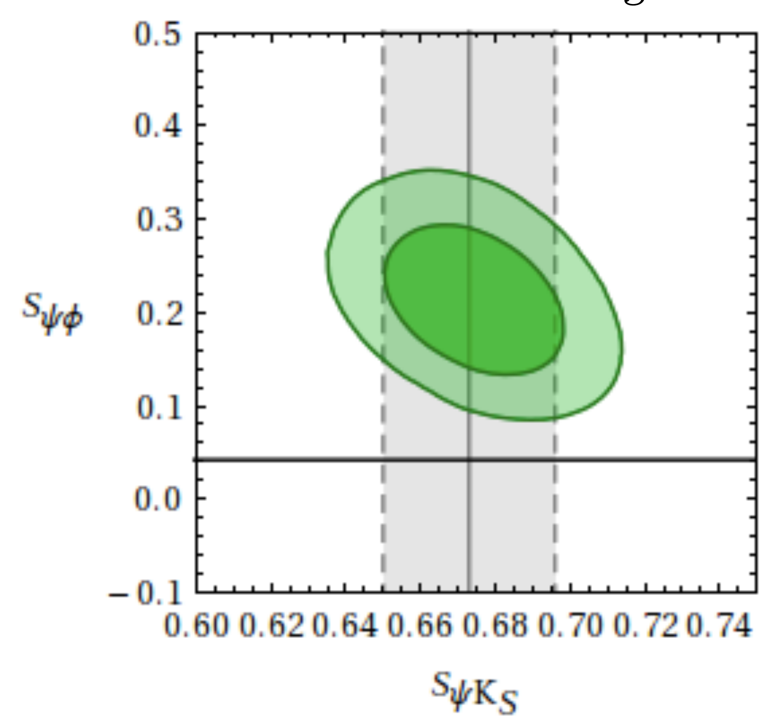




$$\mathcal{M}(B_d \to \bar{B}_d) = \mathcal{M}^{SM}(B_d \to \bar{B}_d)(1 + h_B e^{-2i\gamma})$$

$$\frac{\mathcal{M}_d}{\mathcal{M}_s} = \frac{\mathcal{M}_d^{SM}}{\mathcal{M}_s^{SM}}$$





$\Delta F = 1$ – (under study)

No large effect (for moderate tanβ)
as in $\Delta F=2$

More operators involved

More parameters: $\tan\beta = \frac{m_t}{m_b}\frac{\lambda_b}{\lambda_t},\ m_{H^\pm},\ m_{\tilde{g},\tilde{h}},$
trilinear terms, “flavour-blind” phases

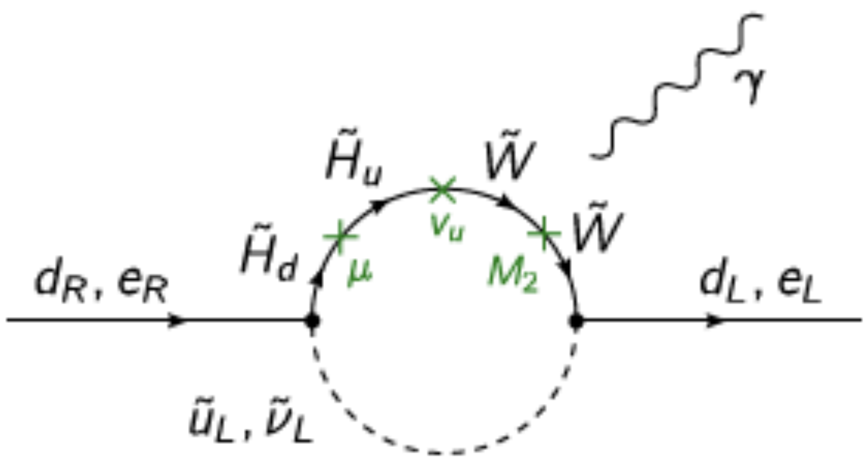
Processes of interest mostly in B-physics

Consider flavour-blind phases as
illustrative example

Electric Dipole Moments with flavour blind phases only

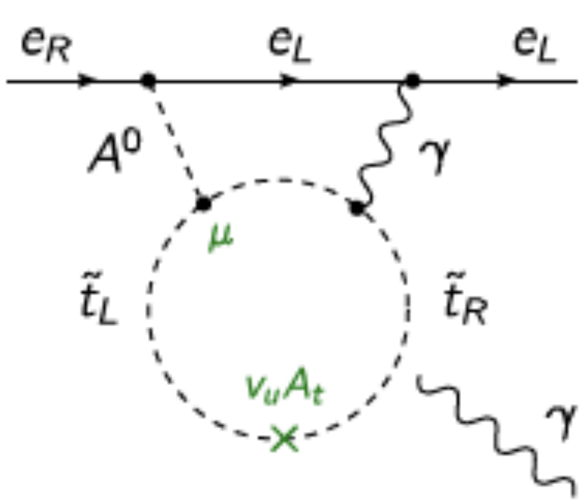
Flavour blind phases lead to contributions to electric dipole moments.

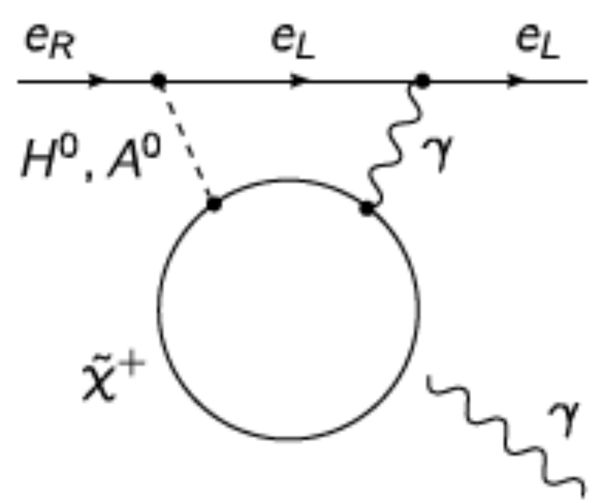
$$\text{Exp.:} \qquad |d_e| < 1.6\times10^{-27}\, e\,\text{cm}\,, \qquad |d_n| < 2.9\times10^{-26}\, e\,\text{cm}$$



1-loop contributions **suppressed** by heavy 1st generation sfermions

$$m_{\tilde{\nu}} > 4.0 \text{ TeV} \;\; \times (\sin\phi_\mu \tan\beta)^{\frac{1}{2}}$$
$$m_{\tilde{u}} > 2.7 \text{ TeV} \;\; \times (\sin\phi_\mu \tan\beta)^{\frac{1}{2}}$$



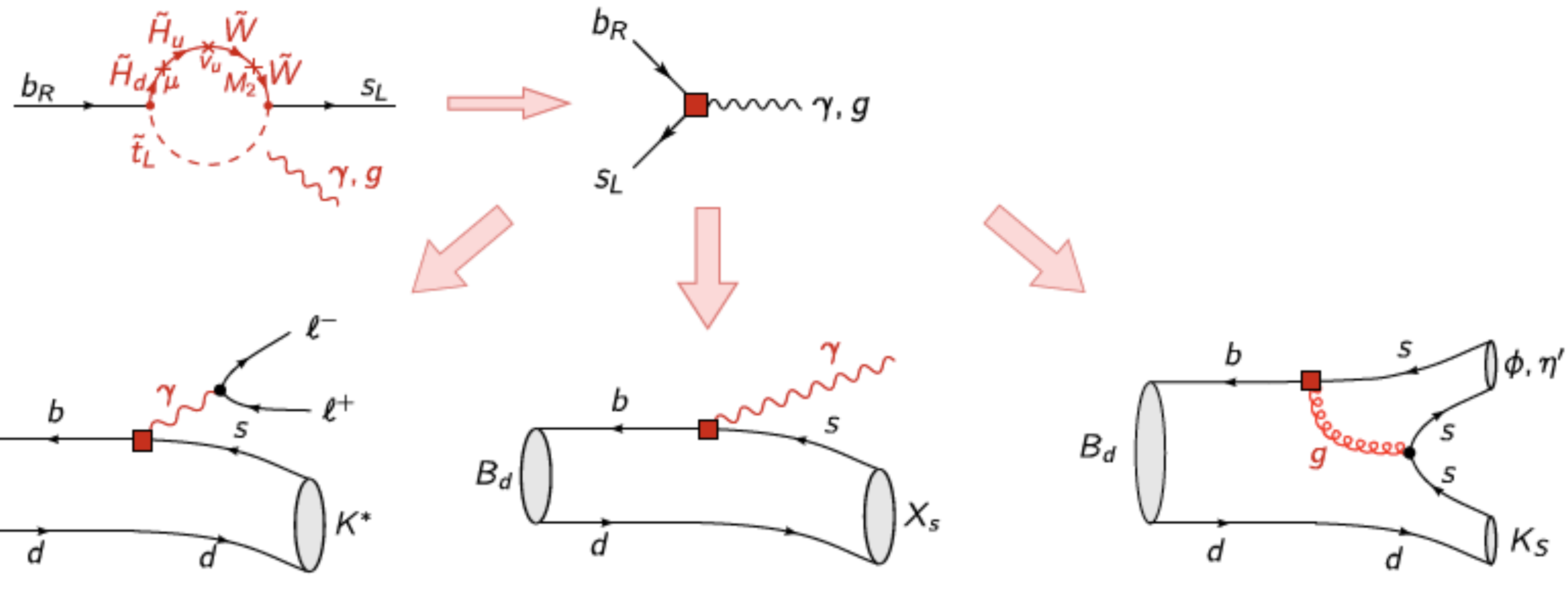


2-loop contributions lead to effects in the ballpark of the experimental bound

CP asymmetries in B-physics

CP violating contributions to dipole operators not suppressed by 1st/2nd generation sfermion masses

e.g.

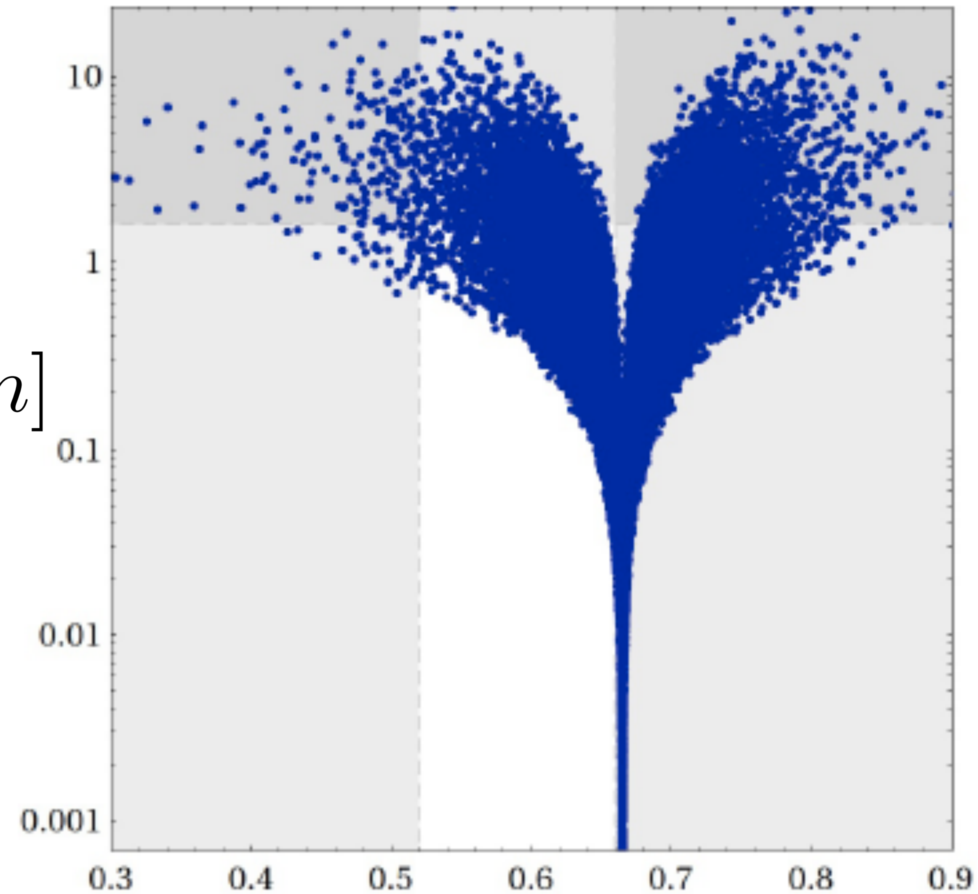


A_7, A_8 in $B \to K^* \ell^+ \ell^-$

Direct CP asymmetry in $B \to X_s \gamma$

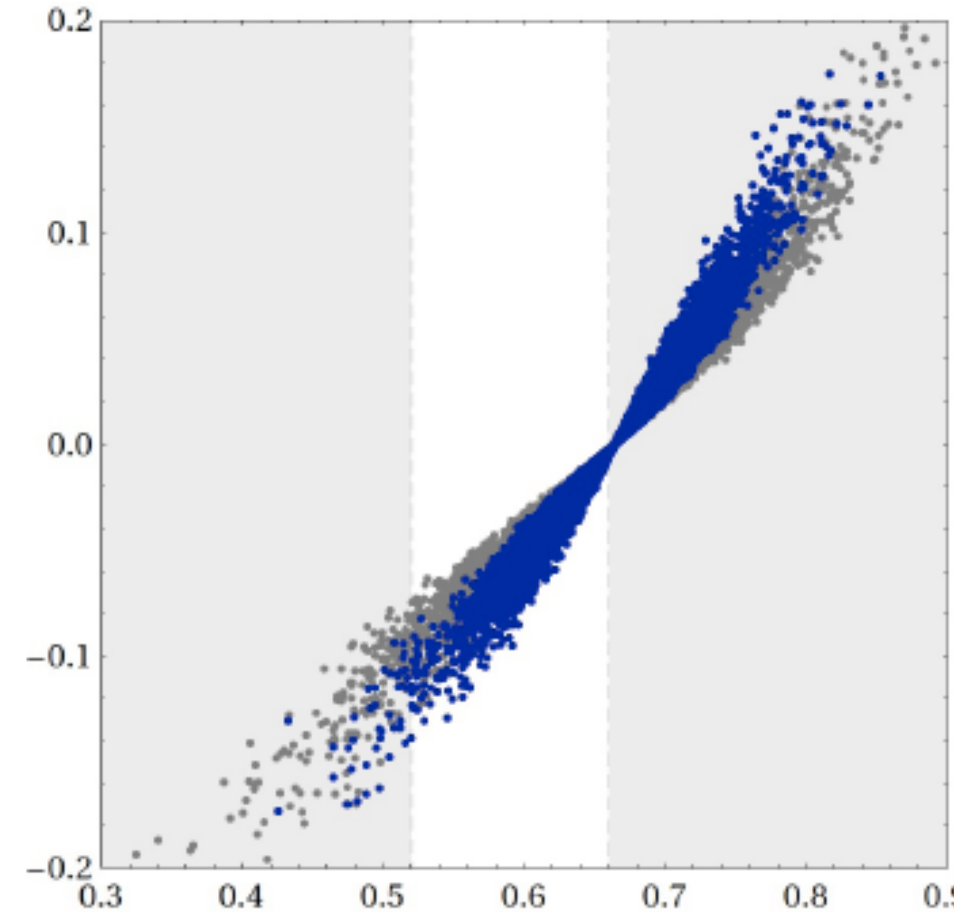
Mixing-induced CP as. in $B \to (\phi, \eta') K_S$

$d_e[10^{-27} e\ cm]$



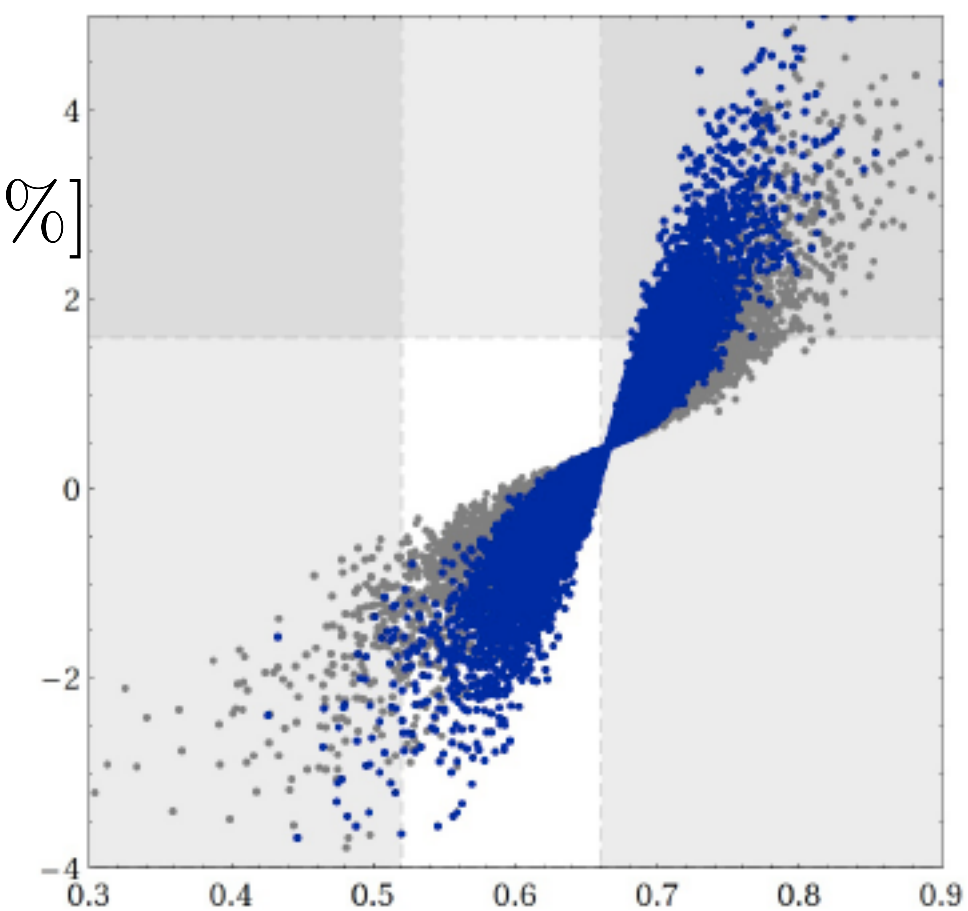
$S_{B_d \to \eta' K_S}$

A_7 in $B \to K^* \ell^+ \ell^-$



$S_{B_d \to \eta' K_S}$

$A_{CP}(b \to s\gamma)[\%]$



Flavour and CPV in charged leptons

A sensible extension of $U(2)^3_q$ to leptons
although with a main unknown $M_{ij}\nu_i^R\nu_j^R$
with no analogue in the quark sector

Educated guesses:

$\mu \to e\gamma$

$$BR(\mu \to e\gamma) \approx 10^{-11\div 14}|\frac{V^l_{\tau\mu}}{V_{ts}}|^2|\frac{V^l_{\tau e}}{V_{td}}|^2$$

$\tau \to \mu\gamma$

$$\frac{BR(\tau \to \mu\gamma)}{BR(\mu \to e\gamma)} \approx |\frac{V^l_{\tau\tau}}{V^l_{\tau e}}|^2 BR(\tau \to \mu\nu\bar{\nu}) \approx 500|\frac{V^l_{\tau\tau}}{V_{tb}}|^2|\frac{V_{td}}{V^l_{\tau e}}|^2$$

d_e

$$d_e \approx \sin\phi\, 10^{-27} e\ cm \sqrt{BR(\mu \to e\gamma)/10^{-12}}$$

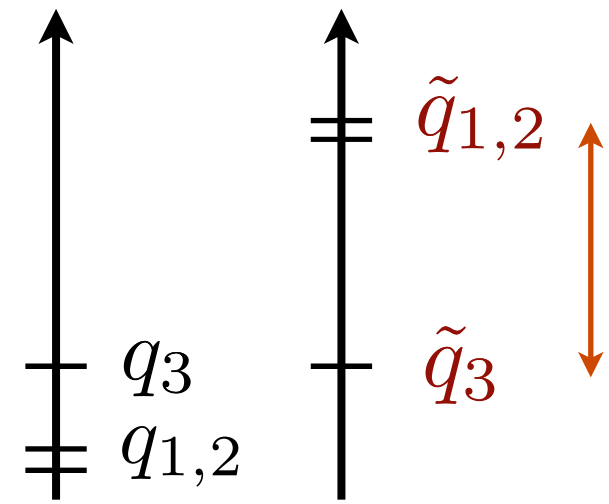
Summary and conclusions

Natural EWSB

Flavour symmetries ⟷ Flavour signals

An approximate U(2): $f_1 \leftrightarrow f_2$ in the quark masses/mixings

Actually: $U(2) \to U(2)_Q \times U(2)_u \times U(2)_d$



From minimal breaking of $U(2)^3$, a definite correlation in ΔF=2

If supersymmetry $S_{B_s \to \Psi\phi} = 0.12 \pm 0.05$ with $m_{\tilde{g}},\ m_{\tilde{b}_L} \lesssim 1 \div 1.5\ TeV$

(SM: 0.041 ± 0.002)

More CPV signals in ΔB=1, EDMs and charged leptons ...

... badly need to understand the origin of flavour breaking at all

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

Taking $c_i = \pm 1$ and considering one operator at a time

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \mathcal{O}/\Lambda^2$$

	operator $\mathcal{O}$	affects	constraint on Λ
	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	μ-decay	10 TeV
	$\frac{1}{2}(\bar{L}\gamma_\mu L)^2$	LEP 2	5 TeV
T→	$\vert H^\dagger D_\mu H\vert^2$	θ_{W} in M_W/M_Z	5 TeV
S→	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	θ_{W} in Z couplings	8 TeV
	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	Z couplings	10 TeV
	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	Z couplings	8 TeV
⇒	$H^\dagger(\bar{D}\lambda_D \lambda_U \lambda_U^\dagger \gamma_{\mu\nu} Q) F^{\mu\nu}$	$b \to s\gamma$	10 TeV
⇒	$\frac{1}{2}(\bar{Q}\lambda_U \lambda_U^\dagger \gamma_\mu Q)^2$	B mixing	10 TeV

1σ-bounds ⊕ a light Higgs

More conservatively: Λ > ~5 TeV