Supersymmetry and the Fermi scale, thirty years after

R. Barbieri
MAIANI 70
Roma, Sept 21-22, 2011

⇒ Luciano (among) the first to suggest SUSY for a natural Fermi scale: 1979

⇒ Out of the 6 papers of mine with Luciano, 5 are on supersymmetry: 1982/84

The Fine Tuning problem of the Fermi scale

1999: "the LEP Paradox" ← LEP 10th anniversary with Luciano as DG

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)

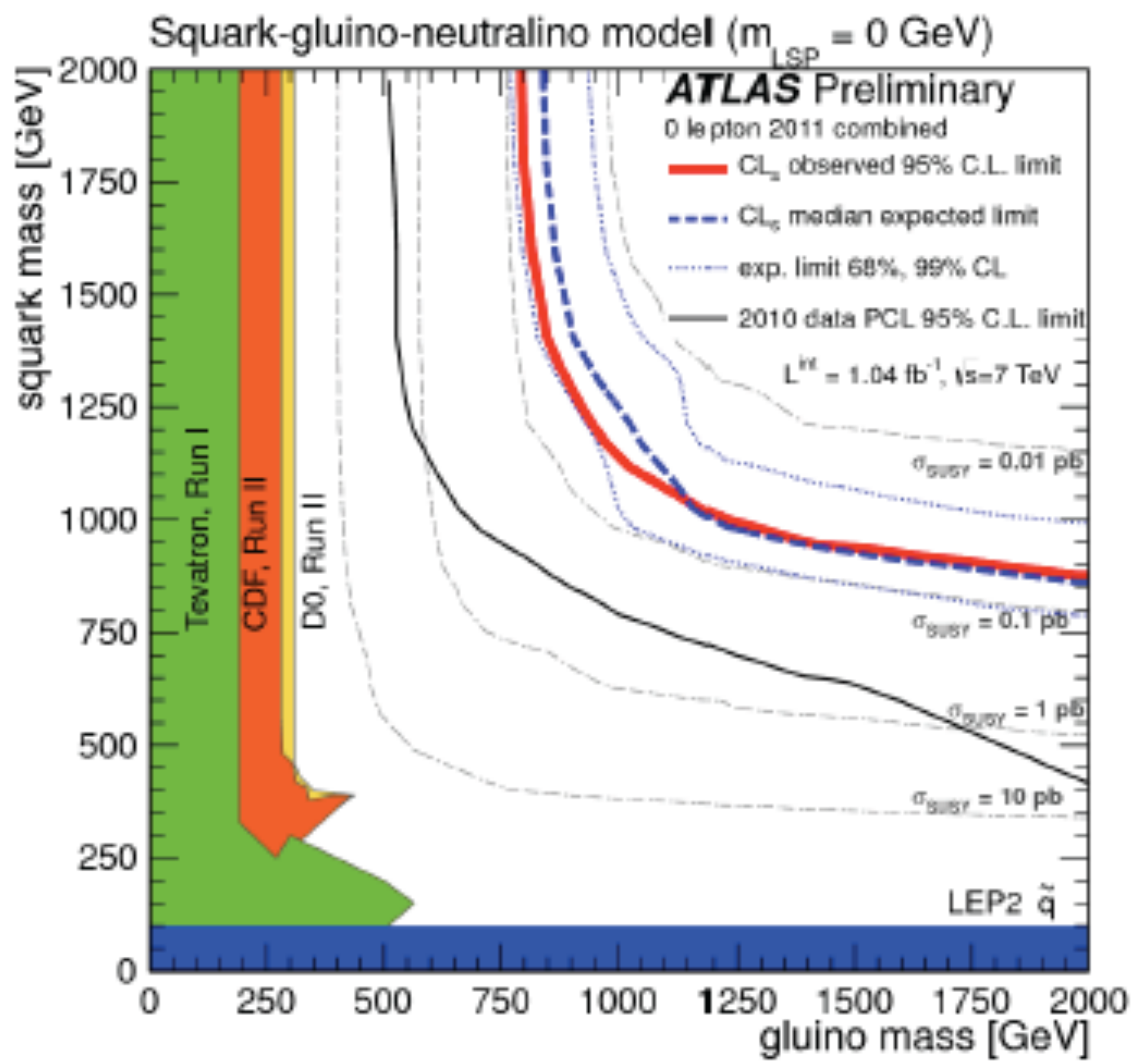
In case you doubted of its relevance:

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, the 10^{120} vacua of string theory

Anything else?

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

No Higgs boson (LEP)
No s-particle (LEP + TEVATRON + LHC)
Flavour and CPV as in CKM picture (almost?)



(one of many similar plots)

$$\tilde{g} \rightarrow q_{1,2}\tilde{q}_{1,2}$$

$$\tilde{q}_{1,2} \rightarrow q_{1,2} + \chi_{LSP} \quad \text{or}$$
$$\tilde{q}_{1,2} \rightarrow q_{1,2} + \chi' \rightarrow q_{1,2} + l's + \chi_{LSP}$$

$\Rightarrow m_{\tilde{g}}, m_{\tilde{q}_{1,2}} \gtrsim 1\ TeV$
with $\tilde{q}_{1,2}$ degenerate squarks of the first two generations

SUSY still well alive,

since no hard info, yet, on the crucial configuration

The key equations:

$m_{\tilde{h}}$

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

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

$m_{\tilde{b}_L}$

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

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

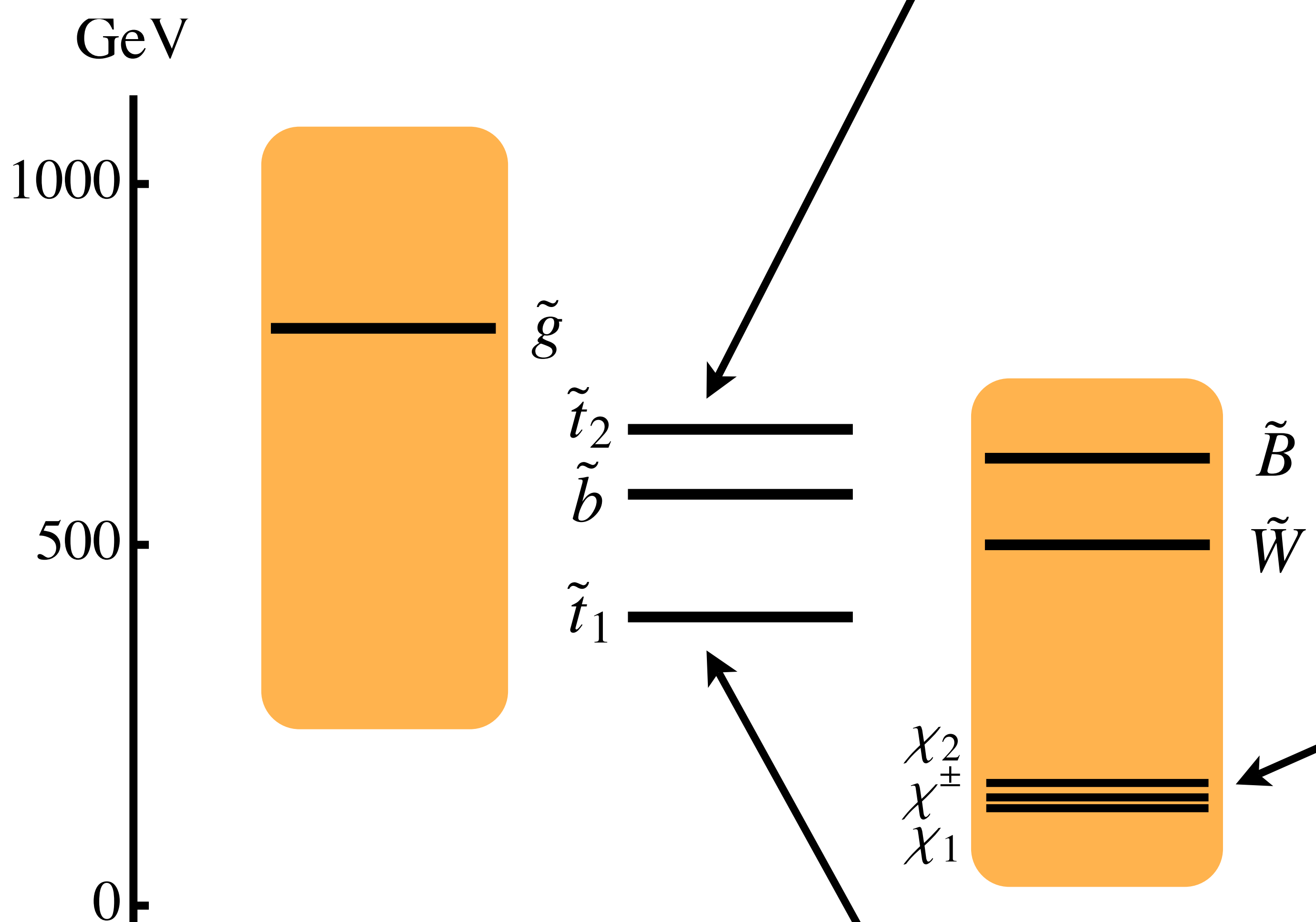
see, e.g., Dimopoulos, Giudice for SUGRA-mediation, 1995

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

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

IF $\mu < M_1, M_2$ then

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

⇒ 4 semi-inclusive final states

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

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

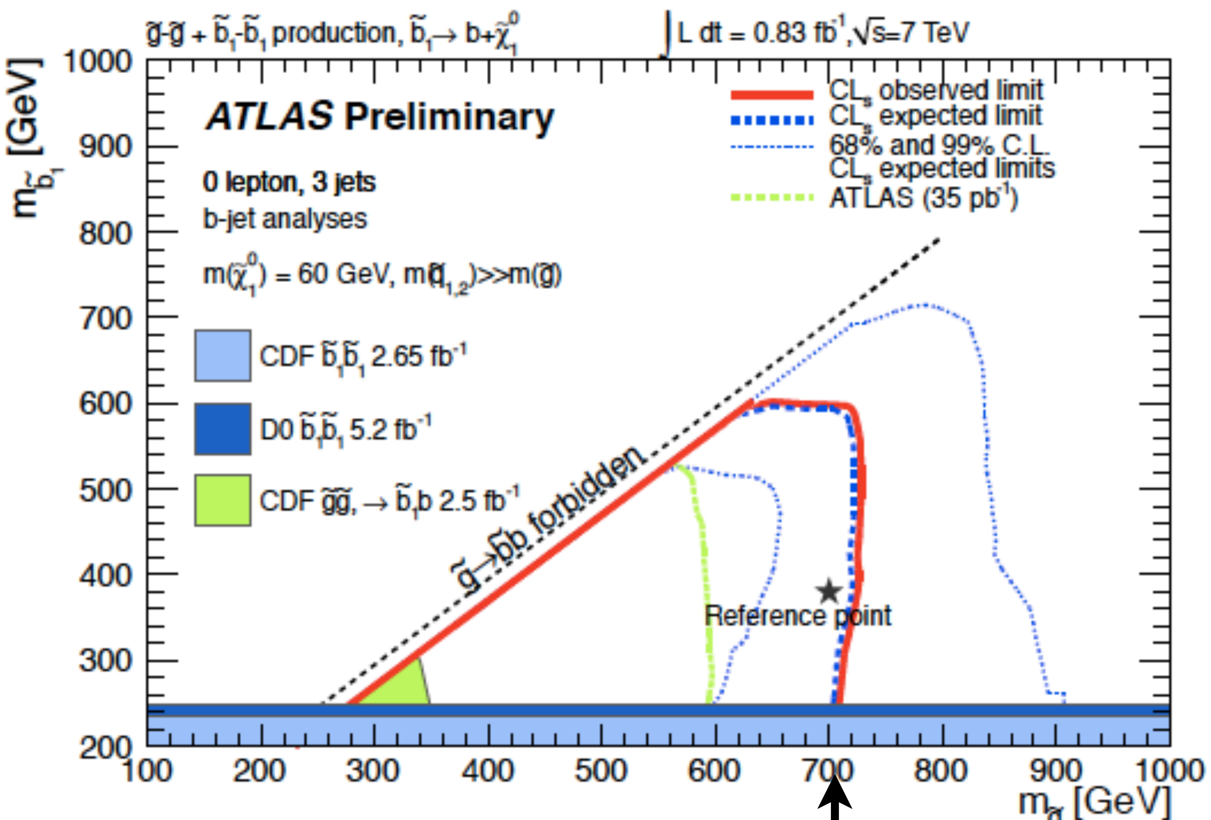
with rates determined by a single BR

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

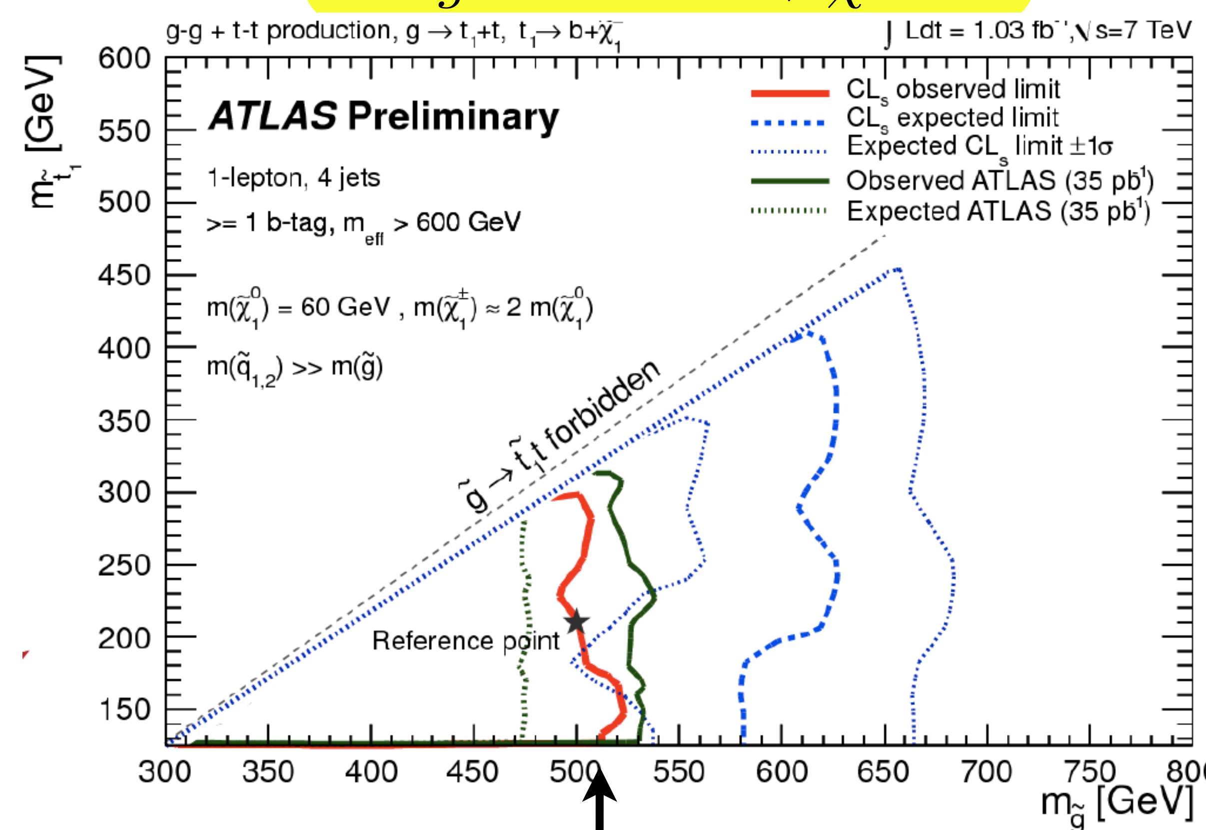
($\chi \to \tilde{G} + Z$)

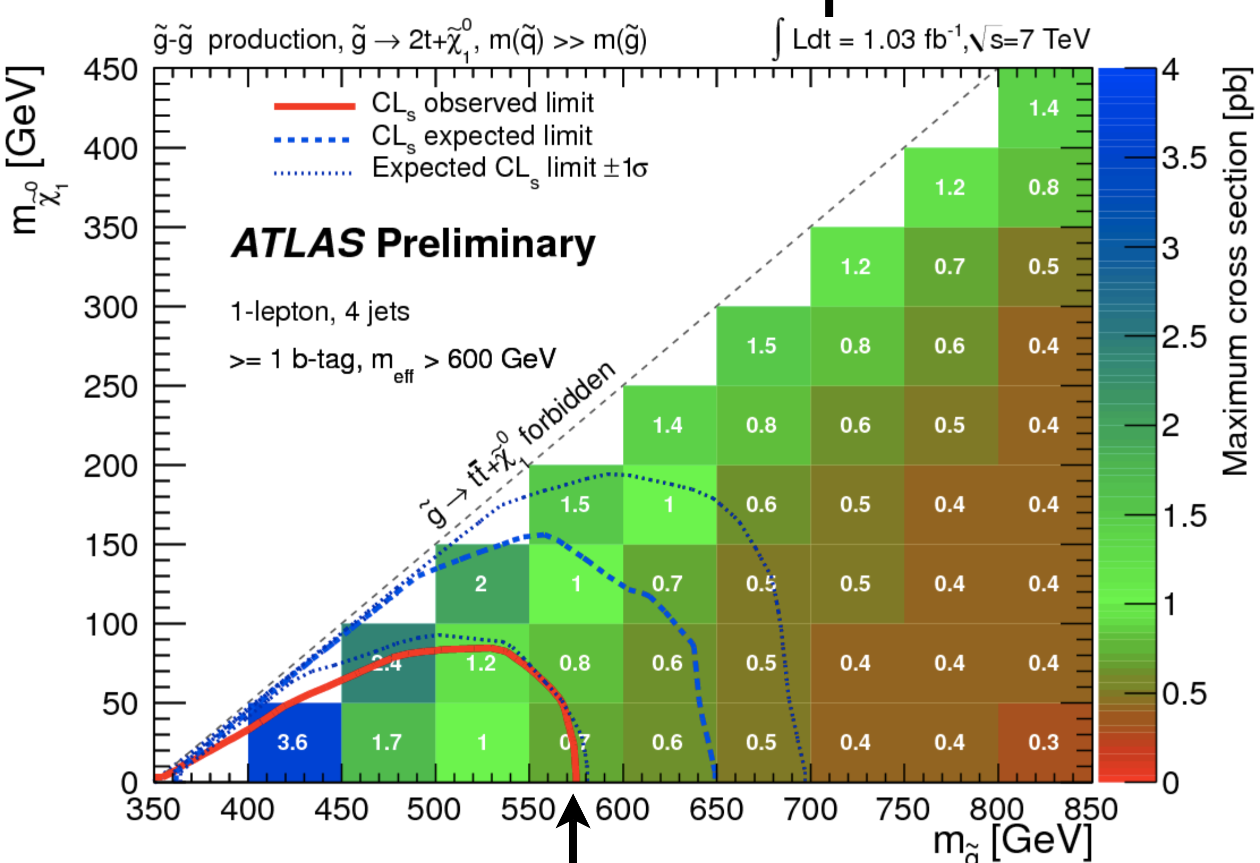
current bounds on $\tilde{g}, \tilde{t}, \tilde{b}$

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



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





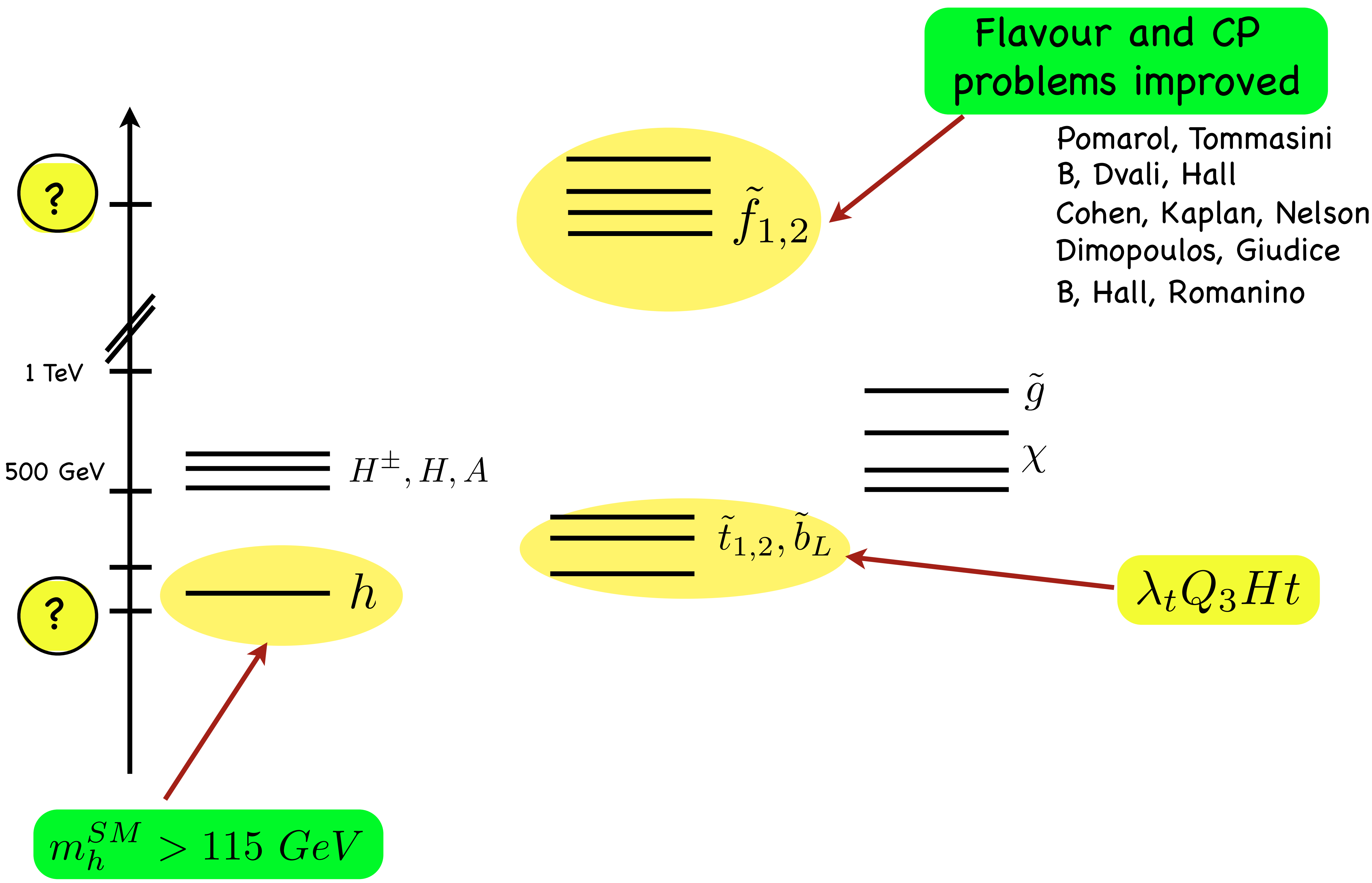
$\tilde{g} \to t\tilde{t} \to t\bar{t} + \chi$

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

$$m_{\tilde{t}}, m_{\tilde{b}} > 100 \div 200\ GeV$$

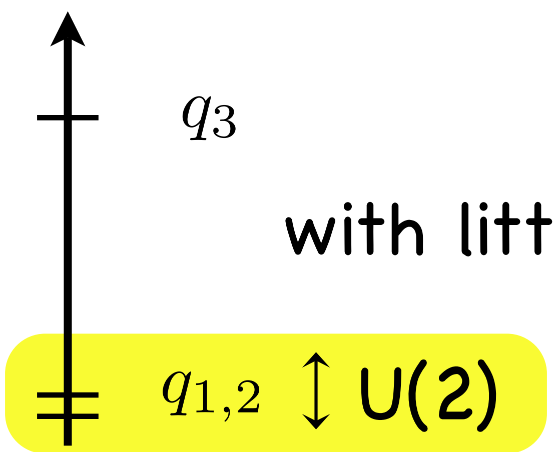
"Beyond mSUGRA"

(well before the LHC)



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

Tomassini, Pomarol 1996
B, Dvali, Hall 1996



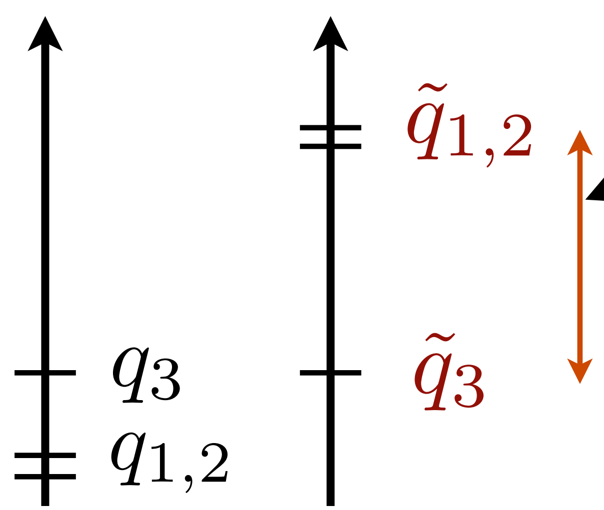
with little communication between $q_{1,2}$ and q_3

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

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

and perhaps also in the SUSY non-data

flavour, EDMs, direct s-particle searches



An inverted spectrum

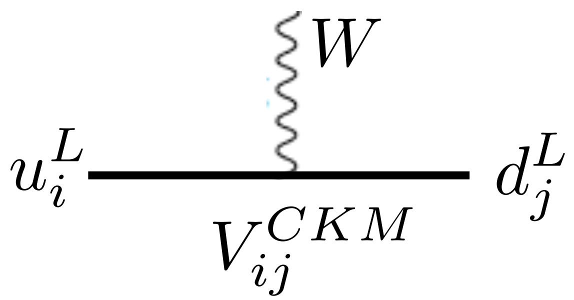
short-distance effects of λ_t

Anomalous U(1), 2-site deconstruction,

B, Isidori, Jones-Perez, Lodone, Straub

Consequences of $U(2)^3$

Flavour changing interactions

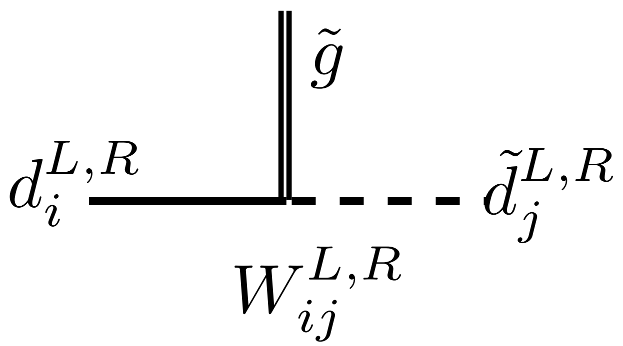


standard, in non standard parametrization

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

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

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



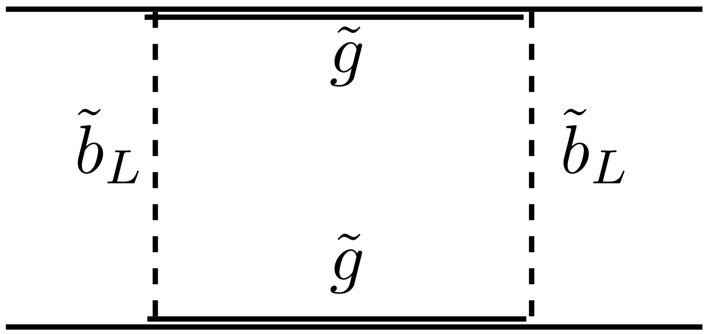
$$W^L = \begin{pmatrix} c_d & s_d e^{-i(\delta+\phi)} & -s_d s_L e^{i\gamma} e^{-i(\delta+\phi)} \\ -s_d e^{i(\delta+\phi)} & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

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

1 new angle s_L and 1 new phase γ

Supersymmetric flavour fit

including:



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

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

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

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

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

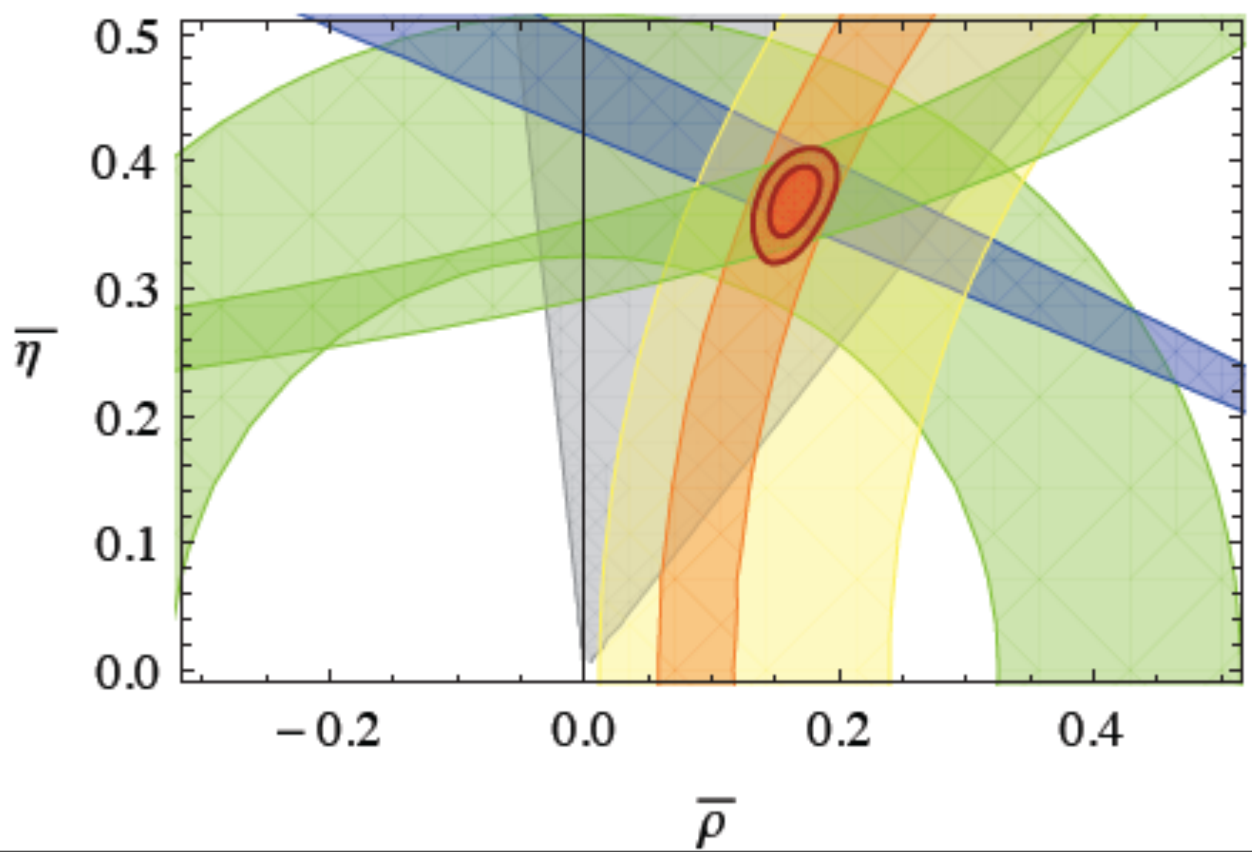
Tree level +

ΔM_d

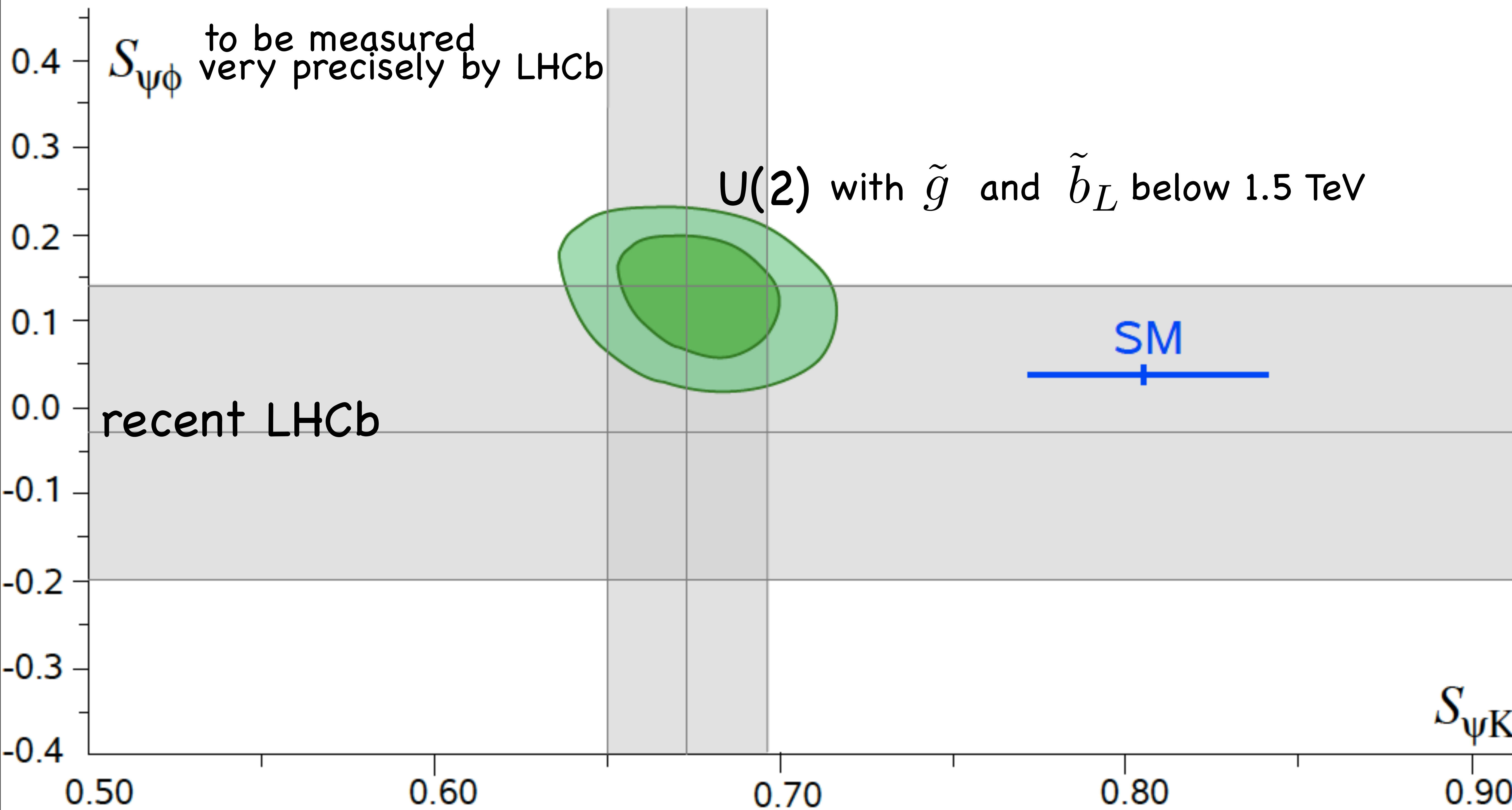
ΔM_s

$S_{B_d \to \Psi K_S}$

ϵ_K



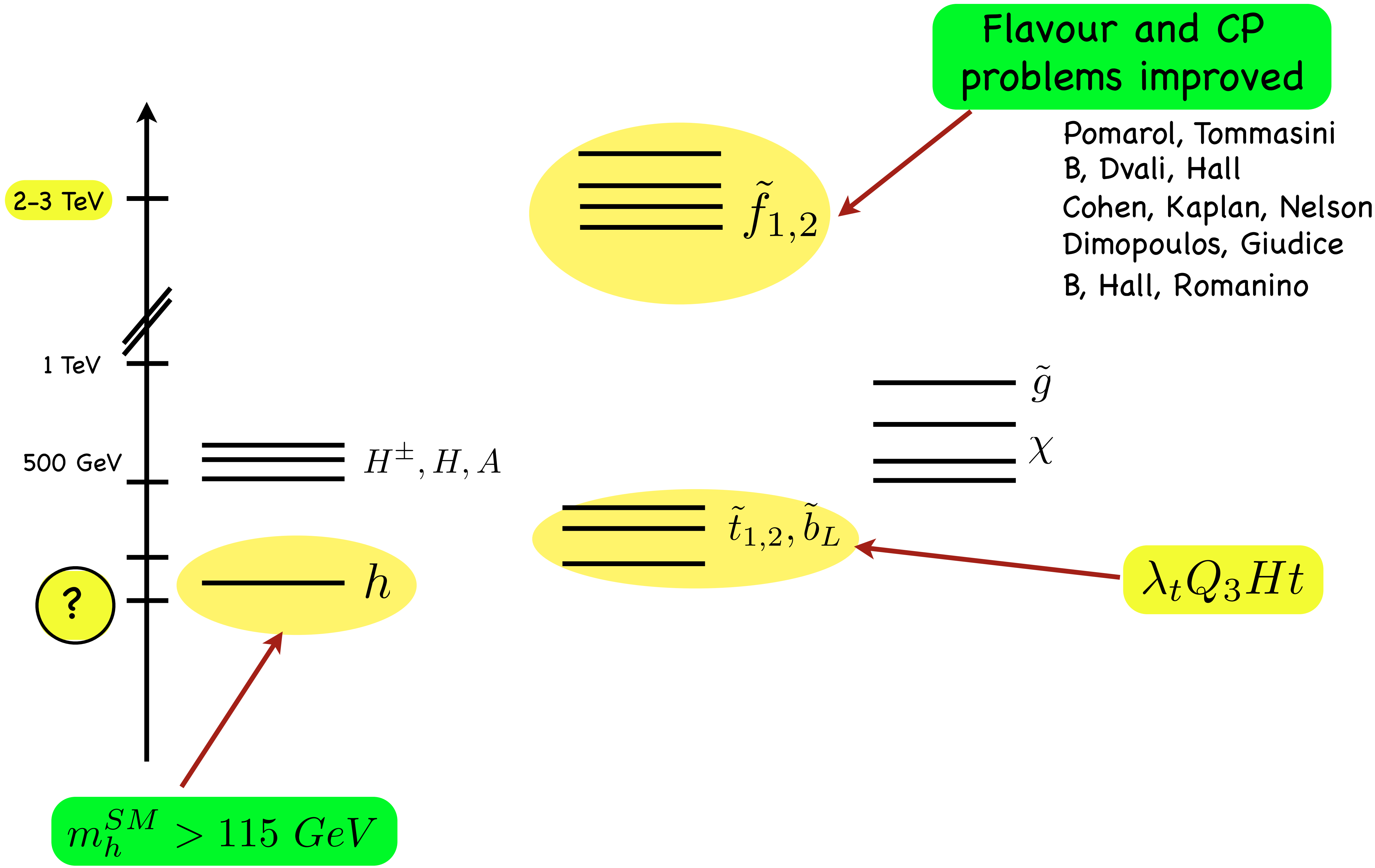
CPV in $\Delta B = 2$



B, Isidori, Jones-Perez, Lodone, Straub

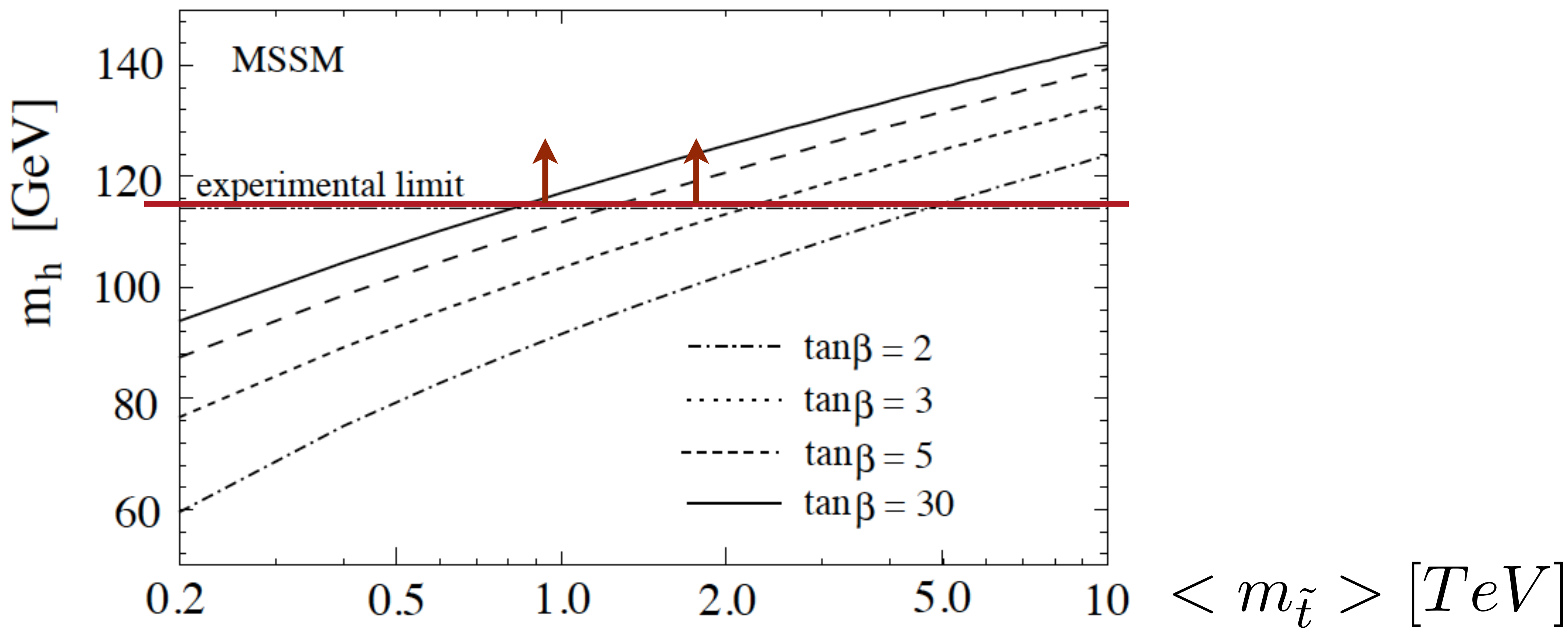
"Beyond mSUGRA"

(well before the LHC)



Where is the supersymmetric Higgs boson?

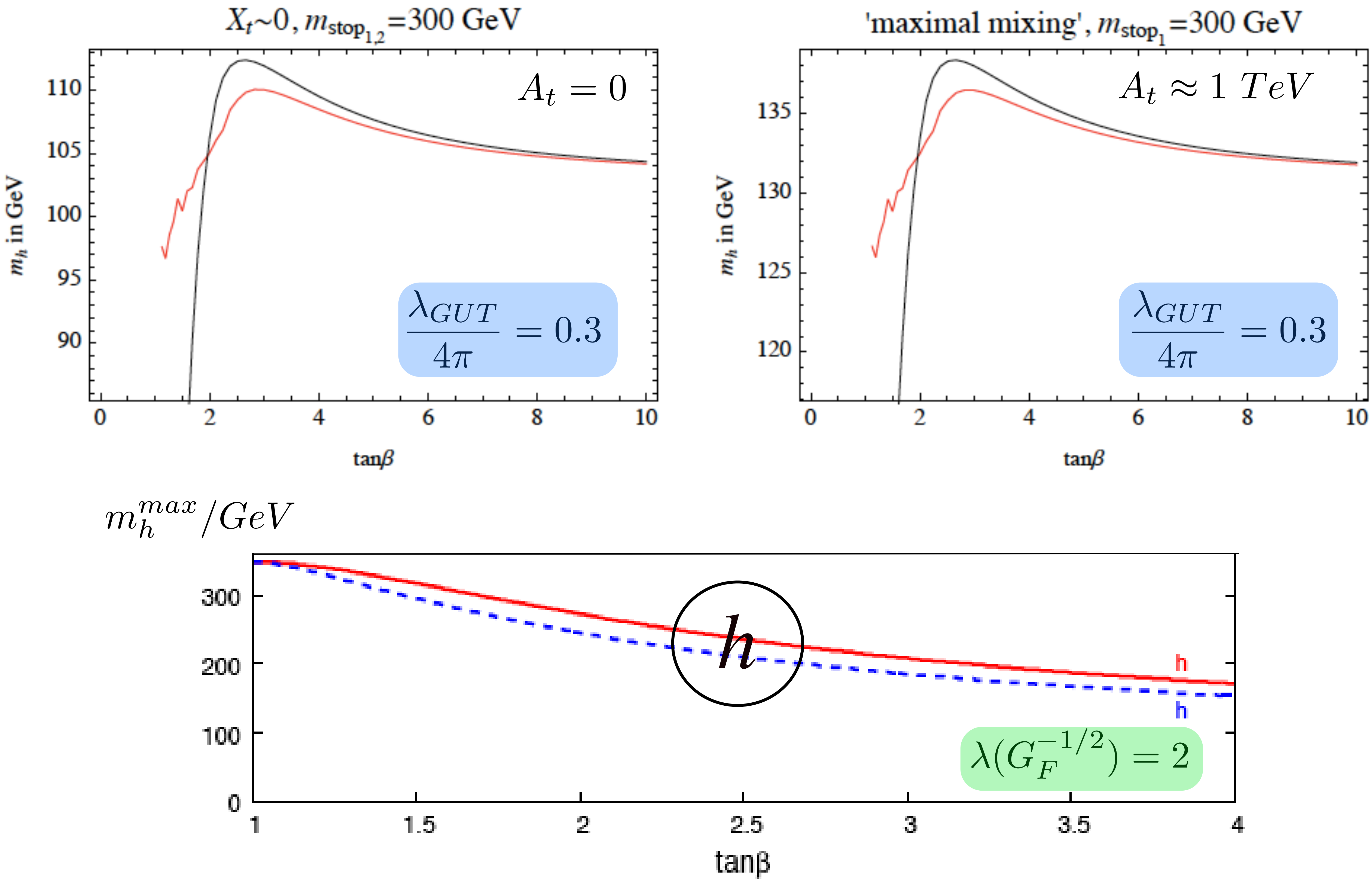
MSSM



⇒ Take large tanβ (muon anomaly?) and large stop mass
but swallow, e.g. in mSUGRA, a large contribution to M_Z ,
to be fine-tuned away

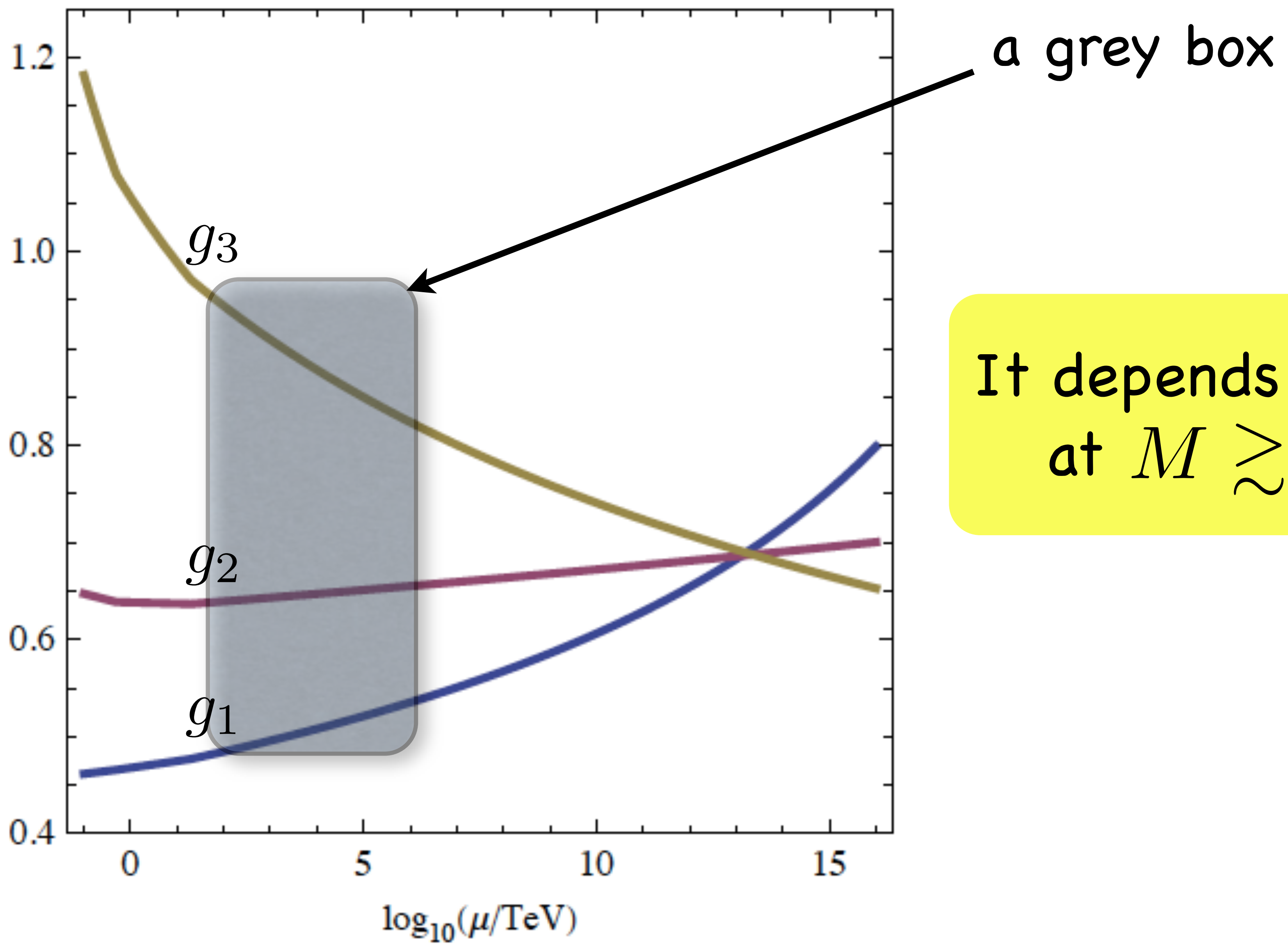
$$\Delta M_Z^2 \approx (2 \div 3) m_{\tilde{t}}^2 \geq 100\ M_Z^2$$

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



* = before mixing

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

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)
  - → $h \to aa \to (b\bar{b},\ \tau\bar{\tau},\ c\bar{c})^2$
  - → $h \to \chi_{DM}\chi_{DM}$

  especially if $\lambda(G_F^{-1/2}) \approx 2$

- ✶ Dark Matter: relic abundance and detection affected

- ✶ Flavour and CPV signals (at low tanβ) ✓

$\lambda = 2, \quad \tan\beta = 1.5$

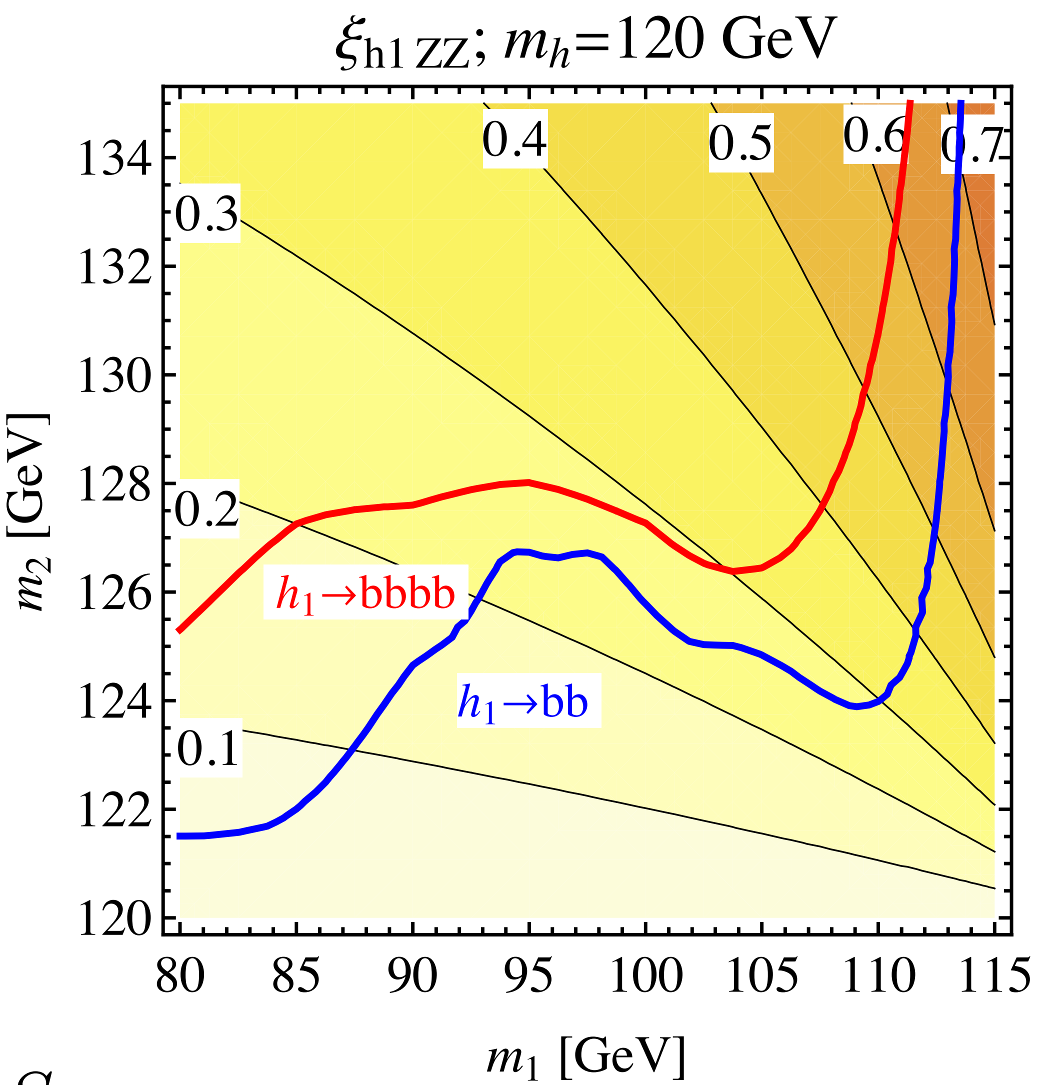
$k=-0.2$	μ (GeV)	m_H (GeV)	m_{s_1} (GeV)	m_{A_1} (GeV)	$m_{\chi 1}$ (GeV)
a	180	340	252	103	130
b	105	180	163	95	77
c	130	200	173	108	96
$k=-0.6$					
d	105	180	160	166	78
e	160	280	232	195	120

$k=-0.2$	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

$\lambda = 0.7$

after mixing



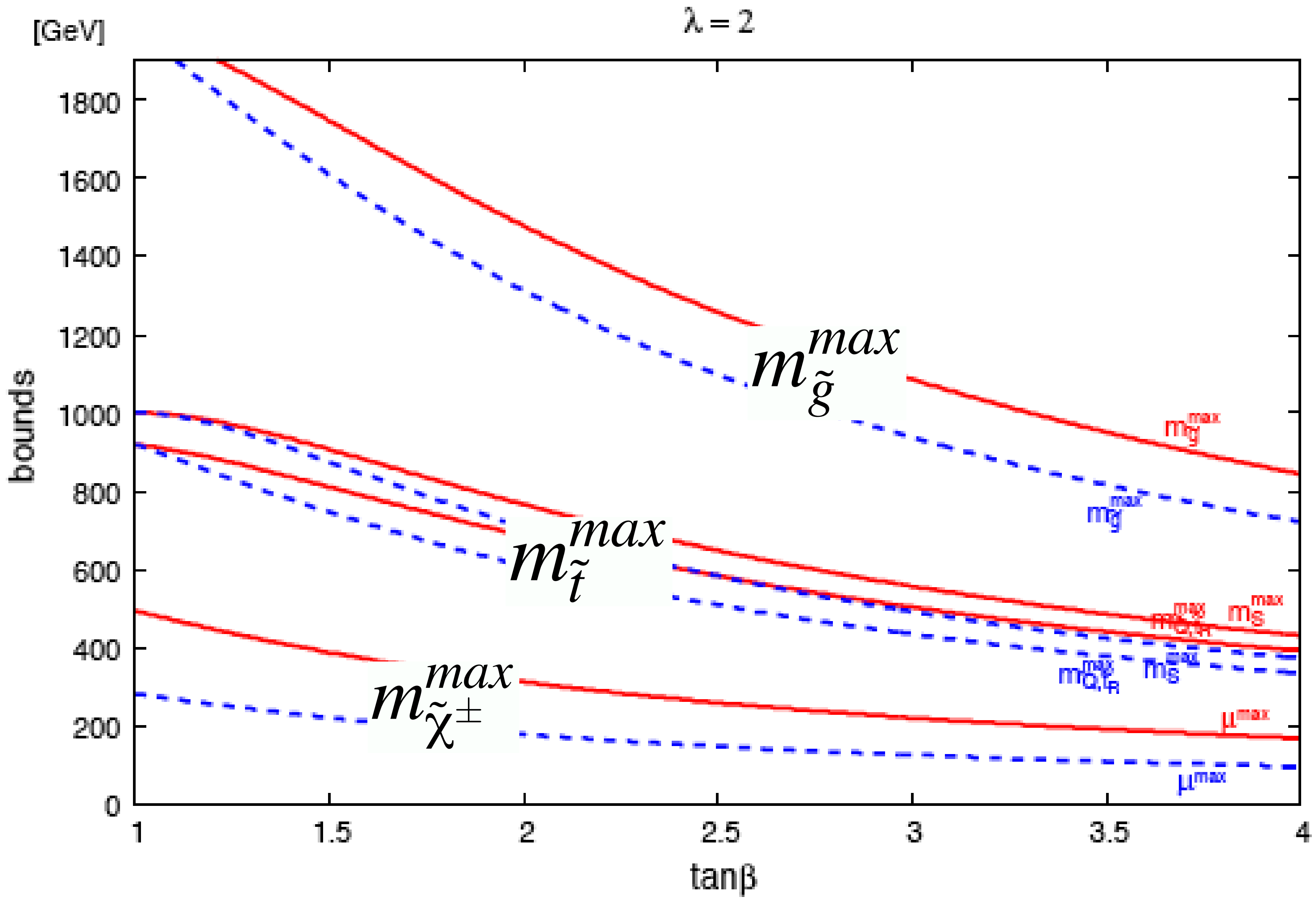
$$m_{S_3} > m_{S_2} > m_{S_1}$$

	Production coupling	Branching ratios
S_1	$\xi_{S_1tt}, \xi_{S_1VV} \lesssim 20\%$ (Fig. 8)	$BR(GG) \geq 98\%)$ $G \to b\bar{b}$
S_2	$\xi_{S_2tt}, \xi_{S_2VV} \simeq 100\%$	See Fig.9: $BR(\chi_1\chi_1) = 50 \div 90\%$ $BR(GG) \simeq 1 - BR(\chi_1\chi_1)$
S_3	$\xi_{S_3tt} \simeq 20\%$, ξ_{S_3VV} negligible	See Fig.9: $BR(\chi_i\chi_j) \simeq 35\%$ (of which 50% into $\chi_1\chi_1$) $BR(ZG) \simeq 30\%$ $BR(S_iS_j) \simeq 20\%$

B, Hall, Pappadopulo, Rychkov, Papaioannou

Particle spectrum (naturalness bounds)

λSUSY $\lambda = 2$



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

$\Lambda_{mess} = 100\ TeV$

B, Hall, Nomura, Rychkov

Summary

1. Crucial to know where $m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}$ are when $\tilde{q}_1,\ \tilde{q}_2$ are heavy (> 1 TeV)

2. The simplest way to be consistent with $m_h > 115\ GeV$ is to have $\Delta f = \lambda S H_1 H_2$, in which case beware of non-standard Higgs phenomenology

(At LHC1 perhaps 1 easier than 2)

Am I the only remaining nostalgic of supersymmetry?

What about you, Luciano?

Please: let's avoid the "hurry-up" sindrome

Flavour changing interactions

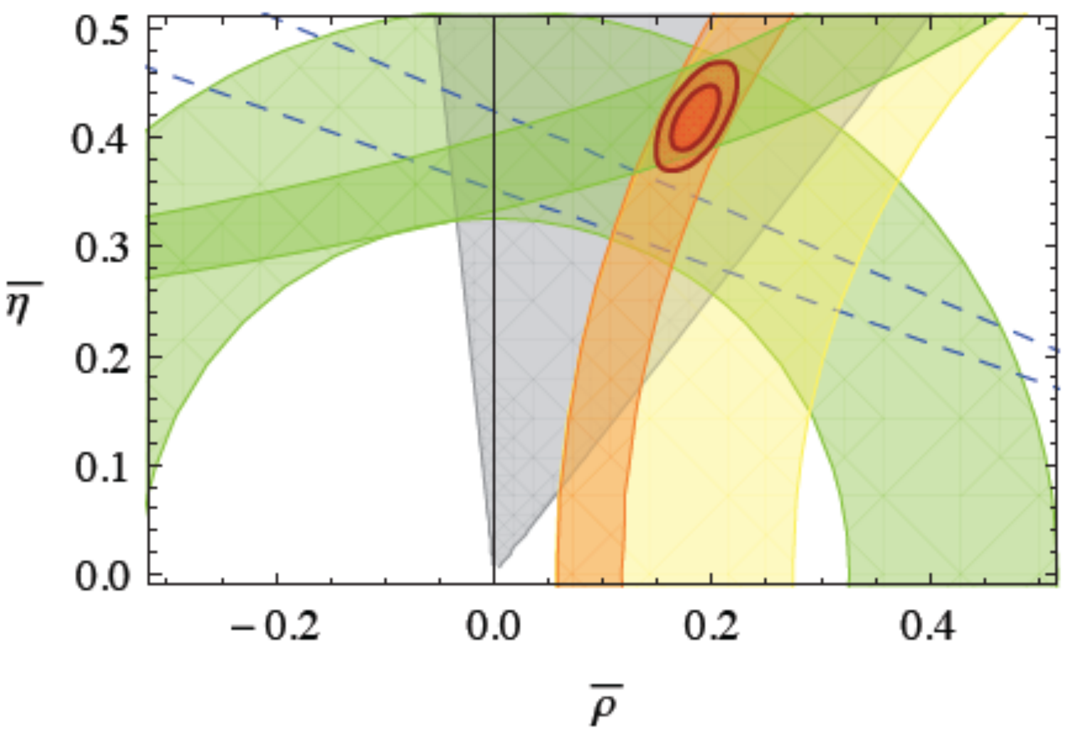
$\Delta F = 2$ - Our own SM fit

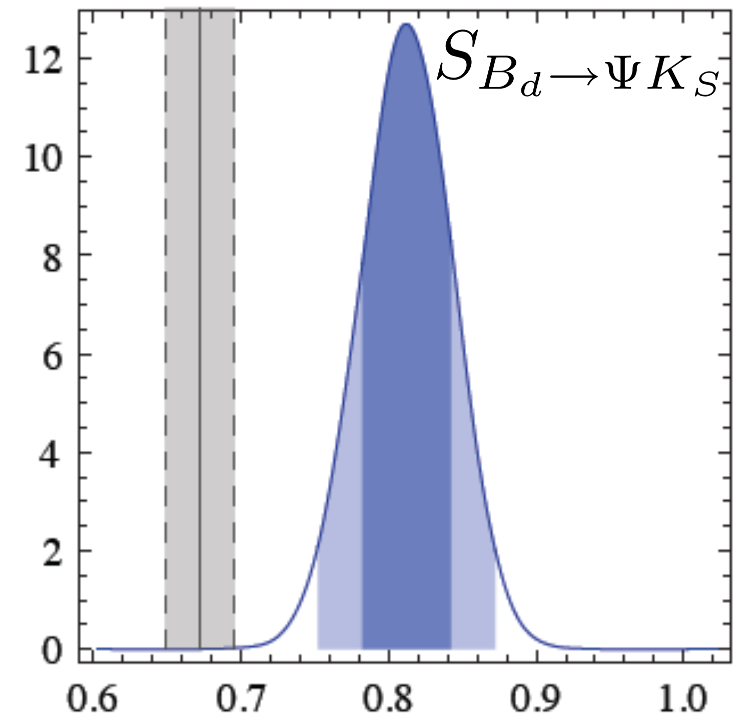
Tree level +

ΔM_d

ΔM_s

ϵ_K



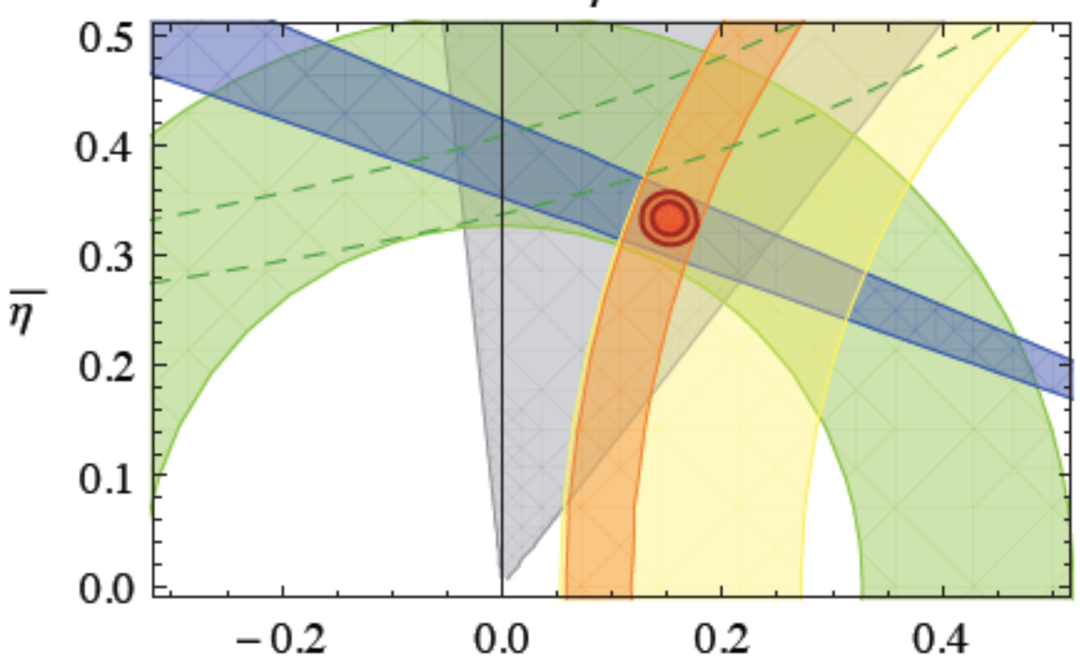


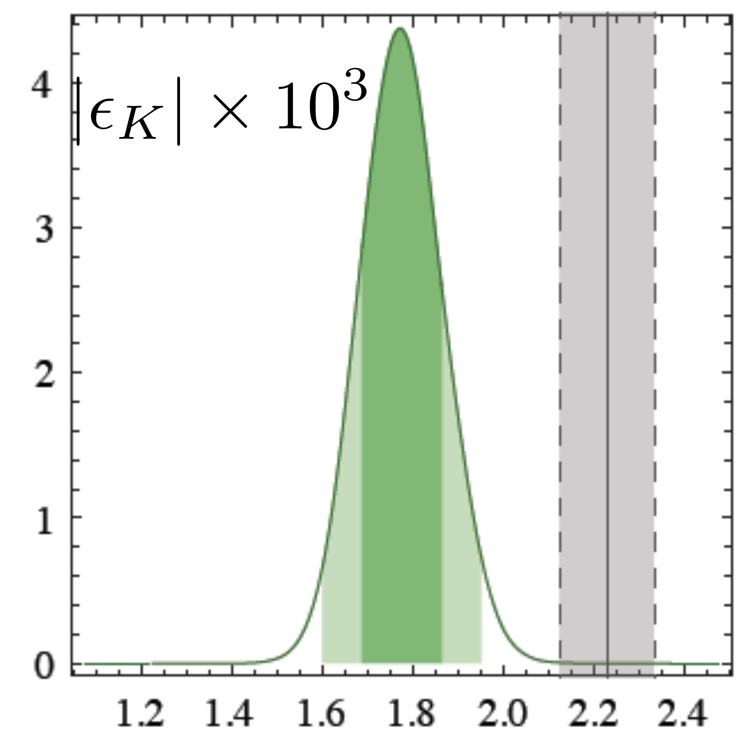
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$

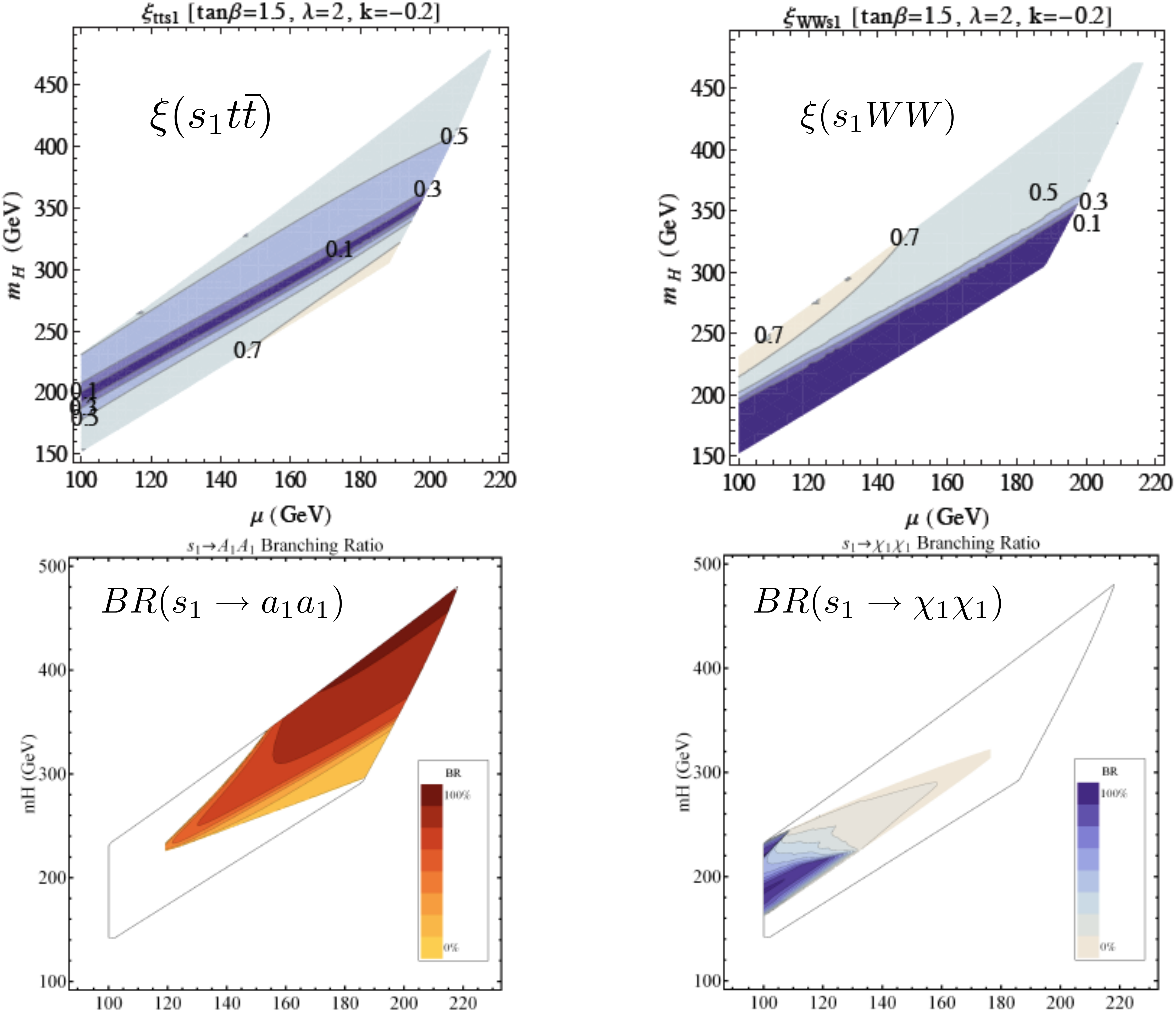




details subject to discussion

a hint of a potential problem for the SM

Lunghi, Soni
Buras, Guadagnoli
UT fit, CKM fit



(λSUSY with a R-invariant superpotential)

Bertuzzo, Farina

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, the 10^{120} vacua of string theory

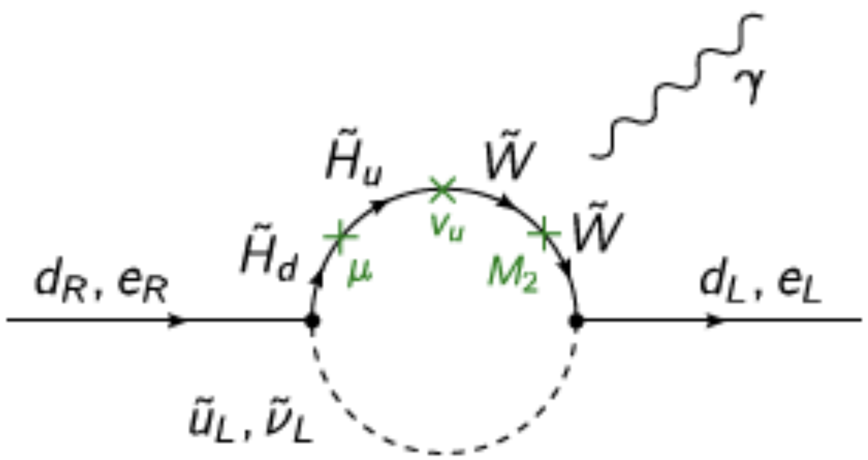
Every theorist should decide where to put his/her money

Aaahhh!! The happy experimentalists!

Electric Dipole Moments with flavour blind phases only

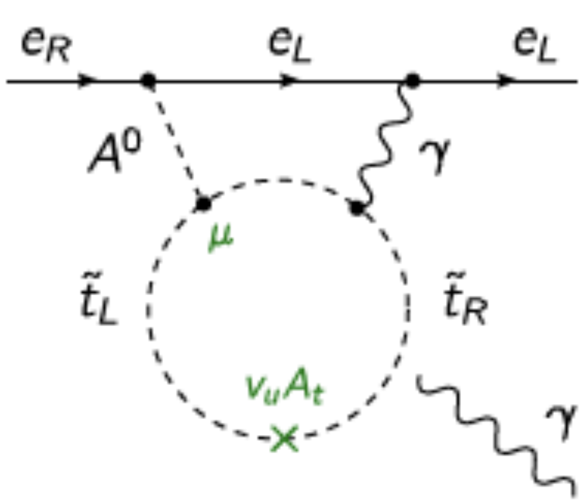
Flavour blind phases lead to contributions to electric dipole moments.

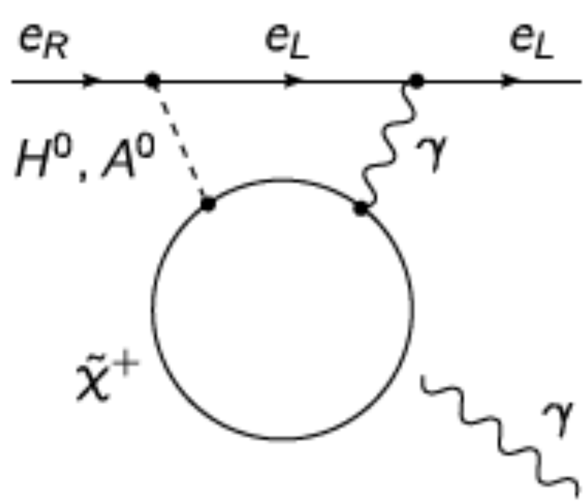
$$\text{Exp.:} \qquad |d_e| < 1.6\times10^{-27}\ e\,\text{cm}\,, \qquad |d_n| < 2.9\times10^{-26}\ e\,\text{cm}$$



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

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



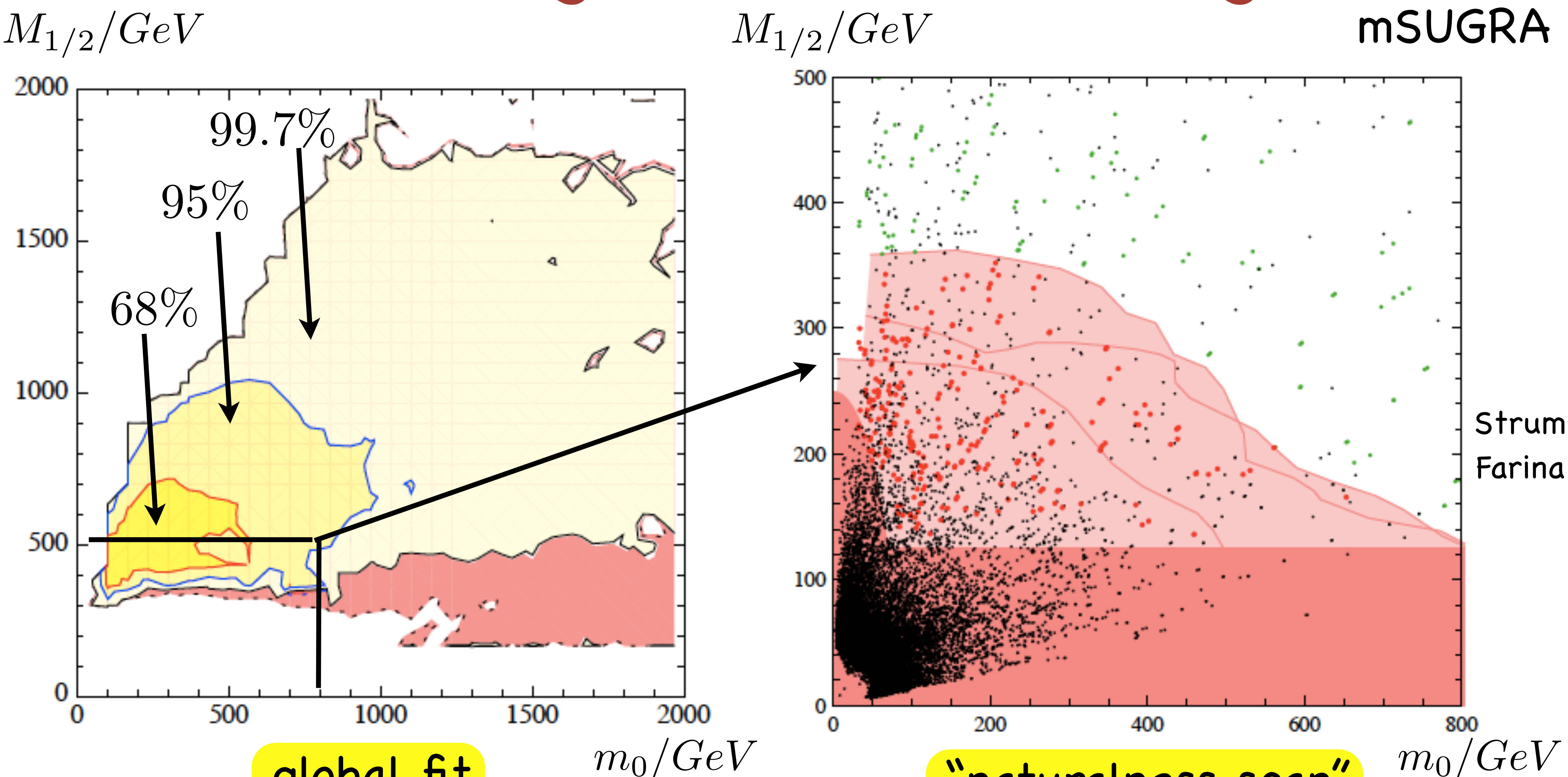


2-loop contributions lead to effects in the ballpark of the experimental bound

B, Lodone, Straub

fine-tuning or not fine-tuning?

mSUGRA



Strumia Farina et al

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?

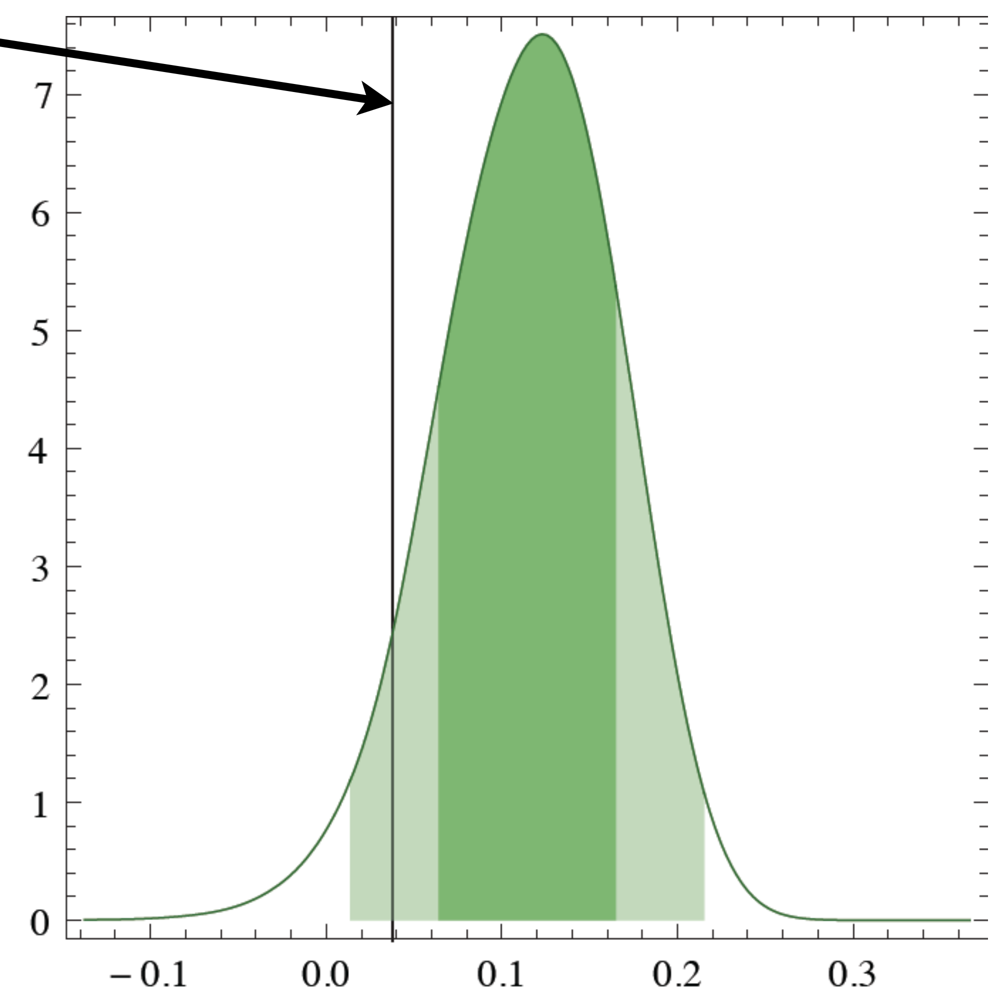
Is mSUGRA true?

mSUGRA still a benchmark, but...

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]
$\gamma_{\rm CKM}$	$(74 \pm 11)^\circ$	[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	$(0.507 \pm 0.004)\,\mathrm{ps}^{-1}$	[22]			
ΔM_s	$(17.77 \pm 0.12)\,\mathrm{ps}^{-1}$	[23]			

(SM: 0.041 ± 0.002)

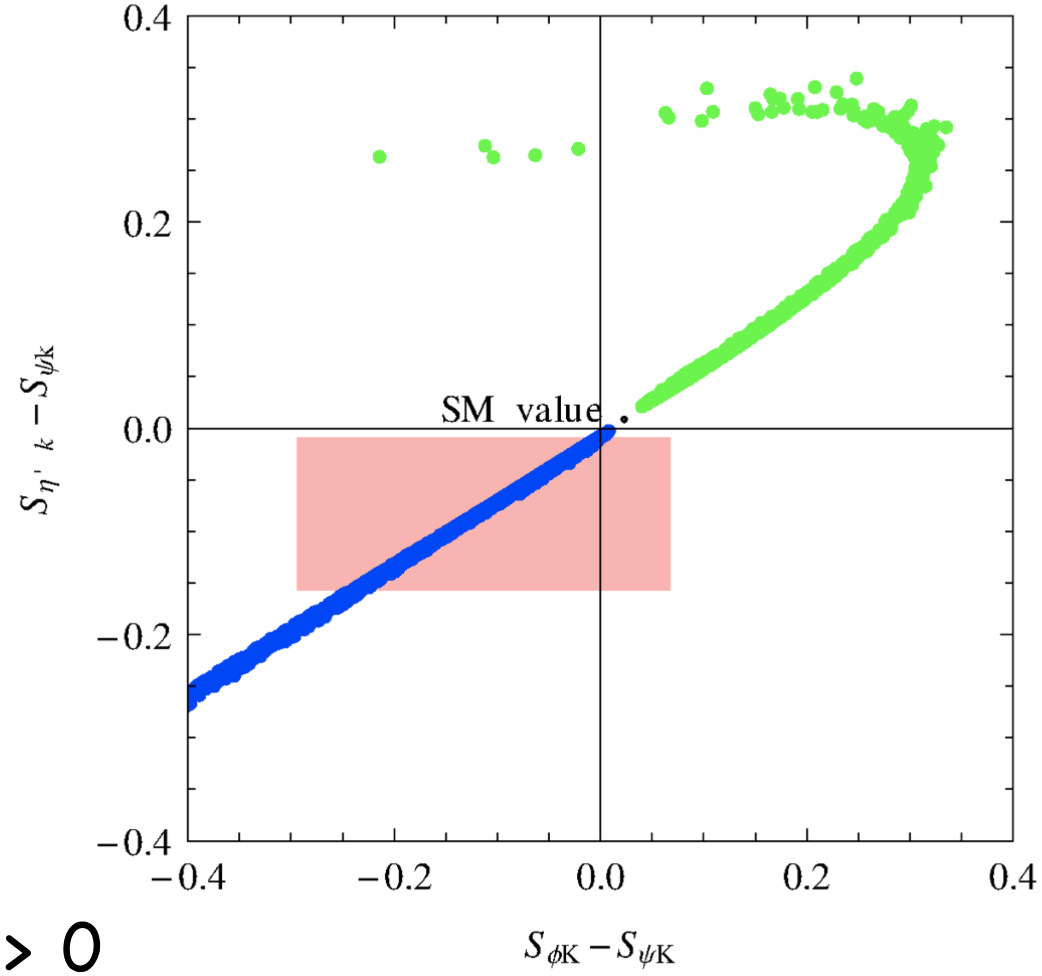


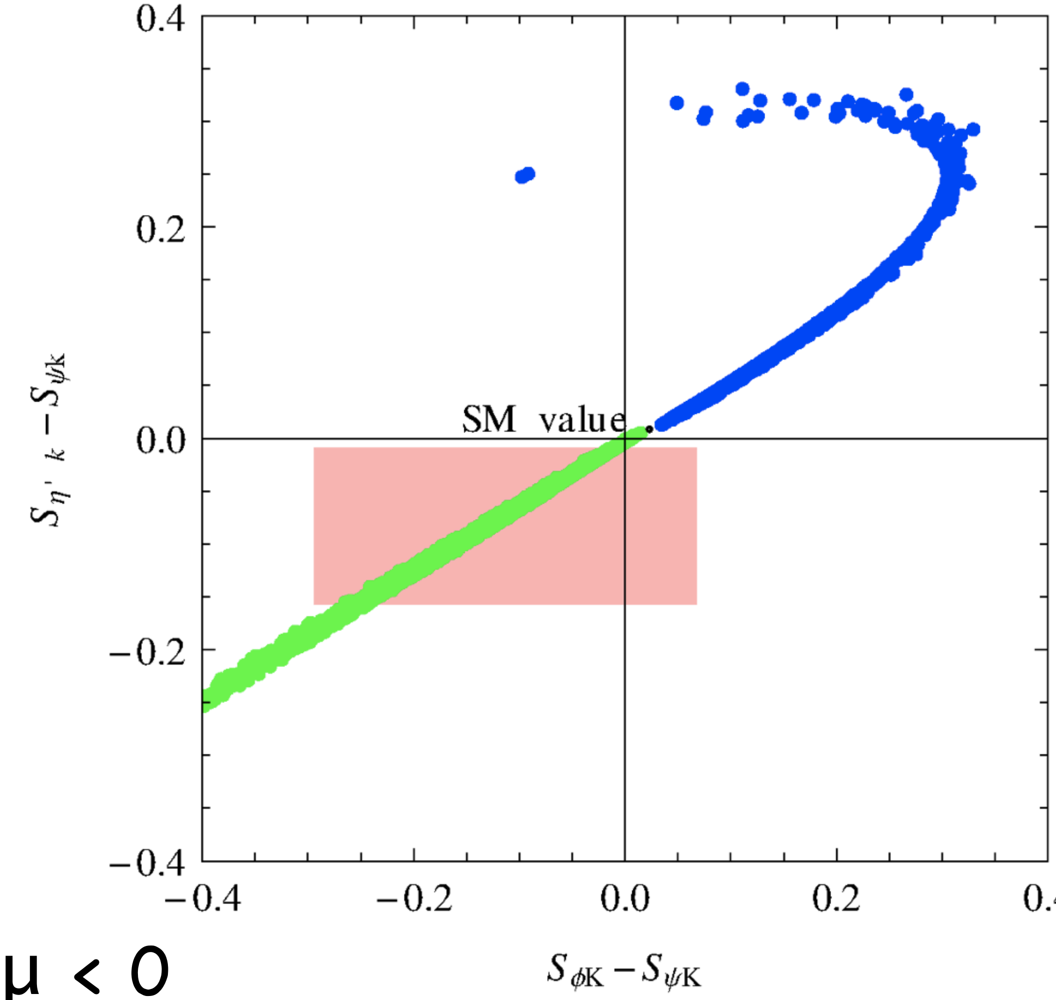
$U(2)^3$ prediction

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

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

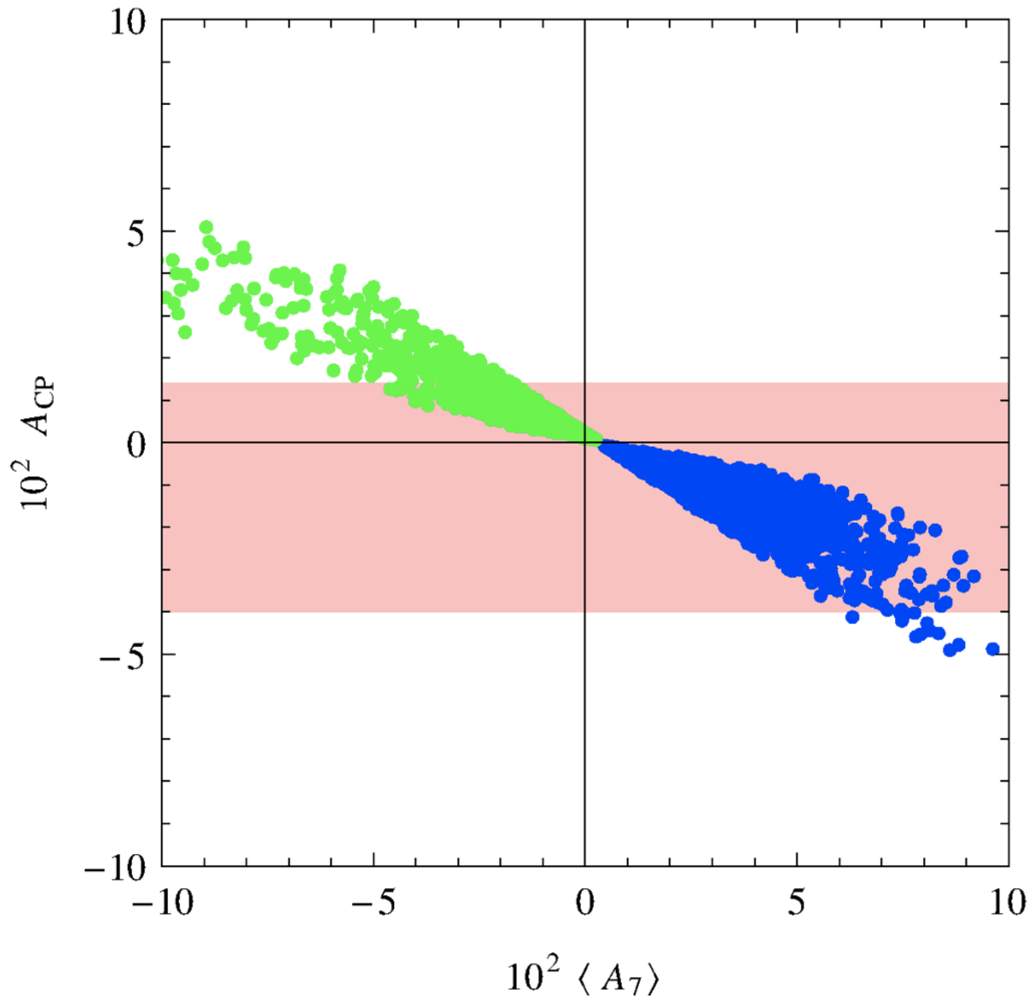
CPV in ΔB = 1

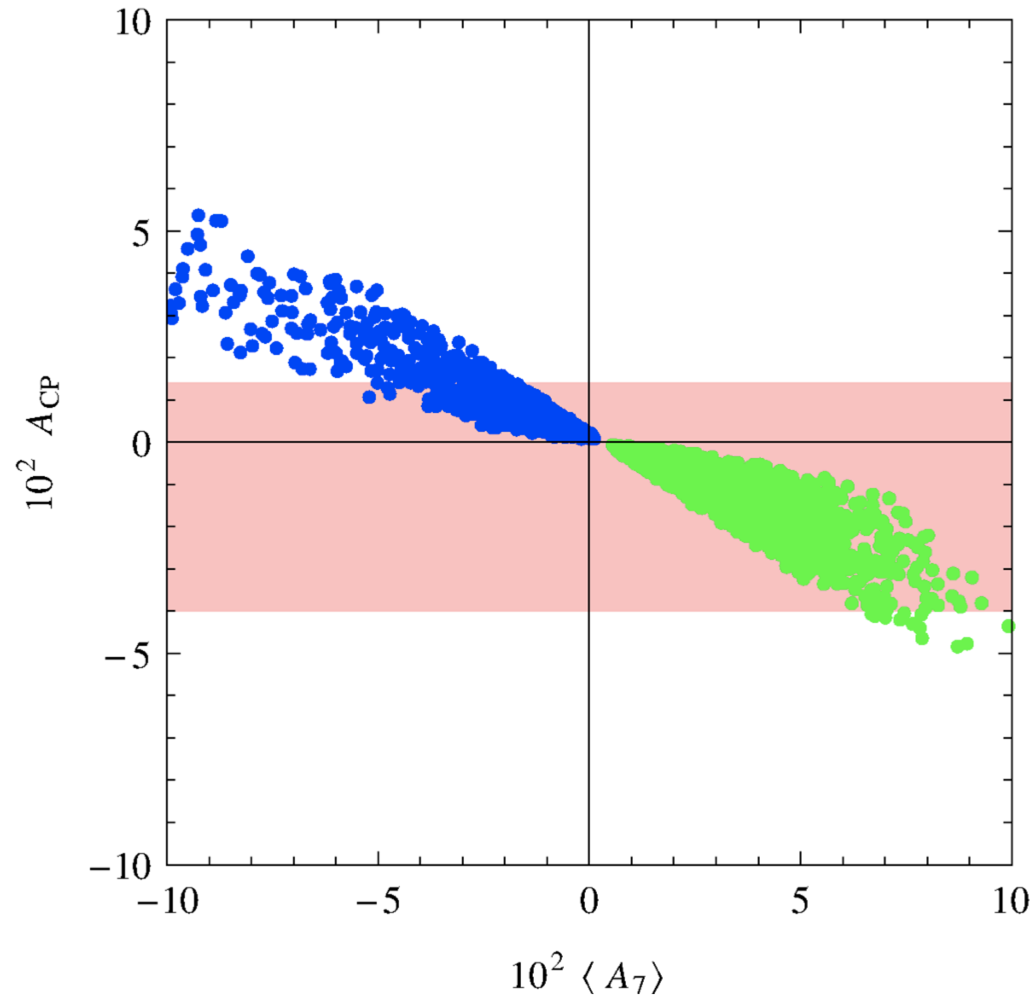




μ > 0

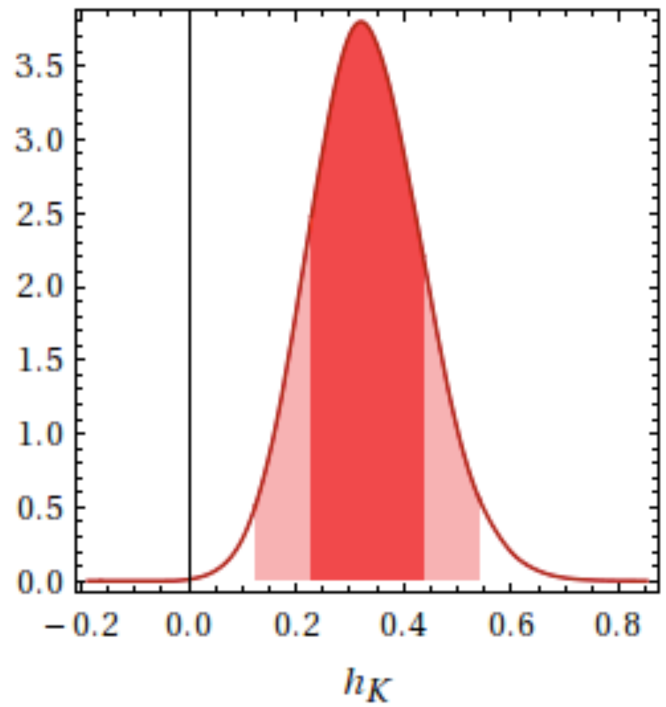
μ < 0

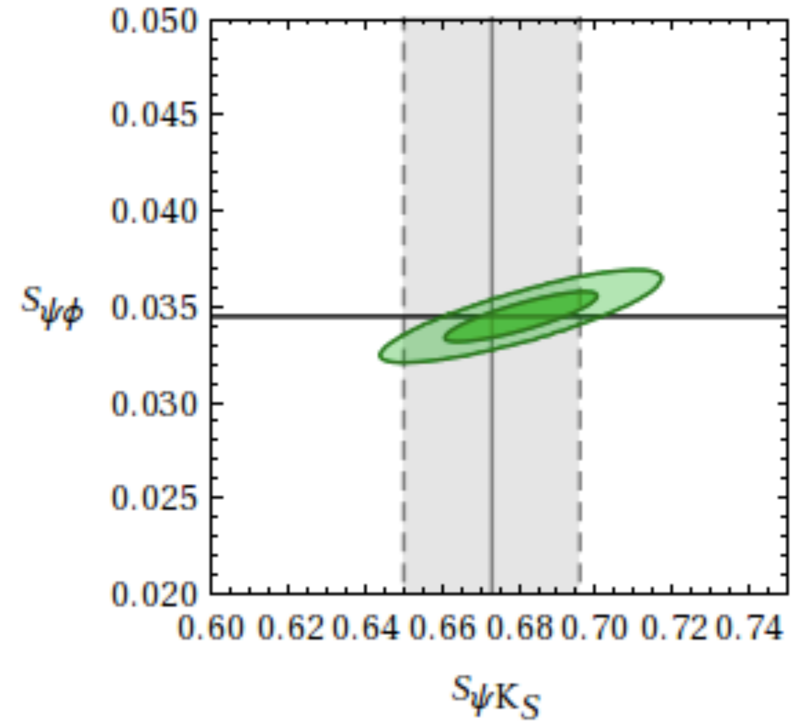




general $U(2)^3$

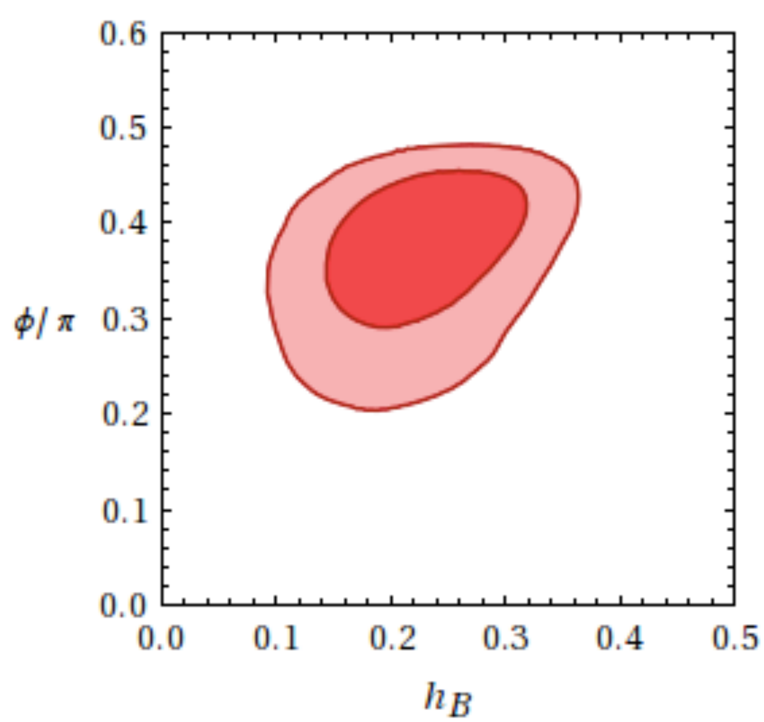
$$\mathcal{M}(K^0 \to \bar{K}^0) = \mathcal{M}^{SM}(K^0 \to \bar{K}^0)(1 + h_K)$$

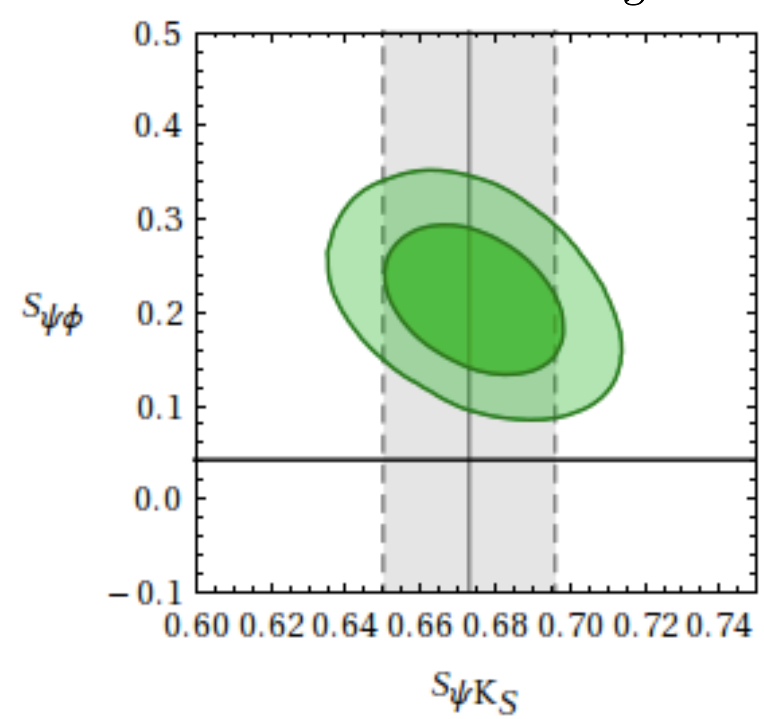




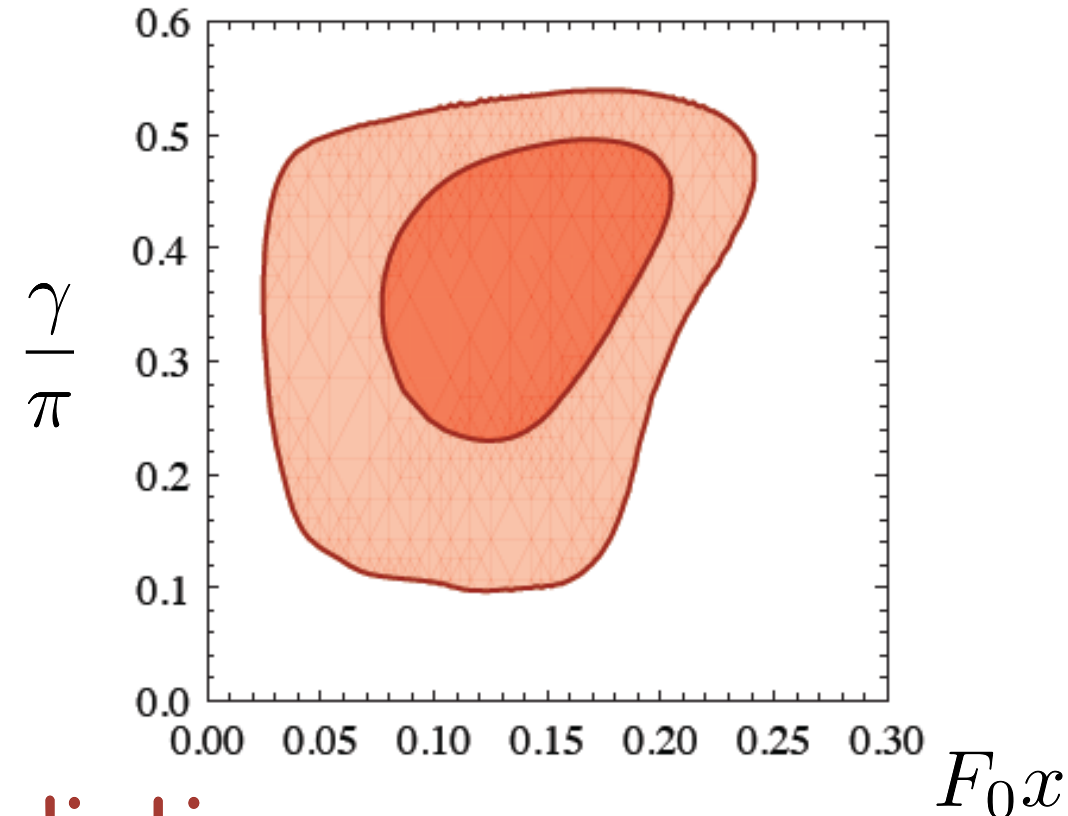
$$\mathcal{M}(B_d \to \bar{B}_d) = \mathcal{M}^{SM}(B_d \to \bar{B}_d)(1 + h_B e^{-2i\gamma})$$

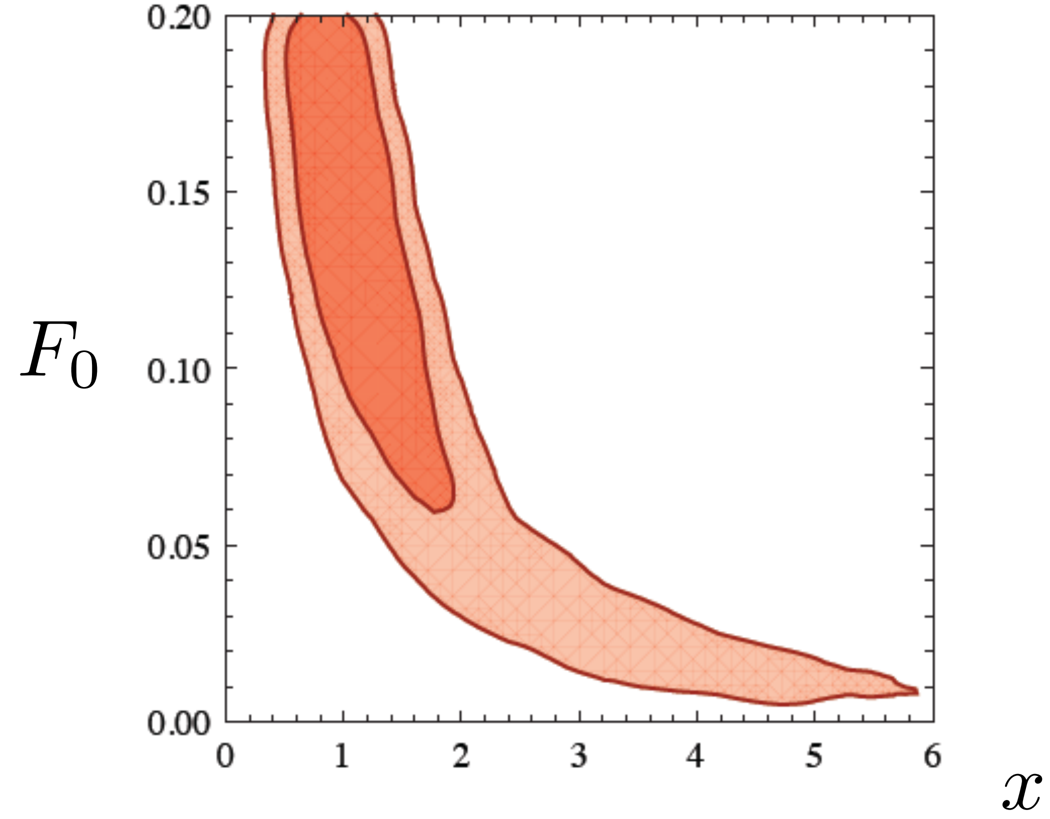
$$\frac{\mathcal{M}_d}{\mathcal{M}_s} = \frac{\mathcal{M}_d^{SM}}{\mathcal{M}_s^{SM}}$$



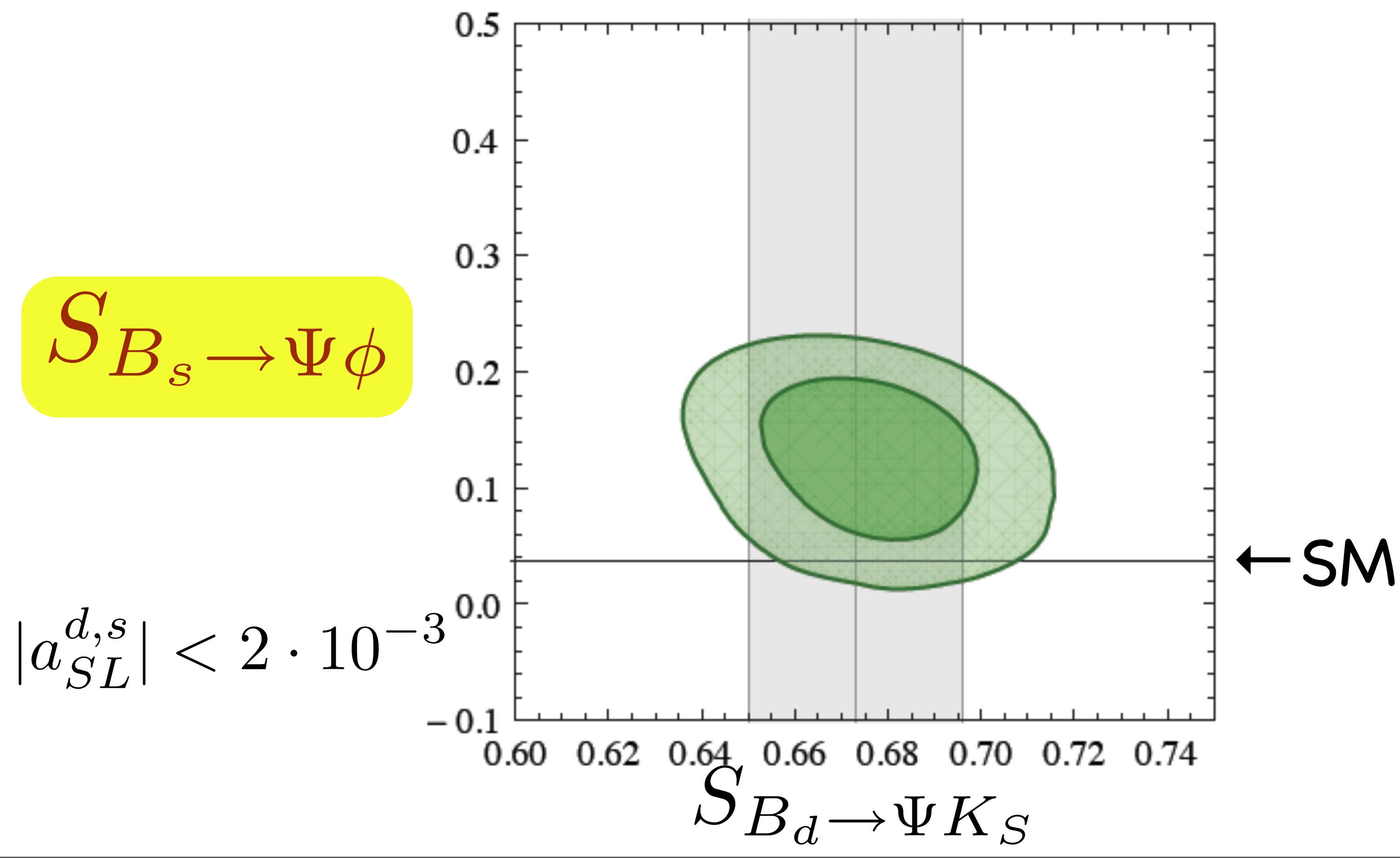


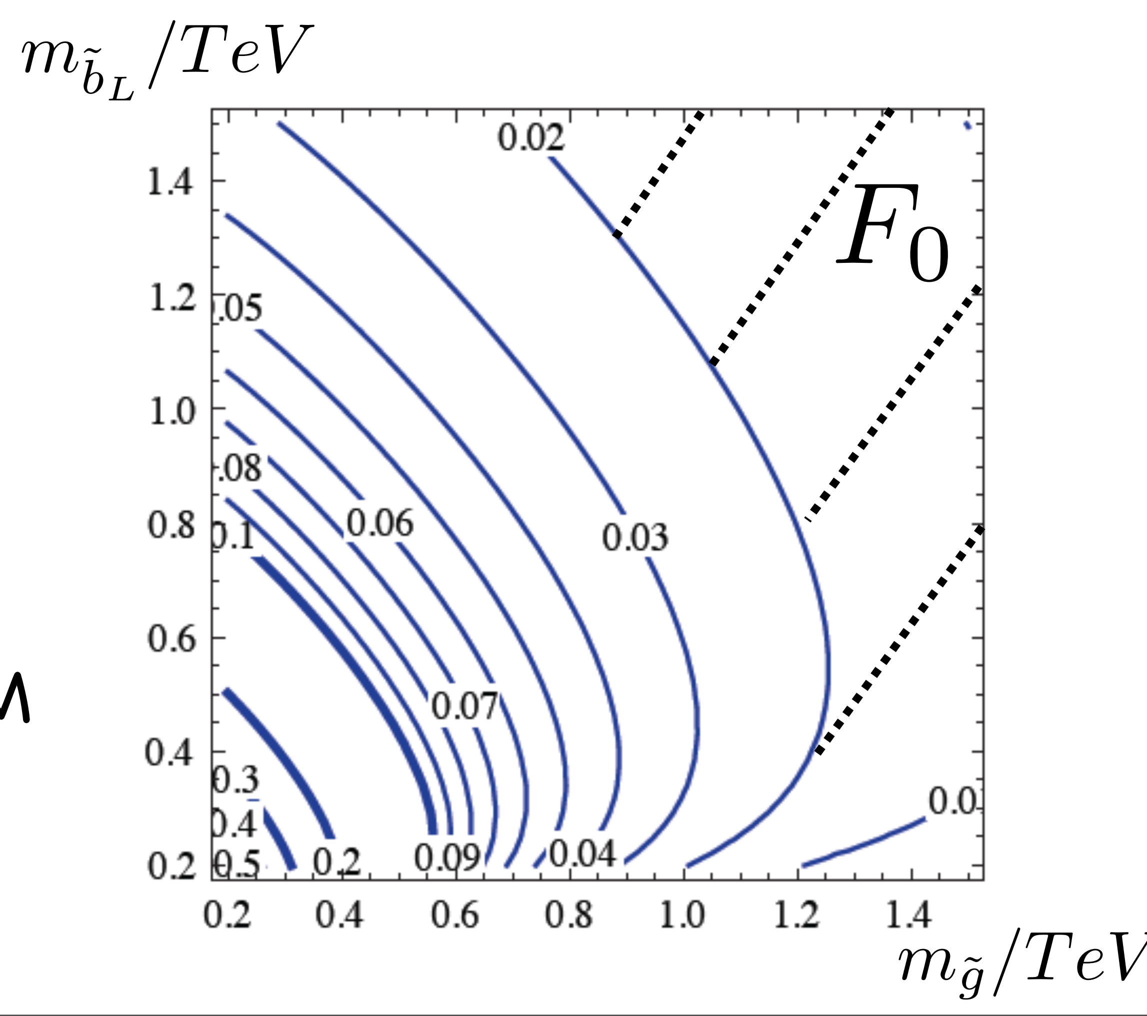
Constraints on extra parameters:





Prediction:





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:

$\mu \to e\gamma$

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

$\tau \to \mu\gamma$

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

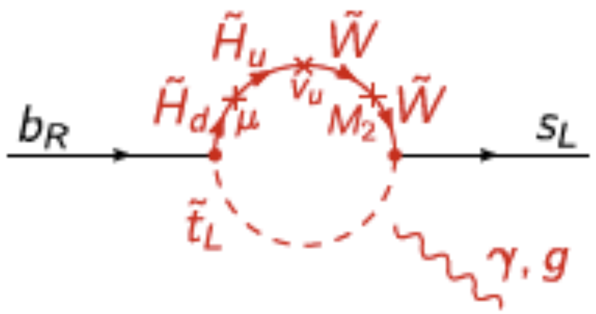
d_e

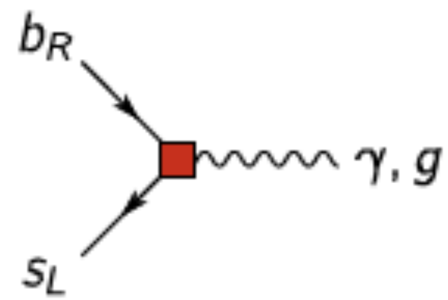
$$d_e \approx \sin\phi\ 10^{-27} e\ cm\sqrt{BR(\mu \to e\gamma)/10^{-12}}$$

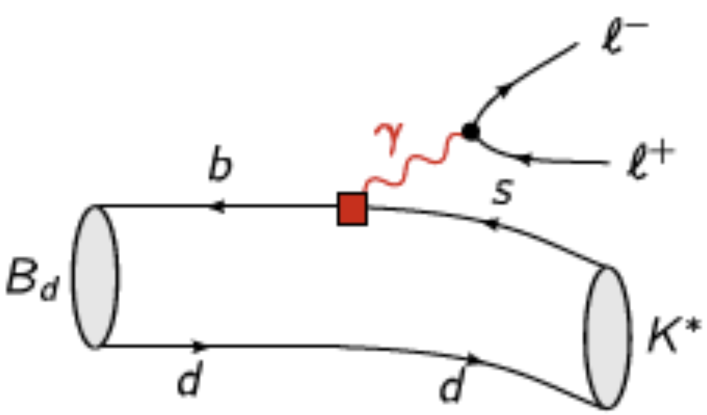
CP asymmetries in B-physics

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

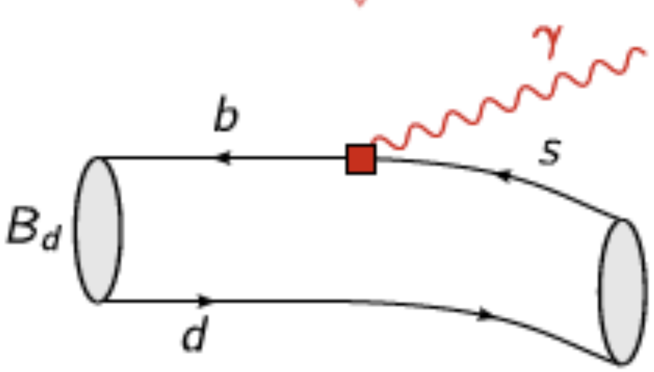
e.g.



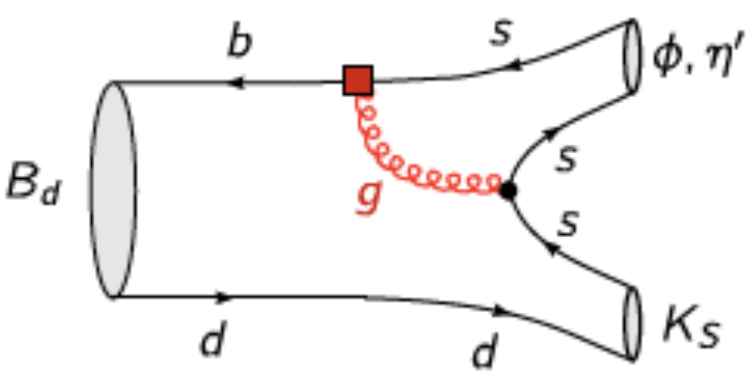




A_7, A_8 in $B \to K^* \ell^+ \ell^-$



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



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

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}

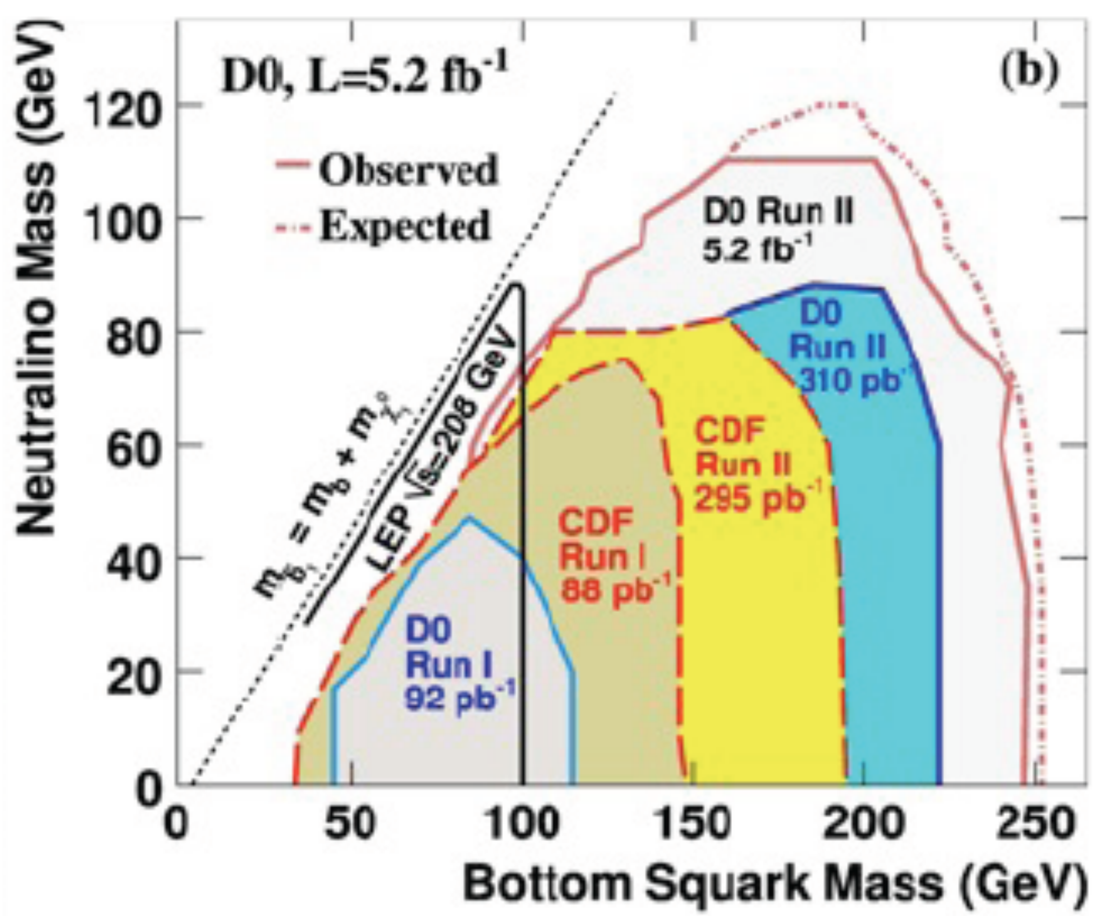
$$m_h \lesssim 130 \div 140\ GeV$$

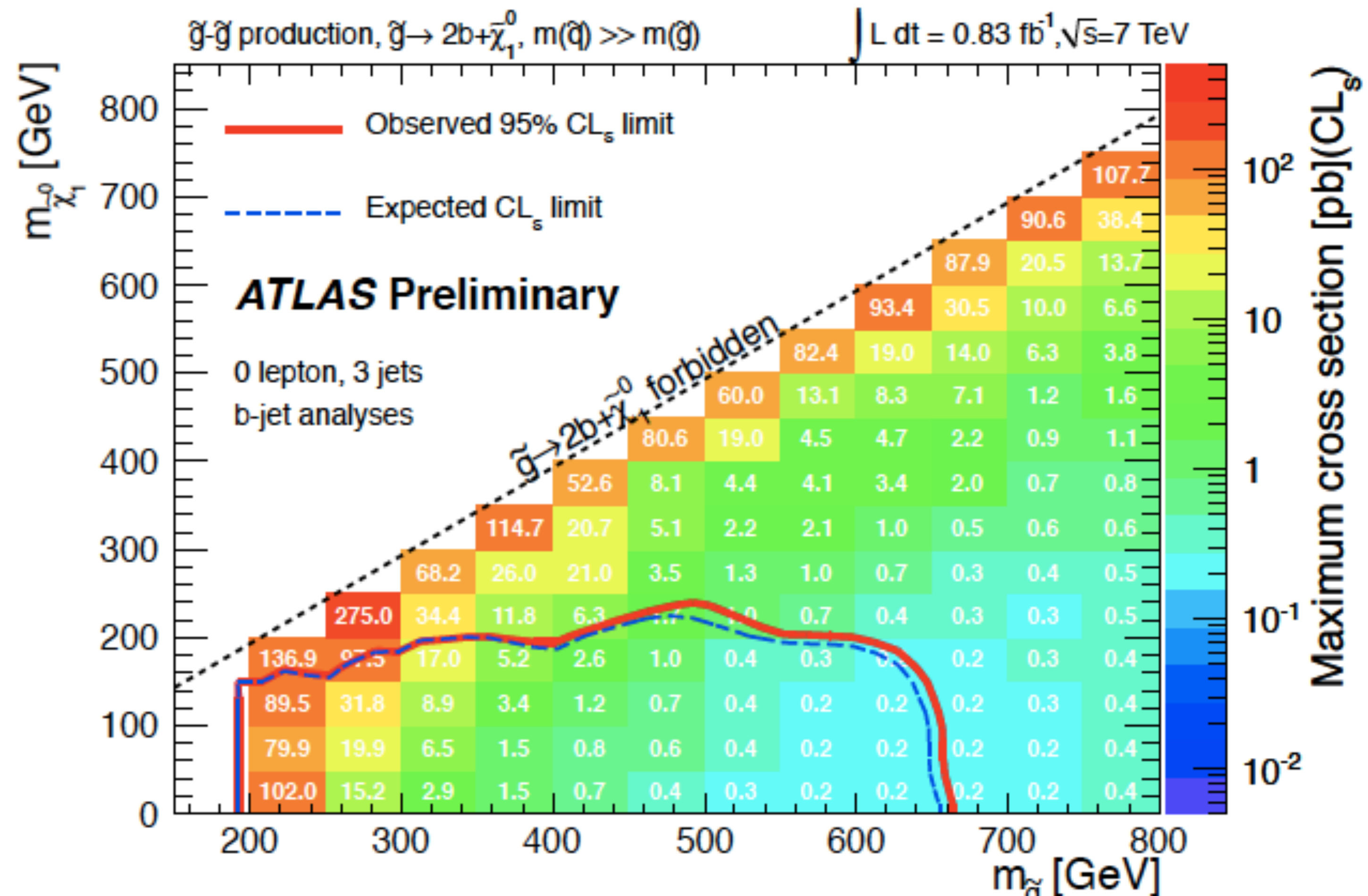
$\lambda \lesssim 2$ to preserve the EWPT

$$m_h \lesssim 250\ GeV$$

A "more ambitious" approach:

See my talk of last week


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+χ̃₁⁰, 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+χ̃₁⁰ forbidden
m_χ̃₁⁰ [GeV]
m_g̃ [GeV]
Maximum cross section [pb](CLs)