The plan

1. The Standard Model: the “indirect” informations
2. “Higgsless”
3. The Higgs boson as a PGB
4. Beyond mSUGRA

A fast supersymmetry primer

1. The general Lagrangian

$$\mathcal{L} = i\bar{\psi}\, \not{D}\psi - (m\psi\psi + h.c.) + |D_\mu\phi|^2 - m^2|\phi|^2$$

has a supersymmetry, under which $\psi \Leftrightarrow \phi$

which can be extended to include gauge inv. int.s

$$V^\alpha = (A_\mu^\alpha, \lambda^\alpha) \qquad \hat{\phi}_a = (\psi_a, \phi_a)$$

$$\mathcal{L} = \mathcal{L}^{gauge} + \mathcal{L}^{f}$$

$$\mathcal{L}^{f} = \sum_a |f_a|^2 + (f_{ab}\psi_a\psi_b + h.c.)$$

(R-symmetry)

$\Rightarrow$ No Λ^2 div.s, even after inclusion of appropriate "soft" breaking terms (and excluding trace-full U(1) factors)

$$\mathcal{L} = \mathcal{L}^{gauge} + \mathcal{L}^{f} + \mathcal{L}^{soft}$$

2. The general MSSM

Standard particles into supermultiplets + $\hat{H}_1, \hat{H}_2$

$$f = \lambda_U Q u H_2 + \lambda_D Q d H_1 + \lambda_E L e H_1 + \mu H_1 H_2$$

$$\mathcal{L}^{soft} = \Sigma_\alpha m_\alpha^2 |\phi_\alpha|^2 + (\Sigma_\beta A_\beta^0 f_\beta + \Sigma_i m_{1/2i} \tilde{g}_i \tilde{g}_i + h.c.)$$

3. mSUGRA

$$m_\alpha = m_0, \;\; m_{1/2i} = m_{1/2}, \; A_U = A_D = A_L \equiv A \;\; \text{universal at} \;\; M_{GUT}$$

$$A_\mu = B$$

(5 extra-par.s, as opposed to μ and λ of the SM)

LSP ≡ lightest neutralino ≡ χ^0 stable

3. The MSSM Higgs sector reviewed

$$H_1 \equiv \begin{pmatrix} h_1^0 \\ h^- \end{pmatrix} \in (\underline{\mathbf{2}})_{Y=-1/2}, \qquad H_2 \equiv \begin{pmatrix} h^+ \\ h_2^0 \end{pmatrix} \in (\underline{\mathbf{2}})_{Y=1/2} \qquad f = \mu\, H_1 H_2$$

(d,u) $\Leftrightarrow$ (1,2)

$$V = \widetilde{m}^2_{H_u} H_u^\dagger H_u + \widetilde{m}^2_{H_d} H_d^\dagger H_d - \left(m^2_{ud} H_u H_d + \text{ h.c. } \right)$$
$$+ \frac{g^2}{8} \left[(H_u^\dagger H_u + H_d^\dagger H_d)^2 - 4 (H_u H_d)^\dagger (H_u H_d) \right] + \frac{g'^2}{8} (H_u^\dagger H_u - H_d^\dagger H_d)^2$$

By minimizing the potential:

1. e.m and CP always unbroken
2. In a range of the par.s:

$$H_1 = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \qquad H_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad \tan\beta \equiv \frac{v_2}{v_1} \qquad v = \sqrt{v_1^2 + v_2^2} = 175\ GeV$$

Parameter counting:

$$\tilde{m}_1^2,\ \tilde{m}_2^2,\ m_{12}^2 \Rightarrow v,\ \tan\beta \quad + 1 \text{ extra } (+ 3^{rd} \text{generation})$$

The physical Higgs bosons

A simple counting:

2x4 - (2+1) = 5 = 2 + 1 + 1 + 1

$H^{\pm}$ h H A

Tree level

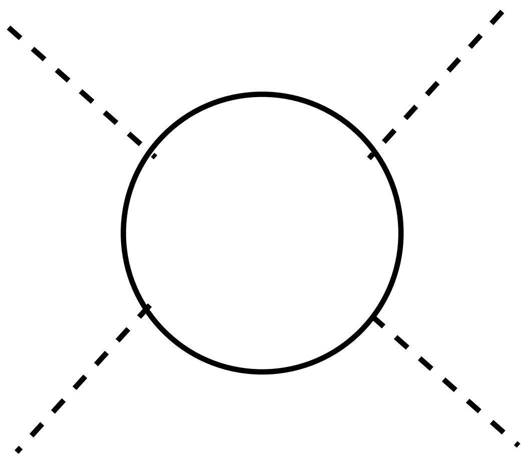
$$m^2_{h,H} = \frac{1}{2}\left[m^2_Z + m^2_A \mp \sqrt{(m^2_A - m^2_Z)^2 + 4m^2_A m^2_Z \sin^2 2\beta}\right]$$

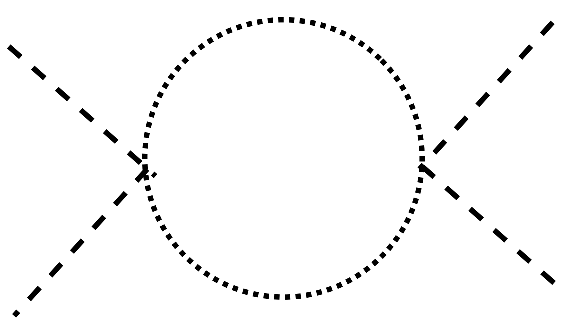
$$m^2_{H^\pm} = m^2_A + m^2_W$$

$$\Rightarrow \; m^2_h \simeq M^2_Z \cos^2 2\beta$$

Including top-loop corrections

$$m^2_h \simeq M^2_Z \cos^2 2\beta + \frac{3G_F m^4_t}{\sqrt{2}\pi^2}\left[\log\frac{m^2_{\tilde{t}}}{m^2_t} + \frac{A^2_t}{m^2_{\tilde{t}}}\left(1 - \frac{A^2_t}{12 m^2_{\tilde{t}}}\right)\right]$$





The key equations

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

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

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

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

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

see Dimopoulos, Giudice for SUGRA-mediation

E.g., take simple supergravity and $\tan\beta = 10$

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

by running from M_G down to M_Z

$$M_Z^2 \simeq -1.9\,\mu^2(M_G) + 5.9\,M_3^2(M_G) + 1.5\,m_{\tilde{t}}^2(M_G)$$

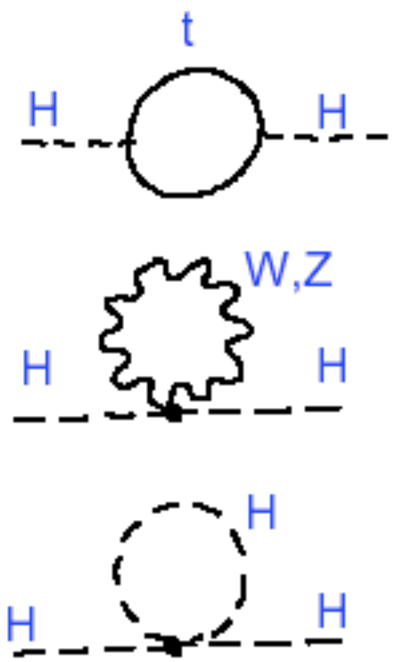
with also

$$m_{\tilde{t}}^2(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m_{\tilde{t}}^2(M_G) + 0.2 A_t(M_G) M_3(M_G)$$

$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

The Higgs boson mass and the fine-tuning

$$V = -\mu^2 H^2 + \lambda H^4 \qquad\qquad m_h^2 = 2\mu^2 = \frac{\lambda}{2\sqrt{2}} G_F^{-1}$$



From loops: $\delta\mu^2 \propto (\lambda_t^2, g^2) m_s^2$

which sets the naturalness upper bounds on m_s^2

for fixed Higgs boson mass, or fixed λ

IF $\lambda \to a^2 \lambda$ then

$$m_h \to a m_h$$

$$m_s^{max} \to a m_s^{max}$$

$$\frac{1}{\Delta} \to a^2 \frac{1}{\Delta}$$

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)

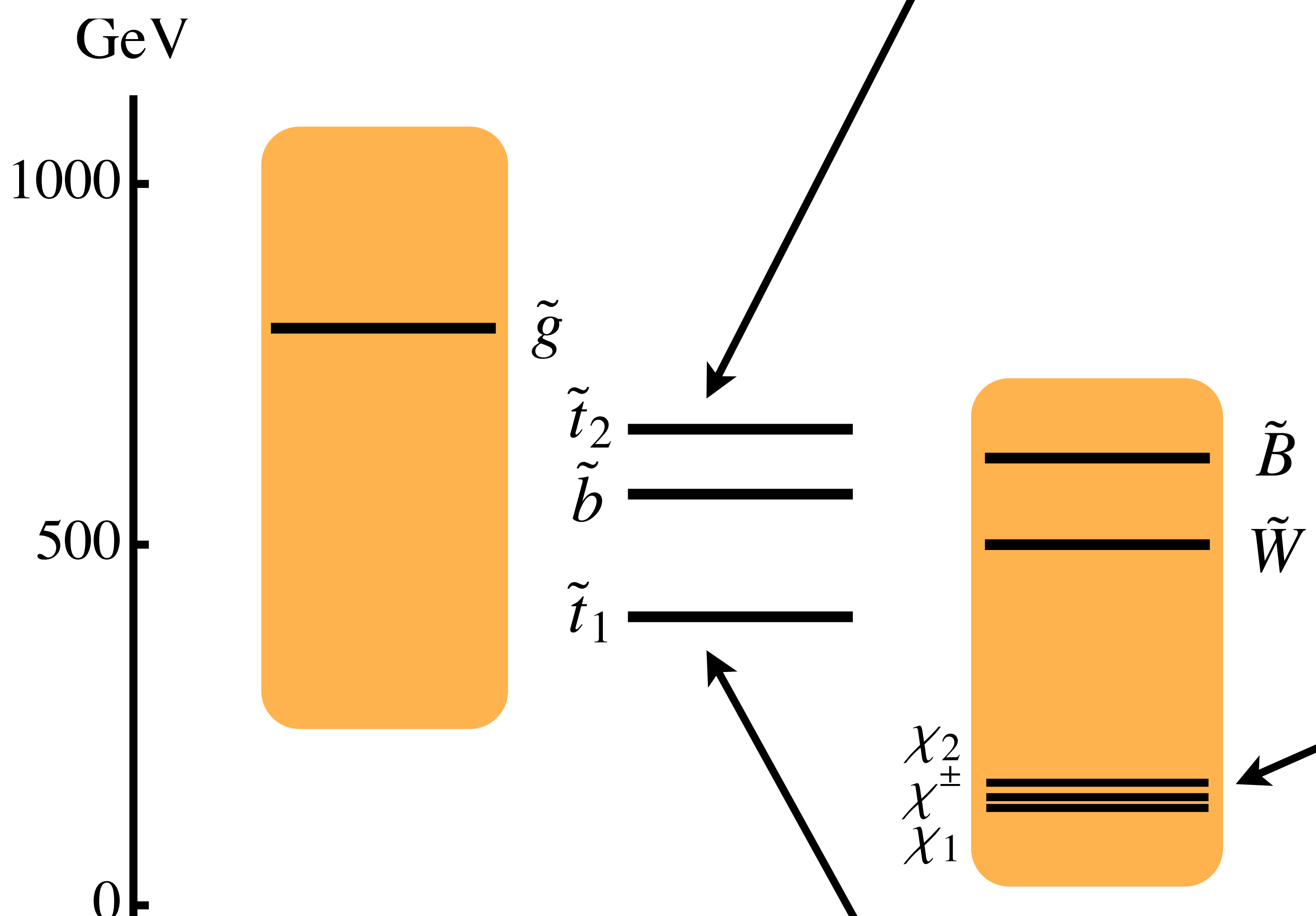
A hard and embarrassing question,
but a clearly inescapable one

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

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

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

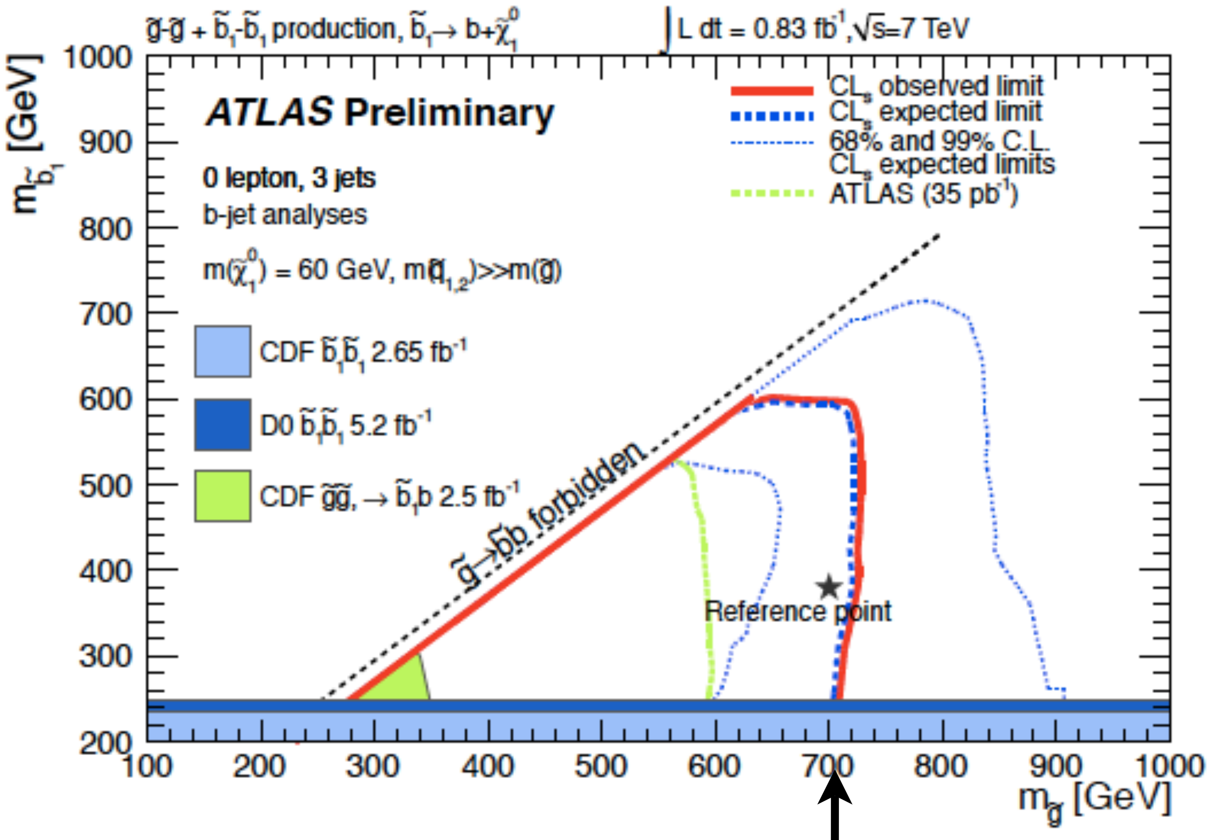
with rates determined by a single BR

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

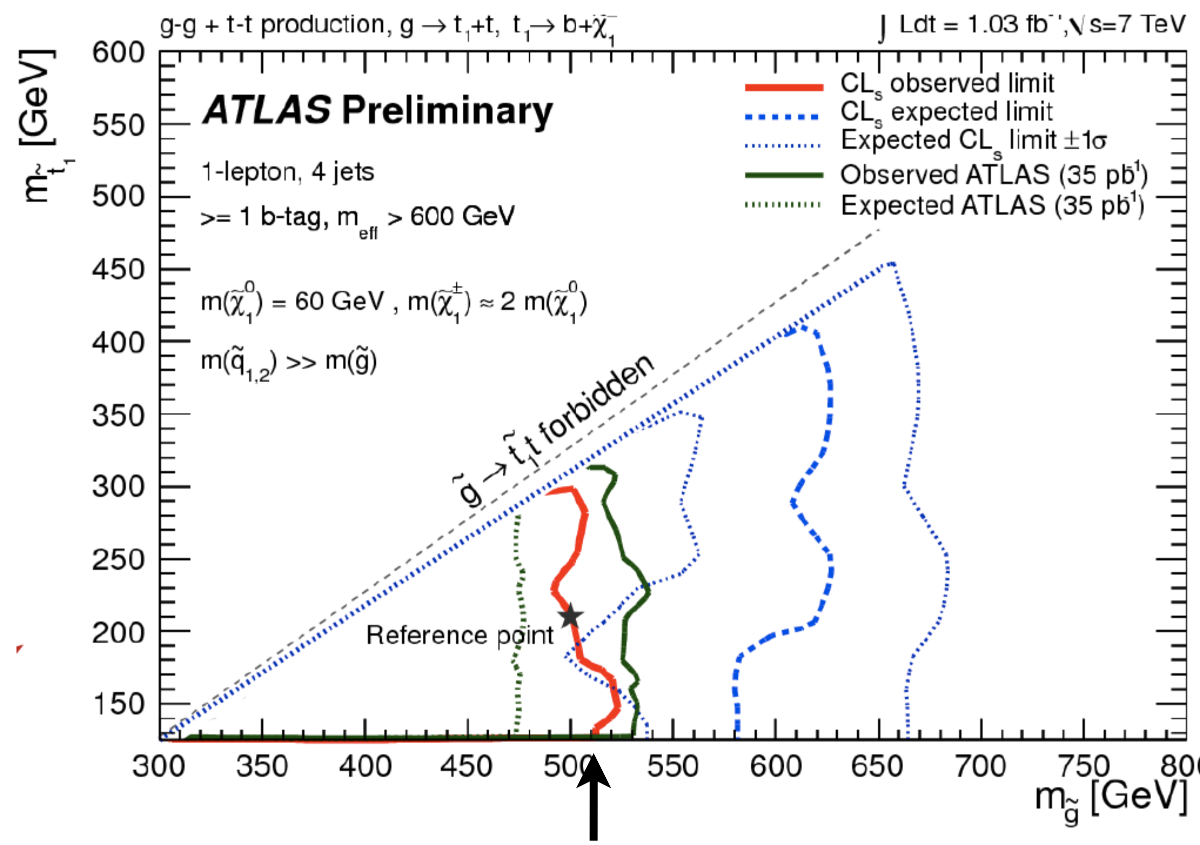
(Kim: $\chi \to \tilde{G} + Z$)

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

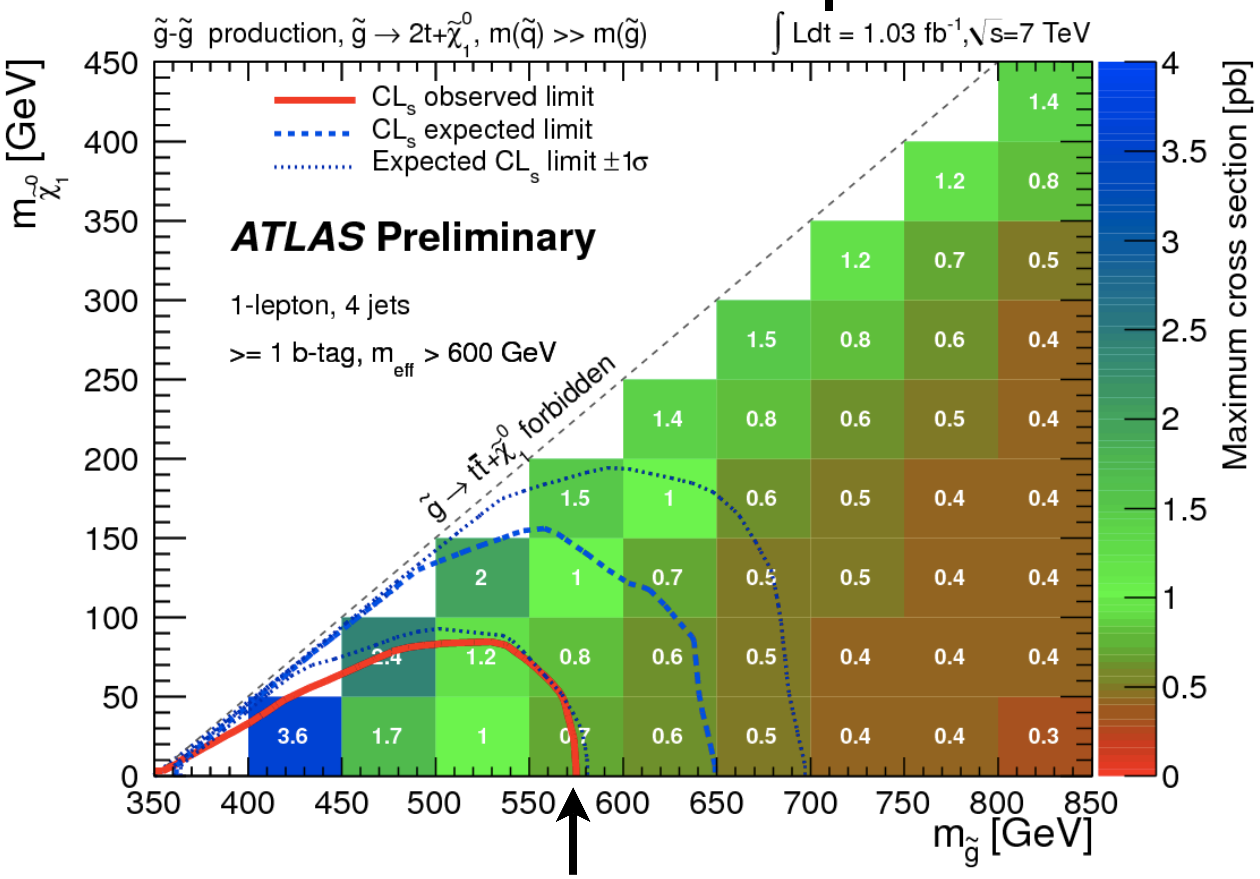
$\tilde{g} \to b\tilde{b} \to b\bar{b} + \chi$



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



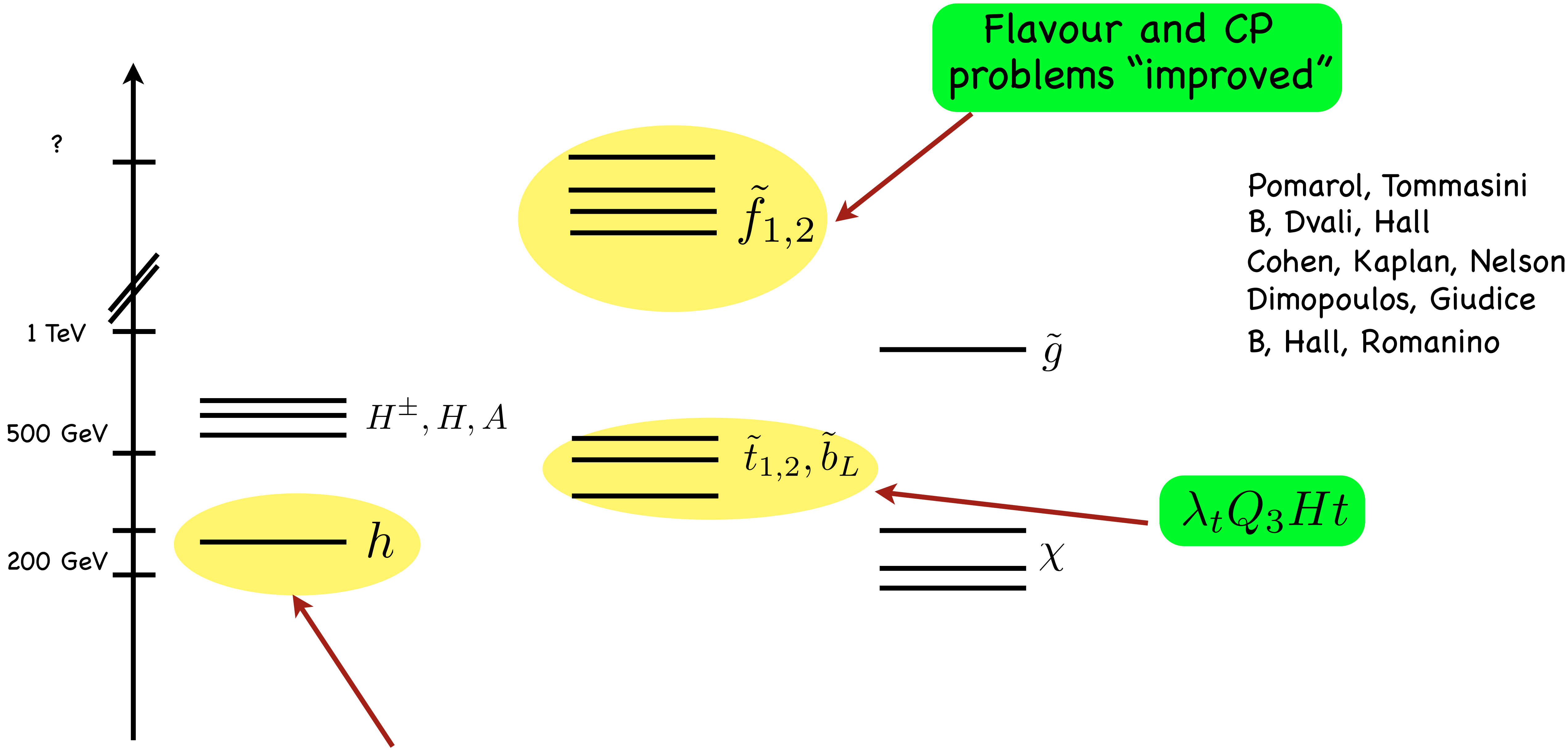
$\tilde{g} \to t\tilde{t} \to t\bar{t} + \chi$



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

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

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

How heavy can the lightest Higgs boson be?

$$f = \mu H_1 H_2 \Rightarrow f = \lambda S H_1 H_2$$

$$\Delta V = |f_S|^2 = \lambda^2 |H_1 H_2|^2$$

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta \quad \Rightarrow m_h^2 \simeq M_Z^2 \cos^2 2\beta \; + \lambda^2 v^2 \sin^2 2\beta$$

$\Rightarrow$ The "NMSSM" motivated

The "μ" problem: $\mu_{eff} = \lambda < S >$

(Other ways less effective, in my view)

The relevant RGEs

The general R-invariant superpotential: $f = \lambda\, S H_1 H_2 + \frac{\kappa}{3} S^3$

$$16\pi^2 \frac{d\lambda^2}{dt} = \lambda^2 \left[4\lambda^2 + 2\kappa^2 + 3h_t^2 - 3g_2^2 - \frac{3}{5}g_1^2\right]$$

$$16\pi^2 \frac{d\kappa^2}{dt} = 6\kappa^2 \left[\lambda^2 + \kappa^2\right]$$

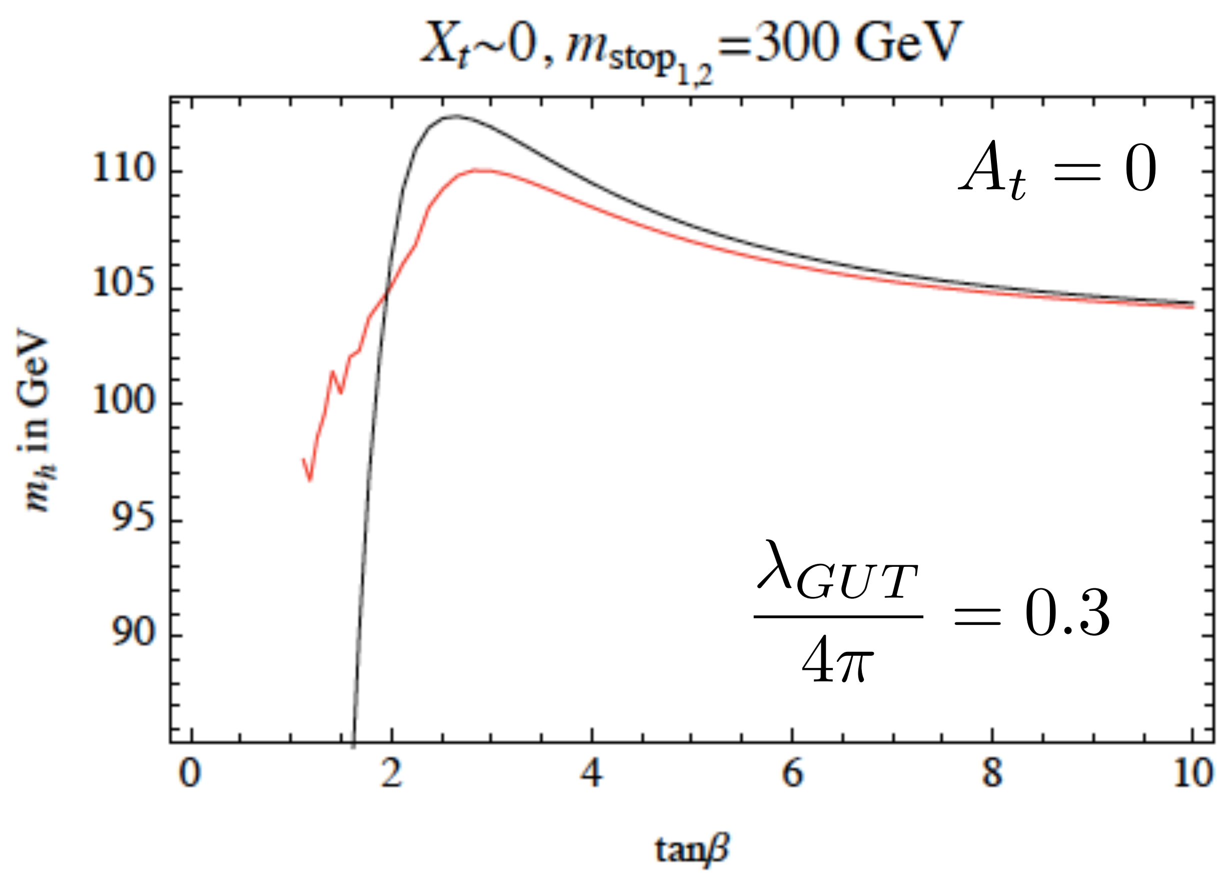
$$16\pi^2 \frac{dh_t^2}{dt} = h_t^2 \left[\lambda^2 + 6h_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right]$$

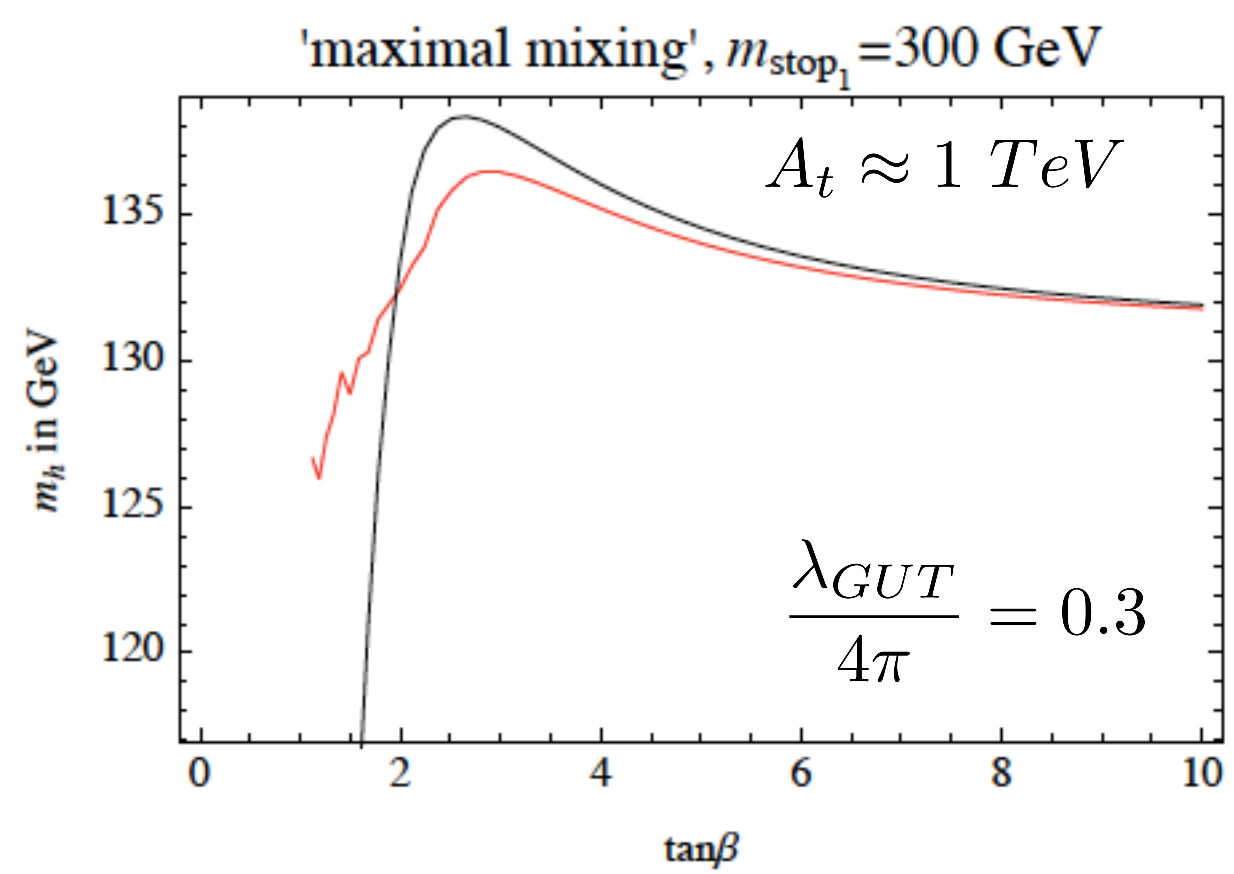
$$\Rightarrow$$

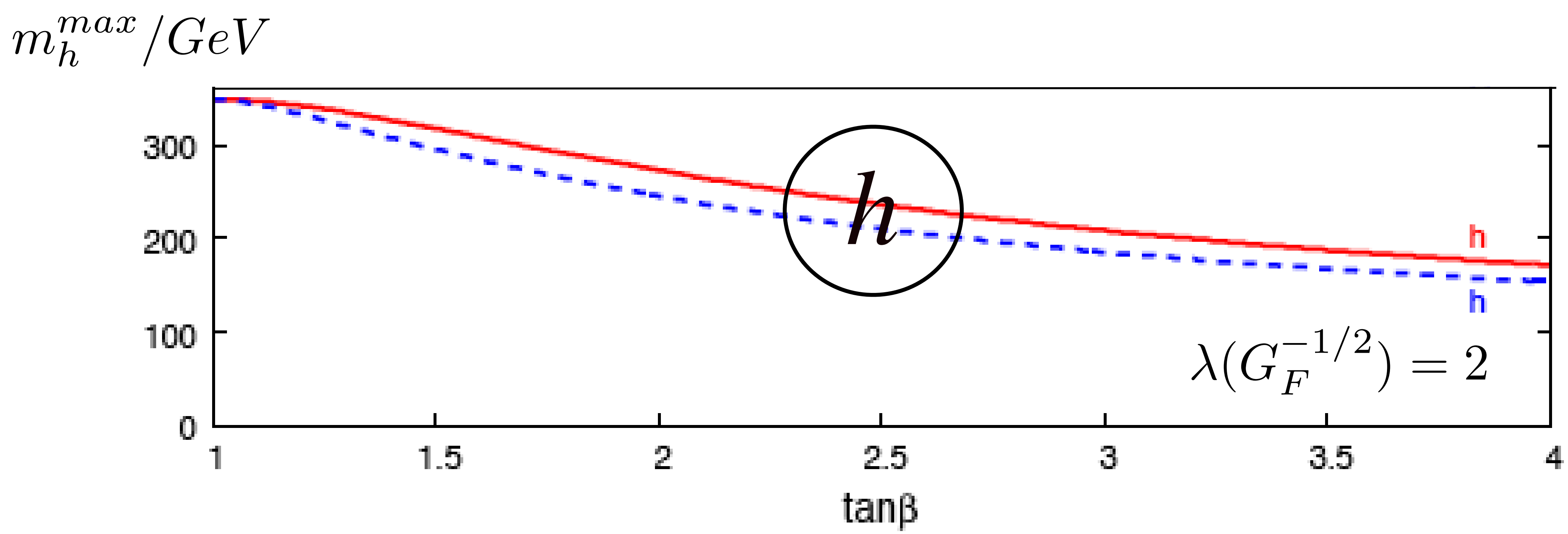
1. $(\frac{\lambda}{4\pi})^2(10TeV) \leq 0.1 \quad \Rightarrow \quad \lambda(G_F^{-1/2}) \leq 2$ "λSUSY"

2. $(\frac{\lambda}{4\pi})^2(M_{GUT}) \leq 0.1 \quad \Rightarrow \quad \lambda(G_F^{-1/2}) \leq 0.7$

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

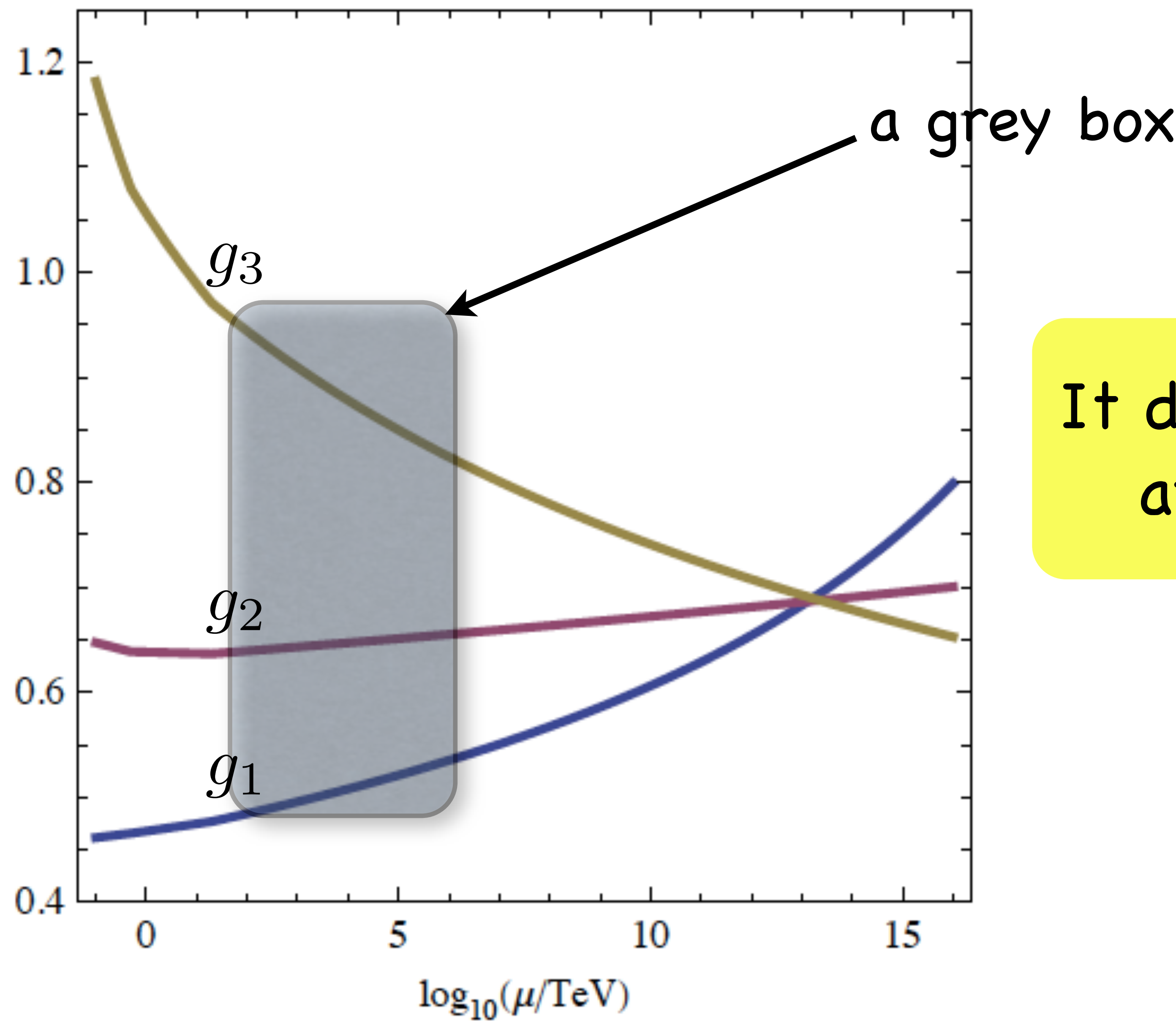






* = before mixing

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)

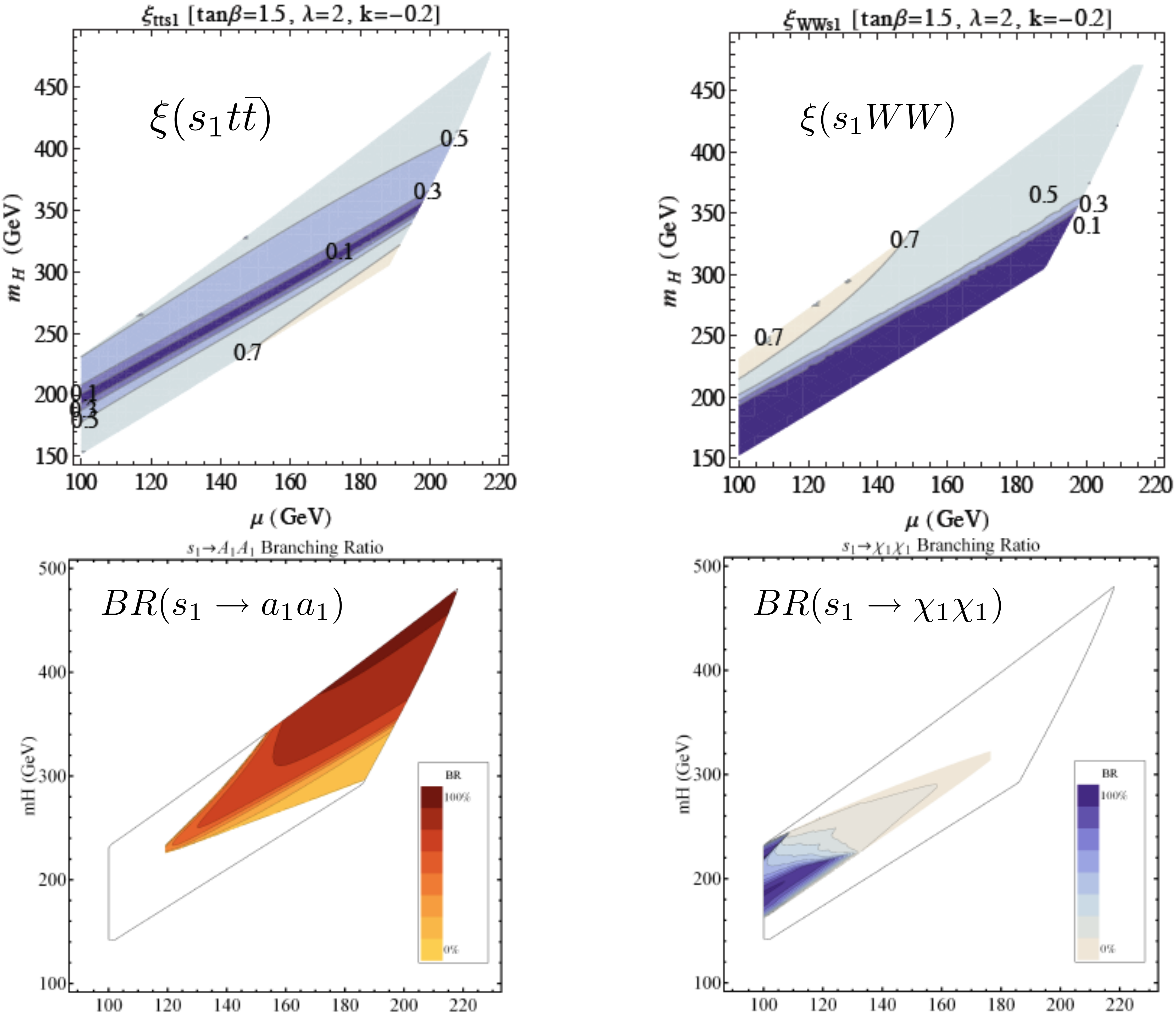
- ✶ gluino pair production and decays into top/bottom-rich final states ✓

- ✶ a largely unconventional Higgs sector
  - $h \to WW, ZZ$ (with reduced rate)
  - → $h \to aa \to (b\bar{b},\ \tau\bar{\tau},\ c\bar{c})^2$
  - $h \to \chi_{DM}\chi_{DM}$

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

- ✶ Dark Matter: relic abundance and detection affected

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



(λSUSY with a R-invariant superpotential)

Bertuzzo, Farina

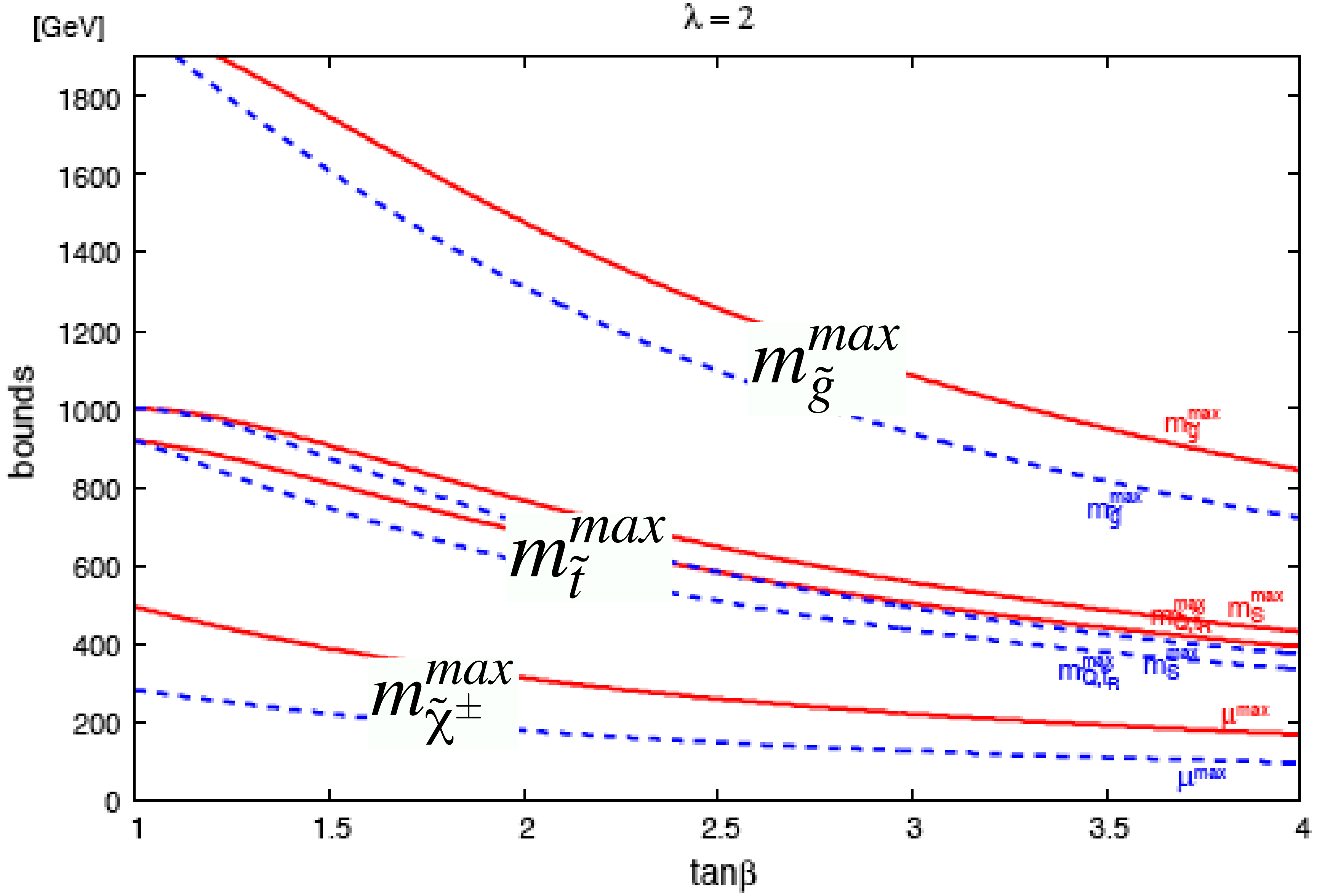
$k = -0.2$	μ (GeV)	m_H (GeV)	m_{s_1} (GeV)	m_{A_1} (GeV)	m_{χ_1} (GeV)
a	180	340	252	103	130
b	105	180	163	95	77
c	130	200	173	108	96
$k = -0.6$					
d	105	180	160	166	78
e	160	280	232	195	120

$k = -0.2$	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 $\quad (m^{max} \propto \sqrt{\Delta/5})$

$\Lambda_{mess} = 100\ TeV$

B, Hall, Nomura, Rychkov

Summary on supersymmetry

1. Crucial to know where $m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}$ are

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 phenomenology

(At LHC1 1 easier than 2?)

Overall Conclusions

Back to lecture 1

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

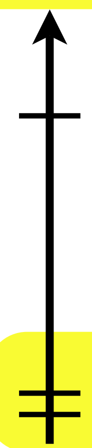
Every theorist should decide where to put his/her money

Aaahhh!! The happy experimentalists!

Some (approximate) flavour symmetry must be operative

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

Tomassini, Pomarol 1996
B, Dvali, Hall 1996



q_3

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

$q_{1,2}$ ↕ U(2)

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

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

only weakly broken along minimal directions

$\boxed{V = (2,1,1)}$ $\quad \Gamma_u = (2,\bar{2},1) \quad \Gamma_d = (2,1,\bar{2})$ $\quad$ all $\lesssim \mathcal{O}(\lambda^2)$ with $\lambda = 0.2254$

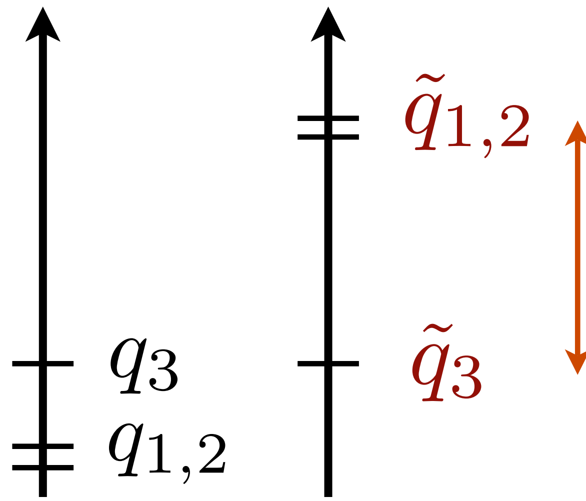
(If $V = (1,2,1)$ or $V = (1,1,2)$ then $\approx \mathcal{O}(1)$)

and perhaps also in the SUSY non-data

flavour, EDMs, direct s-particle searches

A relevant example: supersymmetry

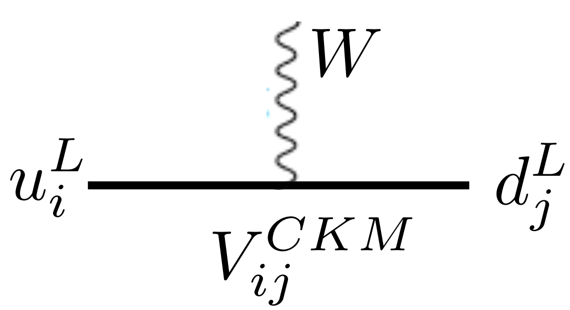
Particle spectrum



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

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

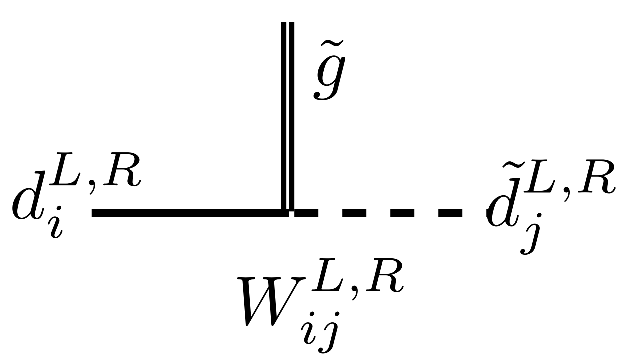
Flavour changing interactions



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

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

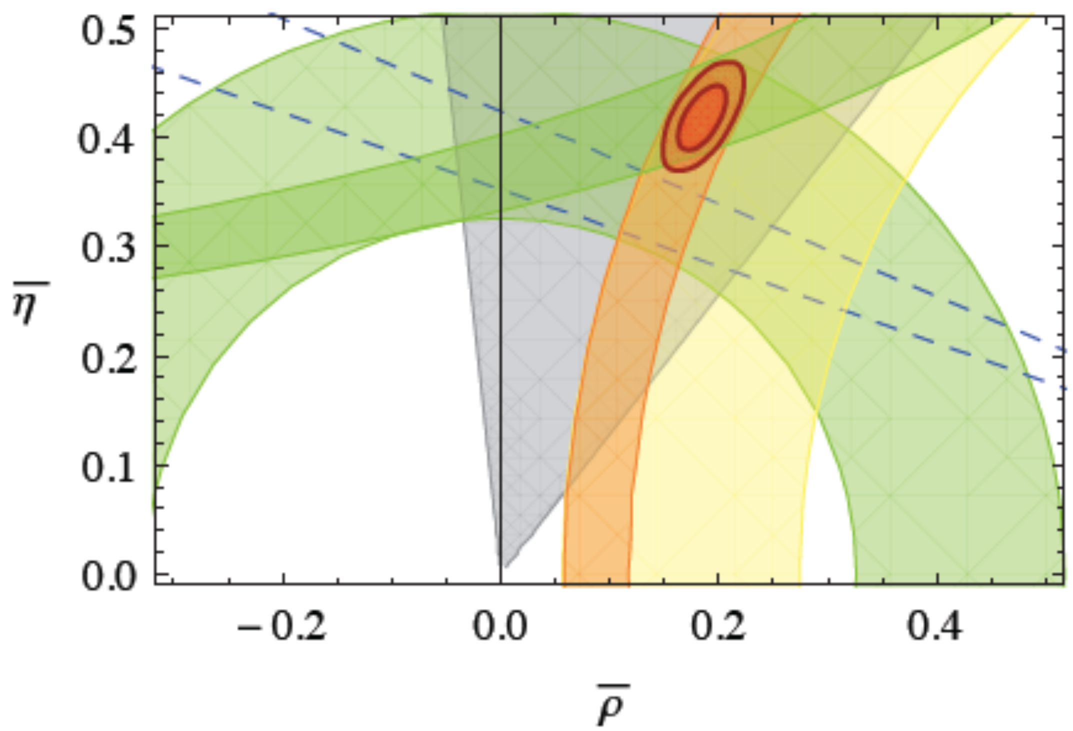
No B_s-input

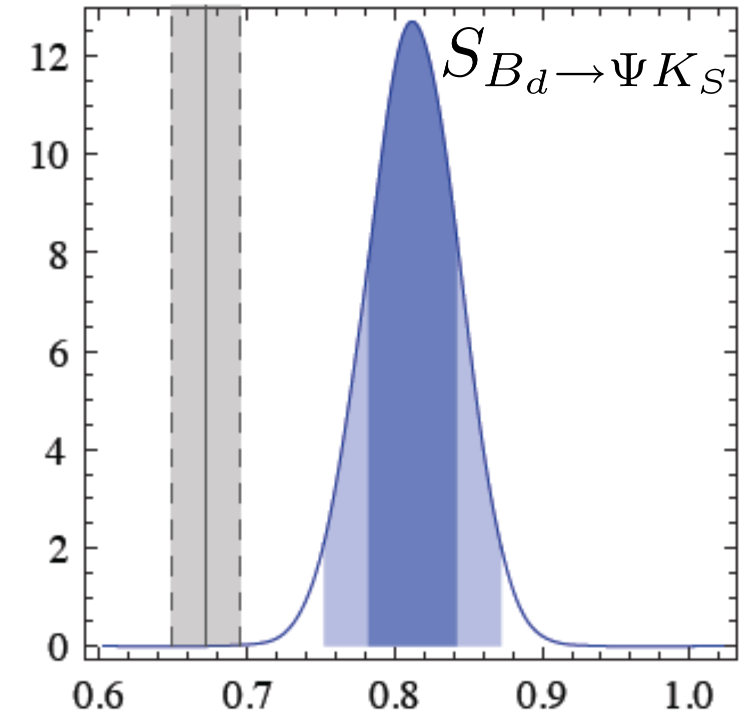
Tree level +

ΔM_d

ΔM_s

ϵ_K



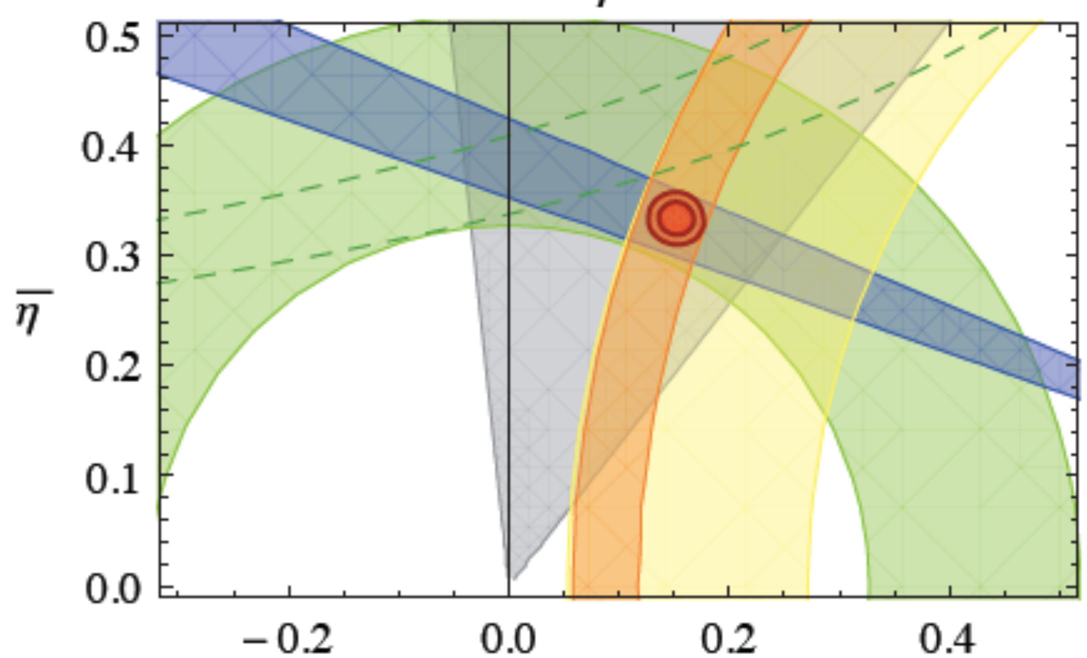


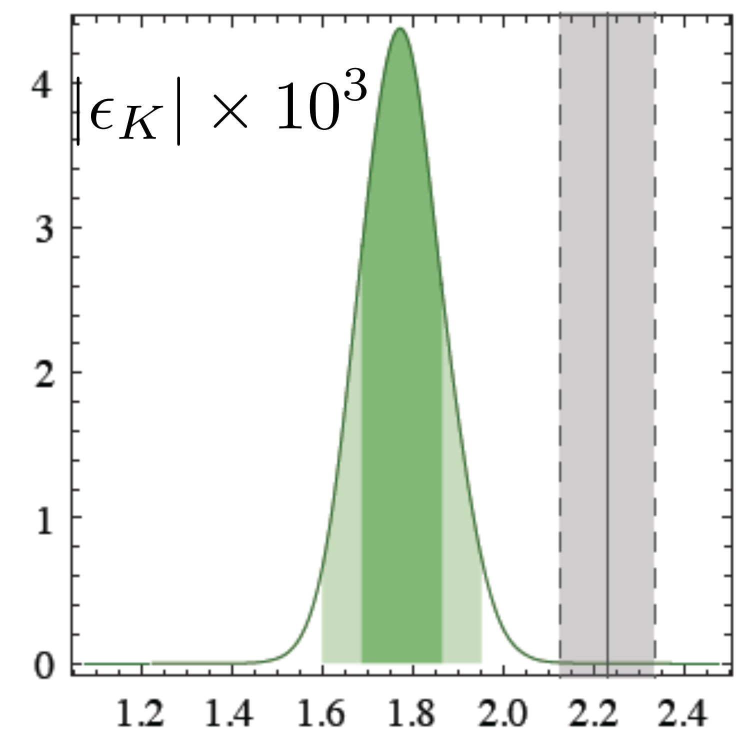
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$



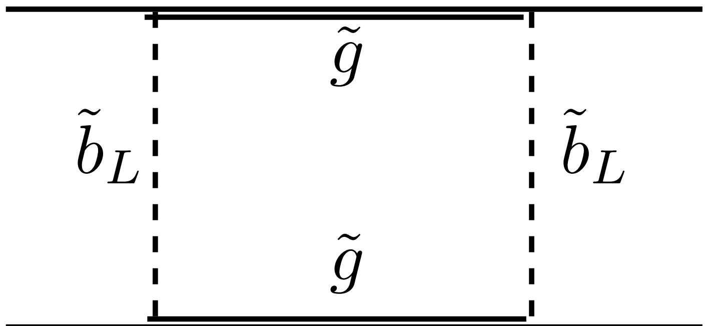


details subject to discussion

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

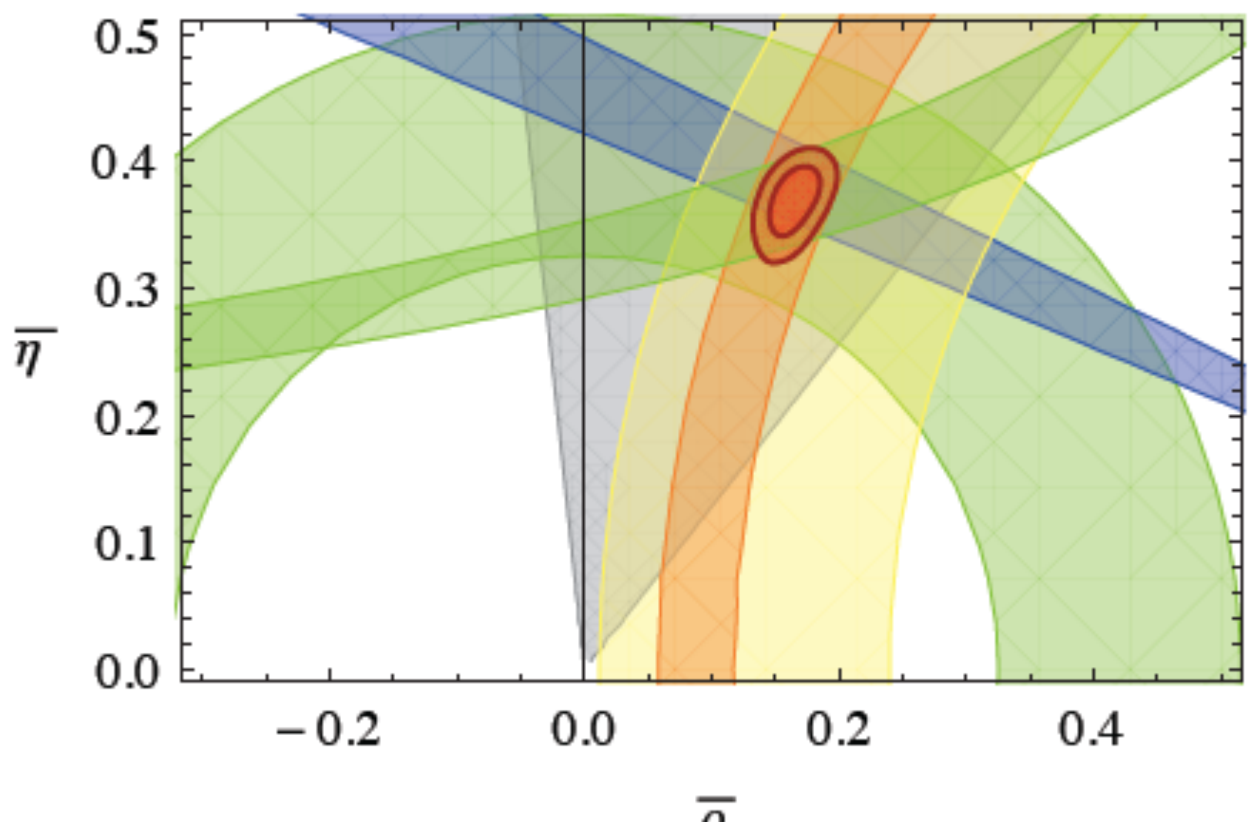
Tree level +

ΔM_d

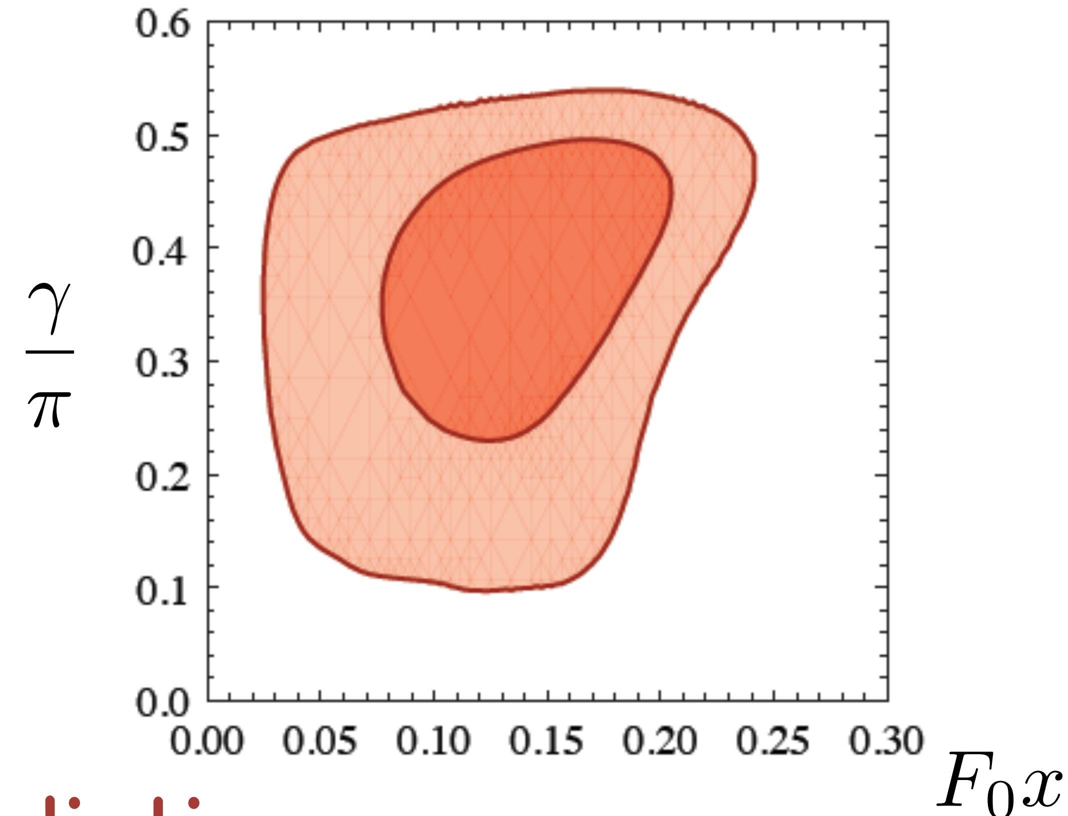
ΔM_s

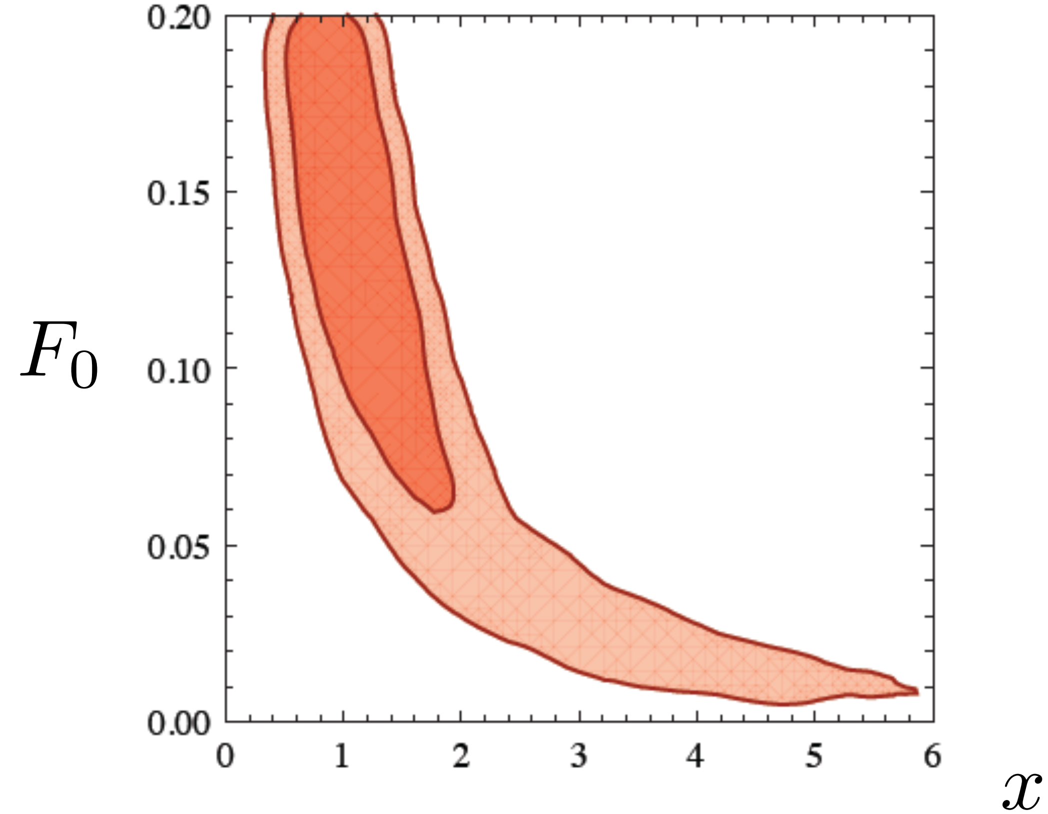
$S_{B_d \to \Psi K_S}$

ϵ_K



Constraints on extra parameters:

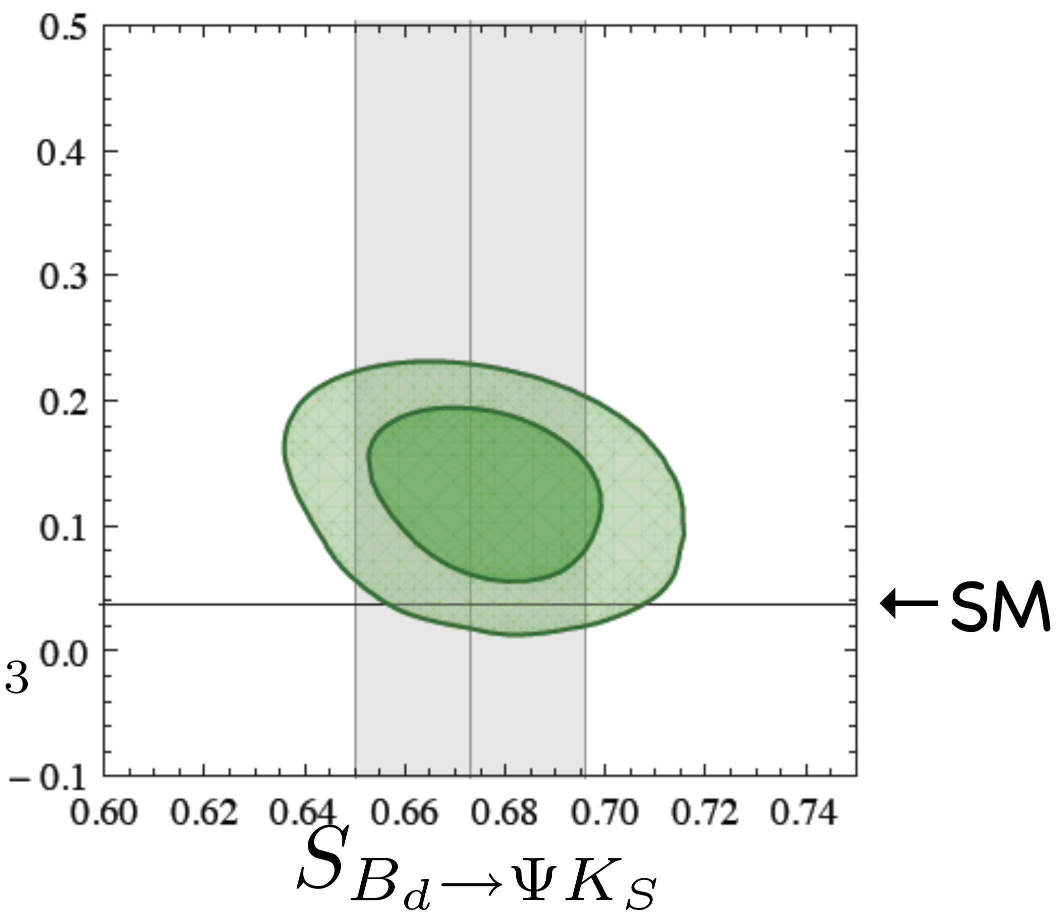


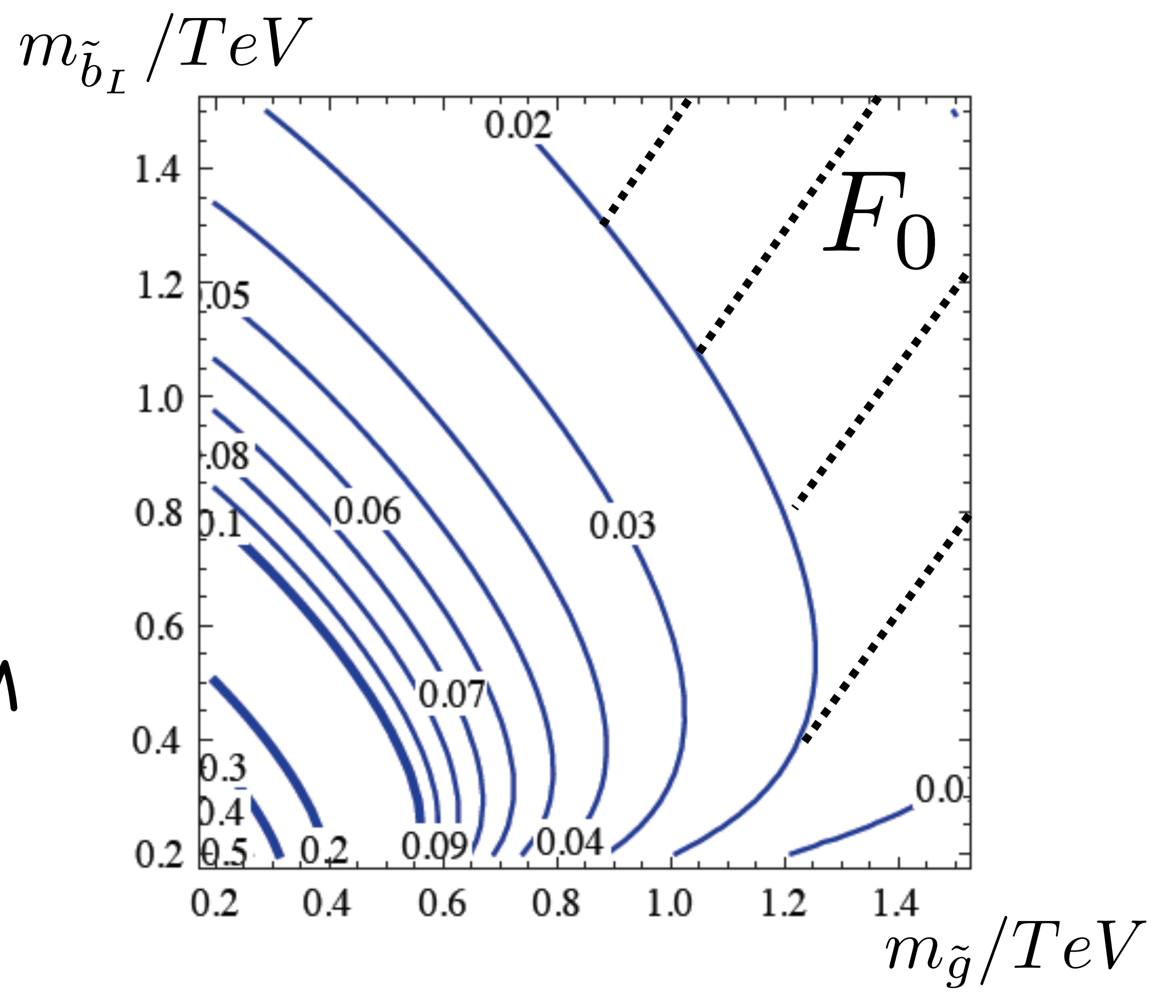


Prediction:

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

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



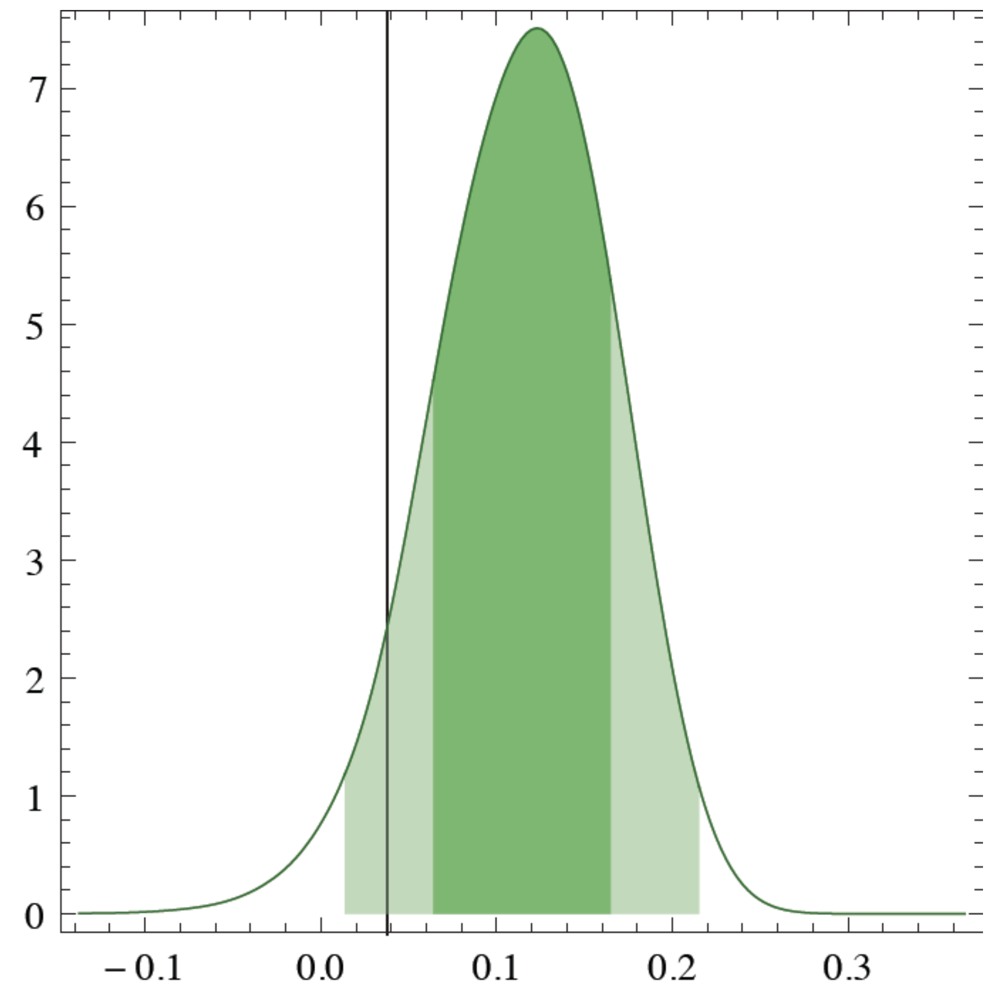


Input data

$\|V_{ud}\|$	$0.97425(22)$	[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]
$\gamma_{\rm CKM}$	$(74 \pm 11)^\circ$	[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	$(0.507 \pm 0.004)\,{\rm ps}^{-1}$	[22]			
ΔM_s	$(17.77 \pm 0.12)\,{\rm ps}^{-1}$	[23]			

$U(2)^3$ prediction

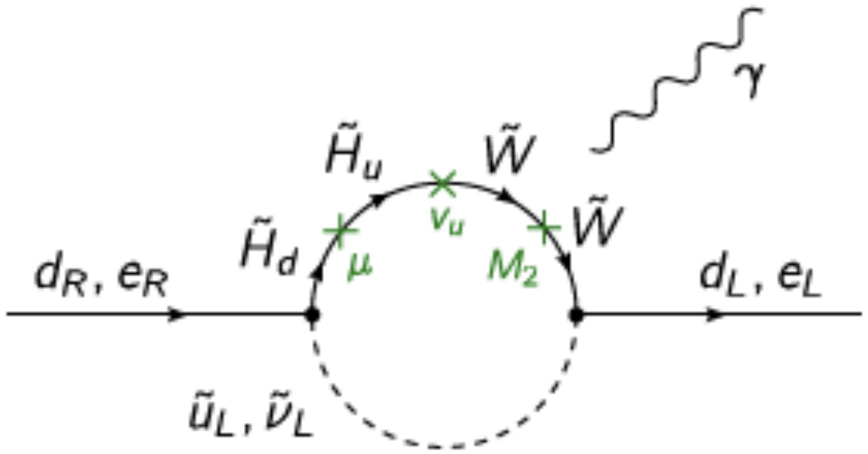
$$S_{B_s \to \Psi\phi} = 0.12 \pm 0.5$$



Electric Dipole Moments with flavour blind phases only

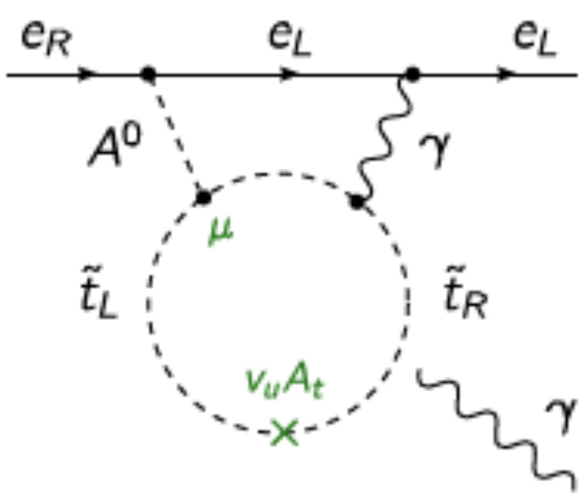
Flavour blind phases lead to contributions to electric dipole moments.

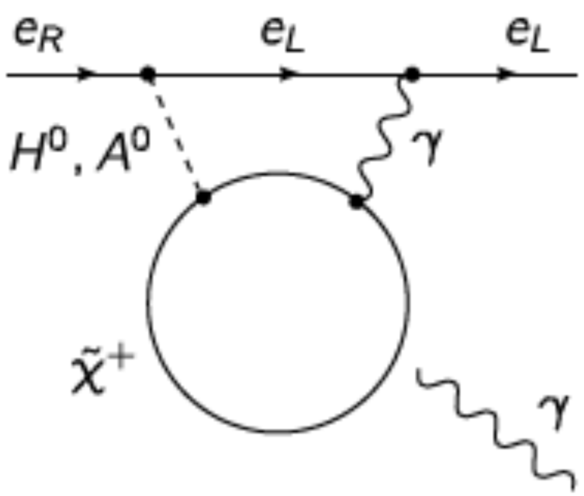
$$\text{Exp.:} \qquad |d_e| < 1.6\times10^{-27}\, e\,\text{cm}\,, \qquad |d_n| < 2.9\times10^{-26}\, e\,\text{cm}$$



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

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



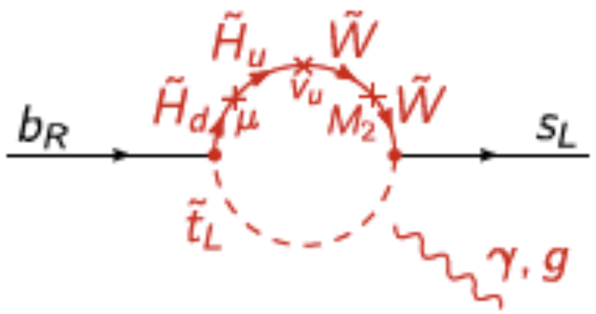


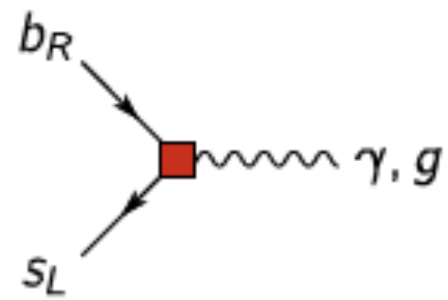
2-loop contributions lead to effects in the ballpark of the experimental bound

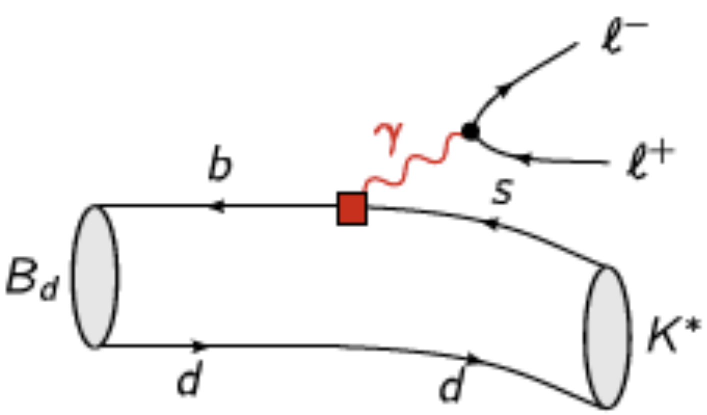
CP asymmetries in B-physics

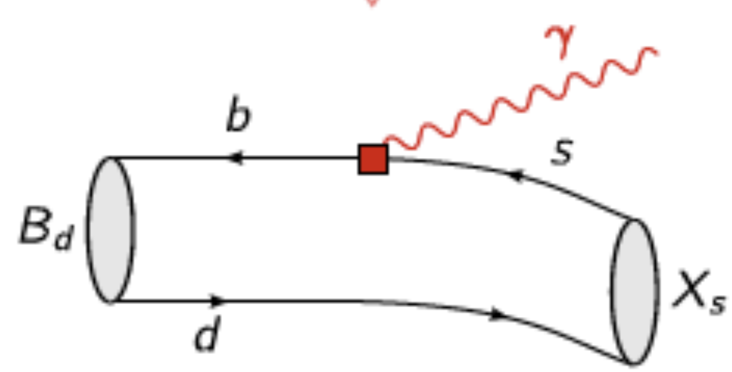
CP violating contributions to dipole operators not suppressed by 1st/2nd generation sfermion masses

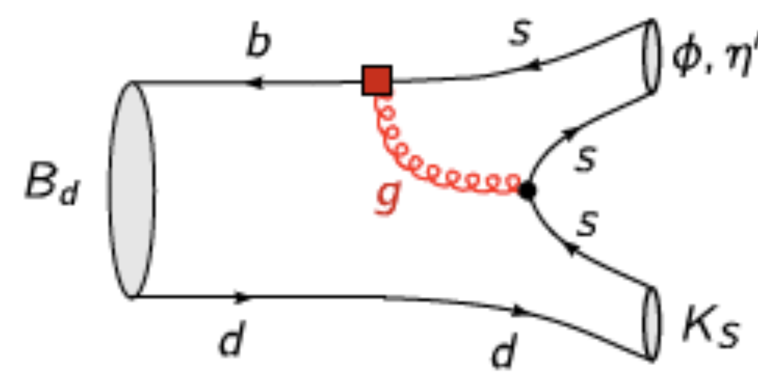
e.g.









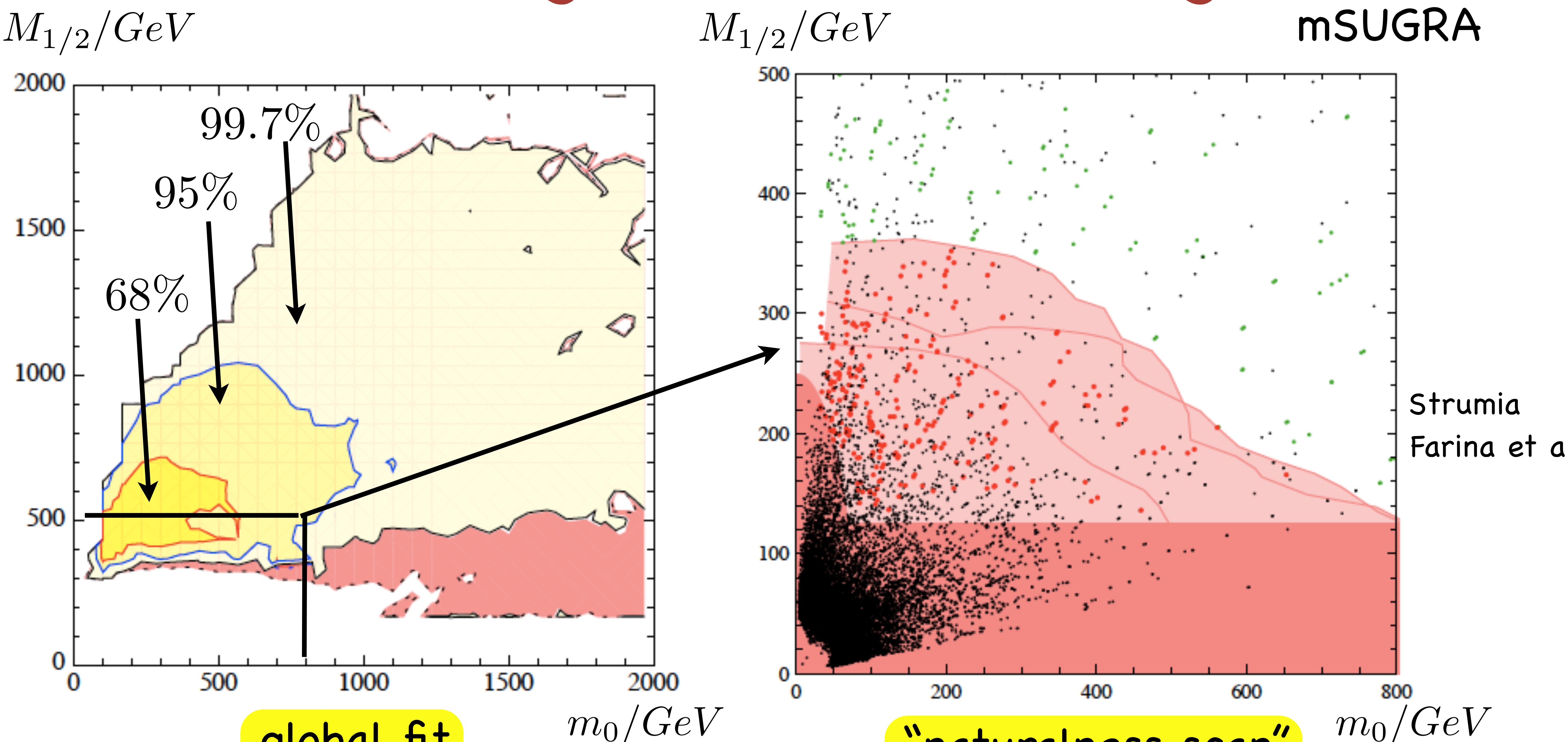


A_7, A_8 in $B \to K^* \ell^+ \ell^-$

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

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

fine-tuning or not fine-tuning



global fit

LHC, Ω_{DM}, δg_μ, $\Delta B = 1$

(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 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

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