Fine Tuning and the scale of new physics

R. Barbieri
Implications from LHC results for TeV-scale physics
CERN - Aug 29/Sept 12, 2011

⇒ The (many) reactions to the FT problem

⇒ When shall ~~we~~ I give up on SUSY?

⇒ The benchmark SUSY "model"

The Fine Tuning problem of the Fermi scale

1999: "the LEP Paradox" B, Strumia

2001: "the little hierarchy" problem

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,
driving our view about what can/will happen at the LHC

The (many) reactions to the FT problem

0. Ignore it and view the SM in isolation (untenable)

In case you doubted of its relevance:

1. Cure it by symmetries: SUSY, Higgs as PGB, little Higgs
2. A new strong interaction nearby
3. A new strong interaction not so nearby: quasi-CFT
4. Warp space-time: RS
5. Saturate the UV nearby: ADD, classicalons
6. Accept it: the multiverse

Anything else?

When shall I give up on SUSY?

No Higgs boson (LEP)

No s-particle (LEP + TEVATRON + LHC)

Flavour and CPV as in CKM picture (almost?)
(the most important development of the past decade)

A hard and embarrassing question,
but a clearly inescapable one

SUSY still well alive,

since no hard info, yet, on the crucial configuration

The key equations:

$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2 + \dots$$

$$\delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log M/m_{\tilde{t}}$$

$$m_{\tilde{b}_L}$$

$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log M/m_{\tilde{t}}$$

to be made more precise in any given SB-mediation scheme

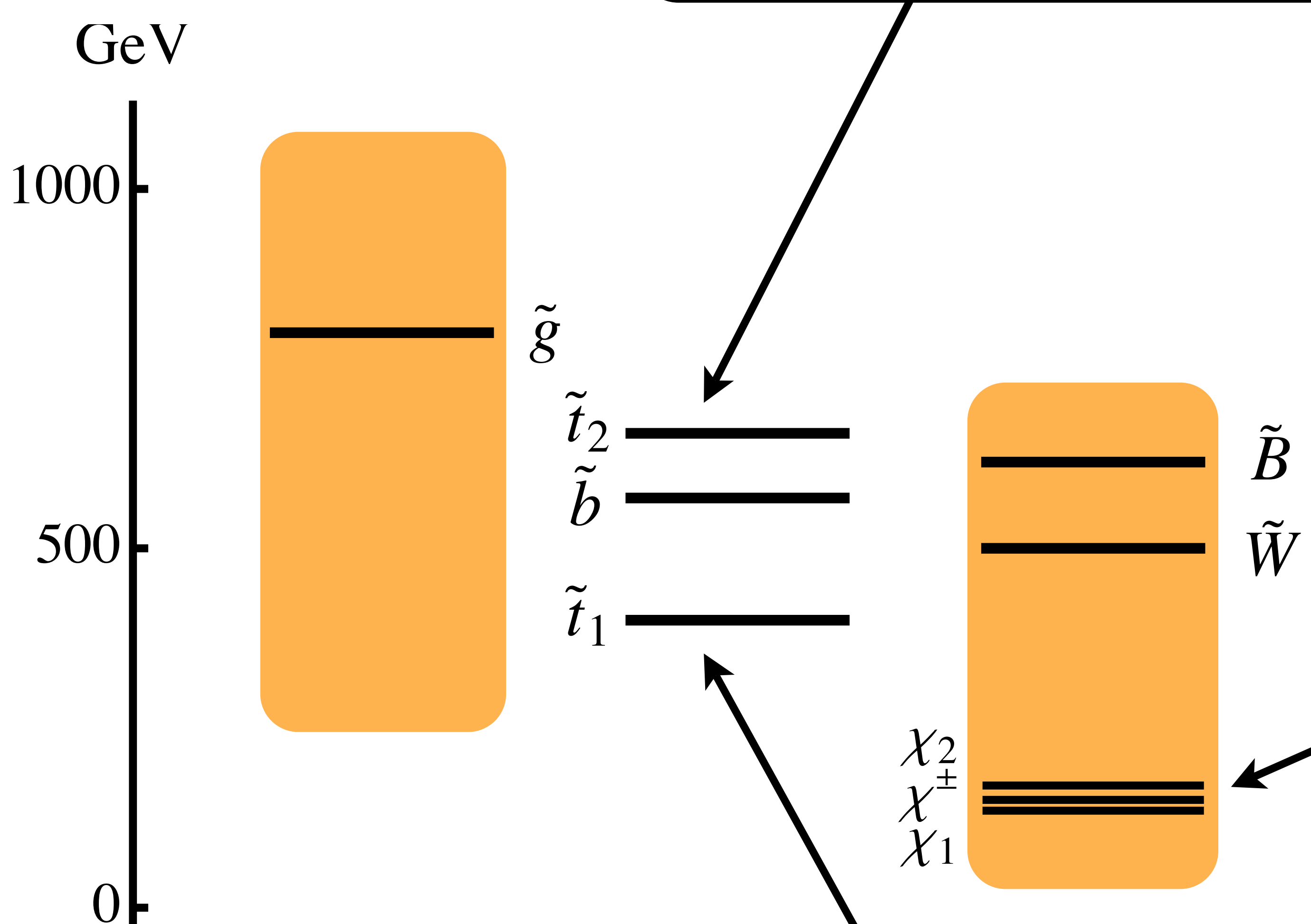
see Dimopoulos, Giudice for SUGRA-mediation

The crucial configuration

"s-particles" at their naturalness limit

B, Pappadopulo

$\tilde{t}_1, \tilde{t}_2, \tilde{b}_L$ ⇔ strongest coupling to the Higgs system



(μ ⇔ M_Z at tree level)

$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ heavy enough (≥ $\tilde{g}$) to be ~ irrelevant

(where the s-leptons are almost doesn't matter)

A synthetic description of the LHC phenomenology

3 semi-inclusive decays (up to < few % in any case)

direct or by cascade

$\tilde{g} \to t\bar{t}\chi$ $\tilde{g} \to t\bar{b}\chi^-(\bar{t}b\chi^+)$ $\tilde{g} \to b\bar{b}\chi$

IF $\mu < M_1, M_2$ then

forget cascades inside χ's $b\bar{b}$ almost irrelevant

$\Rightarrow$ 4 semi-inclusive final states

$$\begin{aligned}
pp &\to \tilde{g}\tilde{g} \to tt\bar{t}\bar{t} + \chi\chi \\
pp &\to \tilde{g}\tilde{g} \to tt\bar{t}\bar{b}(\bar{t}\bar{t}tb) + \chi\chi \\
pp &\to \tilde{g}\tilde{g} \to tt\bar{b}\bar{b}(\bar{t}\bar{t}bb) + \chi\chi \\
pp &\to \tilde{g}\tilde{g} \to t\bar{t}b\bar{b} + \chi\chi
\end{aligned}$$

$$\chi = \chi^\pm, \chi_1, \chi_2$$

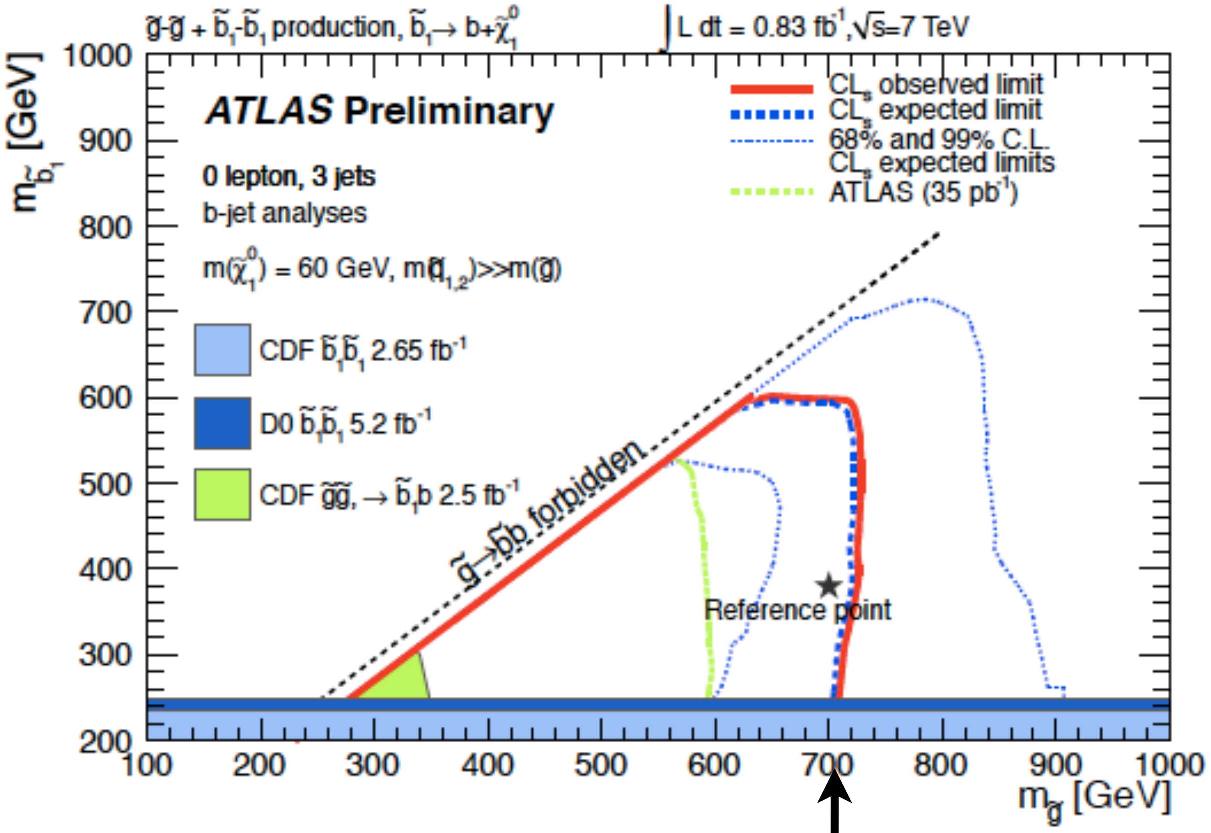
with rates determined by a single BR

$$B_{tb} \equiv BR(\tilde{g} \to t\bar{b}\chi^-) = BR(\tilde{g} \to \bar{t}b\chi^+) \approx \frac{1}{2}(1 - BR(\tilde{g} \to t\bar{t}\chi))$$

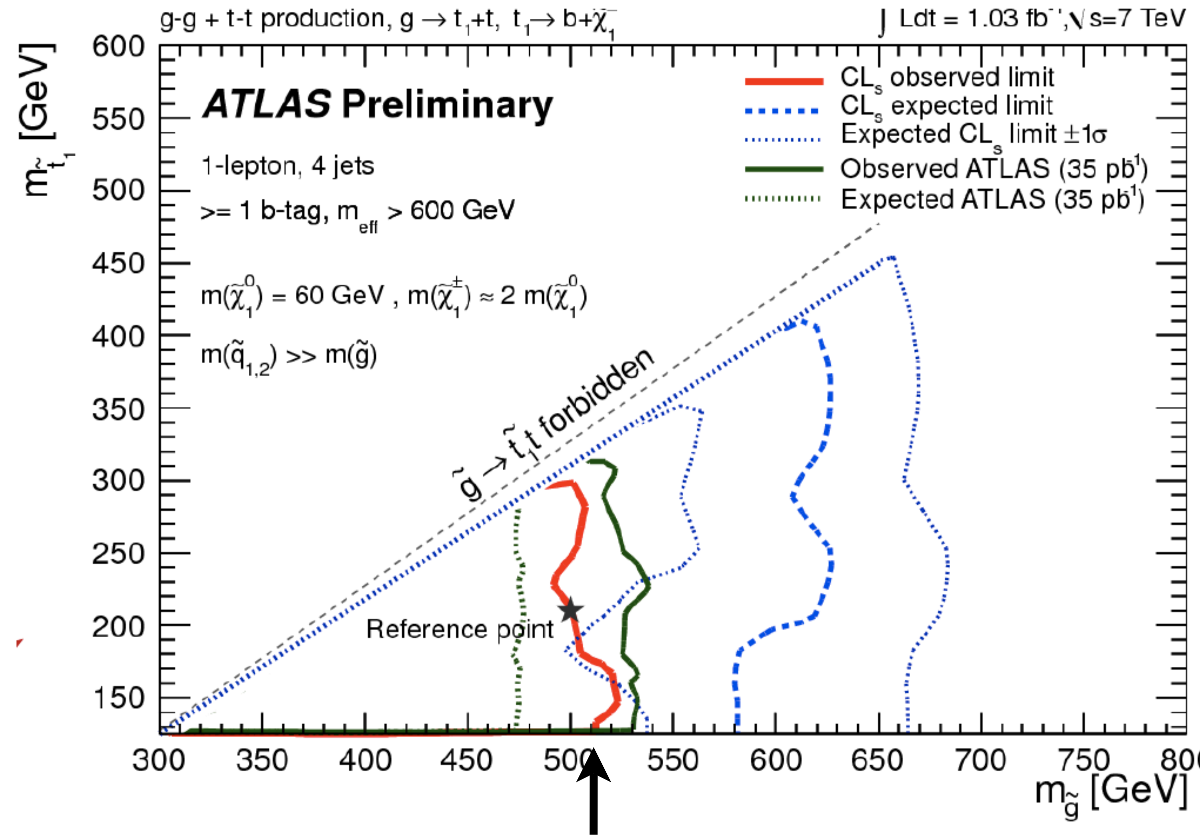
(Kim: $\chi \to \tilde{G} + Z$)

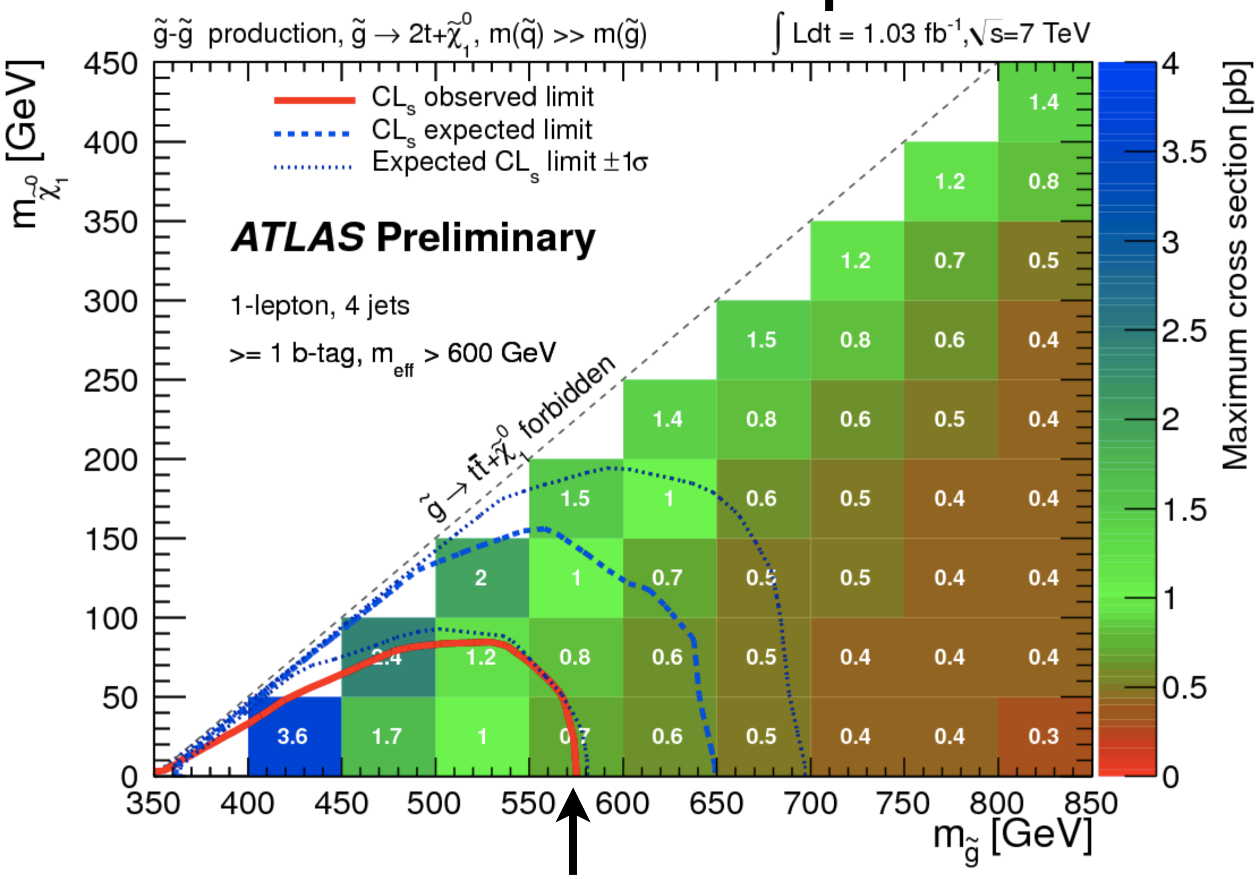
current bounds on $\tilde{g}, \tilde{t}, \tilde{b}$

$$\tilde{g} \rightarrow b\tilde{b} \rightarrow b\bar{b} + \chi$$



$$\tilde{g} \rightarrow t\tilde{t} \rightarrow t\bar{b} + \chi^-$$





$$\tilde{g} \rightarrow t\tilde{t} \rightarrow t\bar{t} + \chi$$

$$m_{\tilde{g}} \gtrsim 500\ GeV$$

$$m_{\tilde{t}} > ? \qquad m_{\tilde{b}} \gtrsim 200\ GeV$$

Is there a decent model behind this picture?

A "minimalistic" attitude:

1. $$\mathcal{L}_{SUSY\,break} = m_Q^2(\mathbf{1} + aY_uY_u^+) + m_u^2(\mathbf{1} + bY_u^+Y_u) + \ldots$$

can produce the 1-2/3 splitting and gives MFV

2. $$\Delta f = \lambda S H_u H_d$$

as a way to raise the Higgs boson mass

How heavy (and how visible) the Higgs can be crucially depends on λ

$\lambda \lesssim 0.7$ to keep manifest perturbativity up to M_{GUT}

$$m_h \lesssim 130 \div 140\ GeV$$

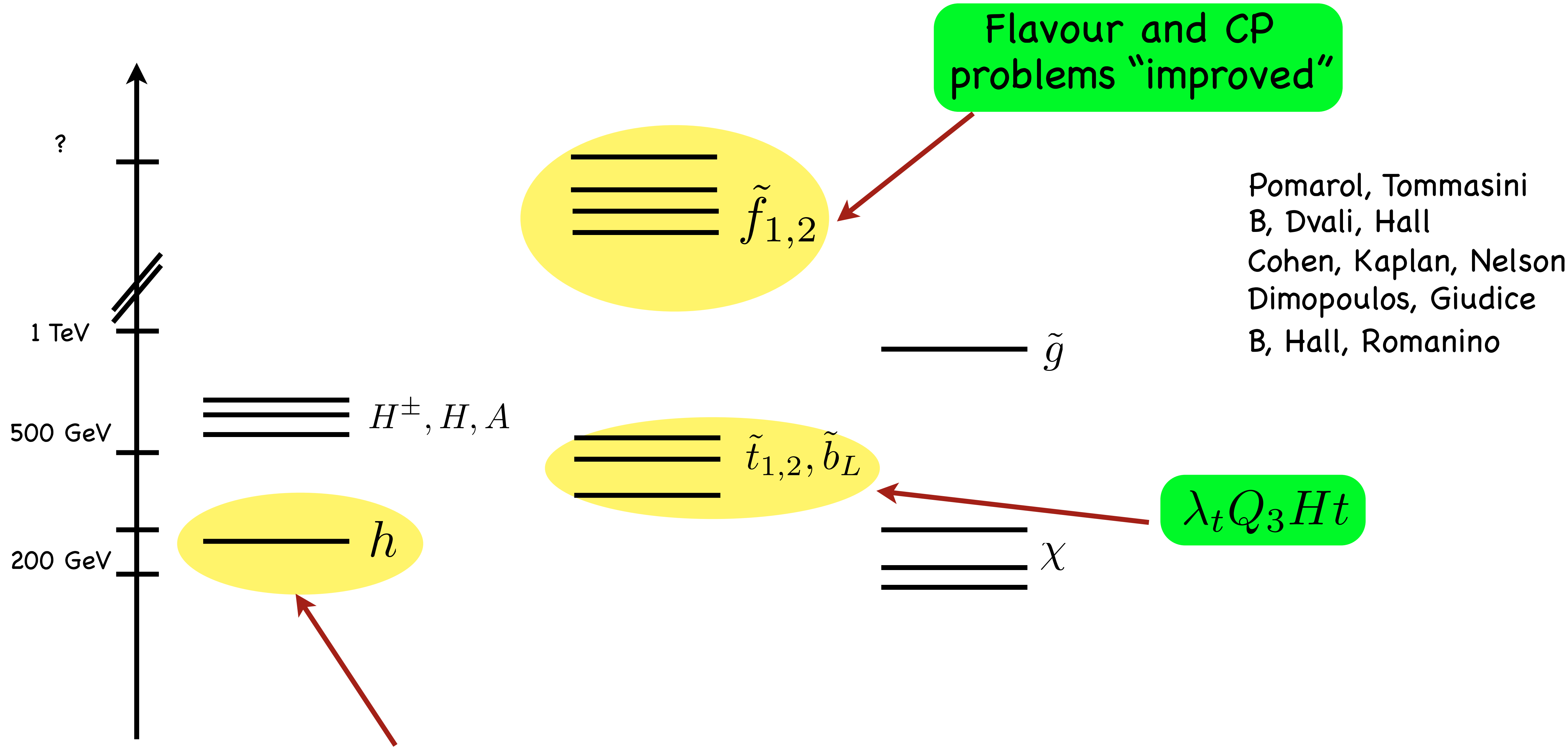
$\lambda \lesssim 2$ to preserve the EWPT

$$m_h \lesssim 250\ GeV$$

A "more ambitious" approach:

See my talk of last week

Two issues (logically almost independent)

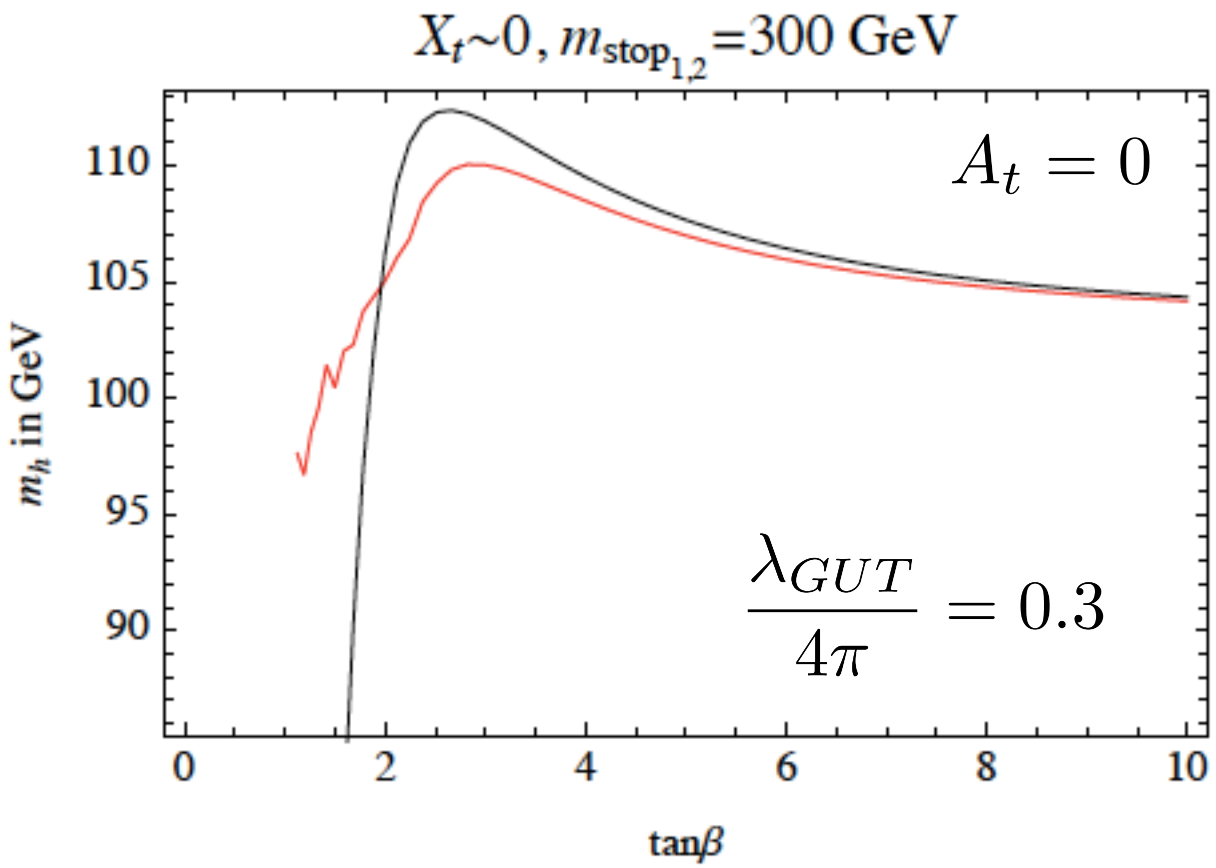


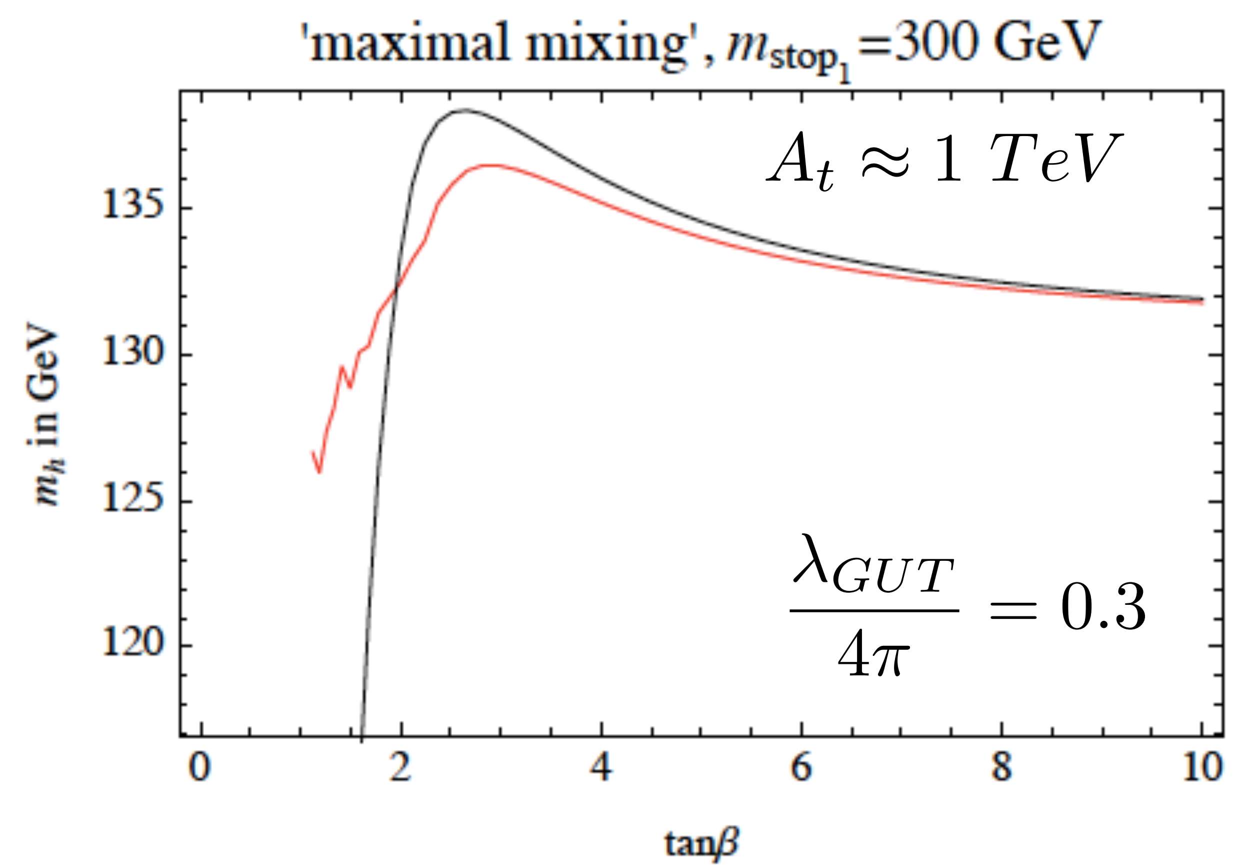
$\Leftrightarrow$

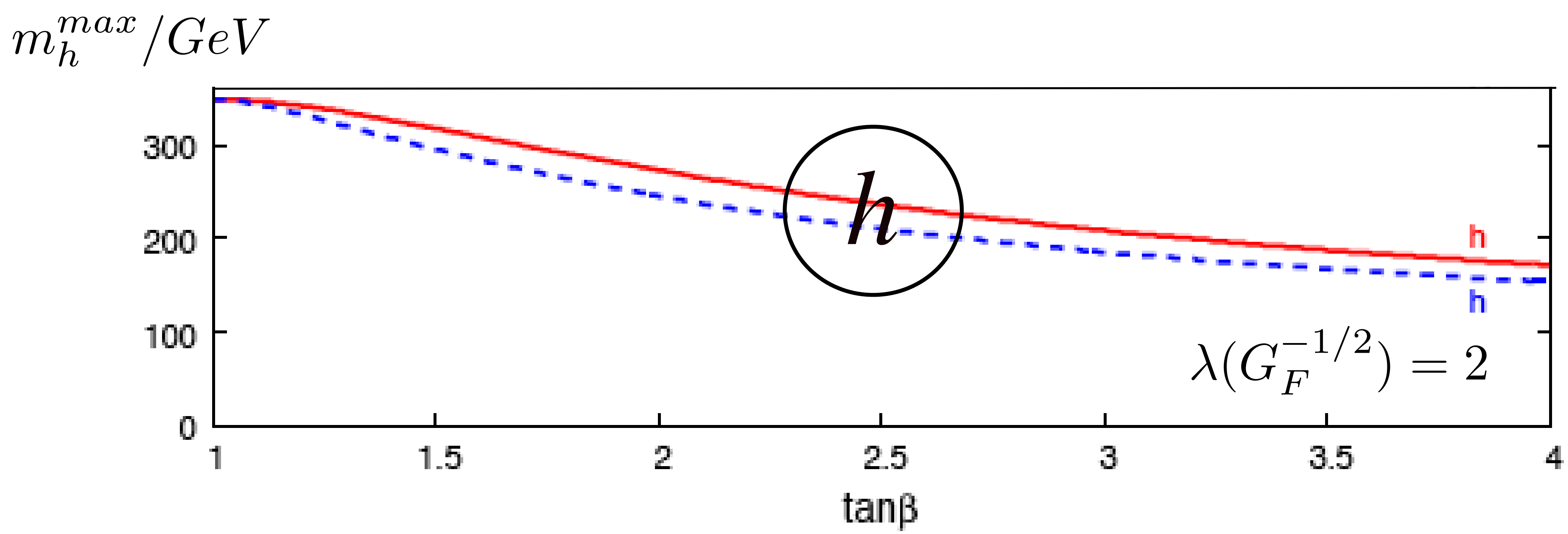
$$m_h \to a m_h \quad \Rightarrow \quad \begin{array}{c} m_s^{max} \to a m_s^{max} \\ 1/\Delta \to a^2 1/\Delta \end{array}$$

B, Hall, Nomura, Rychkov

Maximal Higgs boson mass with $\Delta f = \lambda S H_u H_d$

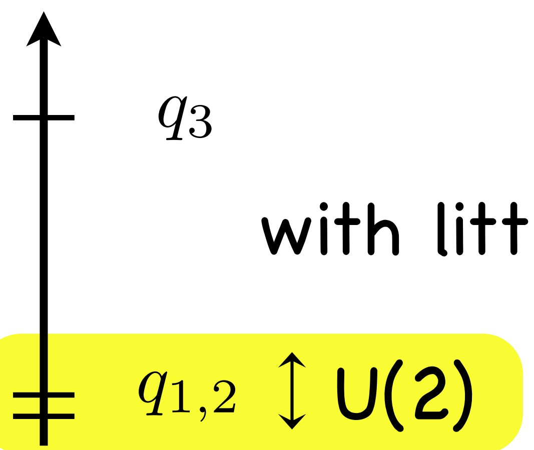






U(2) in the data on quark masses and mixings

Tomassini, Pomarol 1996
B, Dvali, Hall 1996



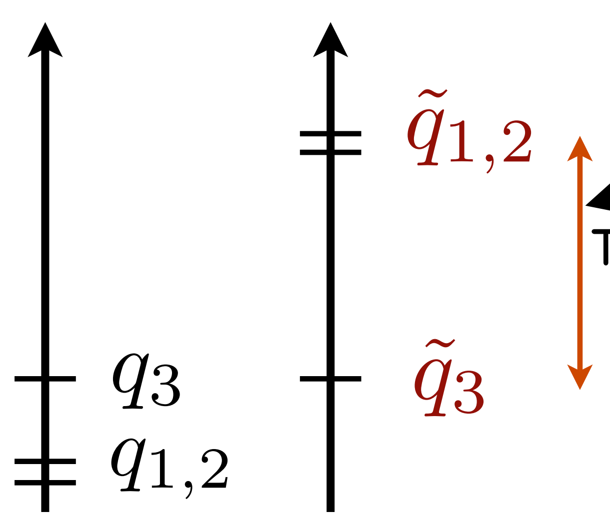
with little communication between $q_{1,2}$ and q_3

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

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

and perhaps also in the SUSY non-data

flavour, EDMs, direct s-particle searches



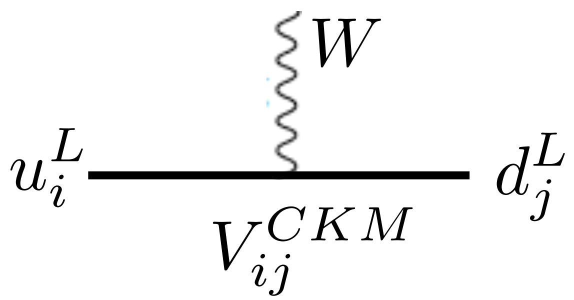
Anomalous U(1), 2-site deconstruction, short-distance effects of λ_t

TeV's, not controlled by symmetry breaking nor by naturalness, to some extent

B, Isidori, Jones-Perez, Lodone, Straub

Consequences of $U(2)^3$

Flavour changing interactions

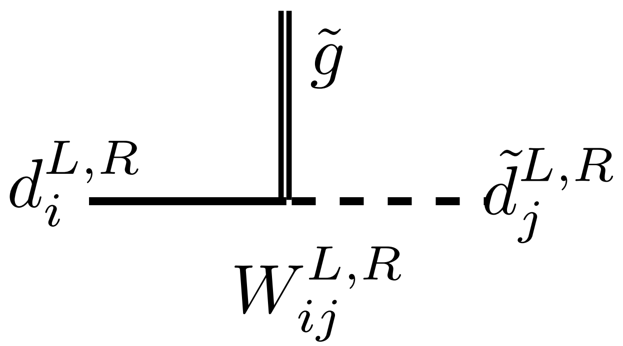


standard, in non standard parametrization

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

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

$s_d = -0.22 \pm 0.01$
$s_u = 0.086 \pm 0.003$
$s = 0.0411 \pm 0.0005$
$\phi = (-97 \pm 9)^\circ$



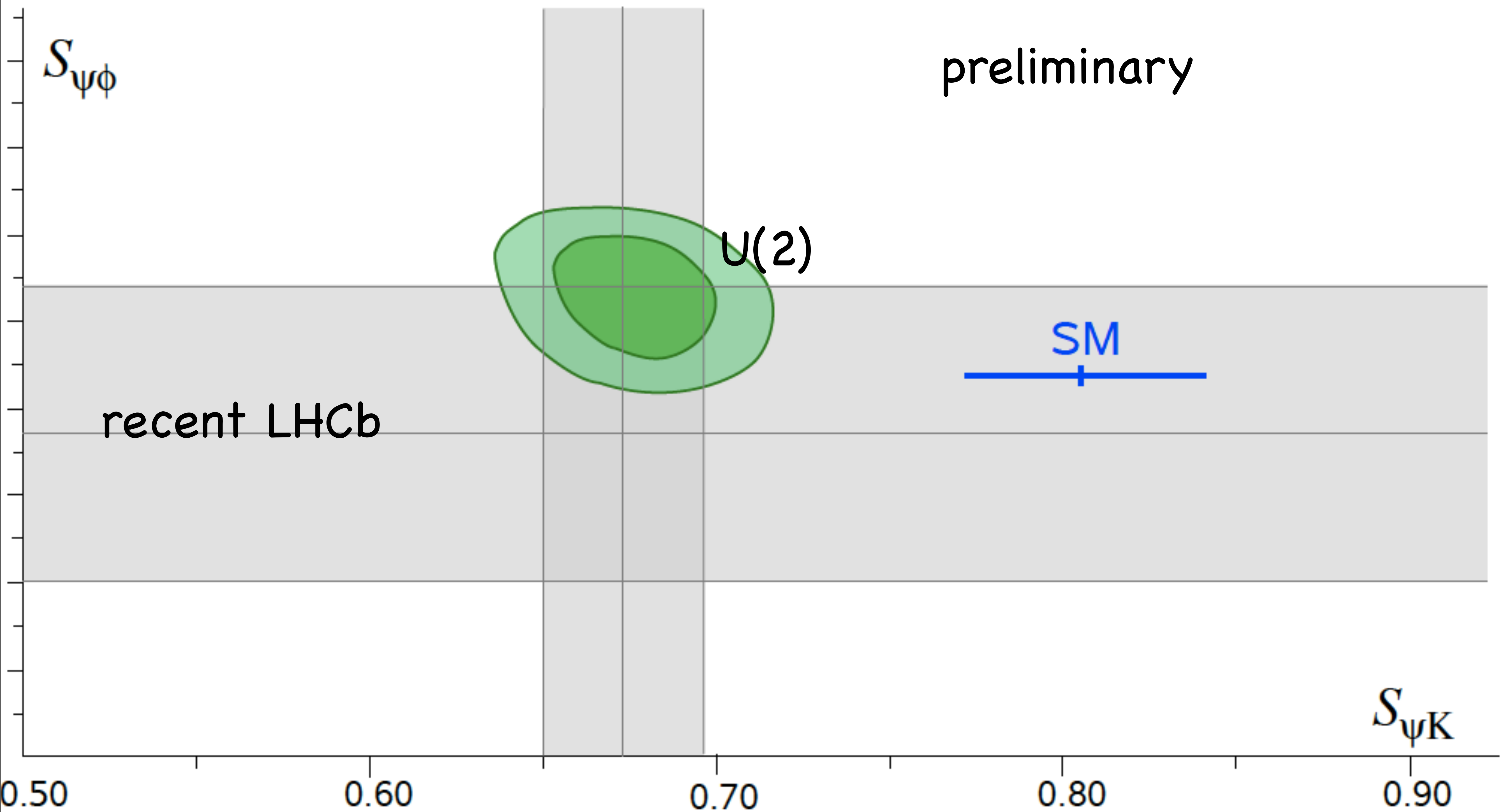
$$W^L = \begin{pmatrix} c_d & s_d e^{-i(\delta+\phi)} & -s_d s_L e^{i\gamma} e^{-i(\delta+\phi)} \\ -s_d e^{i(\delta+\phi)} & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

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

1 new angle s_L and 1 new phase γ

B, Isidori, Jones-Perez, Lodone, Straub

CPV in ΔB = 2



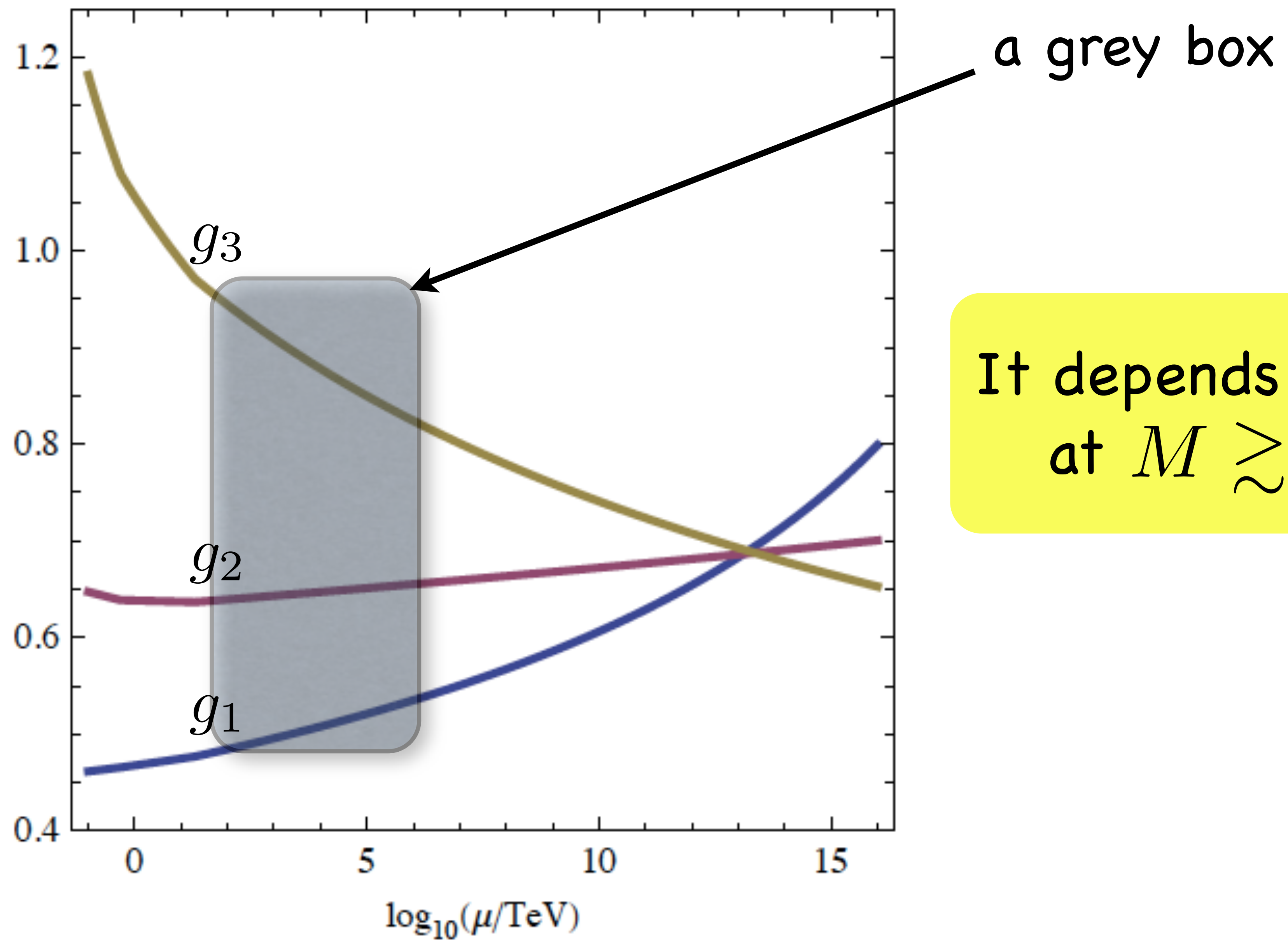
$S_{\psi\phi}$
preliminary
U(2)
SM
recent LHCb
$S_{\psi K}$
0.50
0.60
0.70
0.80
0.90

Phenomenological consequences
(non mSUGRA-like)

- ✶ gluino pair production and decays into top/bottom-rich final states ✓
- ✶ a largely unconventional Higgs sector
  - $h \to WW, ZZ$ (with reduced rate)
  - → $h \to aa \to (b\bar{b},\ \tau\bar{\tau},\ c\bar{c})^2$
  - $h \to \chi_{DM}\chi_{DM}$

  if $\lambda(G_F^{-1/2}) \approx 2$
- ✶ Dark Matter: relic abundance and detection affected
- ✶ Flavour and CPV signals (at low tanβ) ✓

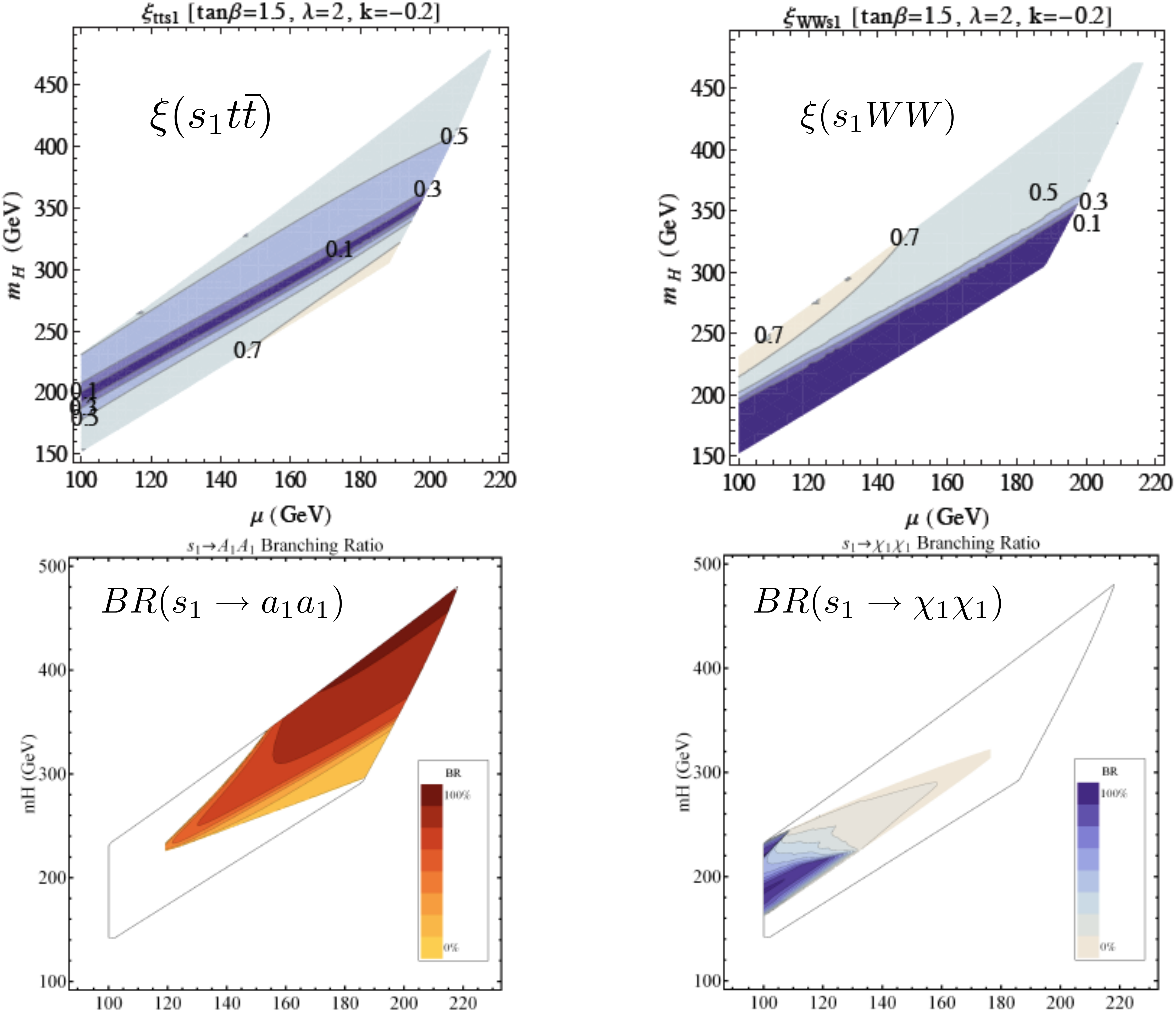
What about gauge-coupling unification if $\lambda \approx 2$?



It depends on what happens at $M \gtrsim 10\ TeV$

We already know of one gauge coupling that crosses the threshold of a strong interaction practically unchanged: α_{em}

If $\Delta f = \lambda S H_u H_d$, then $\lambda \gtrsim 0.8$ should be contemplated



(λSUSY with a R-invariant superpotential) Bertuzzo, Farina

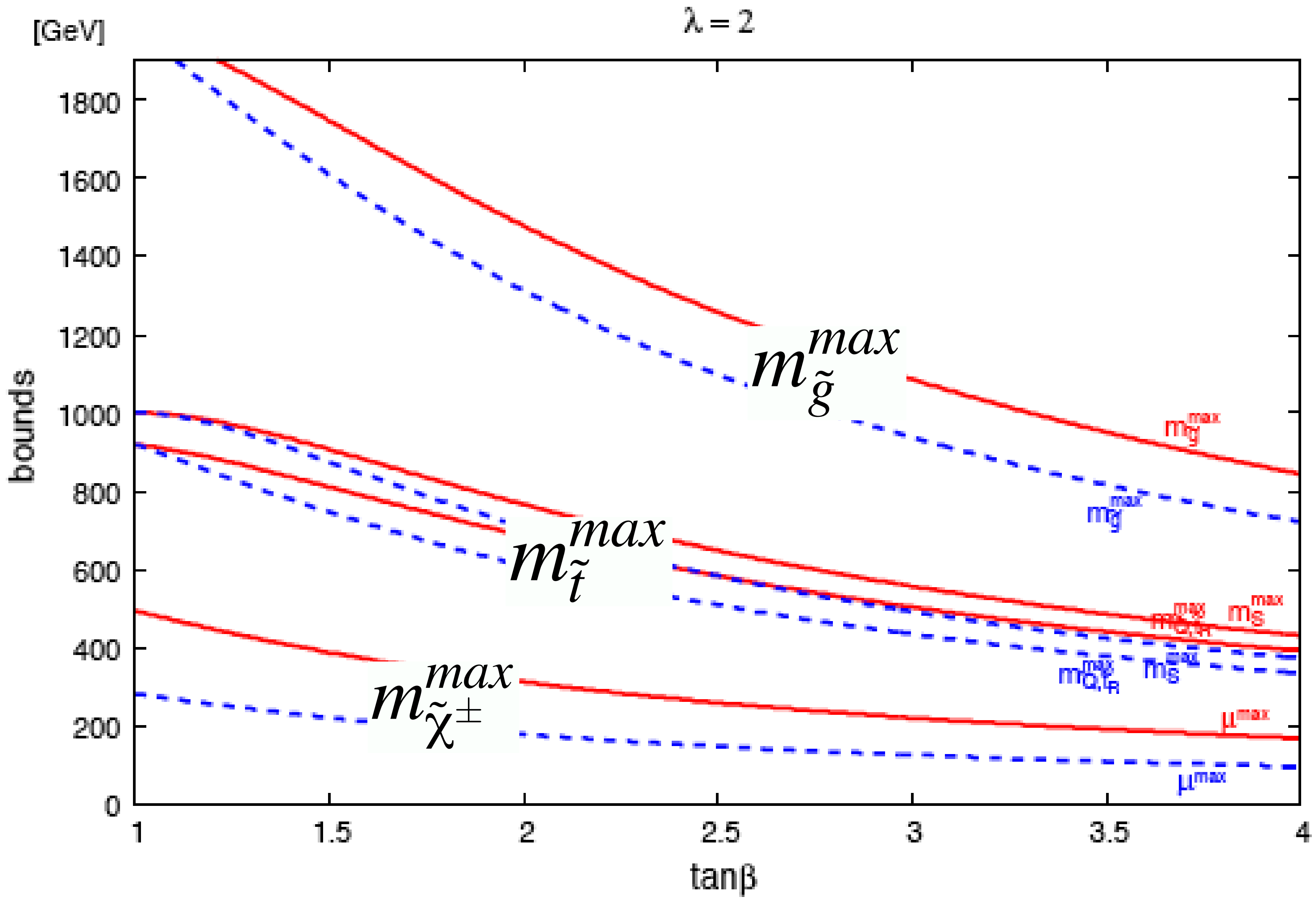
$k=-0.2$	μ (GeV)	m_H (GeV)	m_{s_1} (GeV)	m_{A_1} (GeV)	m_{χ_1} (GeV)
a	180	340	252	103	130
b	105	180	163	95	77
c	130	200	173	108	96
$k=-0.6$					
d	105	180	160	166	78
e	160	280	232	195	120

$k=-0.2$	BR(A_1A_1)	BR(ZA_1)	BR($\chi_1\chi_1$)	BR($ZZ+WW$)	BR($b\bar{b}$)	Γ_{tot} (GeV)
a	0.51	0.09	0	0.38	0	7
b	0	0	0.7	0.05	0.24	0.04
c	0	0	0	0.69	0.31	0.03
$k=-0.6$						
d	0	0	0.57	0	0.43	0.03
e	0	0	0	0.95	0.05	0.3

Bertuzzo, Farina
Franceschini, Gori

Particle spectrum (naturalness bounds)

λSUSY $\lambda = 2$



with up to 20% tuning $\left(m^{max} \propto \sqrt{\Delta/5}\right)$

$\Lambda_{mess} = 100\ TeV$

B, Hall, Nomura, Rychkov

Conclusions

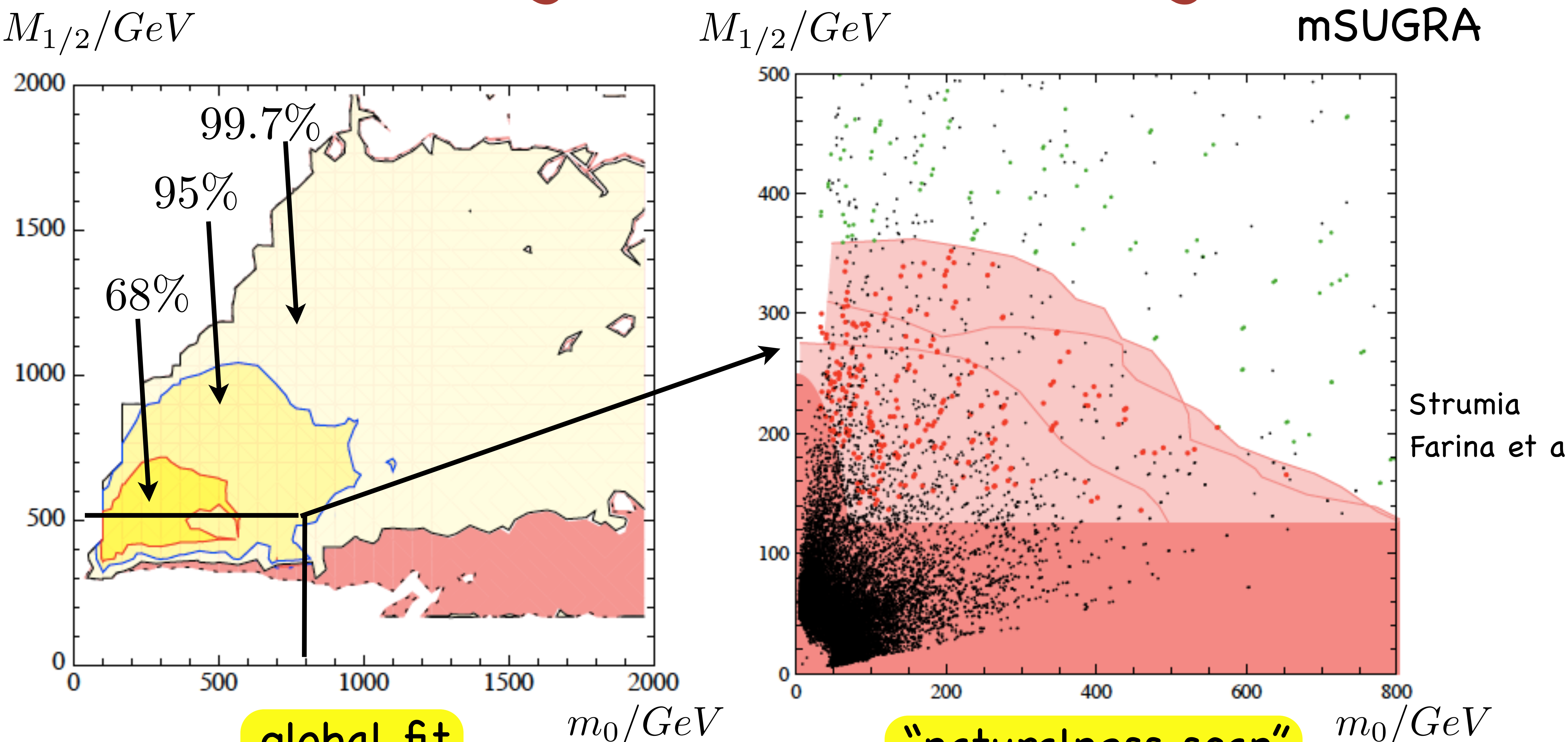
The (many) reactions to the FT problem

1. Cure it by symmetries: SUSY, Higgs as PGB, little Higgs 
2. A new strong interaction nearby 
3. A new strong interaction not so nearby: quasi-CFT
4. Warp space-time: RS
5. Saturate the UV nearby: ADD, classicalons
6. Accept it: the multiverse

Every theorist should decide where to put his/her money

Aaahhh!! The happy experimentalists!

fine-tuning or not fine-tuning?



global fit

LHC, $\Omega_{DM},\ \delta g_\mu,\ \Delta B = 1$

(too much weight on δg_μ!?)

"naturalness scan"

darker pink: excluded by LEP

pink: excluded by early LHC

Which best fit point if mSUGRA assumed true?

Is mSUGRA true?

mSUGRA still a benchmark, but...

Flavour changing interactions

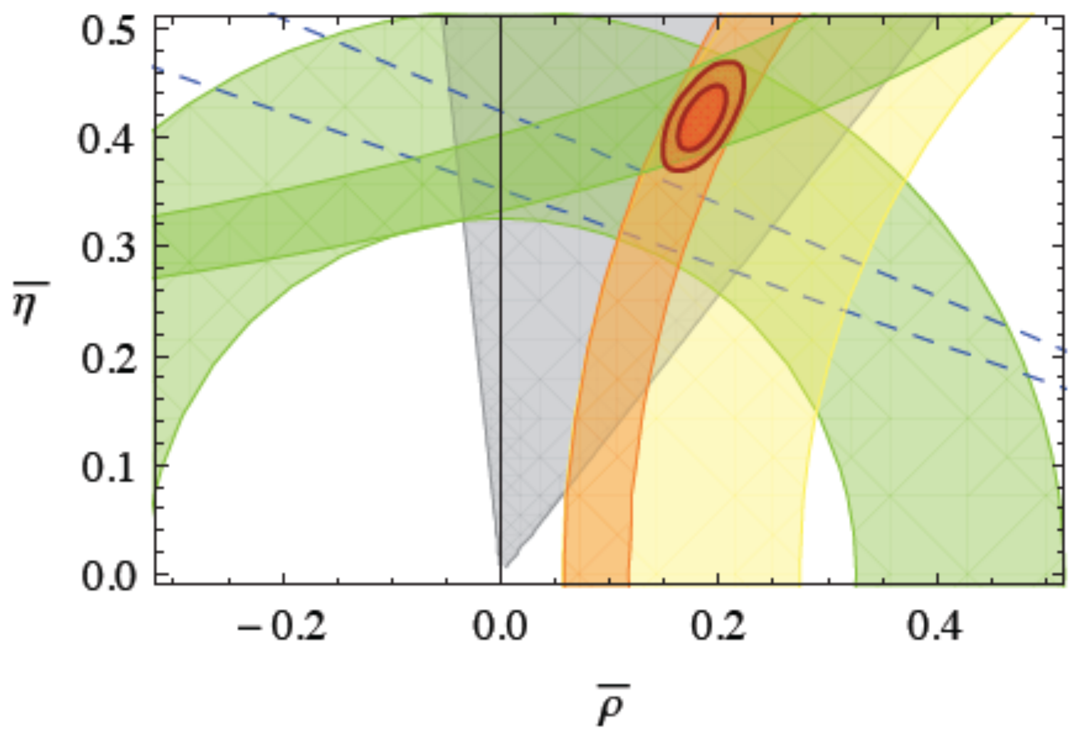
$\Delta F = 2$ - Our own SM fit

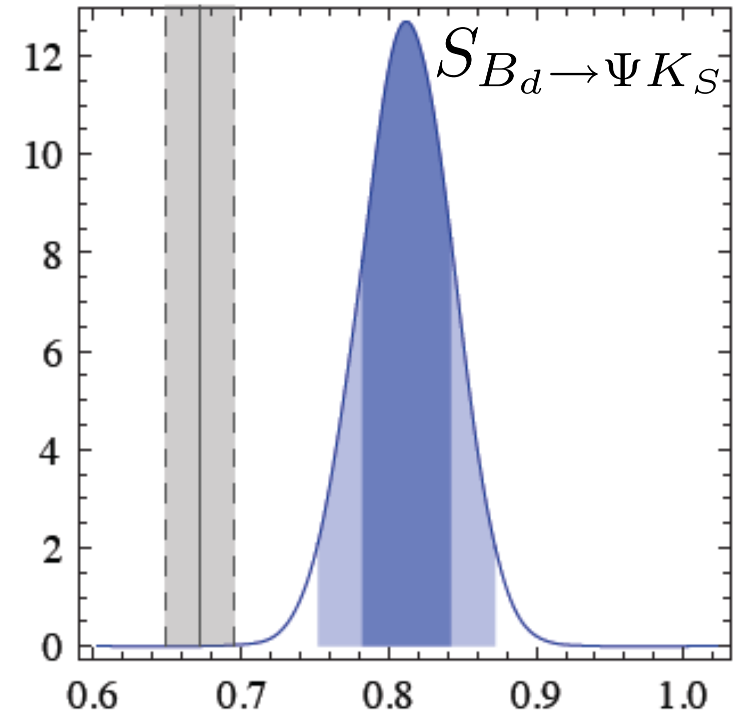
Tree level +

ΔM_d

ΔM_s

ϵ_K



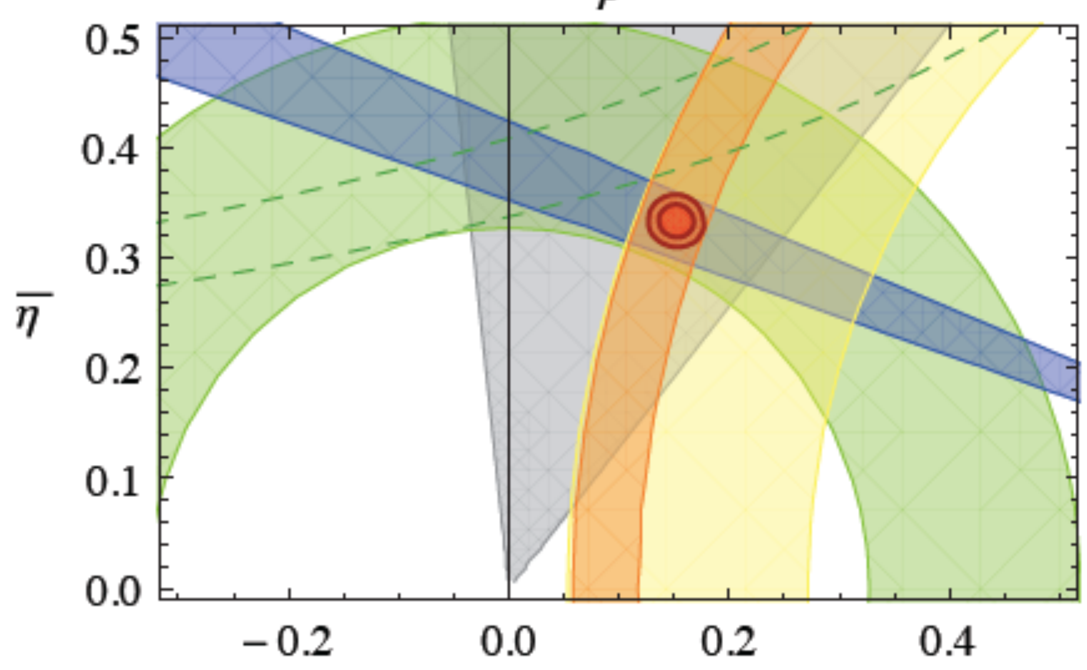


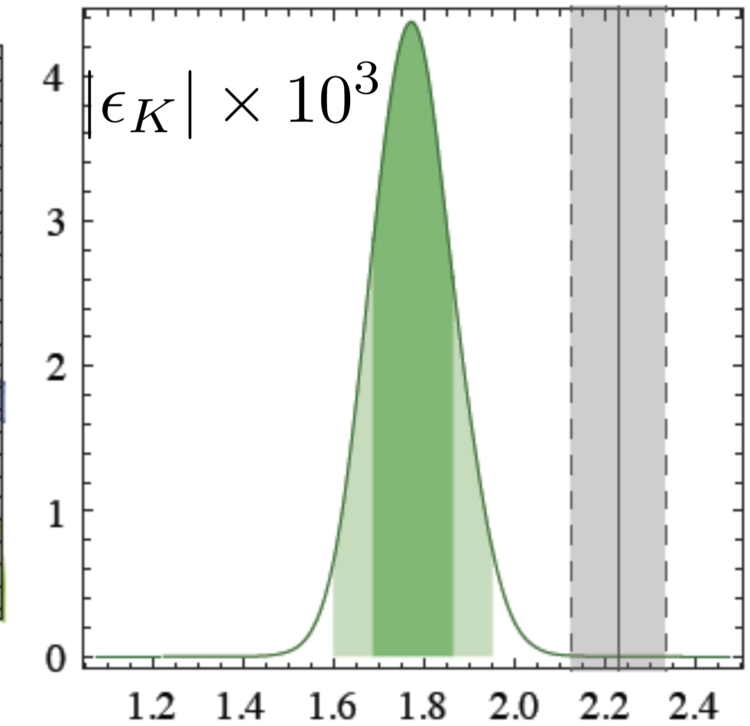
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$





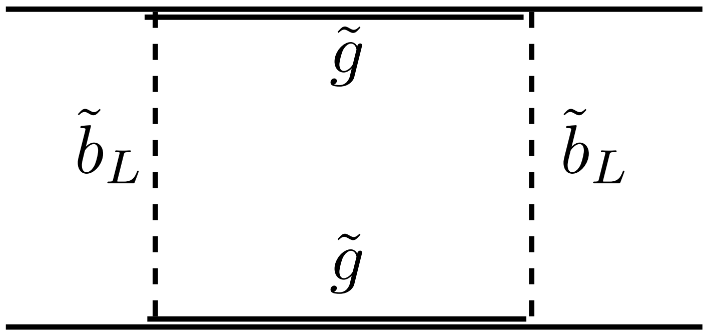
details subject to discussion

a hint of a potential problem for the SM

Lunghi, Soni
Buras, Guadagnoli
UT fit, CKM fit

Supersymmetric 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 $x = \dfrac{s_L^2 c_d^2}{|V_{ts}^2|}$

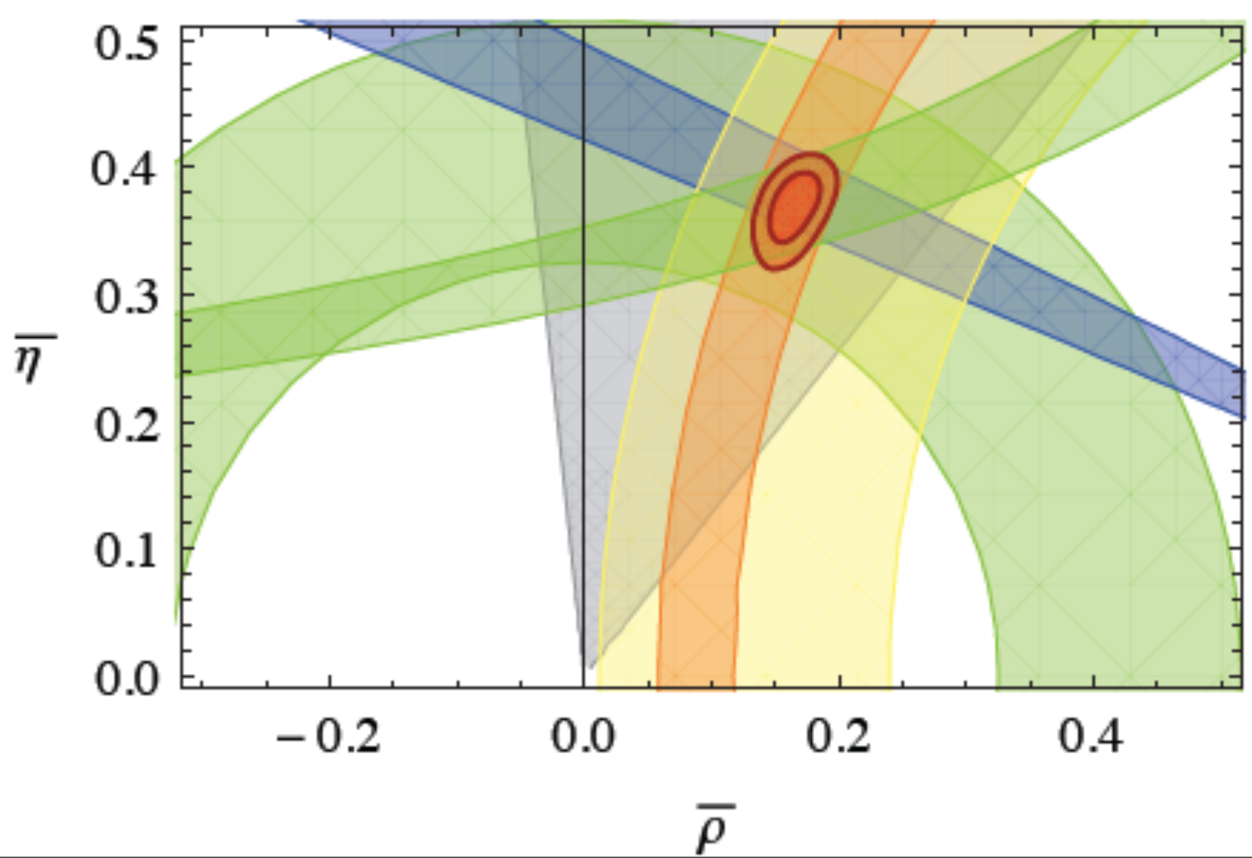
Tree level +

ΔM_d

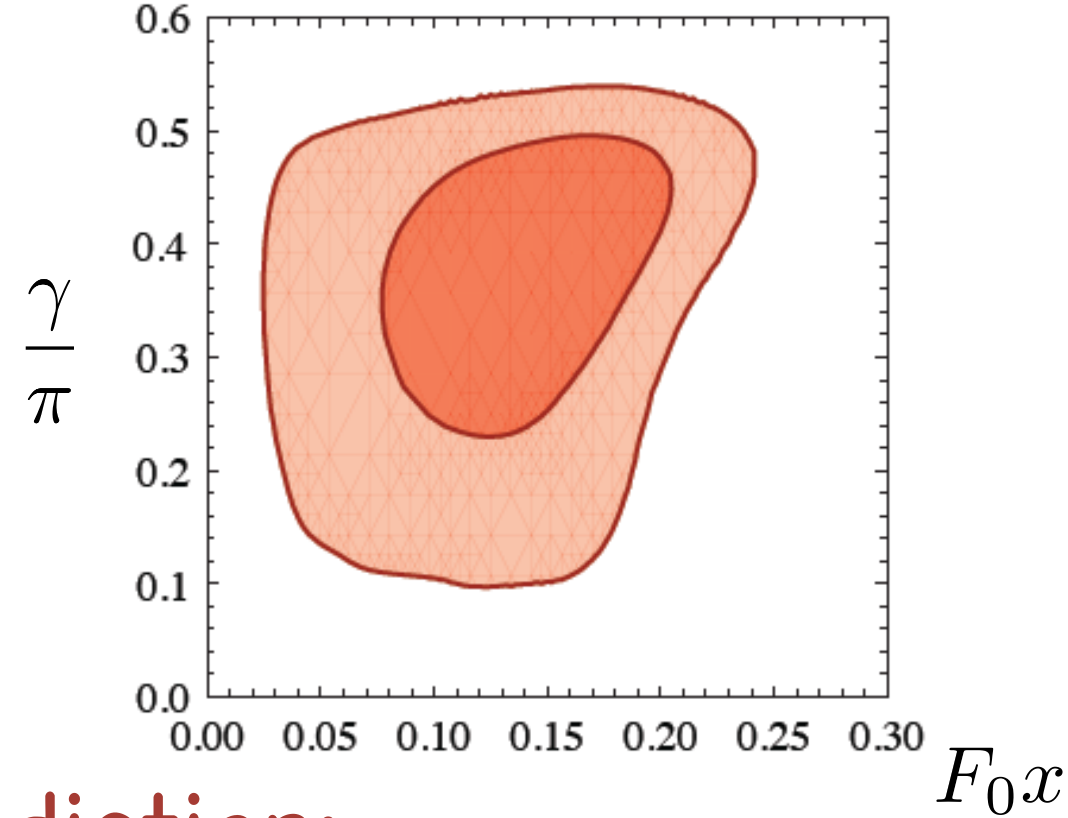
ΔM_s

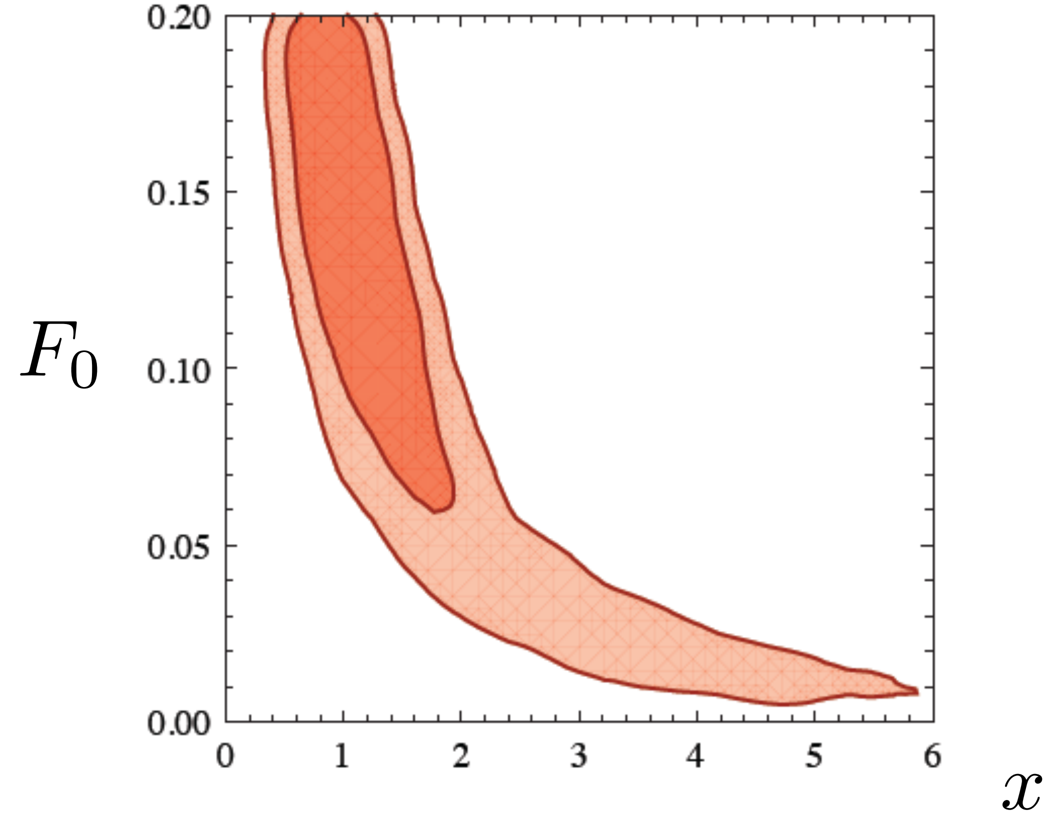
$S_{B_d \to \Psi K_S}$

ϵ_K



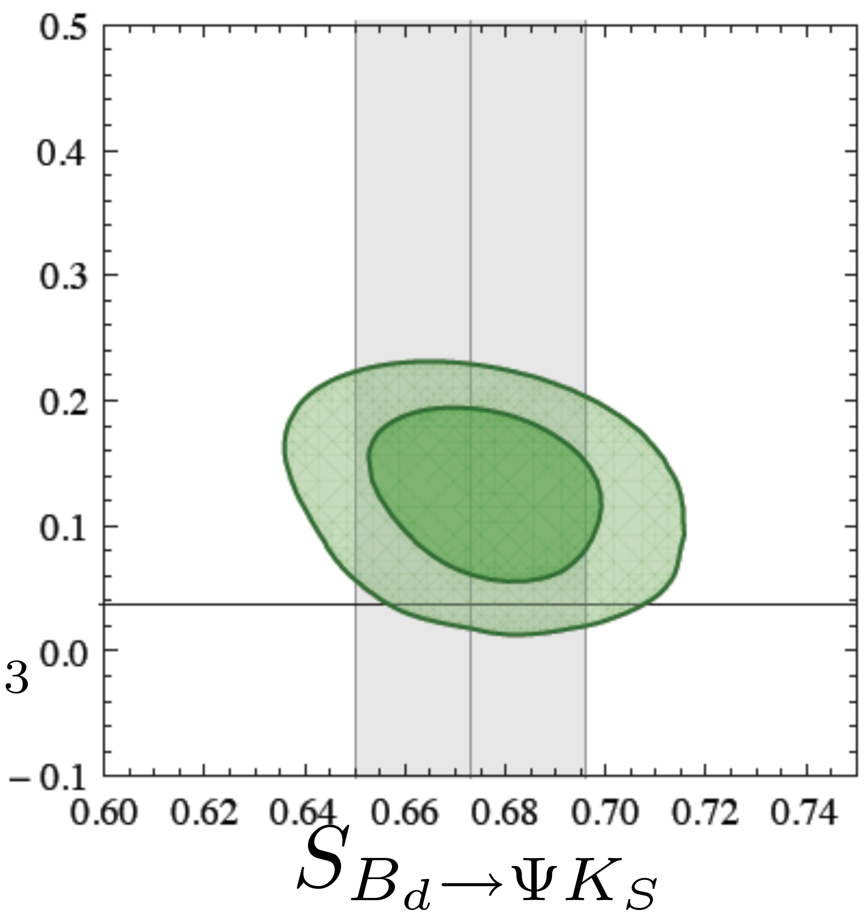
Constraints on extra parameters:





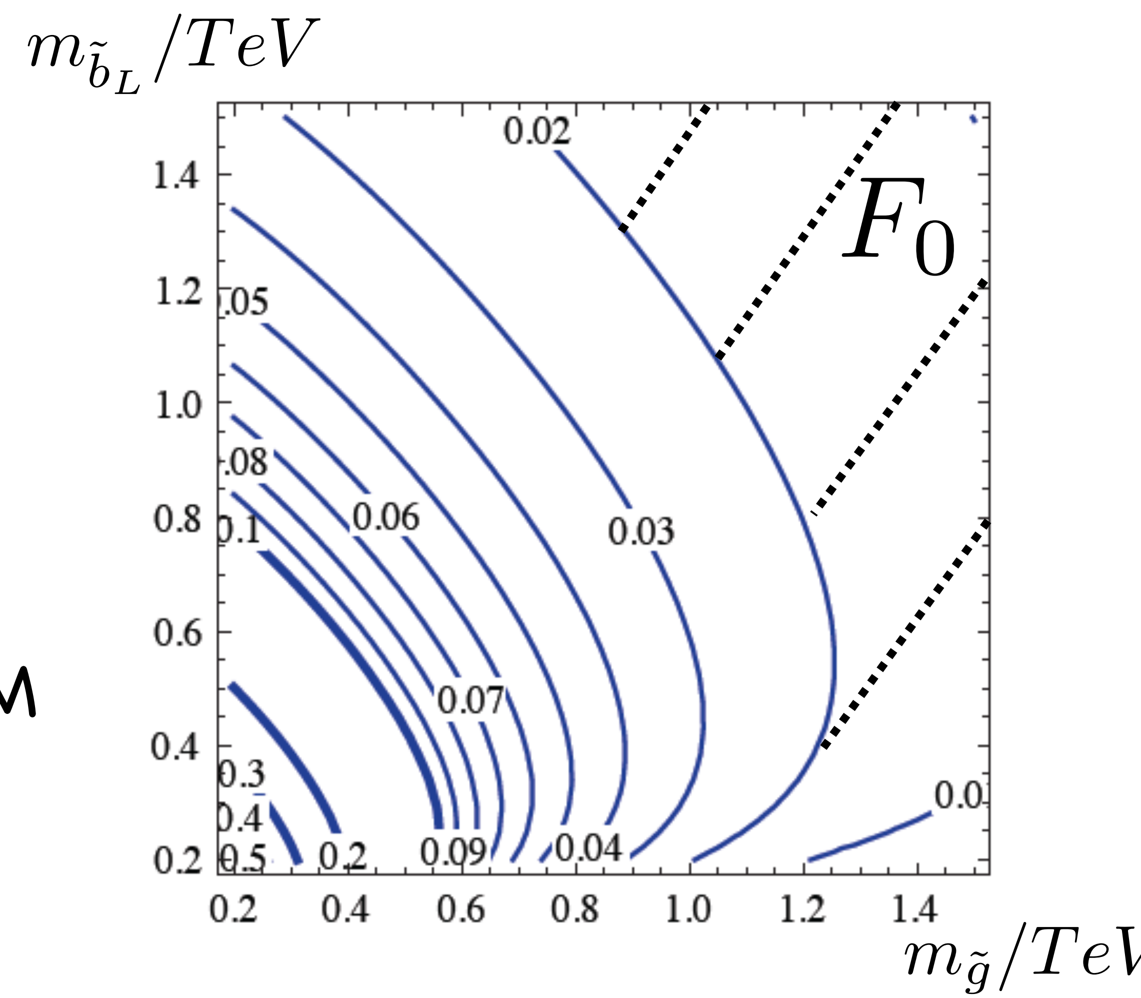
Prediction:

$S_{B_s \to \Psi\phi}$



← SM

$|a_{SL}^{d,s}| < 2 \cdot 10^{-3}$



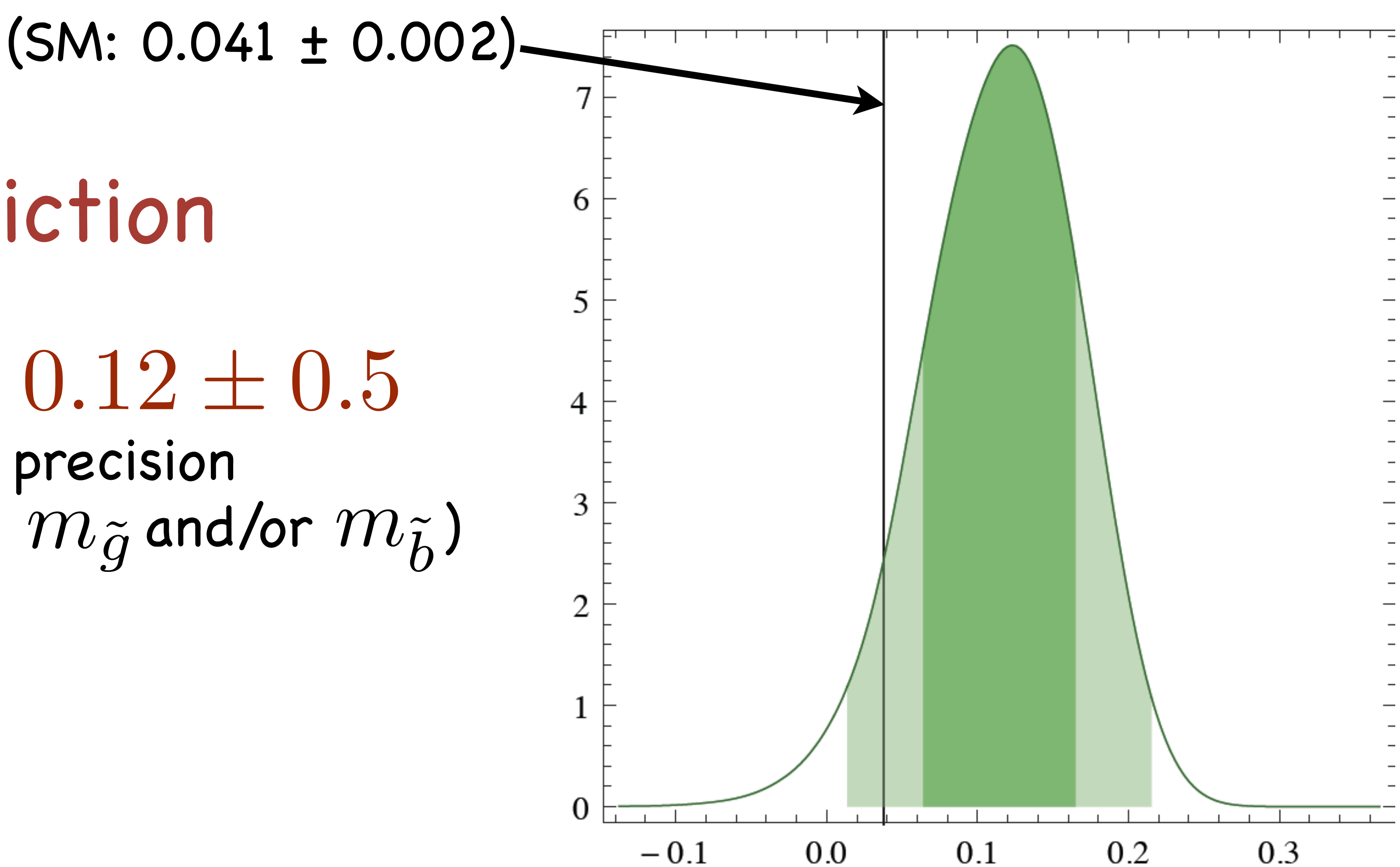
Input data

$\|V_{ud}\|$	$0.97425(22)$	[14]	f_K	(155.8 ± 1.7) MeV	[15]
$\|V_{us}\|$	$0.2254(13)$	[16]	$\hat{B}_K$	0.724 ± 0.030	[17]
$\|V_{cb}\|$	$(40.89 \pm 0.70) \times 10^{-3}$	[13]	κ_ϵ	0.94 ± 0.02	[18]
$\|V_{ub}\|$	$(3.97 \pm 0.45) \times 10^{-3}$	[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]
$\|\epsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$	[21]			
$S_{\psi K_S}$	0.673 ± 0.023	[22]			
ΔM_d	$(0.507 \pm 0.004)\,\mathrm{ps}^{-1}$	[22]			
ΔM_s	$(17.77 \pm 0.12)\,\mathrm{ps}^{-1}$	[23]			

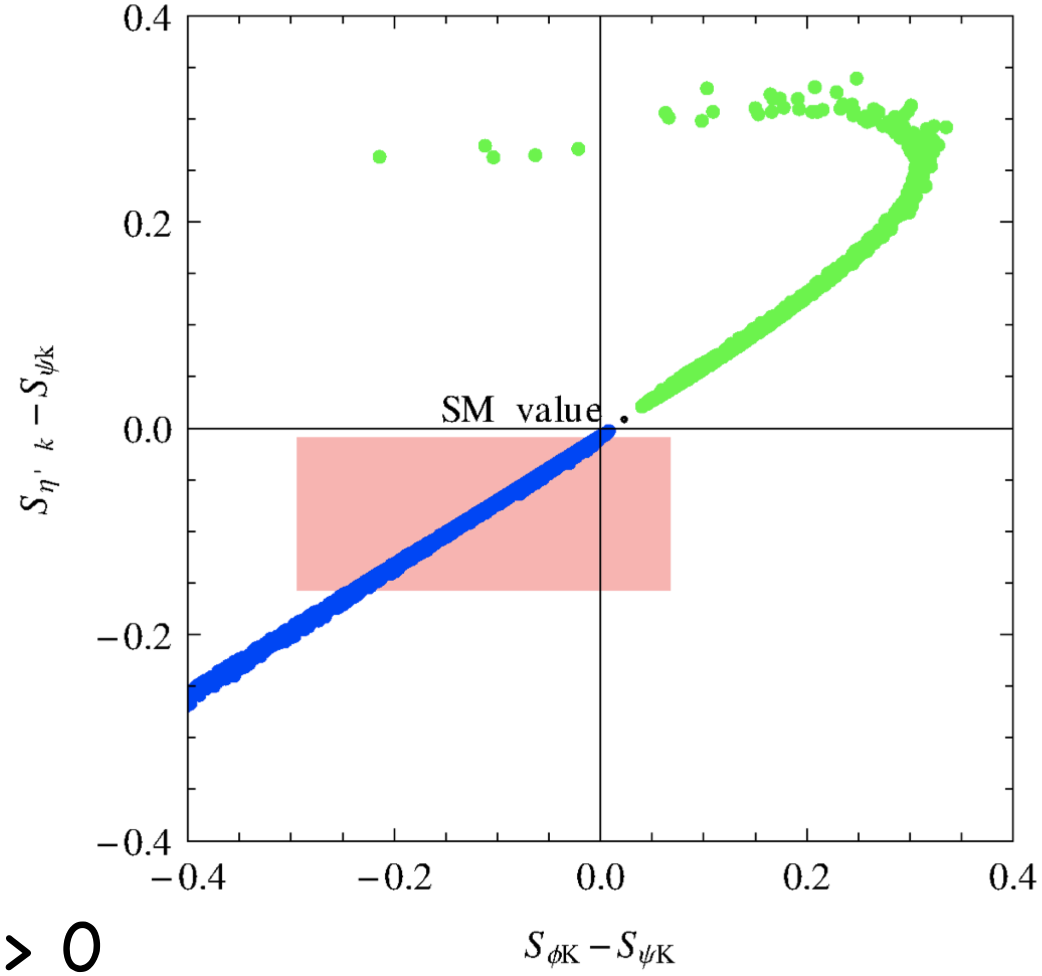
$U(2)^3$ prediction

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

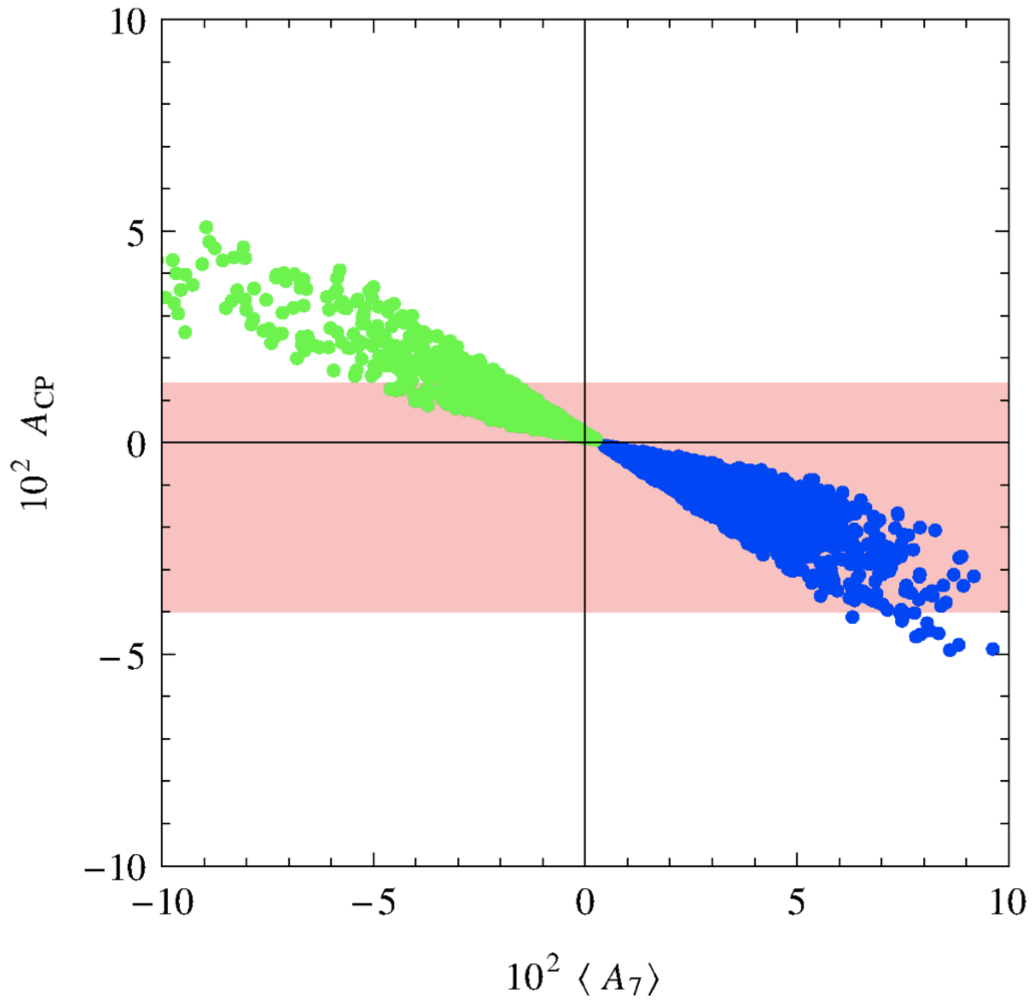
(improvable in precision by measuring $m_{\tilde{g}}$ and/or $m_{\tilde{b}}$)

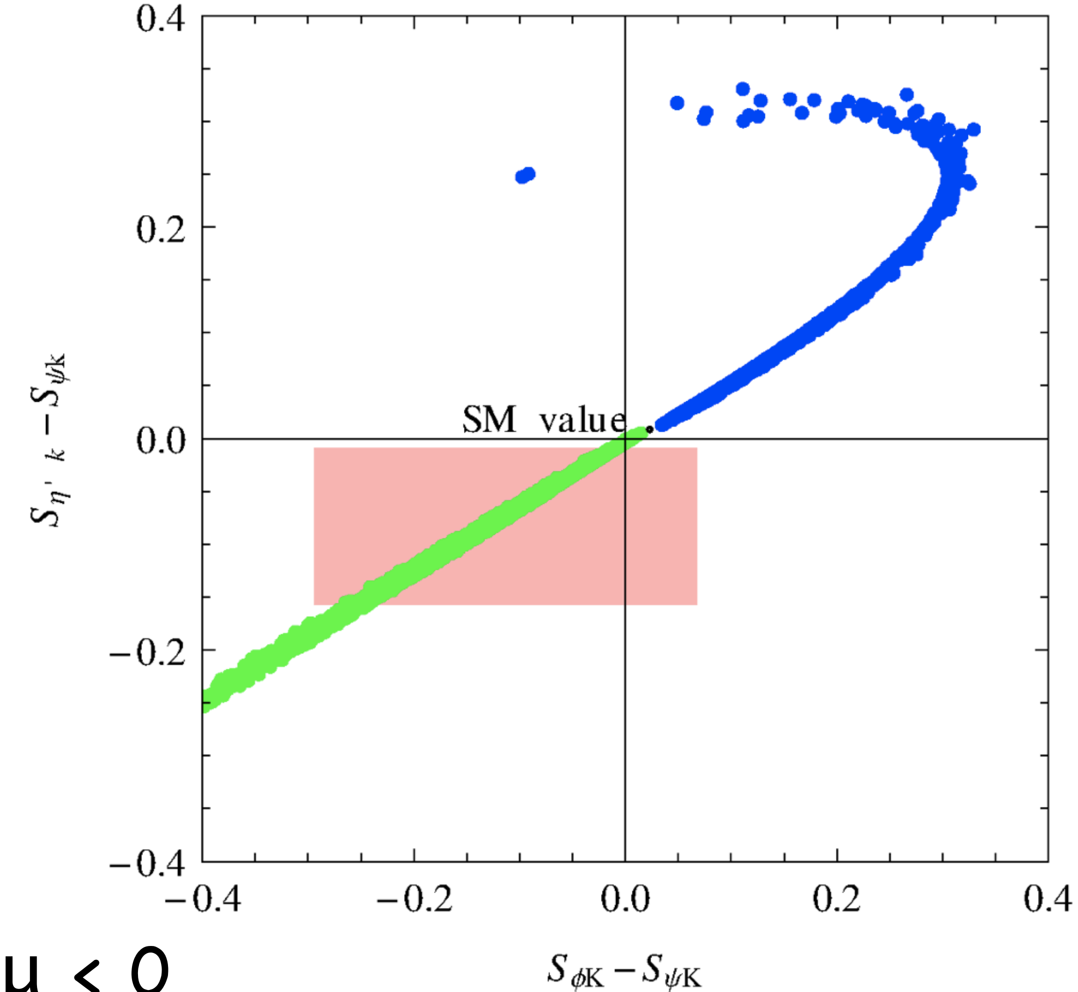


CPV in $\Delta B = 1$

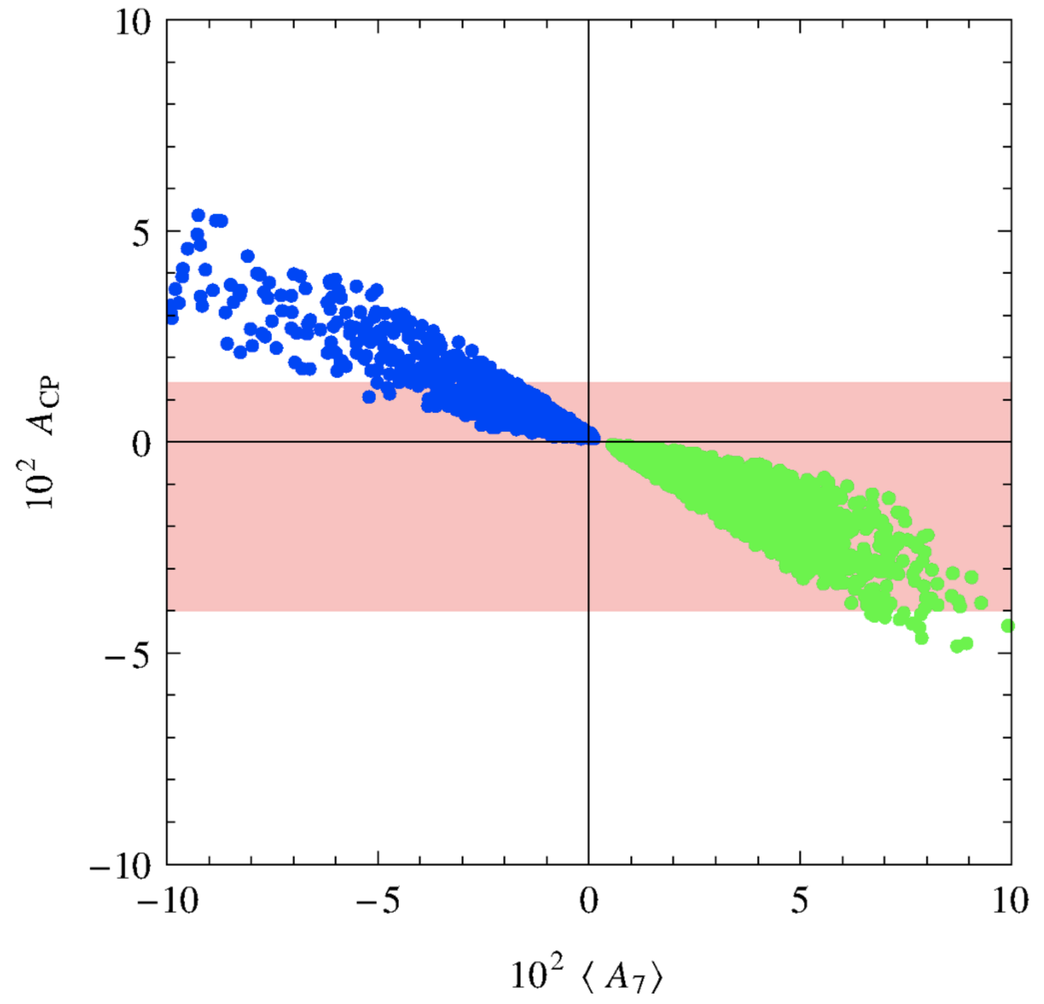


$\mu > 0$



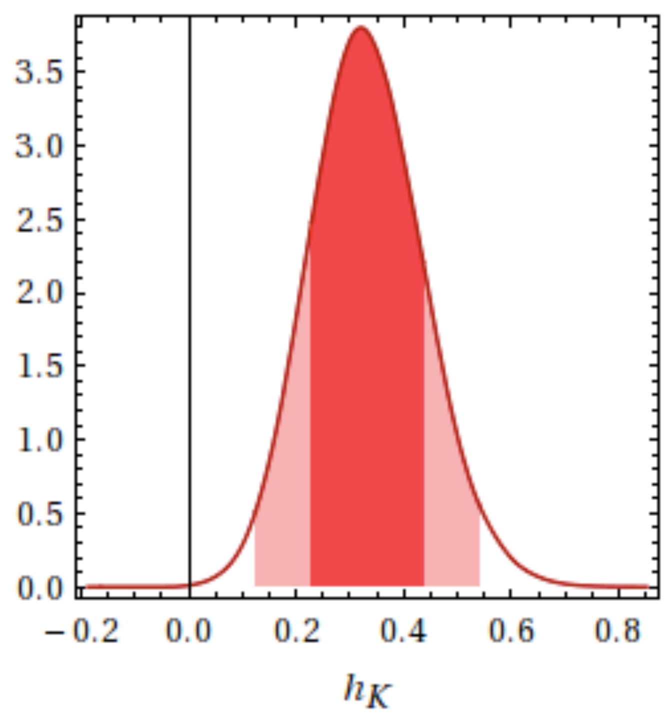


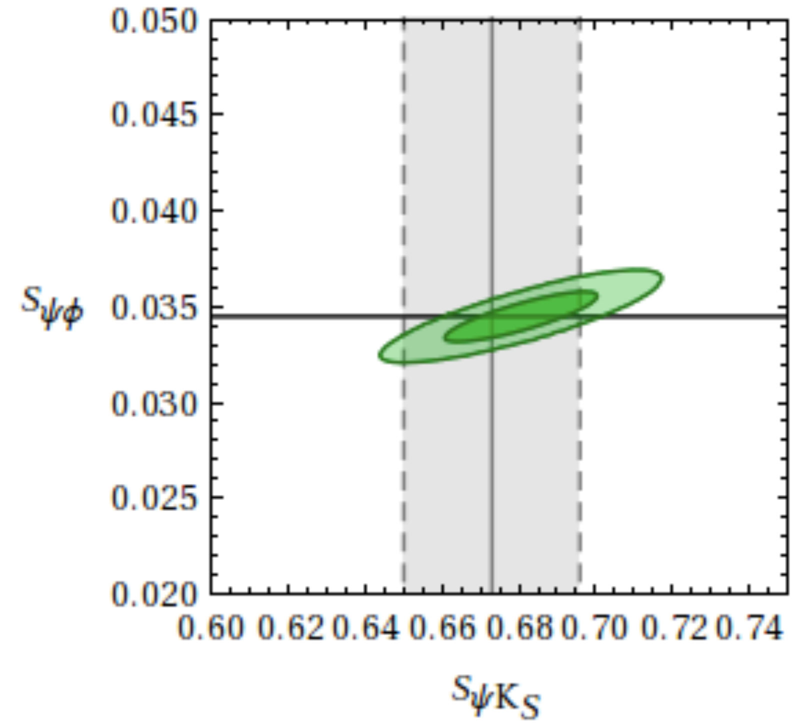
$\mu < 0$



general $U(2)^3$

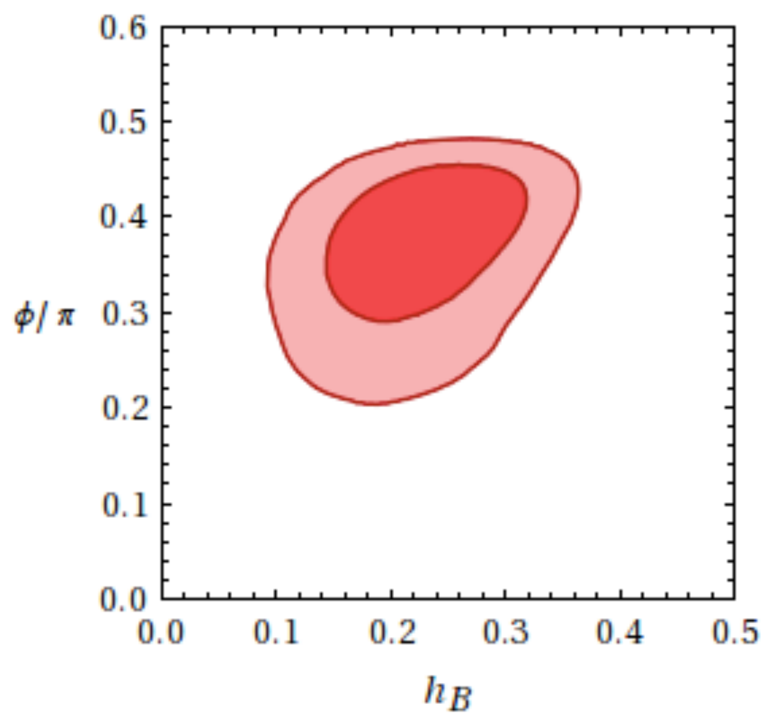
$$\mathcal{M}(K^0 \to \bar{K}^0) = \mathcal{M}^{SM}(K^0 \to \bar{K}^0)(1 + h_K)$$

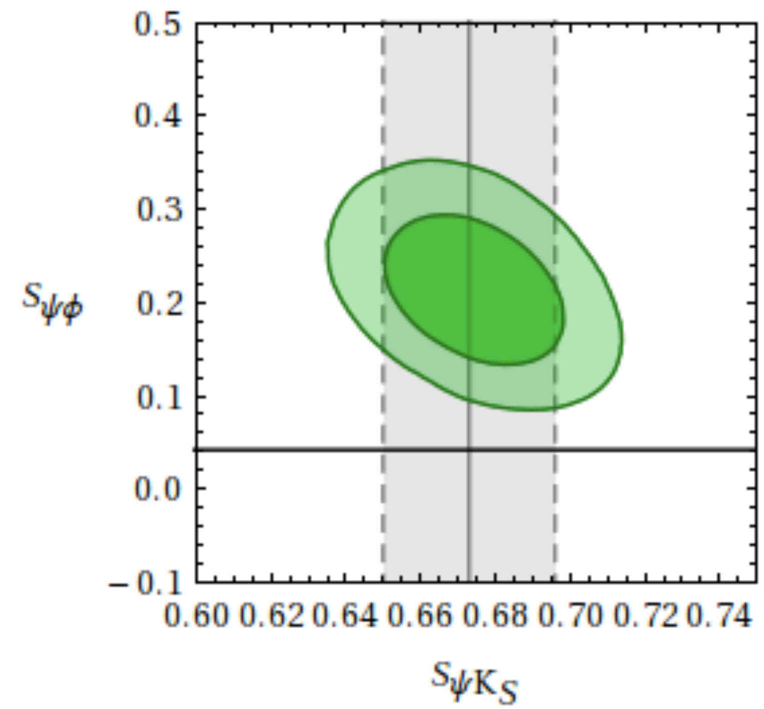




$$\mathcal{M}(B_d \to \bar{B}_d) = \mathcal{M}^{SM}(B_d \to \bar{B}_d)(1 + h_B e^{-2i\gamma})$$

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





Flavour and CPV in charged leptons

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

Educated guesses:

$\mu \to e\gamma$

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

$\tau \to \mu\gamma$

$$\frac{BR(\tau \to \mu\gamma)}{BR(\mu \to e\gamma)} \approx \left|\frac{V^l_{\tau\tau}}{V^l_{\tau e}}\right|^2 BR(\tau \to \mu\nu\bar{\nu}) \approx 2\times 10^3\left|\frac{V^l_{\tau\tau}}{V_{tb}}\right|^2\left|\frac{V_{td}}{V^l_{\tau e}}\right|^2$$

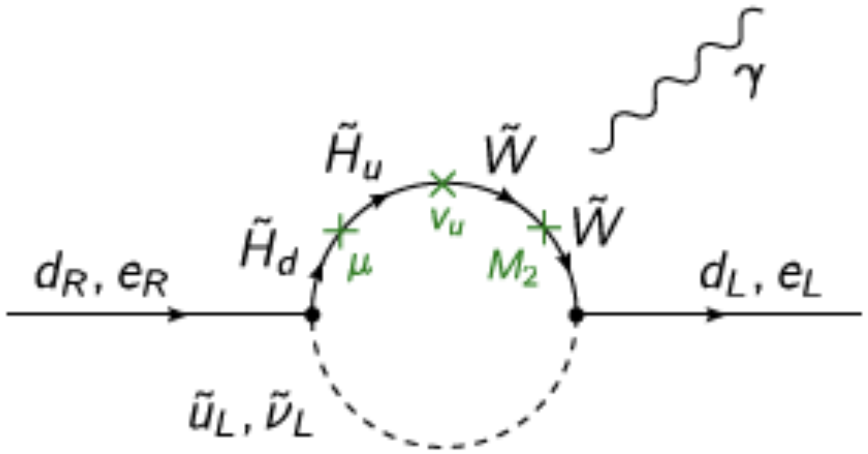
d_e

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

Electric Dipole Moments with flavour blind phases only

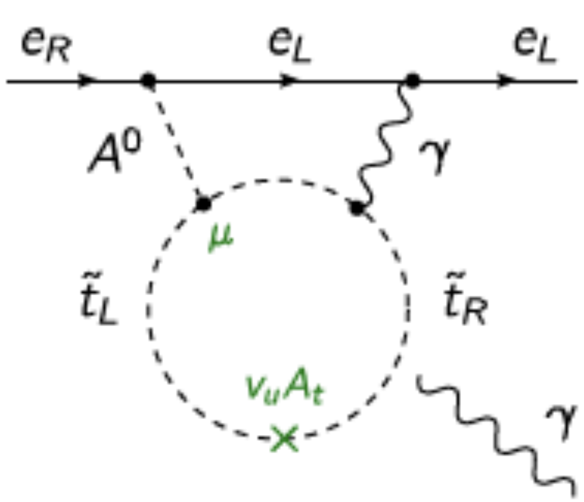
Flavour blind phases lead to contributions to electric dipole moments.

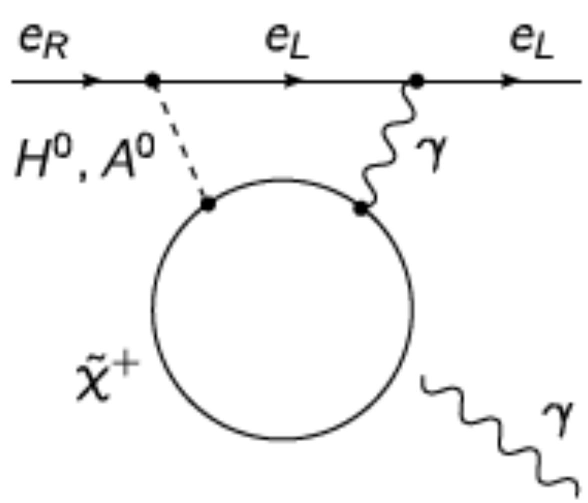
$$\text{Exp.:} \qquad |d_e| < 1.6\times10^{-27}\ e\,\text{cm}\,, \qquad |d_n| < 2.9\times10^{-26}\ e\,\text{cm}$$



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

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





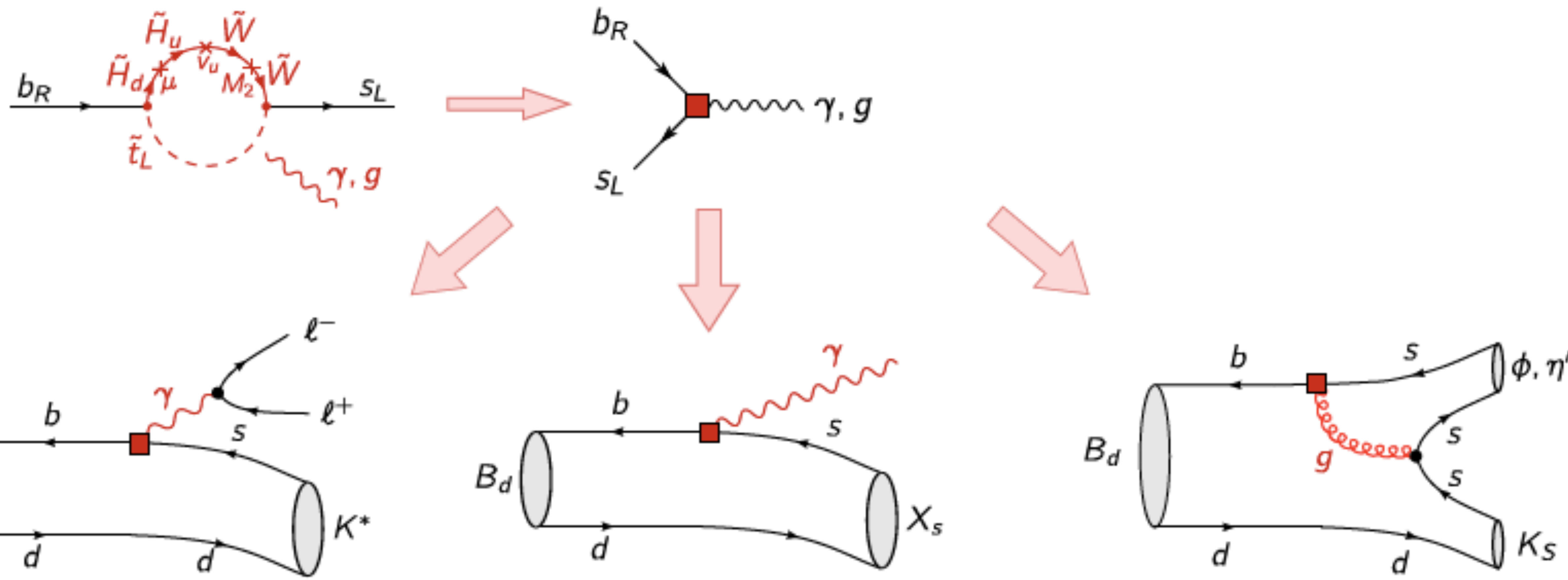
2-loop contributions lead to effects in the ballpark of the experimental bound

B, Lodone, Straub

CP asymmetries in B-physics

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

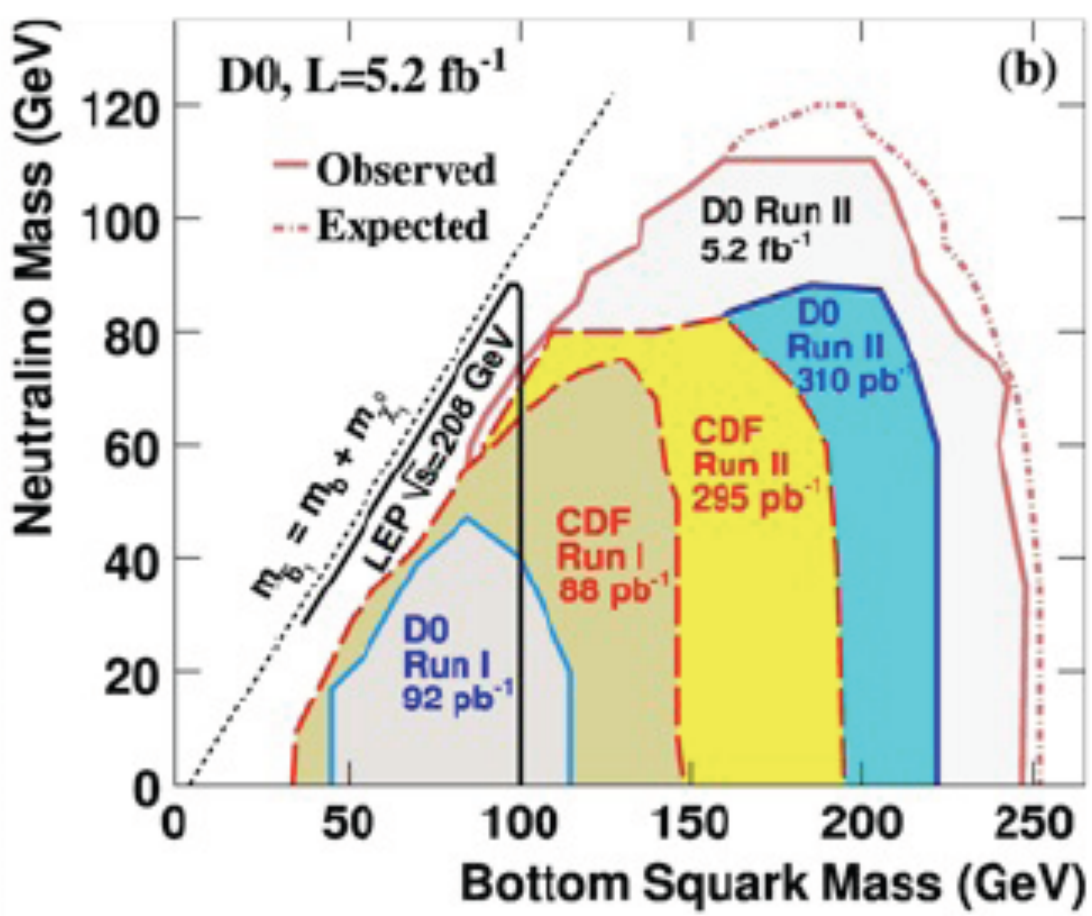
e.g.



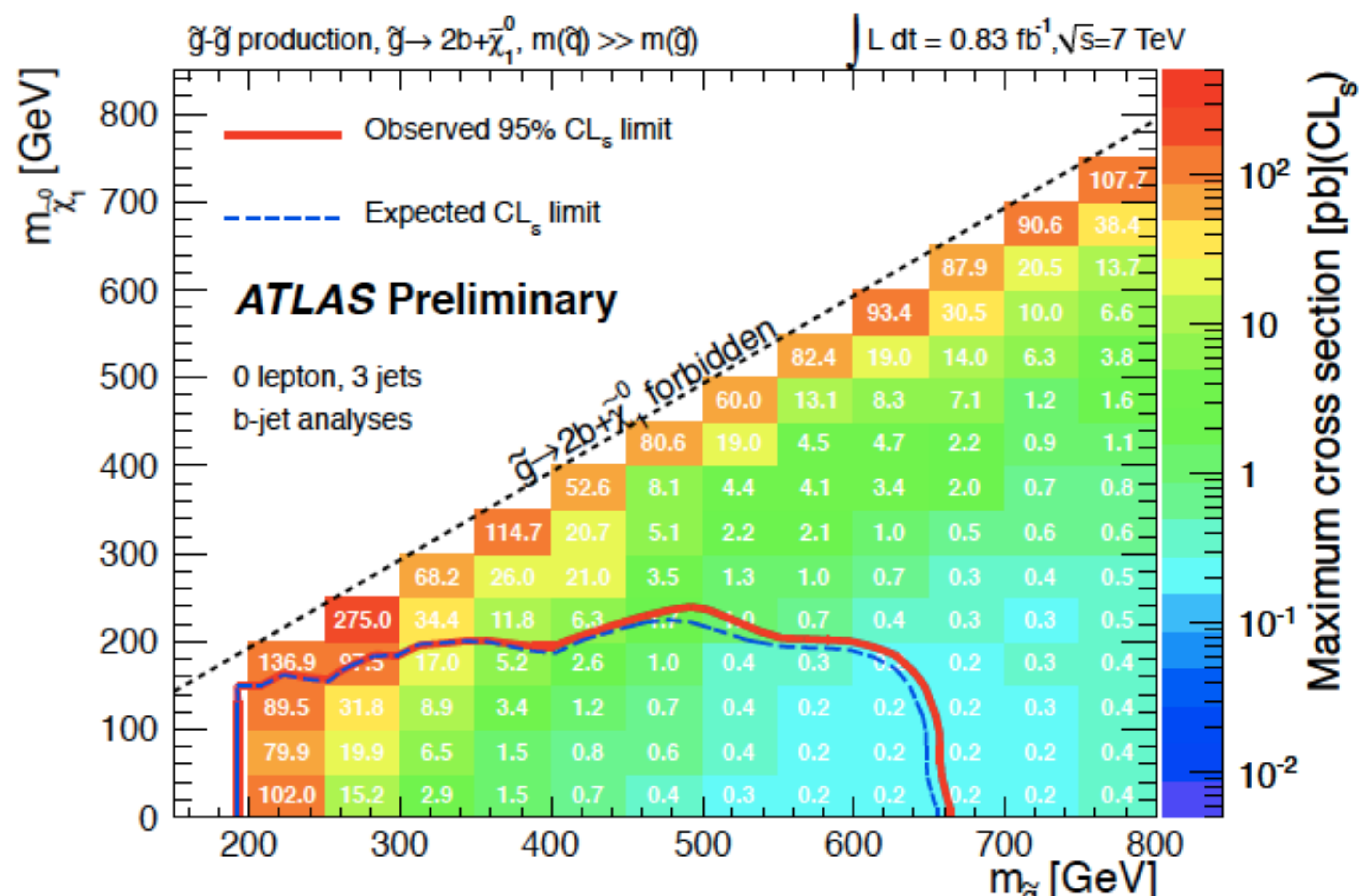
A_7, A_8 in $B \to K^* \ell^+ \ell^-$

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

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



D0, L=5.2 fb-1
(b)
Observed
Expected
D0 Run II
5.2 fb-1
D0
Run II
310 pb-1
CDF
Run II
295 pb-1
CDF
Run I
88 pb-1
D0
Run I
92 pb-1
LEP √s=208 GeV
Neutralino Mass (GeV)
Bottom Squark Mass (GeV)



g̃-g̃ production, g̃→ 2b+χ̃01, m(q̃) >> m(g̃)
∫ L dt = 0.83 fb-1, √s=7 TeV
Observed 95% CLs limit
Expected CLs limit
ATLAS Preliminary
0 lepton, 3 jets
b-jet analyses
g̃→2b+χ̃01 forbidden
Maximum cross section [pb](CLs)