Where are we with the search for supersymmetry?

!!visible at LHC!!

R. Barbieri

GGI workshop, Nov 11, 2011

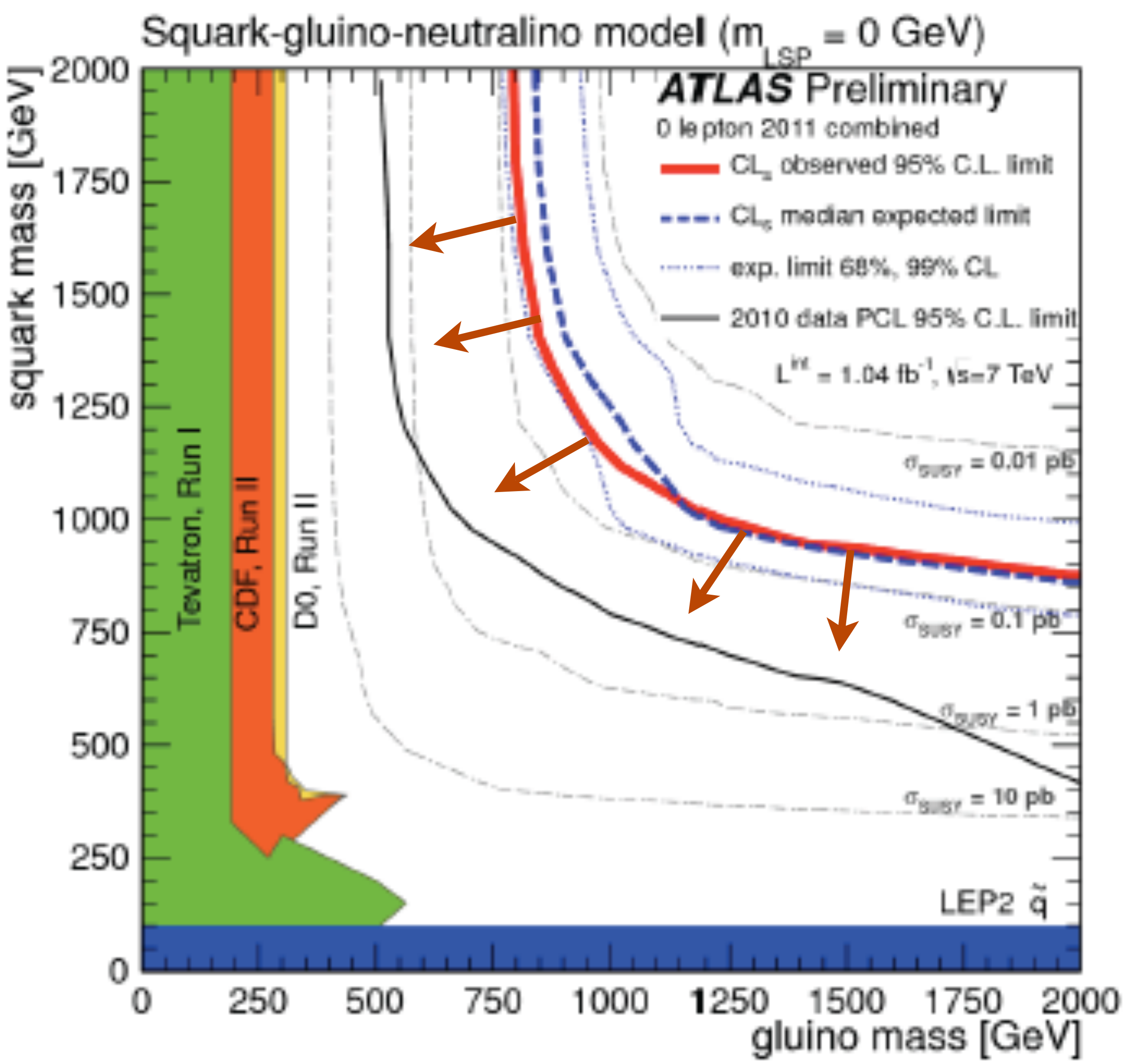
Why no s-particle? (LEP + TEVATRON + LHC)

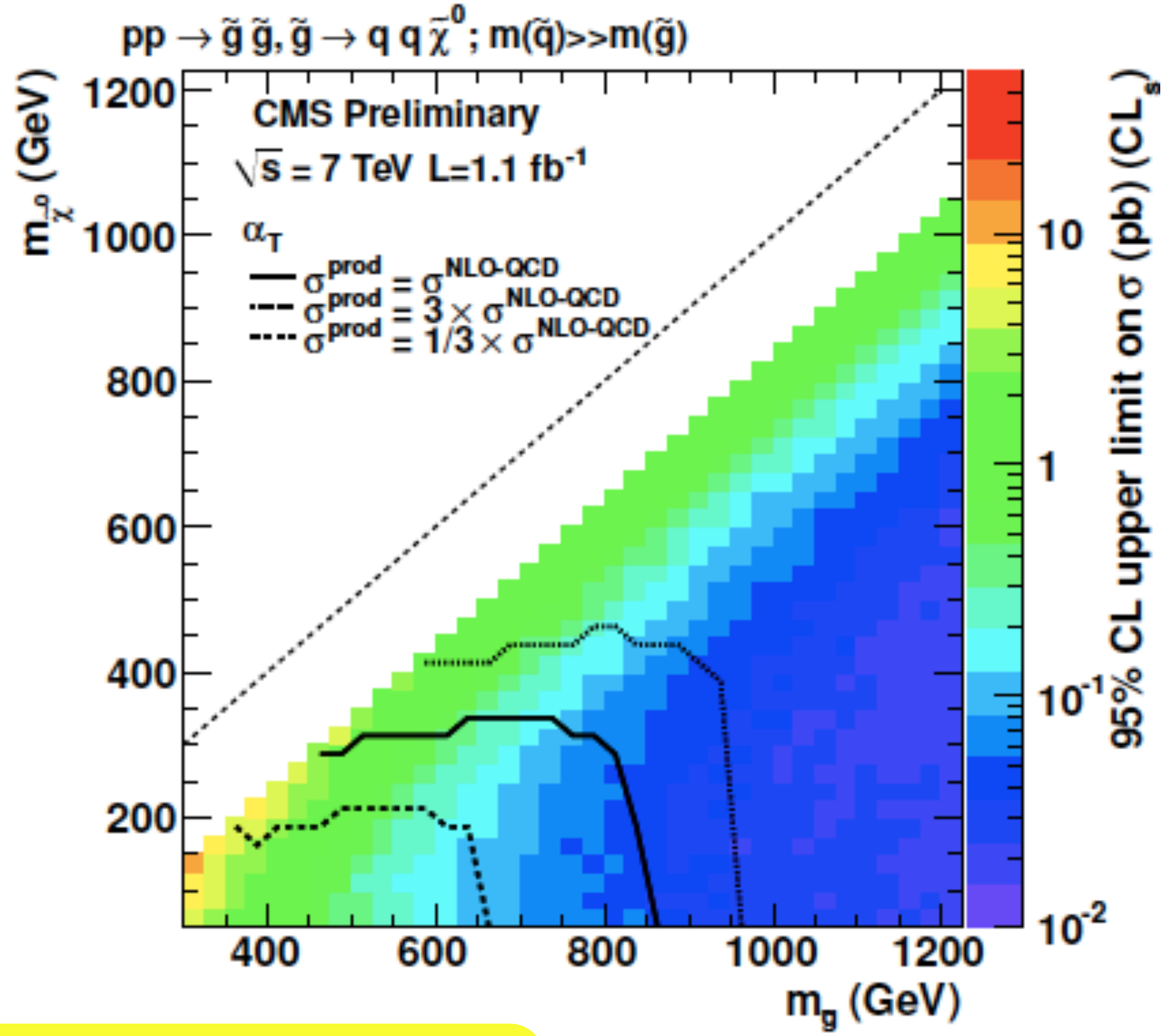
Where is(are) the Higgs boson(s)? (LEP + incoming LHC)

Why flavour and CPV as in the CKM picture?
(many exp inputs in the last decade)

see also talks by Hewett and Wagner

A remarkable new constraint from LHC



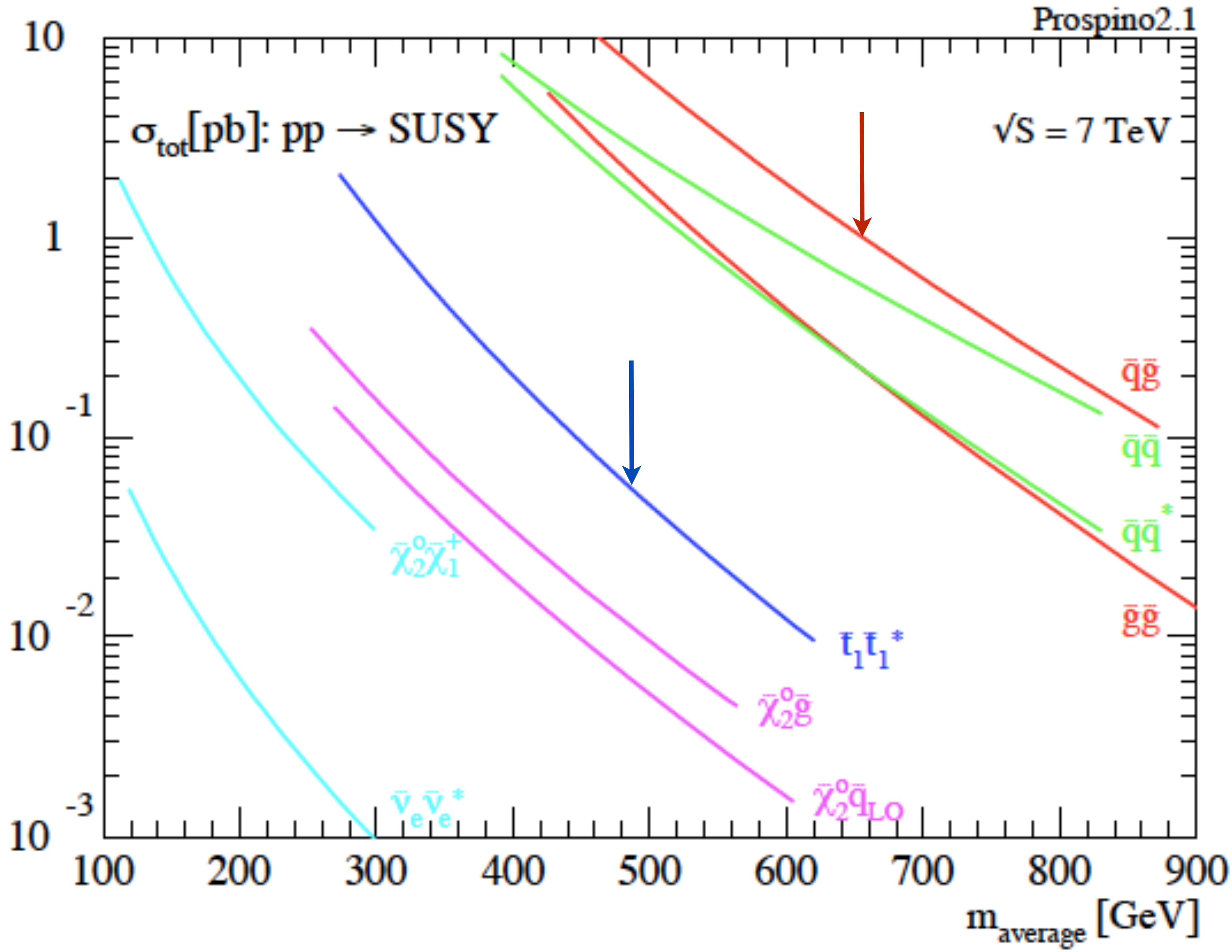


$$\Rightarrow m_{\tilde{g}}, m_{\tilde{q}_{1,2}} \gtrsim 1\ TeV$$

for degenerate squarks of the first two generations $\tilde{q}_{1,2}$
and $\chi^0, \tilde{g}$ not too close in mass

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

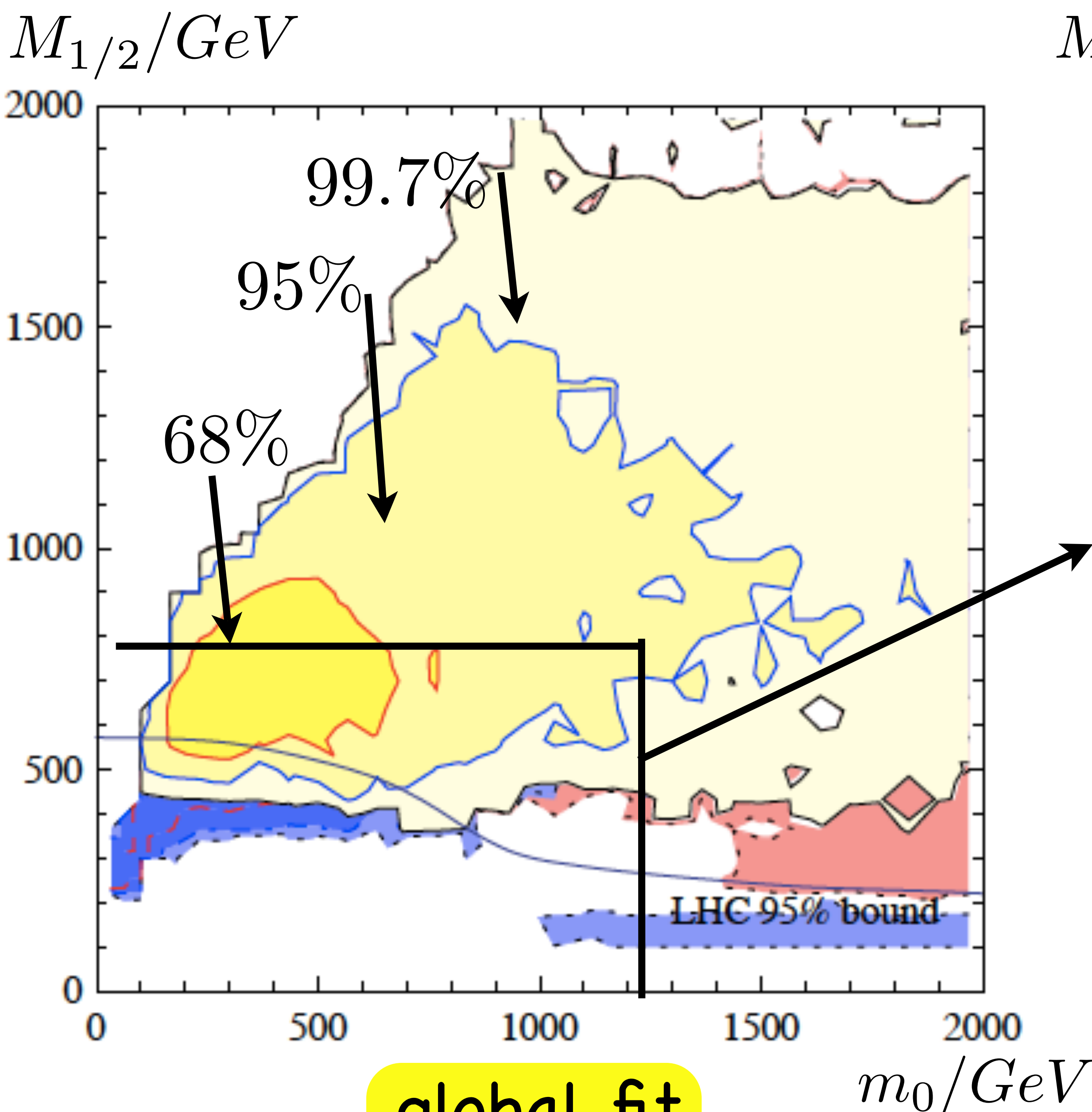
$\tilde{t}, \tilde{b}$ unconstrained



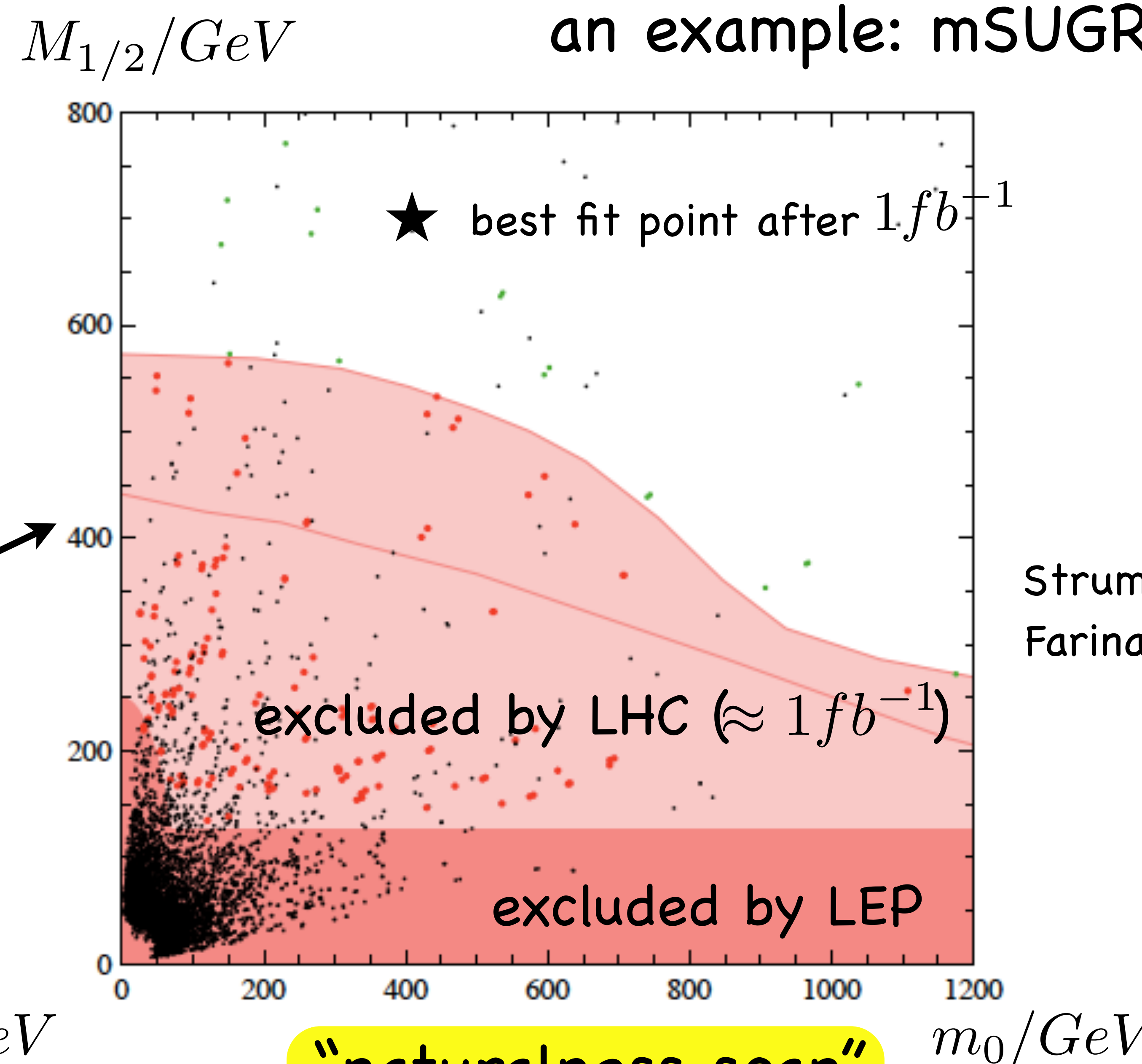
Prospino2.1
σ_tot[pb]: pp → SUSY
√S = 7 TeV
10
1
10^-1
10^-2
10^-3
100
200
300
400
500
600
700
800
900
m_average [GeV]
q̄g̅
q̄q̄
q̄q̄*
g̅g̅
t̄₁t̄₁*
χ̄₂°χ̄₁⁺
χ̄₂°g̅
χ̄₂°q̄_LO
ν̄_eν̄_e*

What if $\tilde{t}, \tilde{b}$ close in mass to $\tilde{q}_{1,2}$?

an example: mSUGRA



global fit



Strumia
Farina et al

"naturalness scan"

Which best fit point if mSUGRA assumed true?

Is mSUGRA "true"?

Need cancellations at more than 1%

mSUGRA still a benchmark, but...

- SUSY without prejudice
- SUSY "with prejudice"

SUSY still well alive,

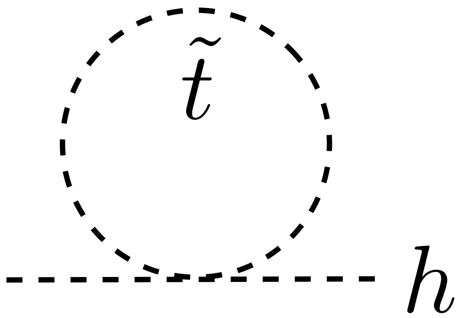
since no hard info, yet, on the crucial configuration

The key equations:

$m_{\tilde{h}}$

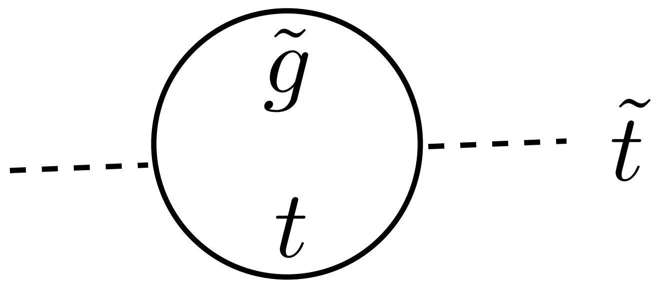
$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2$$

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



$m_{\tilde{b}_L}$

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



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

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

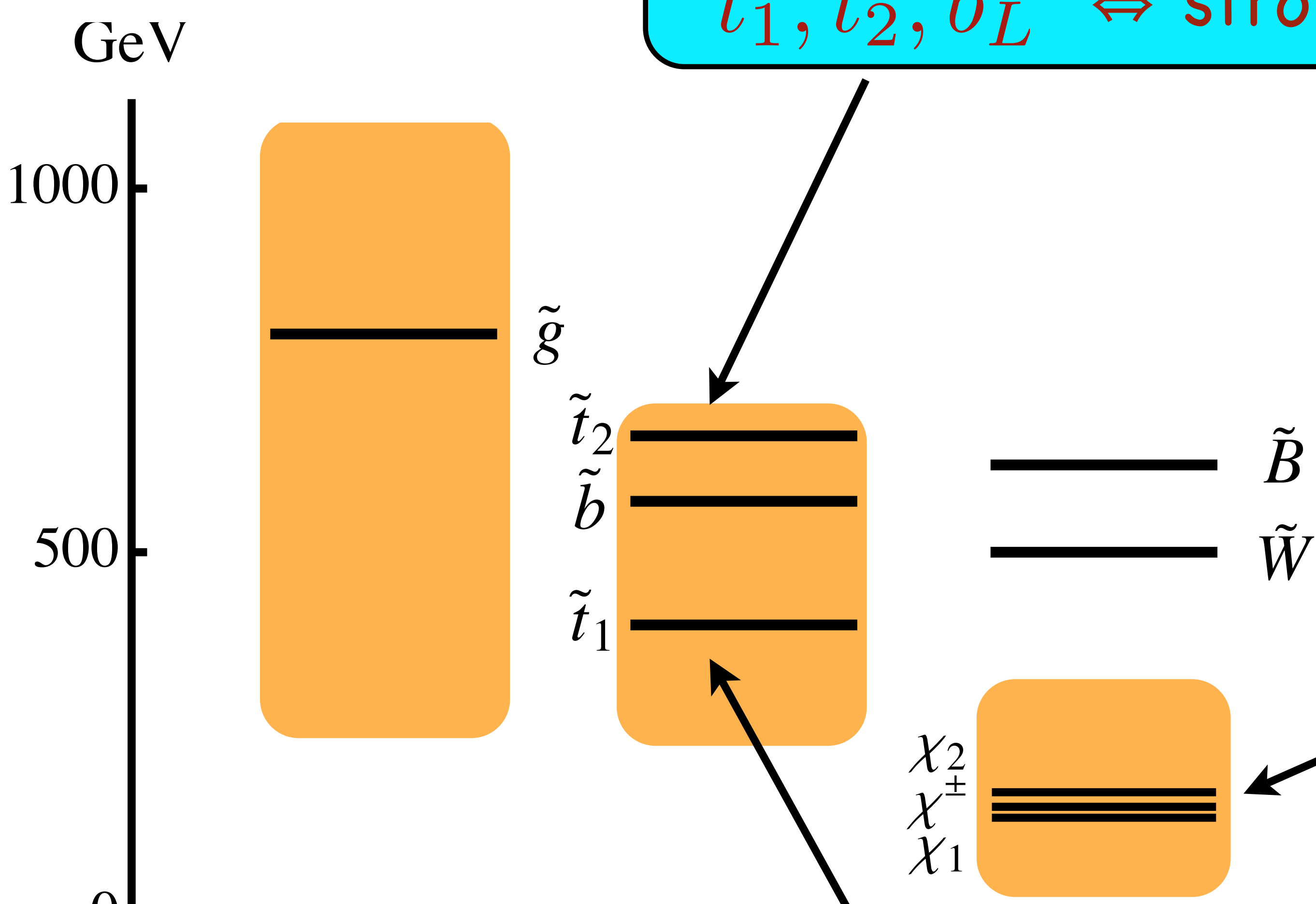
All other s-particle weakly constrained

The crucial configuration

"s-particles" at their naturalness limit

B, Pappadopulo 2009

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



parameters: $\mu, \tan\beta$

m_{Q_3}, m_{u_3}, A_t

M_3

(μ ⇔ M_Z at tree level)

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

natural mass ranges in the orange regions (for $m_h \lesssim 120\ GeV$)

$\tilde{B}, \tilde{W}$ not much contrained but expected below $m_{\tilde{g}}$

A synthetic description of the LHC phenomenology

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

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

IF $\mu < M_1, M_2$ then $\chi^\pm, \chi^0$ close in mass

forget cascades inside χ's $\quad\quad$ $\tilde{g} \to b\bar{b}\chi$ almost irrelevant

⇒ 4 semi-inclusive final states

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

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

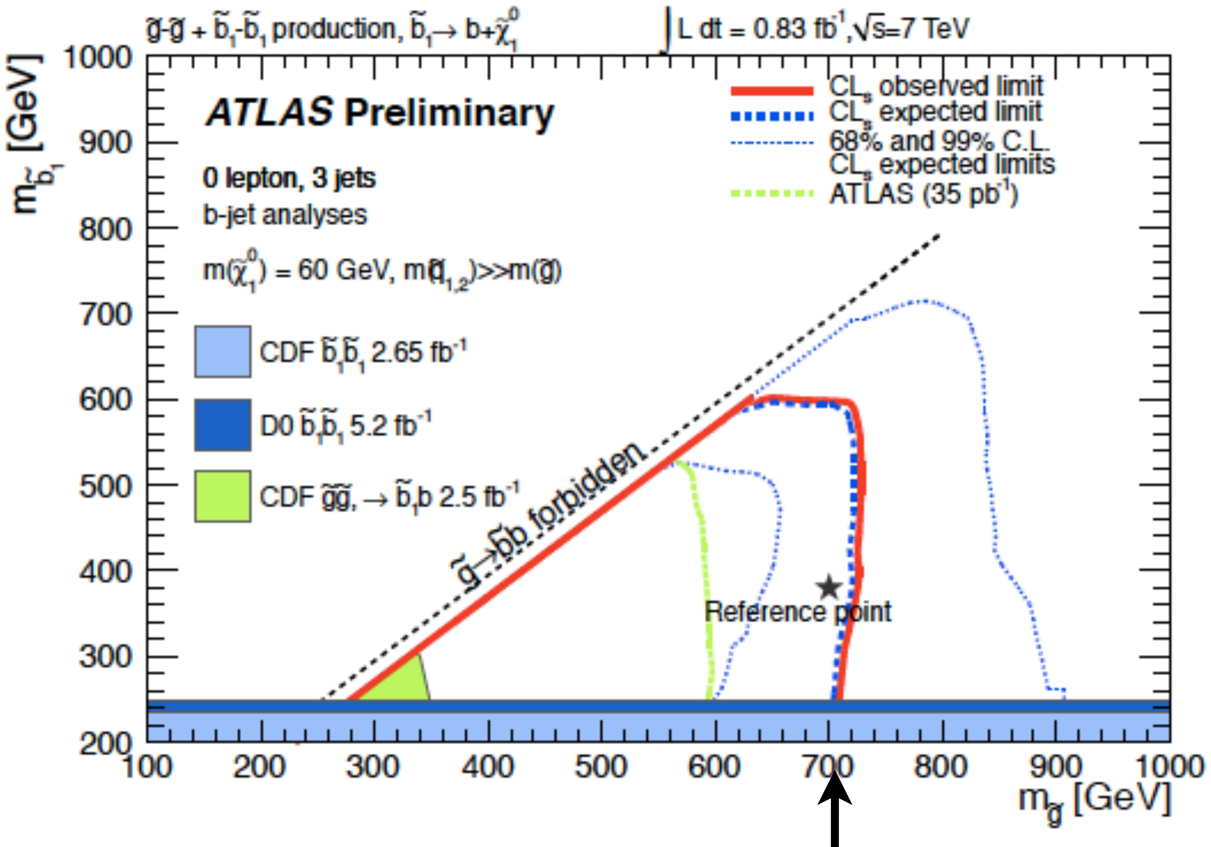
with rates determined by a single BR

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

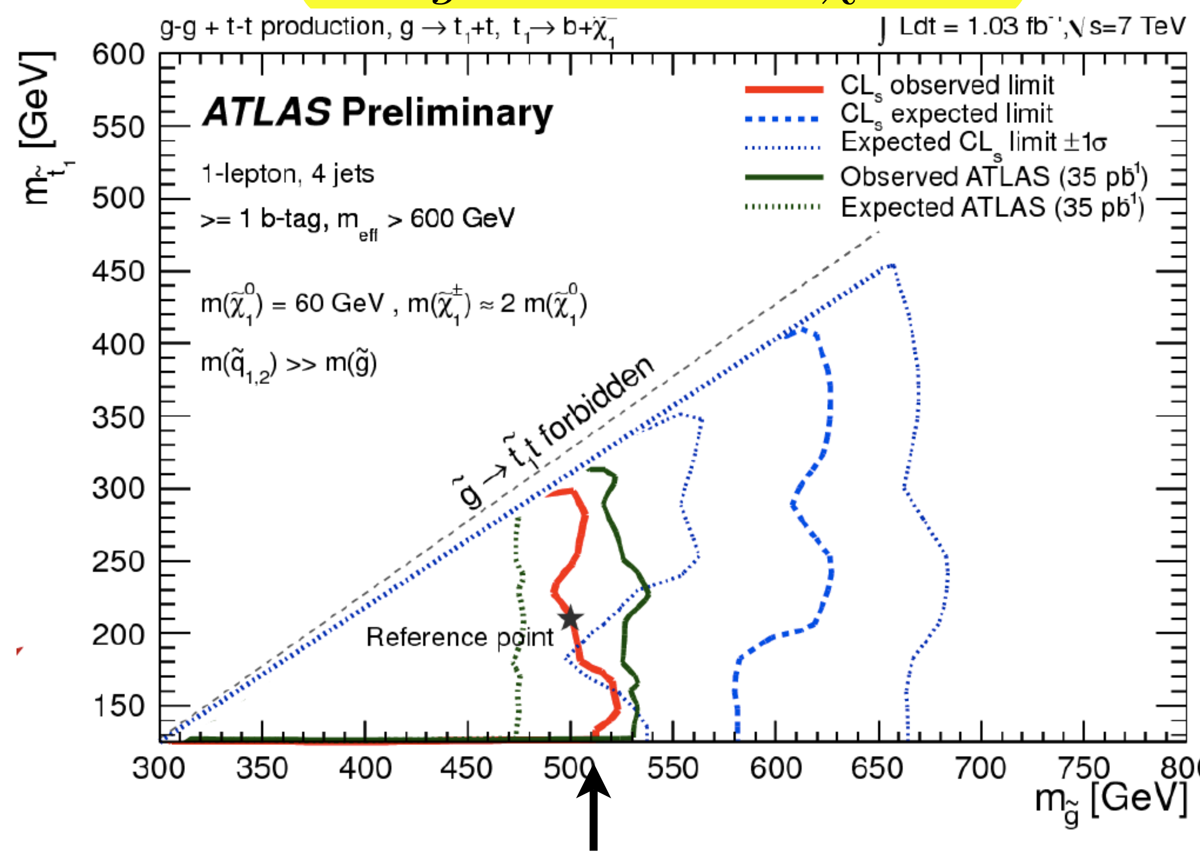
($\chi \to \tilde{G} + Z$)

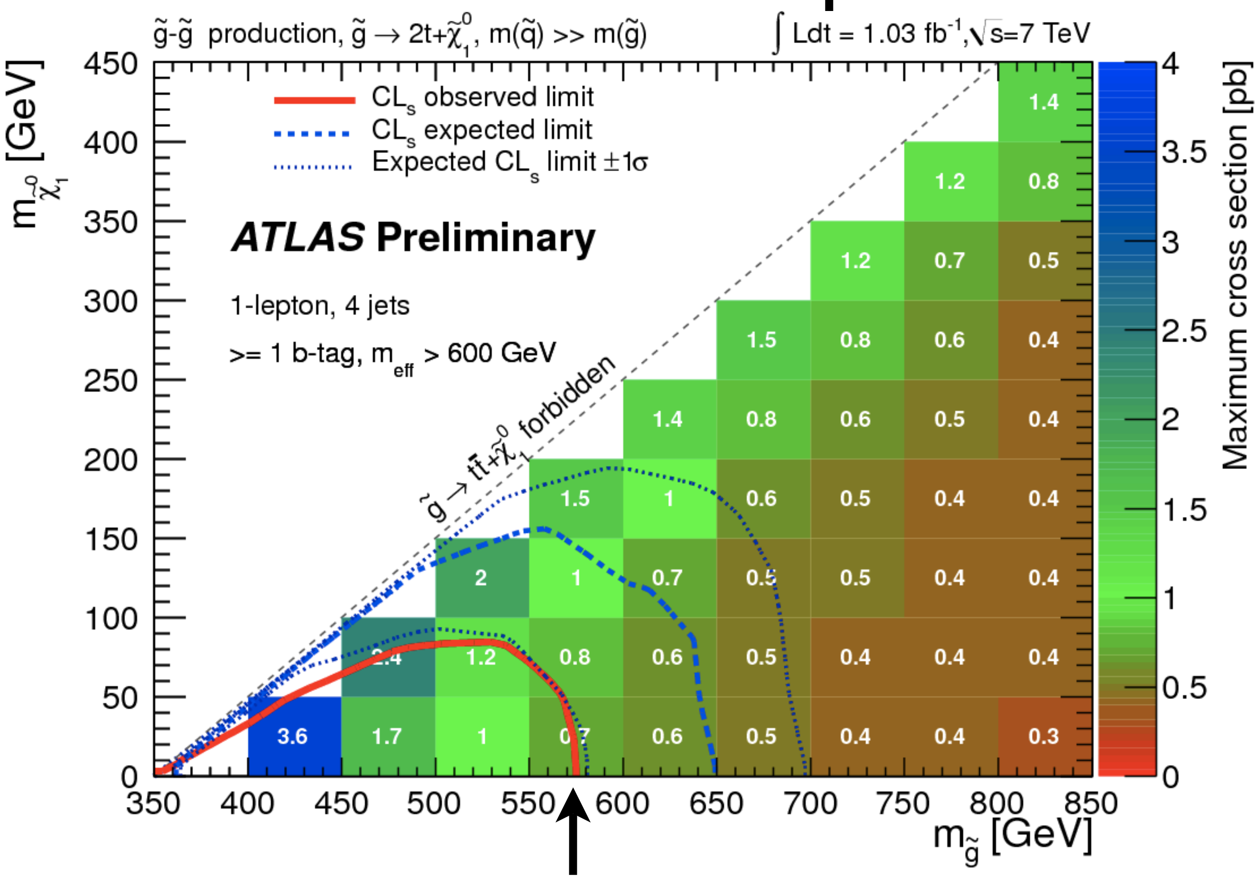
current bounds on $\tilde{g}, \tilde{t}, \tilde{b}$

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



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





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

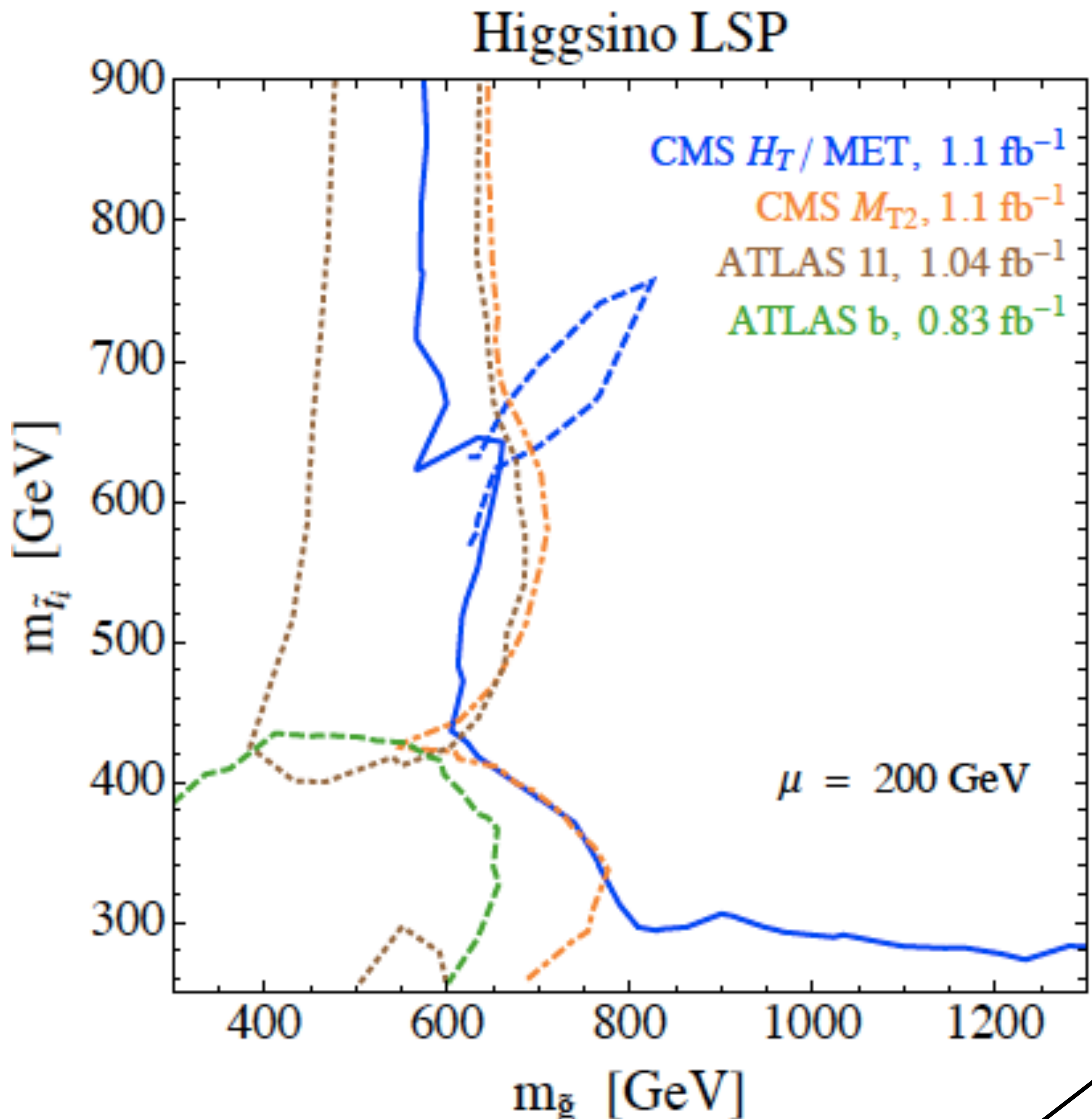
Conservatively:

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

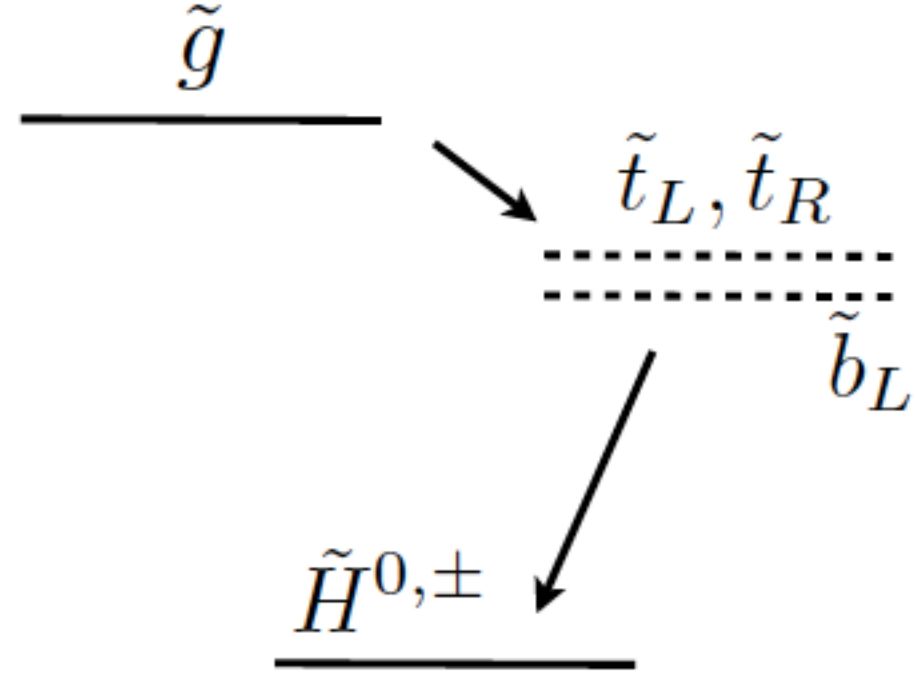
$$m_{\tilde{t}}, m_{\tilde{b}} > 100 \div 200 \ GeV$$

(from the Tevatron)

A theorist's summary (LHC at $\approx 1\ fb^{-1}$) of current bounds on $\tilde{g}, \tilde{t}, \tilde{b}$



Papucci, Ruderman, Weiler 2011



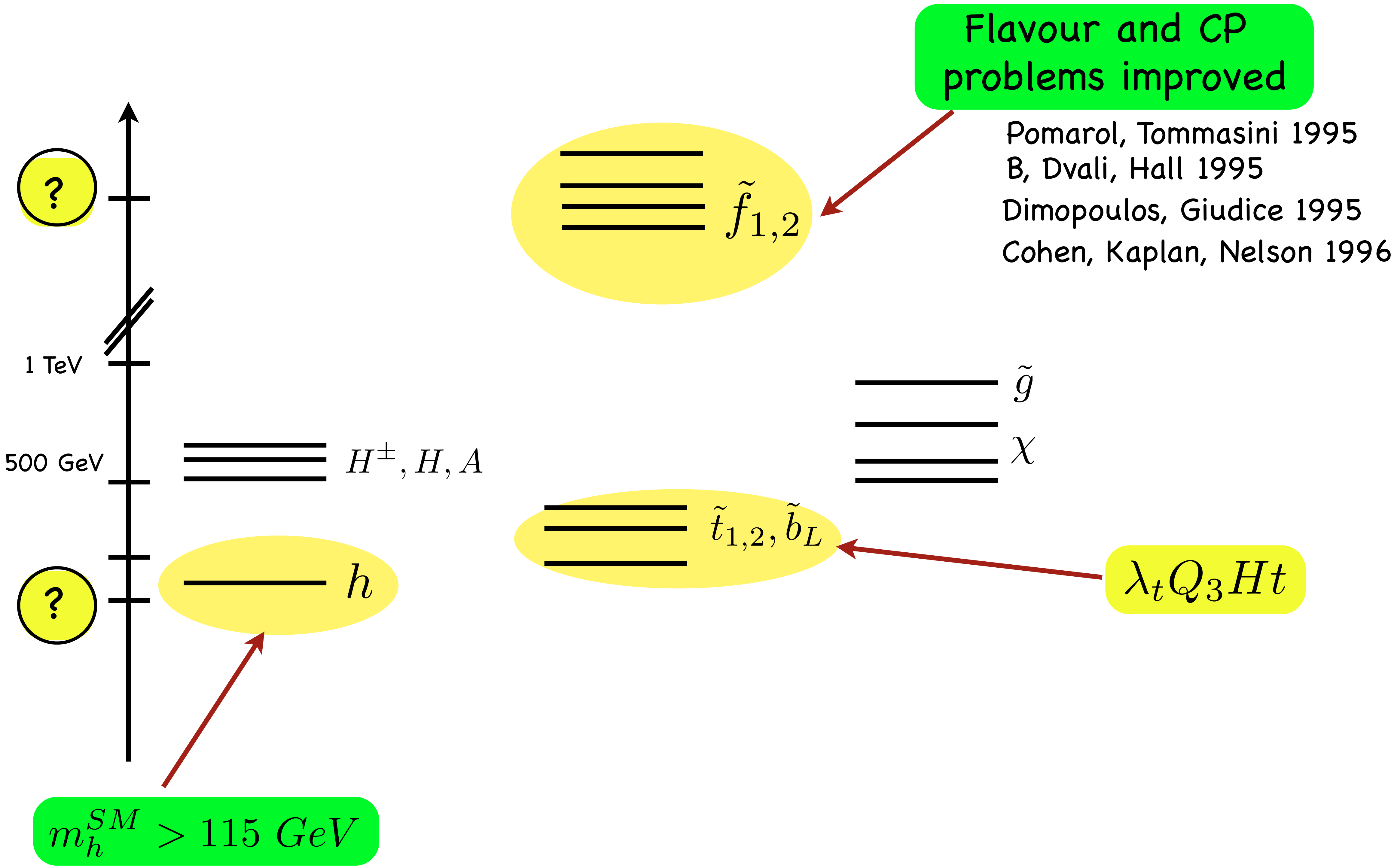
with some caveats for special mass configurations

$m_{\tilde{g}} \gtrsim 700\ GeV$

$m_{\tilde{t}} \gtrsim 300\ GeV$

Which sensitivity with 10xmore data?

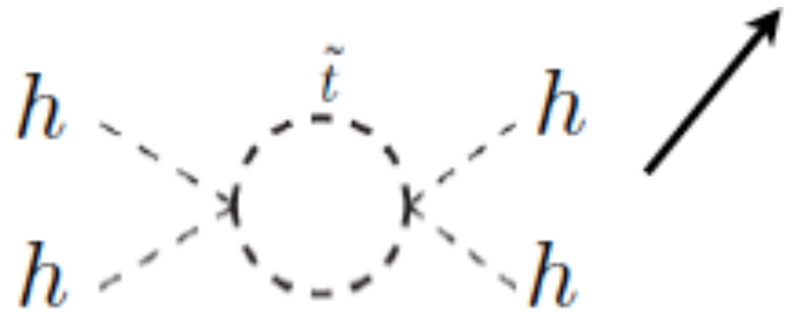
"Beyond mSUGRA"

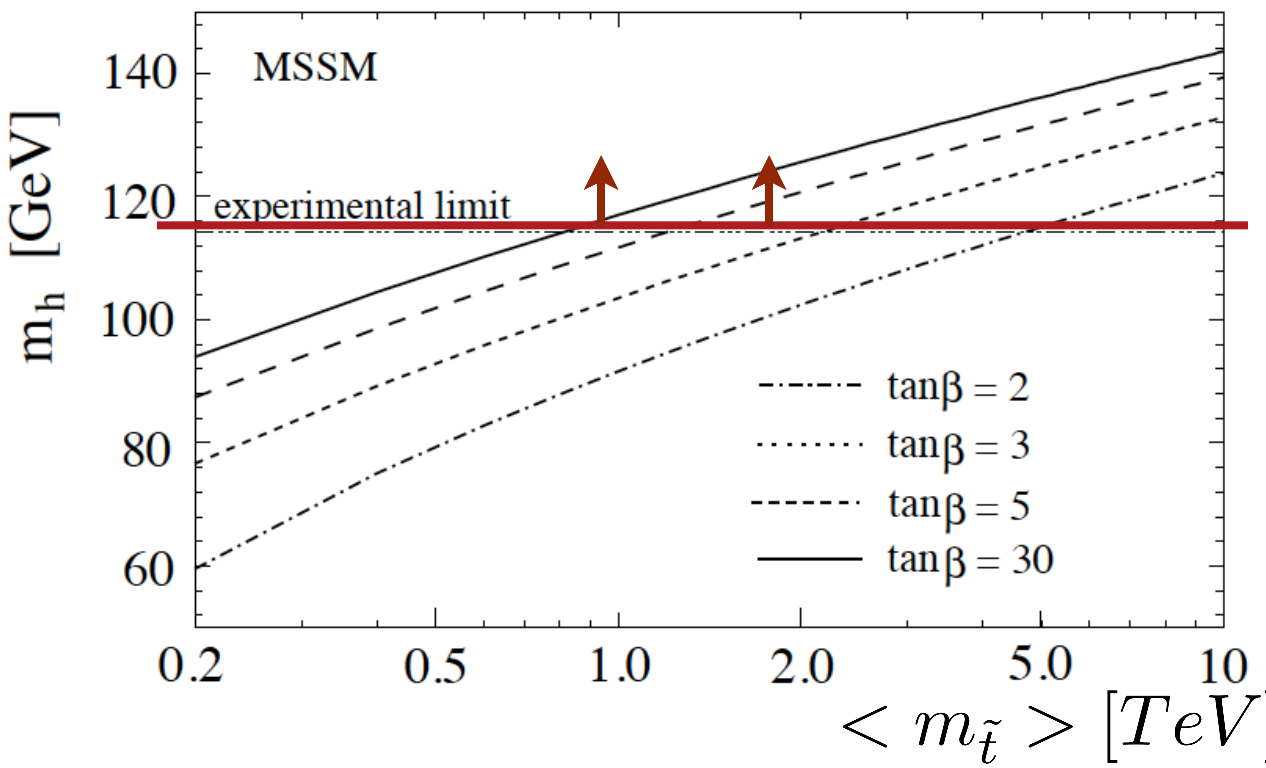


Where is the supersymmetric Higgs boson?

MSSM ≡ 2 Higgs doublets + perturbativity up to ≈10 TeV

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_{top}$$





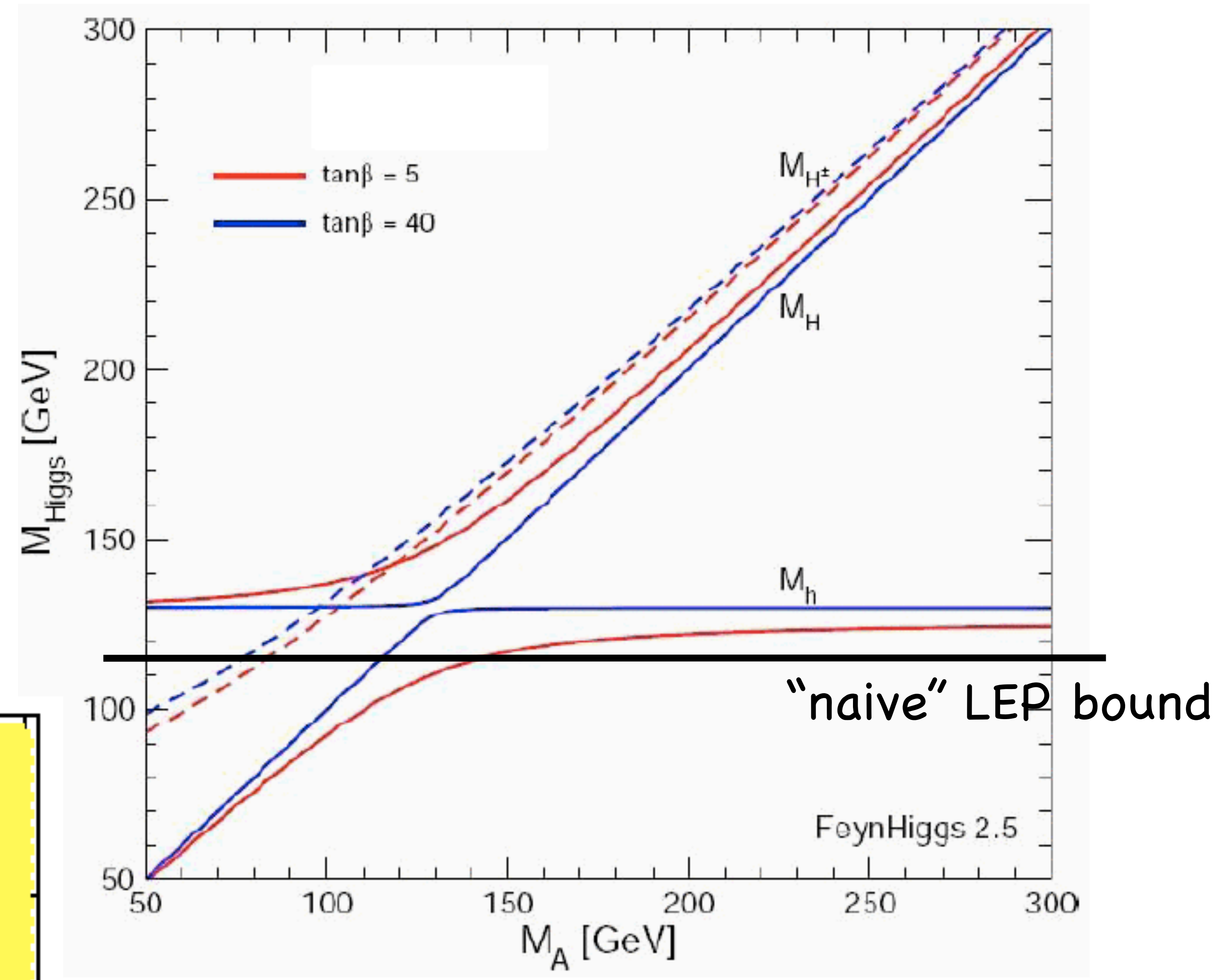
⇒ Take large tanβ (muon anomaly?) and large $m_{\tilde{t}}, A_t$
but swallow, e.g. in mSUGRA, a large contribution to M_Z ,
to be fine-tuned away

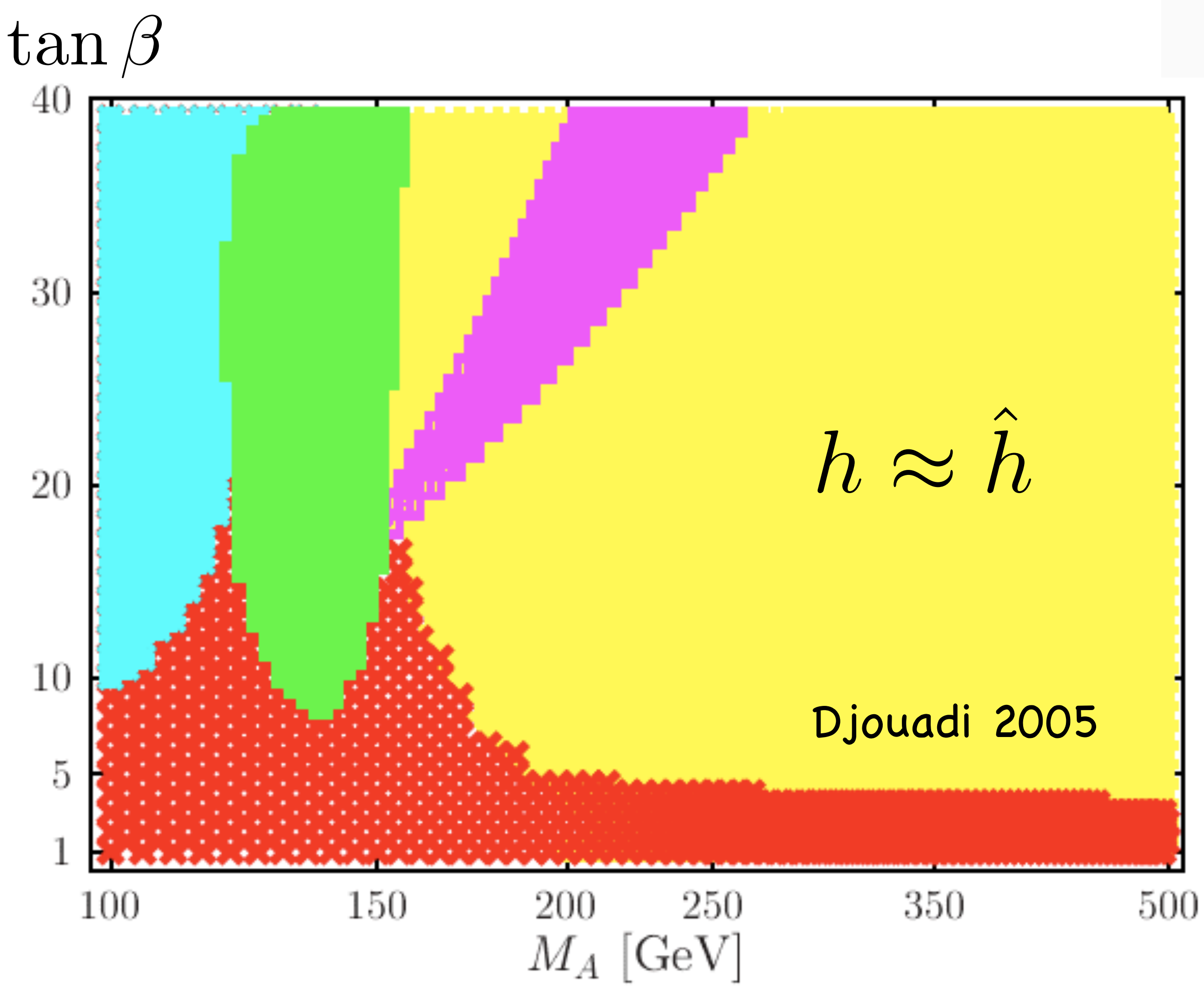
Never mind the ft for a while:

Can one think of excluding a generic MSSM,
no matter what the fine-tuning is?

The Higgs system in the MSSM

$$h_{SM} \to h, H, A, H^{\pm}$$
$$m_{h_{SM}} \to M_A, \tan\beta$$
$$(+\epsilon(m_{\tilde{t}}, A_t))$$





$$h = c\hat{h} + s\hat{H} \qquad c(M_A, \tan\beta)$$
$$H = -s\hat{h} + c\hat{H}$$
$$< \hat{h} >= v$$
$$< \hat{H} >= 0 \qquad g_{\hat{H}b\bar{b}} = \tan\beta$$

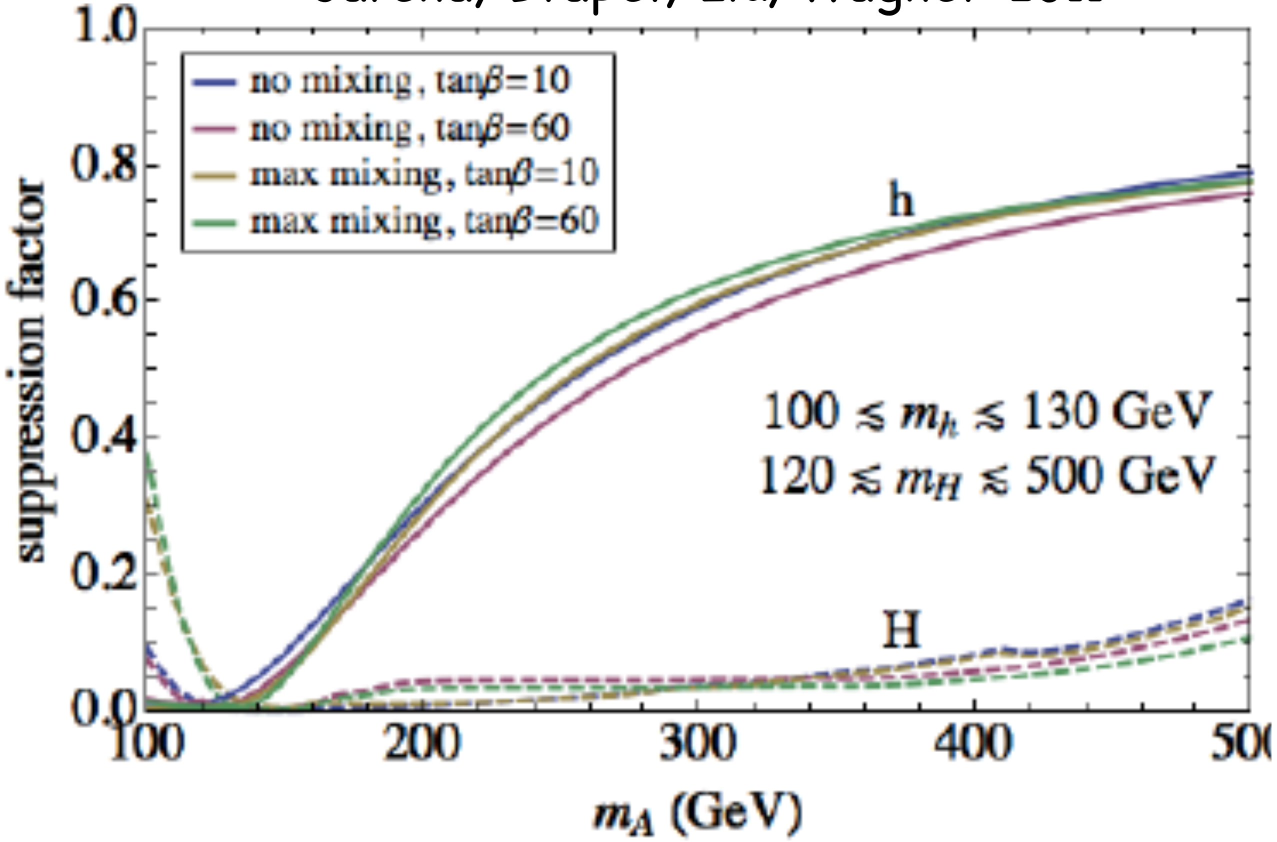
3 ways to deplete σB(γγ)

(with a bit of work in the parameter space)

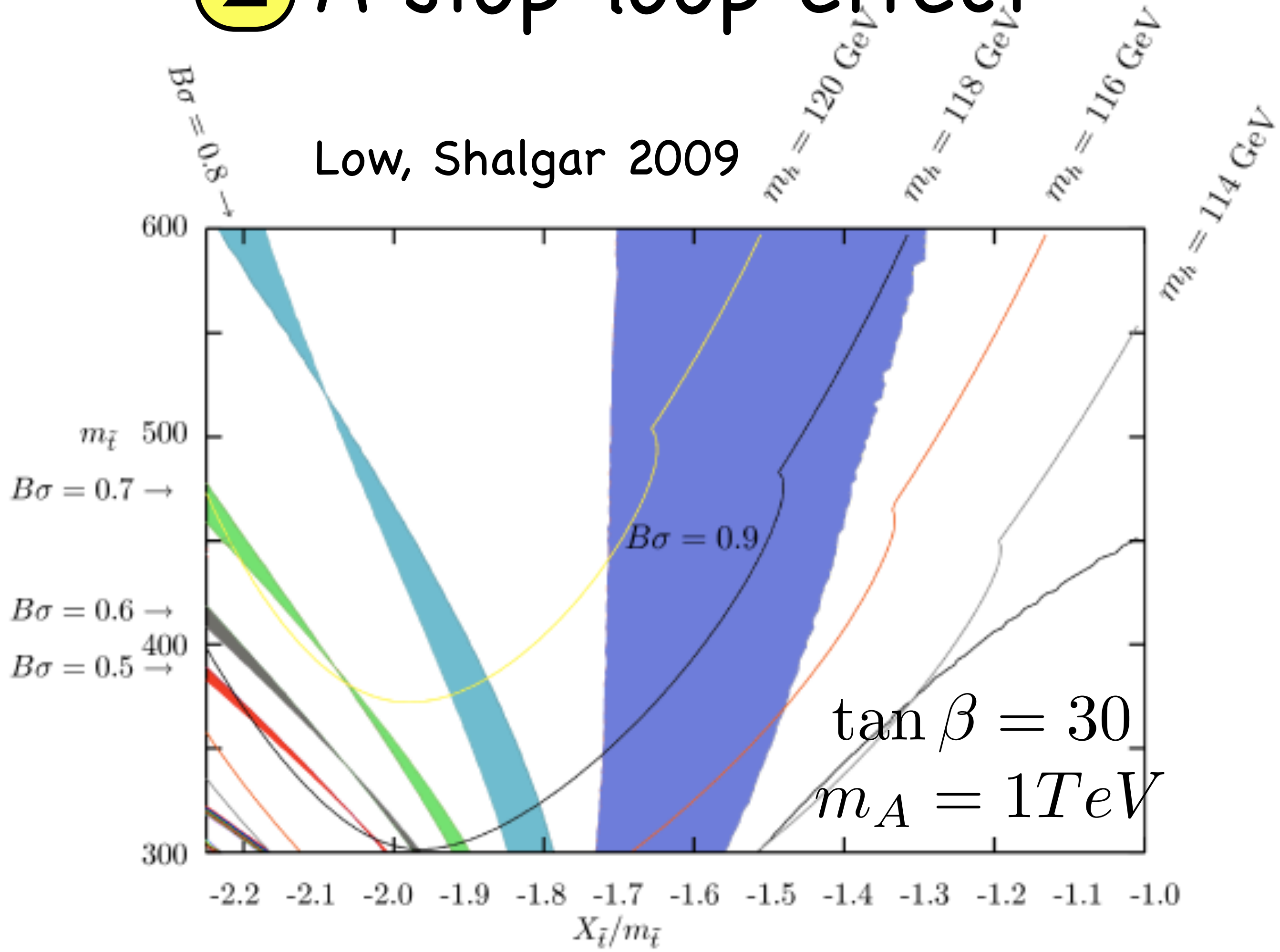
1 A $\hat{h}, \hat{H}$ mixing effect

2 A stop-loop effect

Carena, Draper, Liu, Wagner 2011



Low, Shalgar 2009

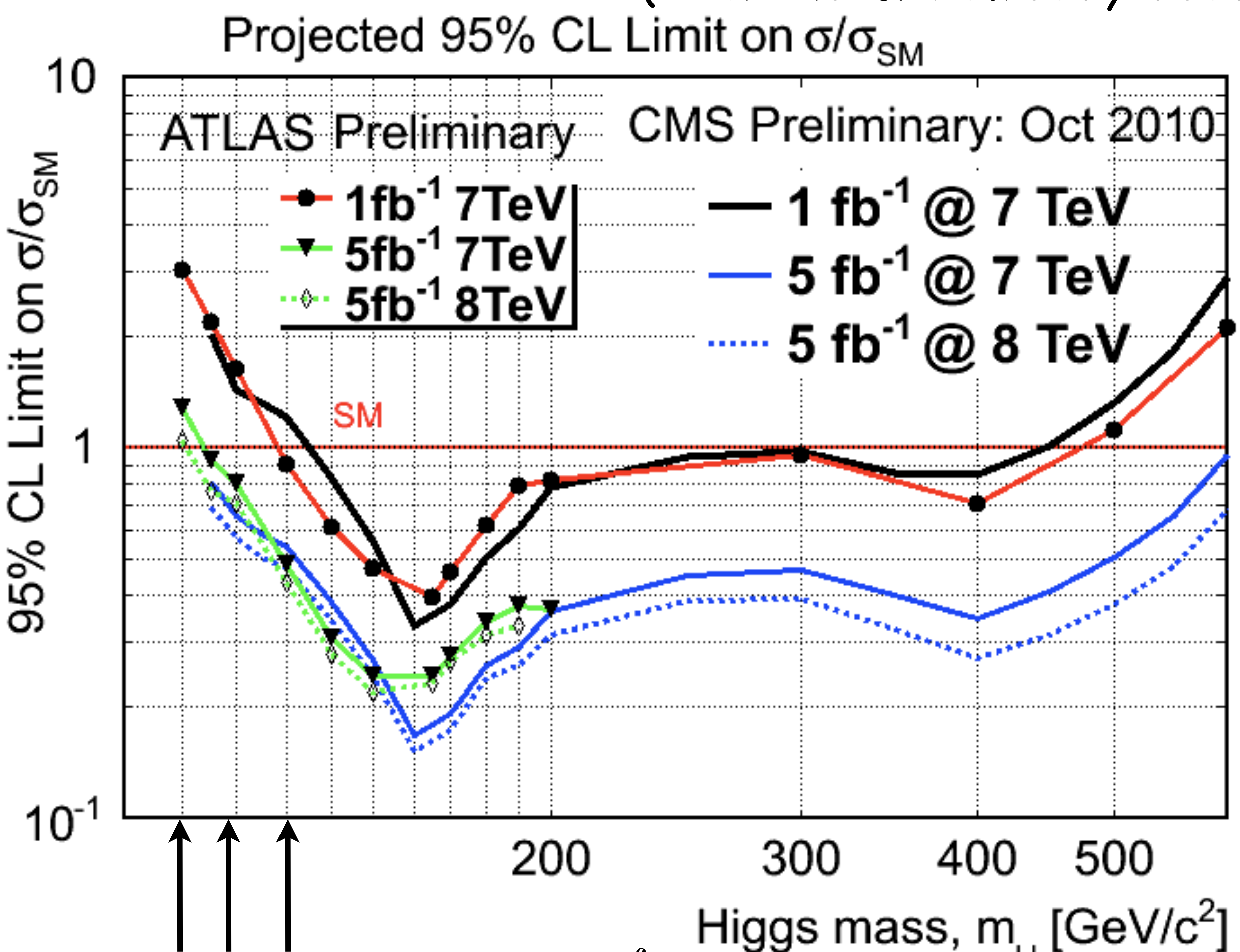


Shaded regions from varying μ

3 $h \rightarrow \chi^0\chi^0$ becoming significant if allowed by phase space

Can one think of excluding a generic MSSM, no matter what the fine-tuning is?

(with the SM already dead!!)



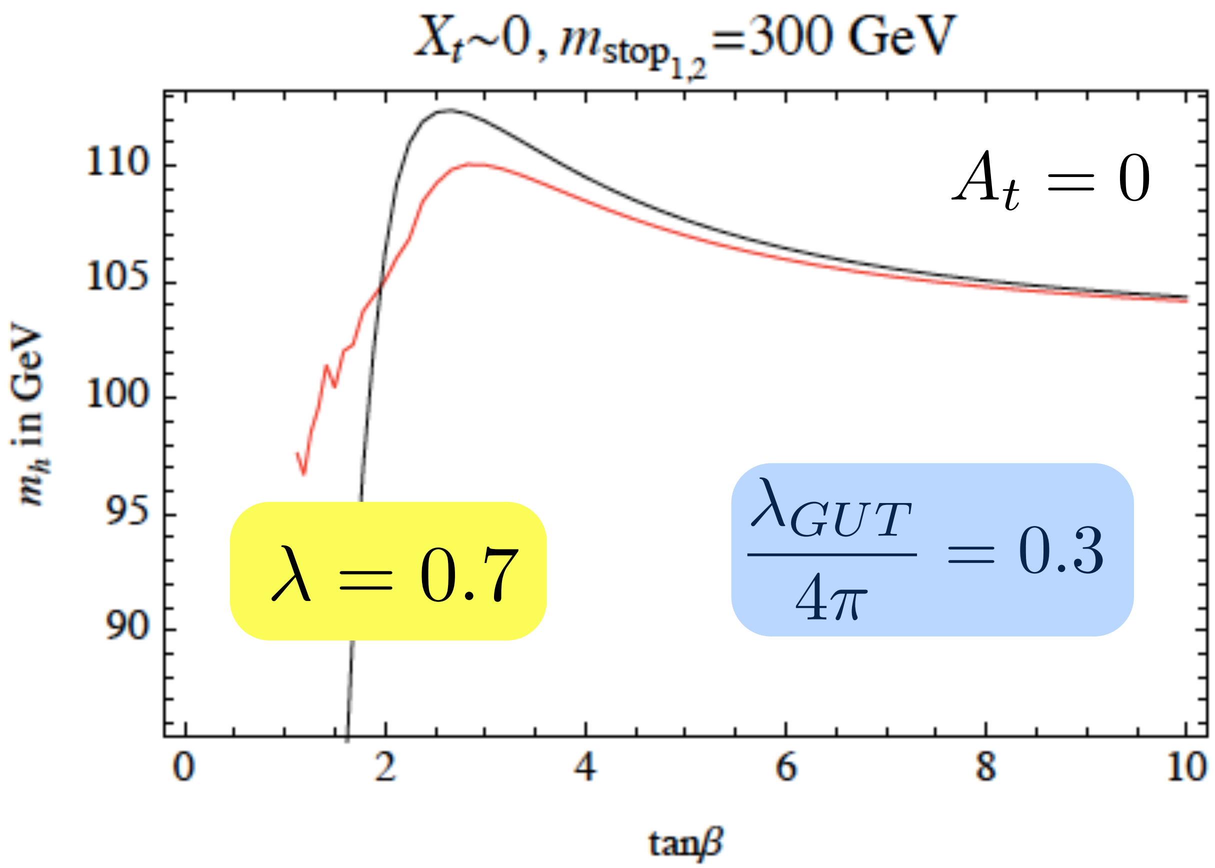
A reinforcement needed $\int \mathcal{L}dt = 10 \div 15\ fb^{-1}$

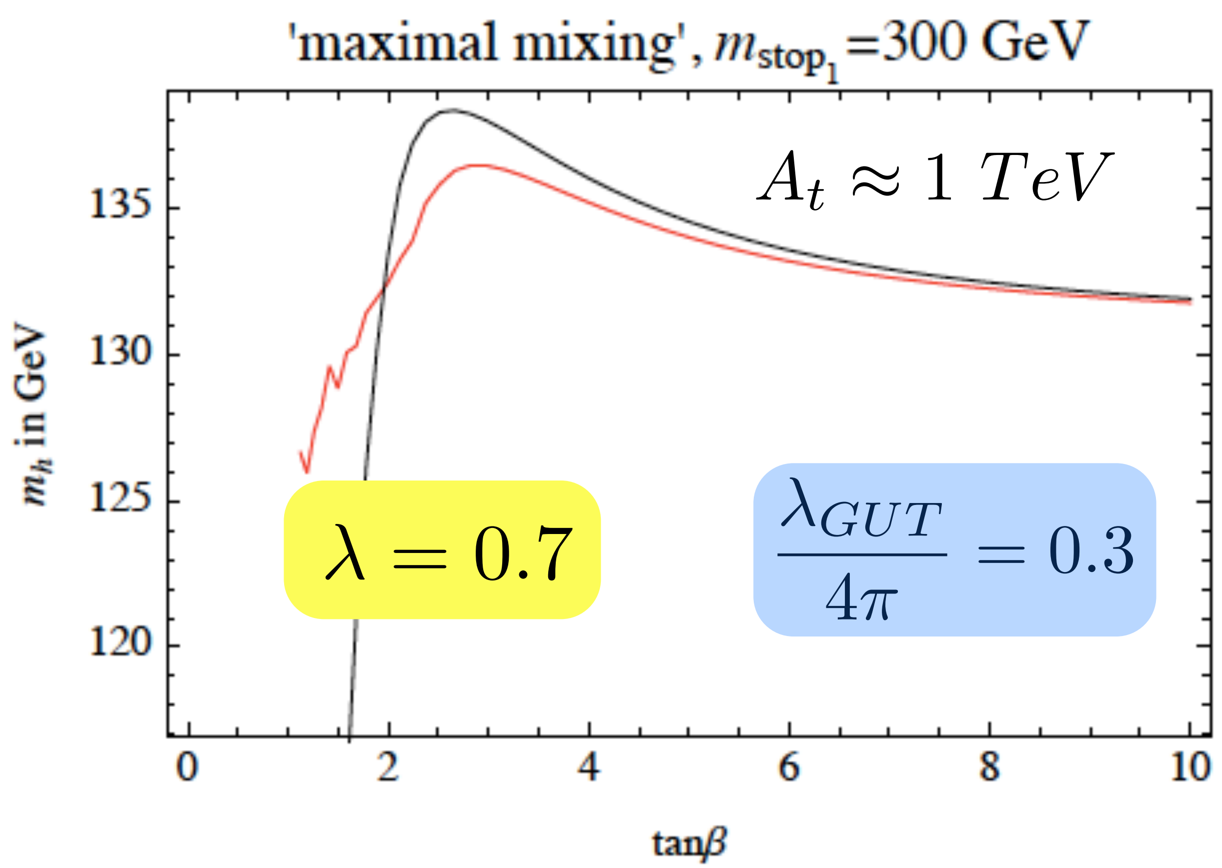
$VBF,\ Wh,\ t\bar{t}h$ $\quad h/H/A \to \tau\bar{\tau}$

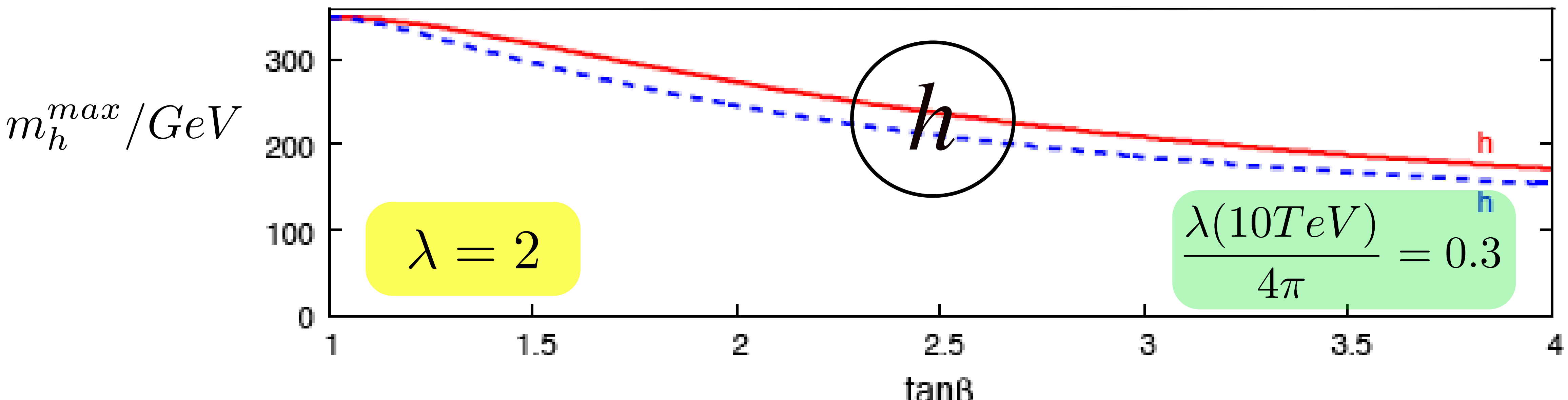
The easiest way to raise the Higgs mass

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

$$m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)$$

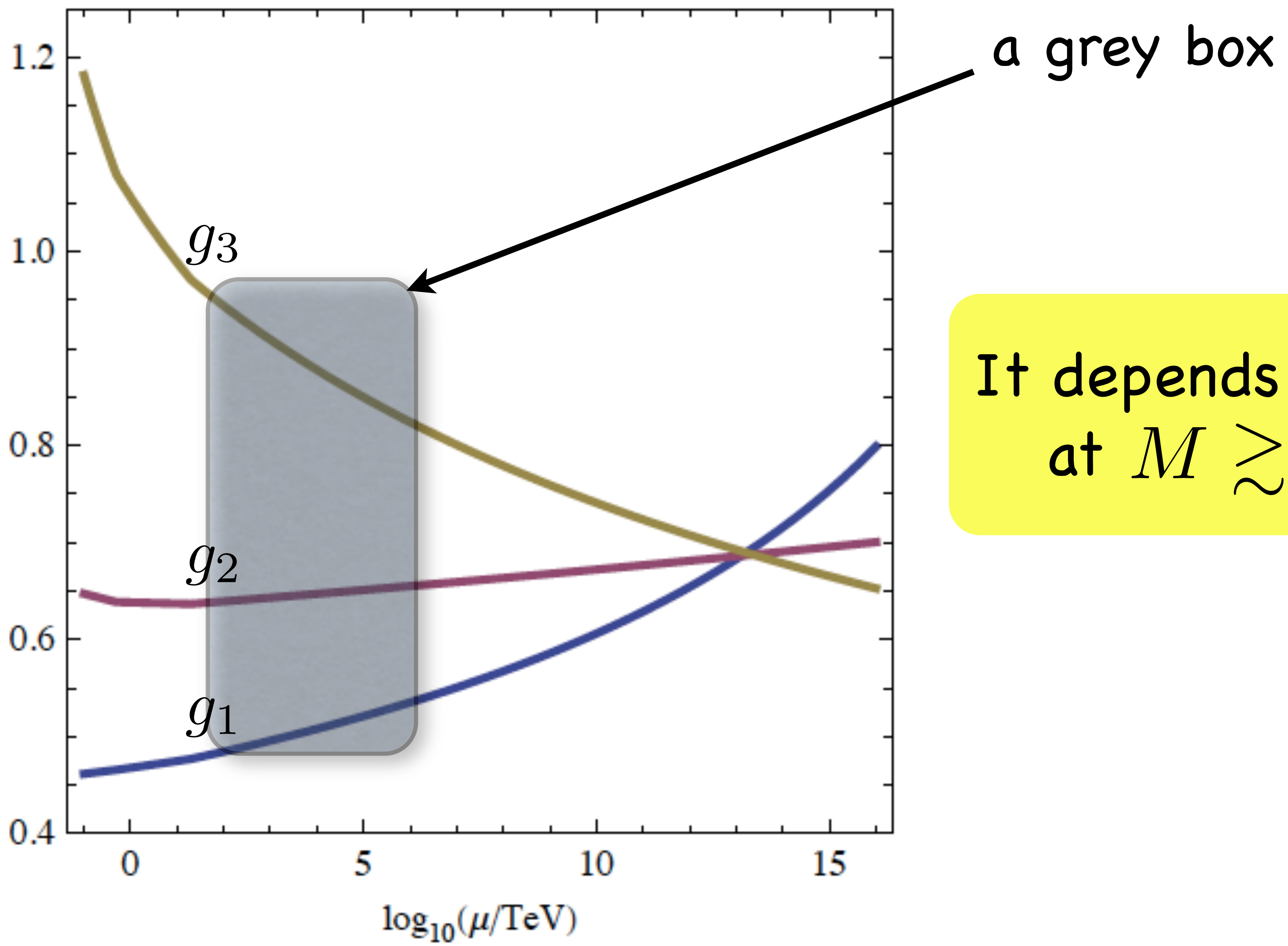






Maximal Higgs boson mass before mixing

What about gauge-coupling unification if $\lambda(G_F^{-1/2}) \approx 2$?



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

Mixing effects in the NMSSM

$$\hat{h},\ \hat{H},\ \hat{s} \Rightarrow s_3\ >\ s_2\ >\ s_1$$

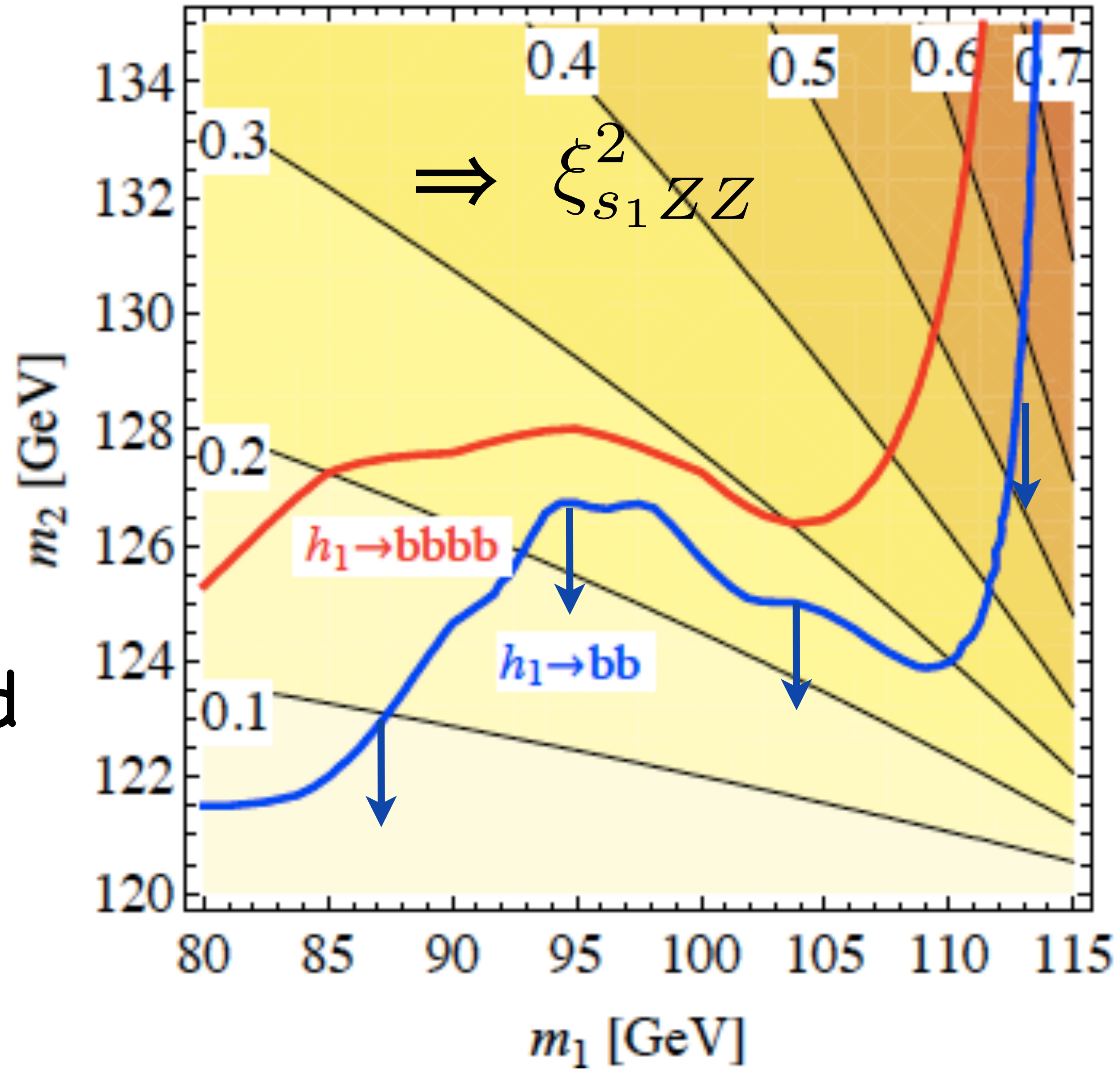
$\lambda = 0.7$

An illustrative 2x2 mixing model: $\hat{h}, \hat{s}$

Take:

$$m_{\hat{h}} = 120\ GeV$$

m_{s_1}, m_{s_2} as shown



below the blue line allowed by current data (LEP)

$\lambda = 0.7$

PQ SUSY (a particular NMSSM)

after mixing between $\hat{h}, \hat{H}, \hat{s}$

$$m_{S_3} \approx 400\ GeV > m_{S_2} \approx 125\ GeV > m_{S_1} \approx 95\ GeV$$

	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 $\chi_1\chi_1$) $BR(ZG) \simeq 30\%$ $BR(S_iS_j) \simeq 20\%$

G = a CP-odd pseudoGoldstone

$$S_1 \to GG \to b\bar{b}\ b\bar{b}$$

$$S_2 \to GG \to b\bar{b}\ b\bar{b}$$

$$S_2 \to \chi_1\chi_1$$

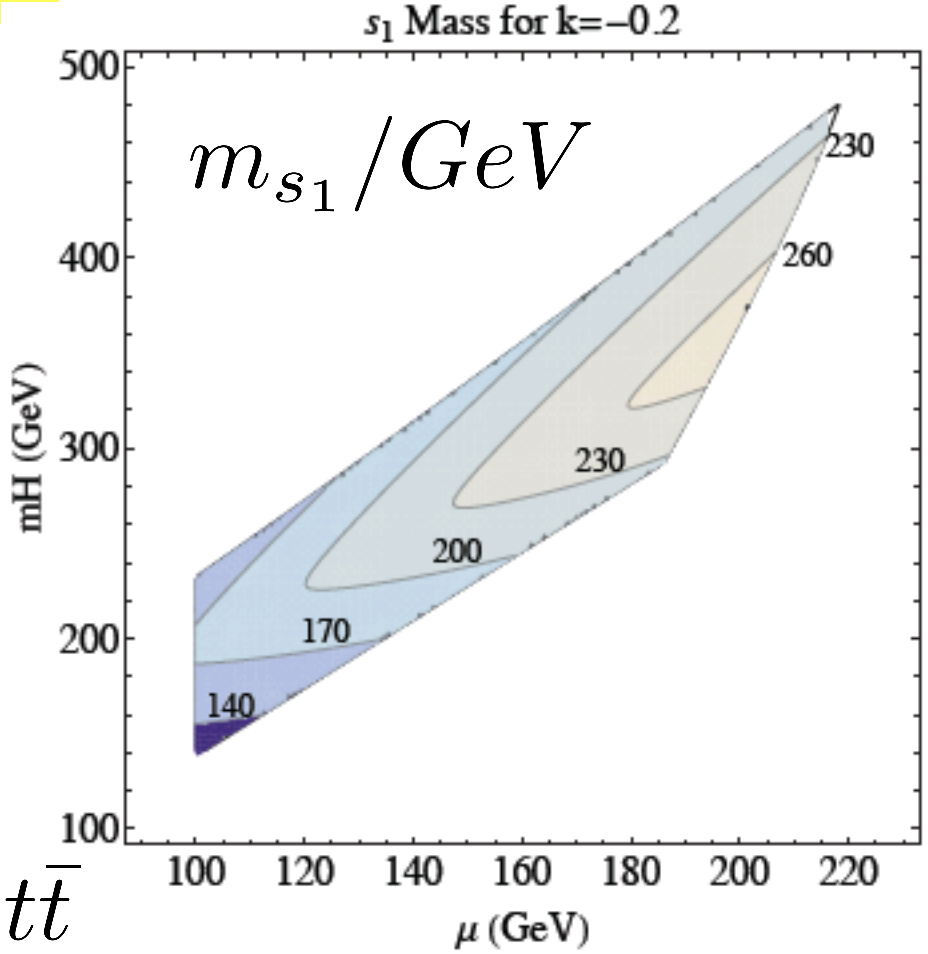
$$S_3 \to ZG \to Z\ b\bar{b}$$

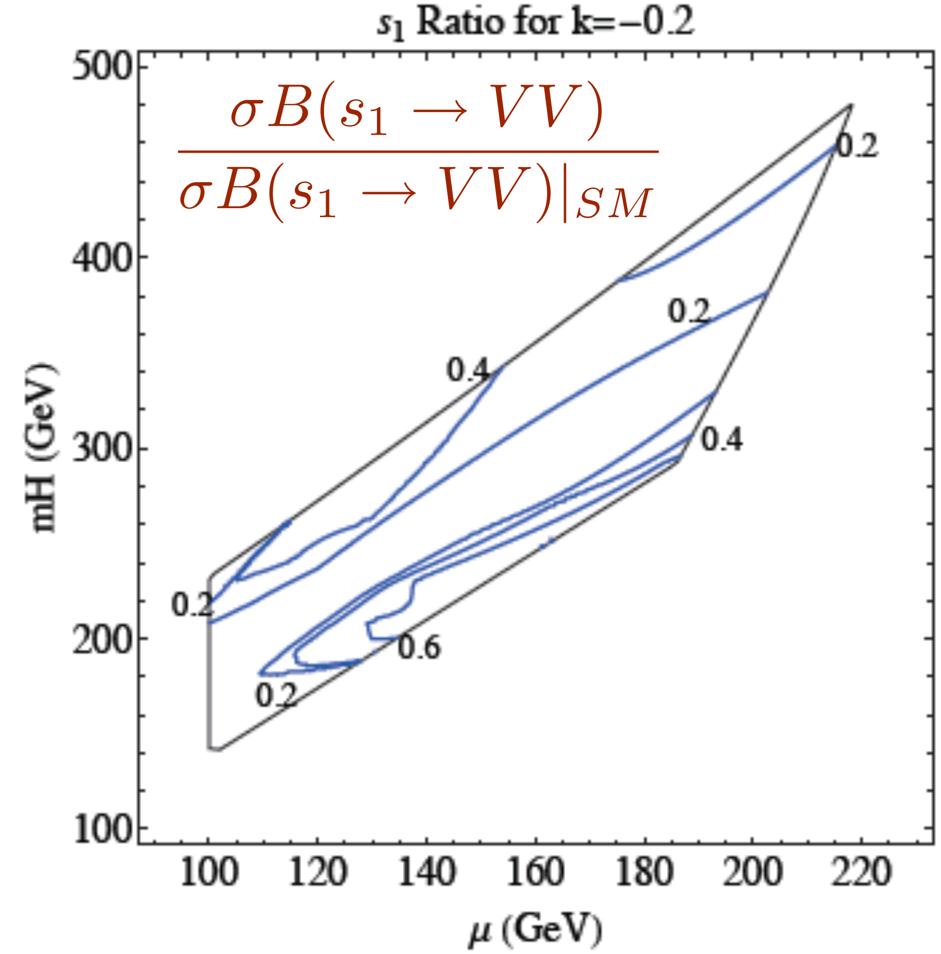
$\Leftarrow$!?!

B, Hall, Pappadopulo, Rychkov, Papaioannou 2007

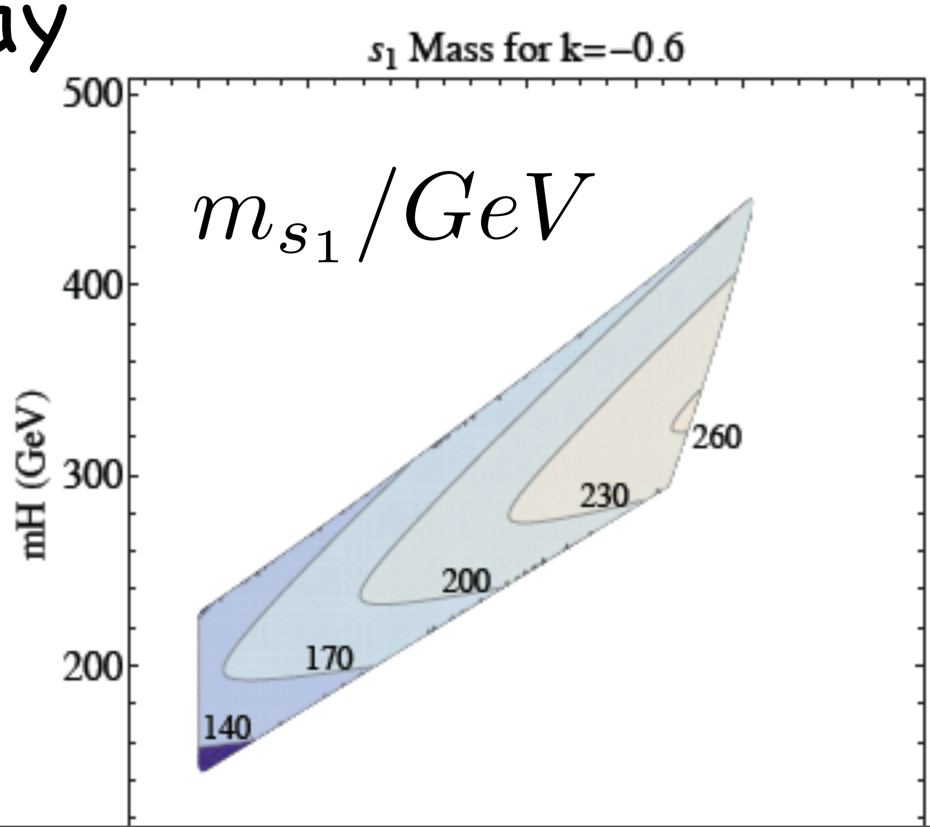
$\lambda = 2, \ \tan\beta = 1.5$

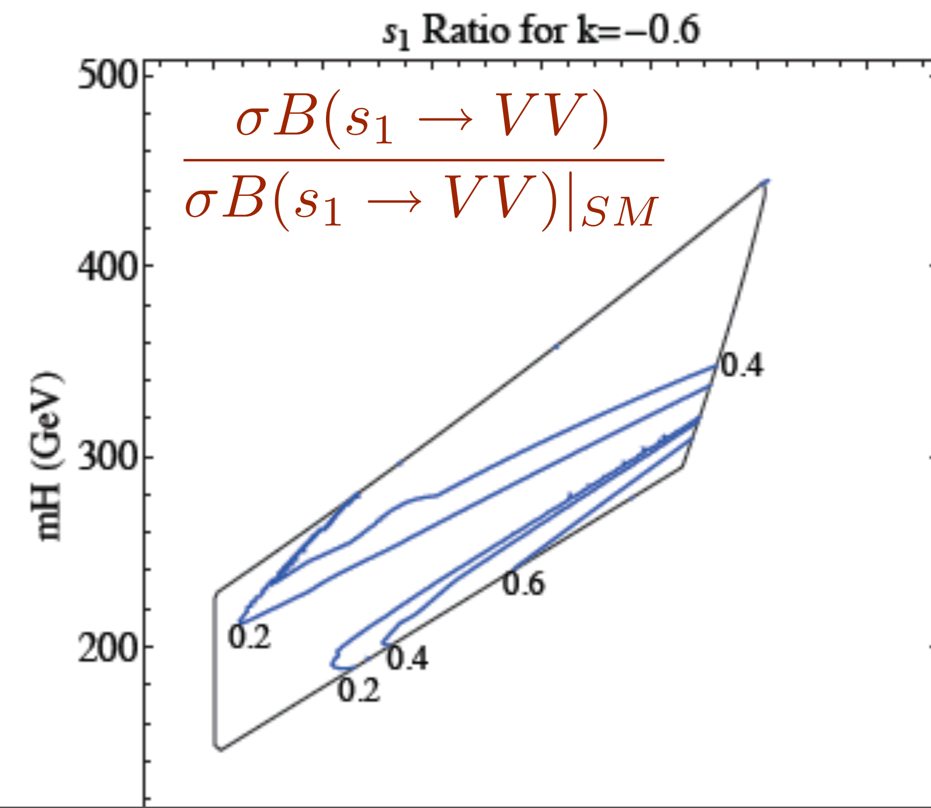
$m_{S_3} > 500 \ GeV > m_{S_2} > m_{S_1}$





s_1 has reduced $s_1 t\bar{t}$ or prefers to decay into $b\bar{b}b\bar{b}$ or $\chi^0\chi^0$

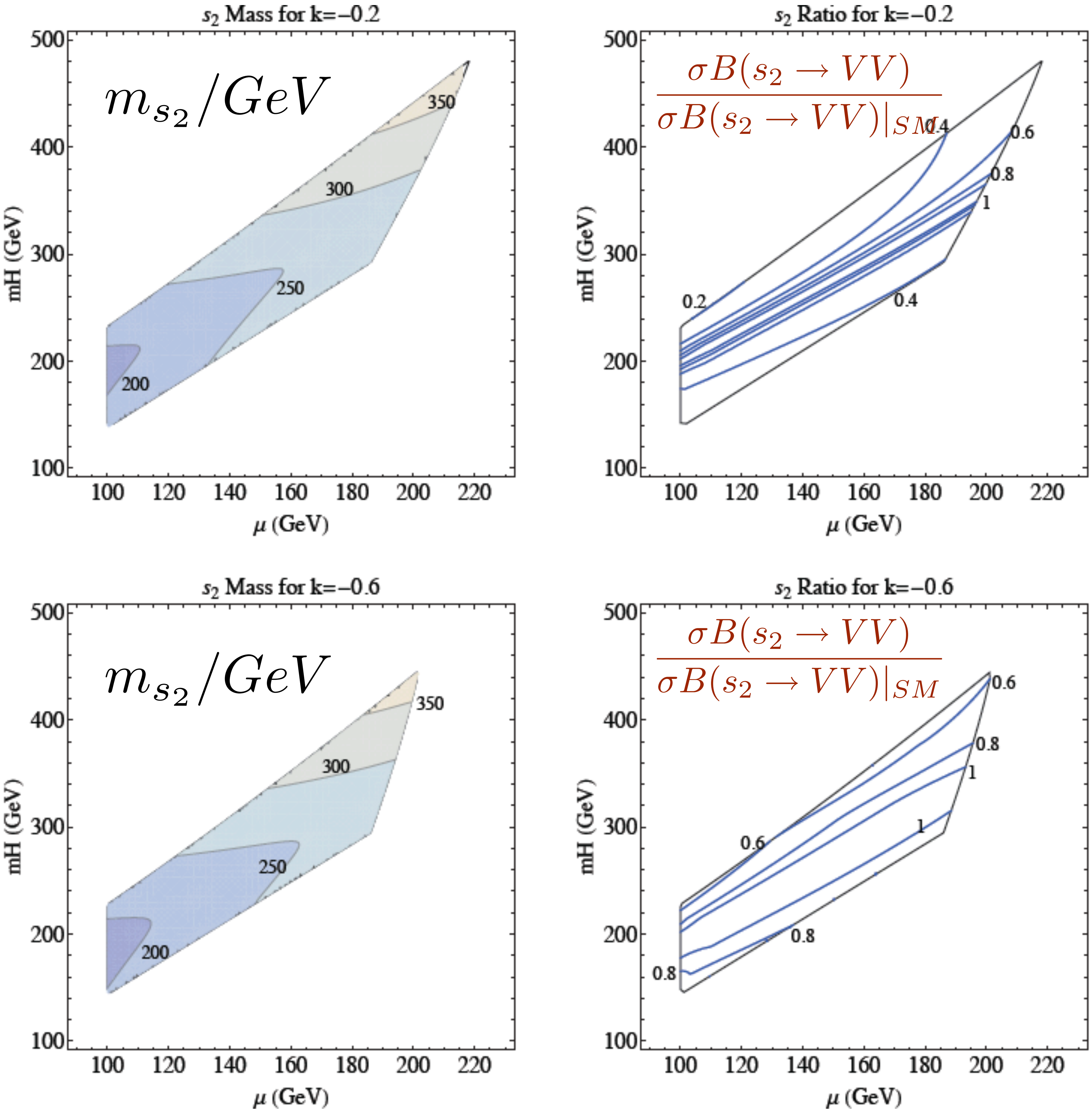




Bertuzzo, Farina 2011

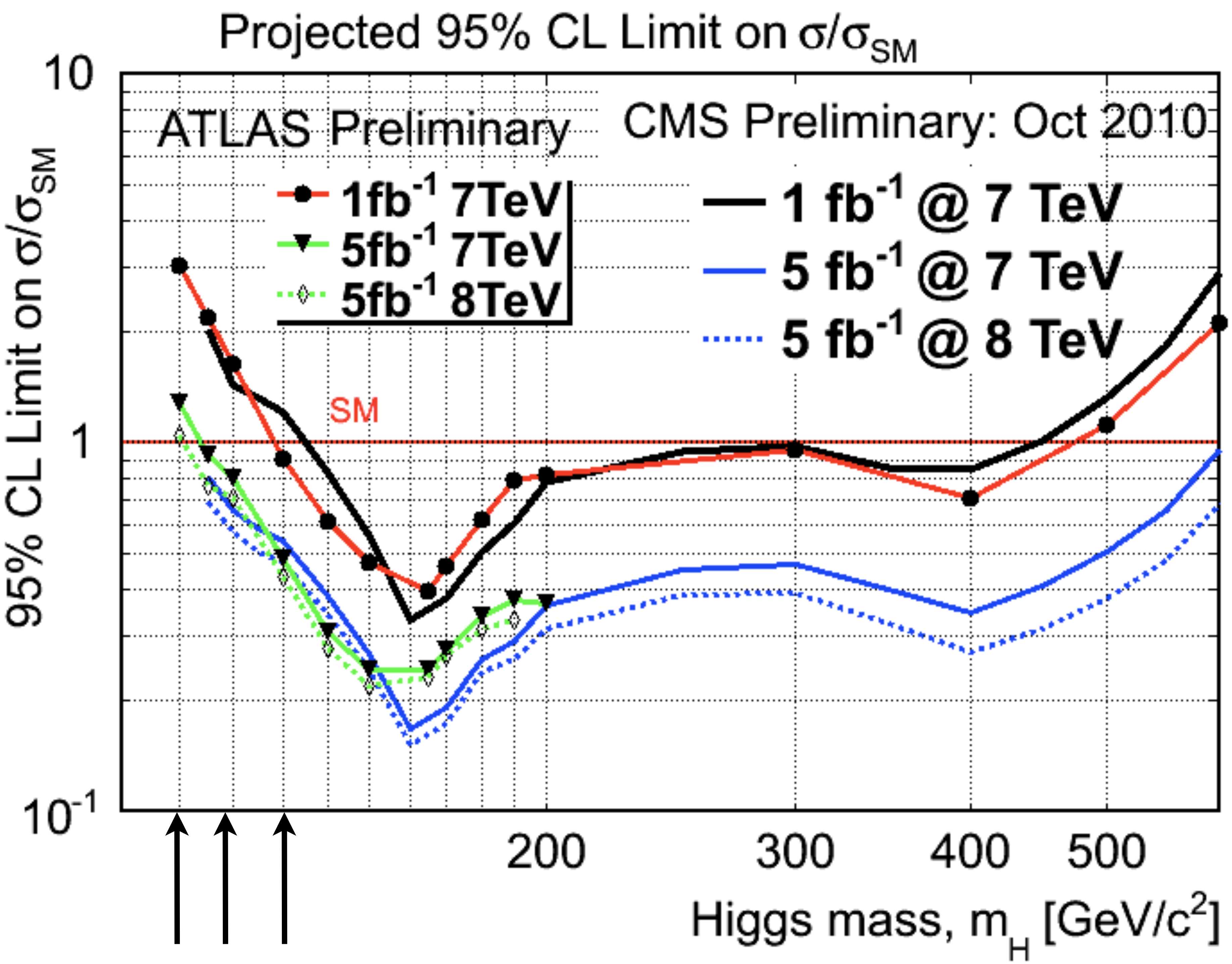
$\lambda = 2, \ \tan\beta = 1.5$

s_2 visible in ZZ with enough lumi



Bertuzzo, Farina 2011

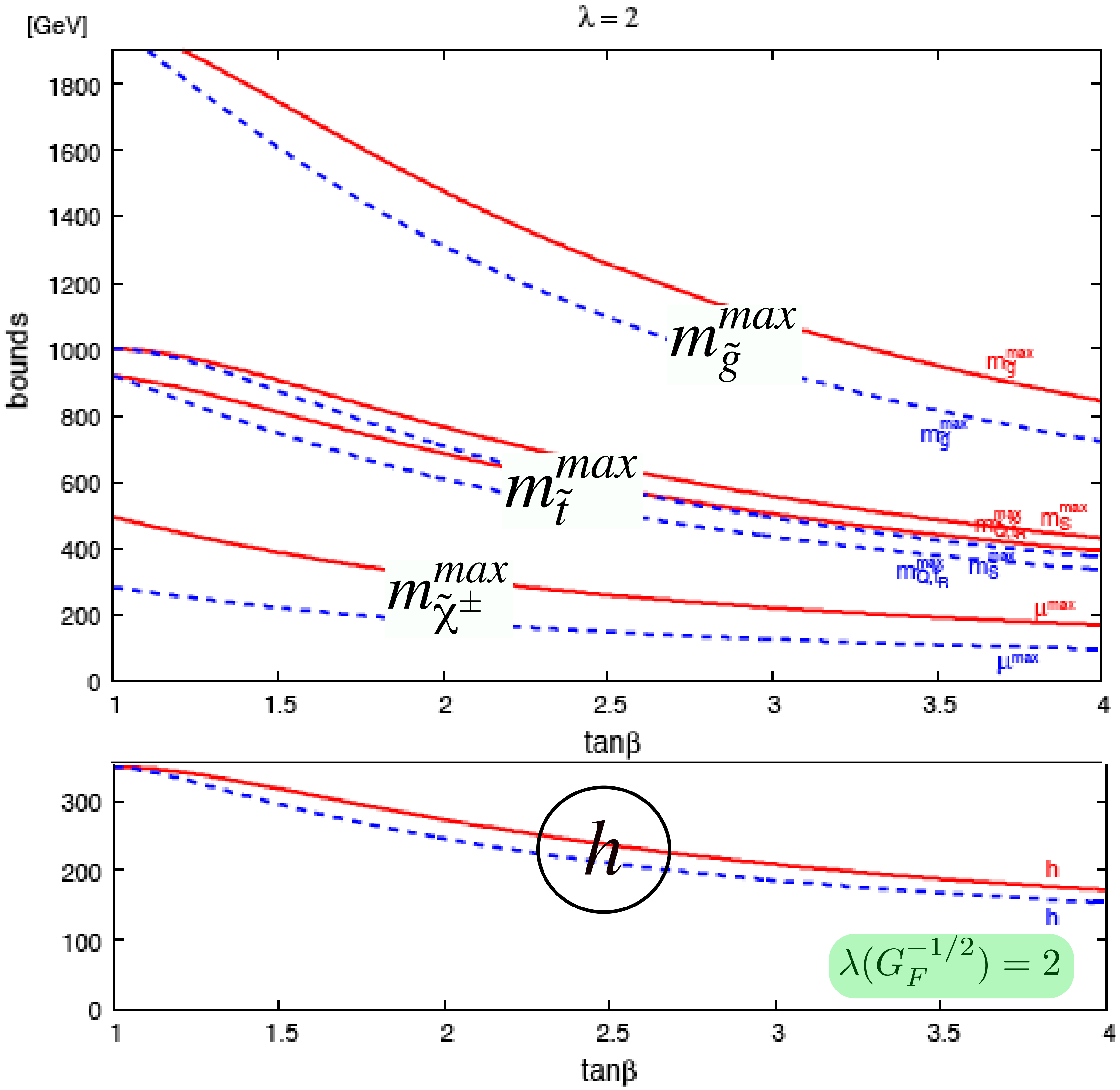
Can one think of excluding a generic NMSSM?



crucial to pay attention to "non-SM" modes in low mass region

"enough" luminosity critical everywhere (up to $\approx 400\ GeV$)

Particle spectrum (naturalness bounds)



$\lambda = 2$

$\Lambda_{mess} = 100\ TeV$

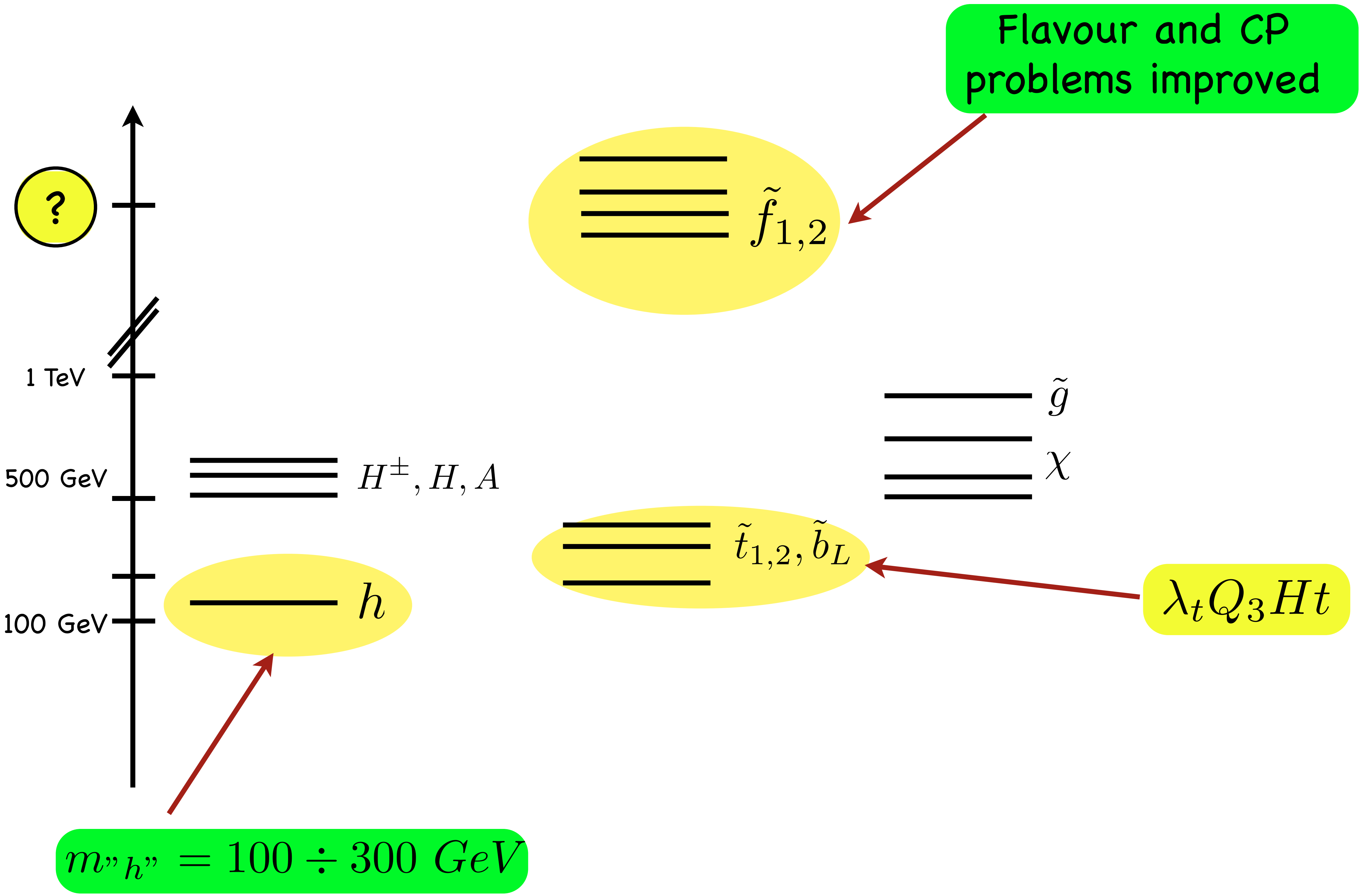
with up to 20% tuning

$m_h = 200\ GeV$
$m_{\tilde{g}} \lesssim 1200\ GeV$
$m_{\tilde{t}} \lesssim 600\ GeV$

$$(m^{max} \propto \sqrt{\Delta/5})$$
$$\Delta = \frac{1}{20\%} = 5$$

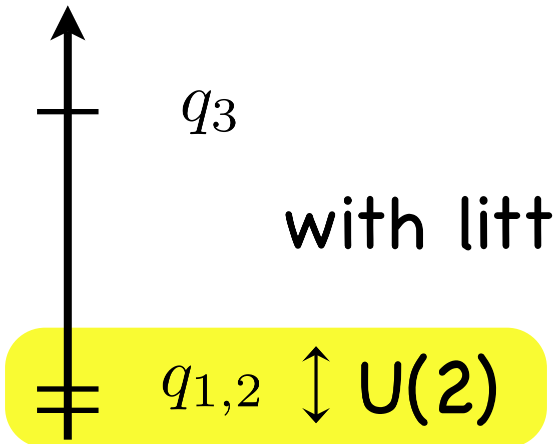
B, Hall, Nomura, Rychkov 2006

"Beyond mSUGRA"



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

Tomassini, Pomarol 1995
B, Dvali, Hall 1995



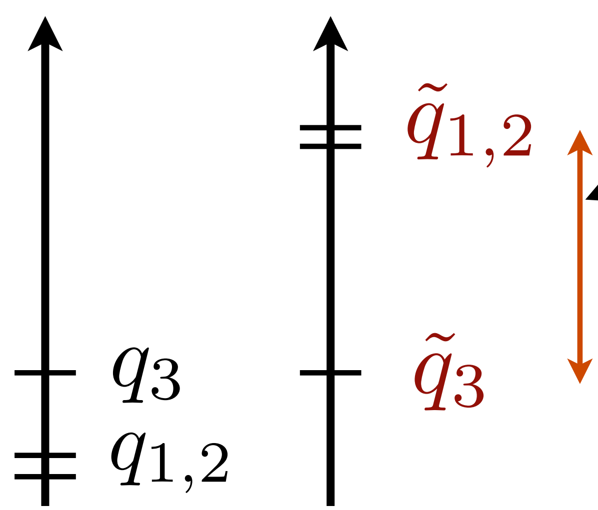
with little communication between $q_{1,2}$ and q_3

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

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

and perhaps also in the SUSY non-data

flavour, EDMs, direct s-particle searches



An inverted spectrum

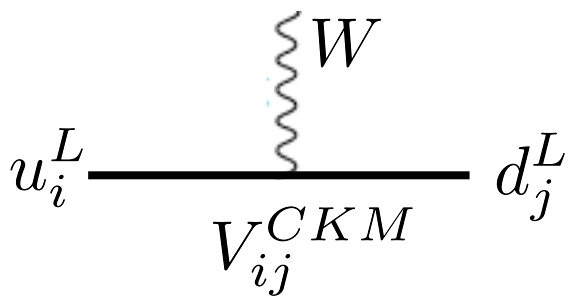
Anomalous U(1), $\hat{q}_{1,2}$ composite (A UV problem)

B, Isidori, Jones-Perez, Lodone, Straub

Consequences of $U(2)^3$

Flavour changing interactions

standard, in non standard parametrization



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

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

$s_d = -0.22 \pm 0.01$

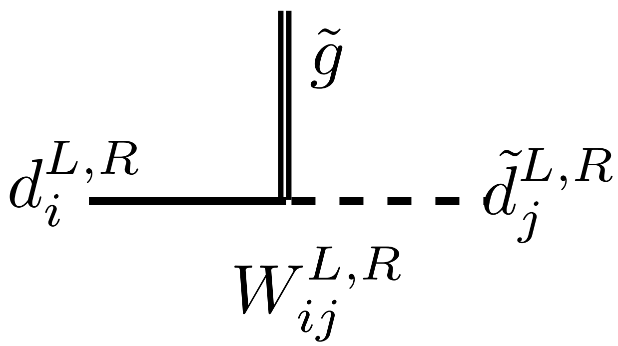
$(\sqrt{m_d/m_s} = 0.220 \pm 0.015)$

$s_u = 0.086 \pm 0.003$

$(\sqrt{m_u/m_c} = 0.055 \pm 0.015)$

$s = 0.0411 \pm 0.0005$

$\phi = (-97 \pm 9)^\circ$



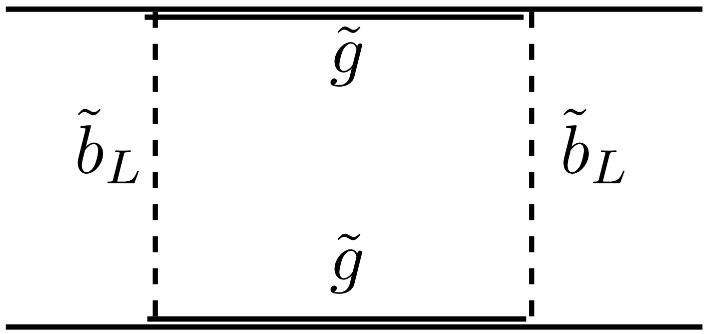
$$W^L = \begin{pmatrix} c_d & s_d e^{-i(\delta+\phi)} & -s_d s_L e^{i\gamma} e^{-i(\delta+\phi)} \\ -s_d e^{i(\delta+\phi)} & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

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

1 new angle s_L and 1 new phase γ

Supersymmetric flavour fit

including:



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

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

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

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

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

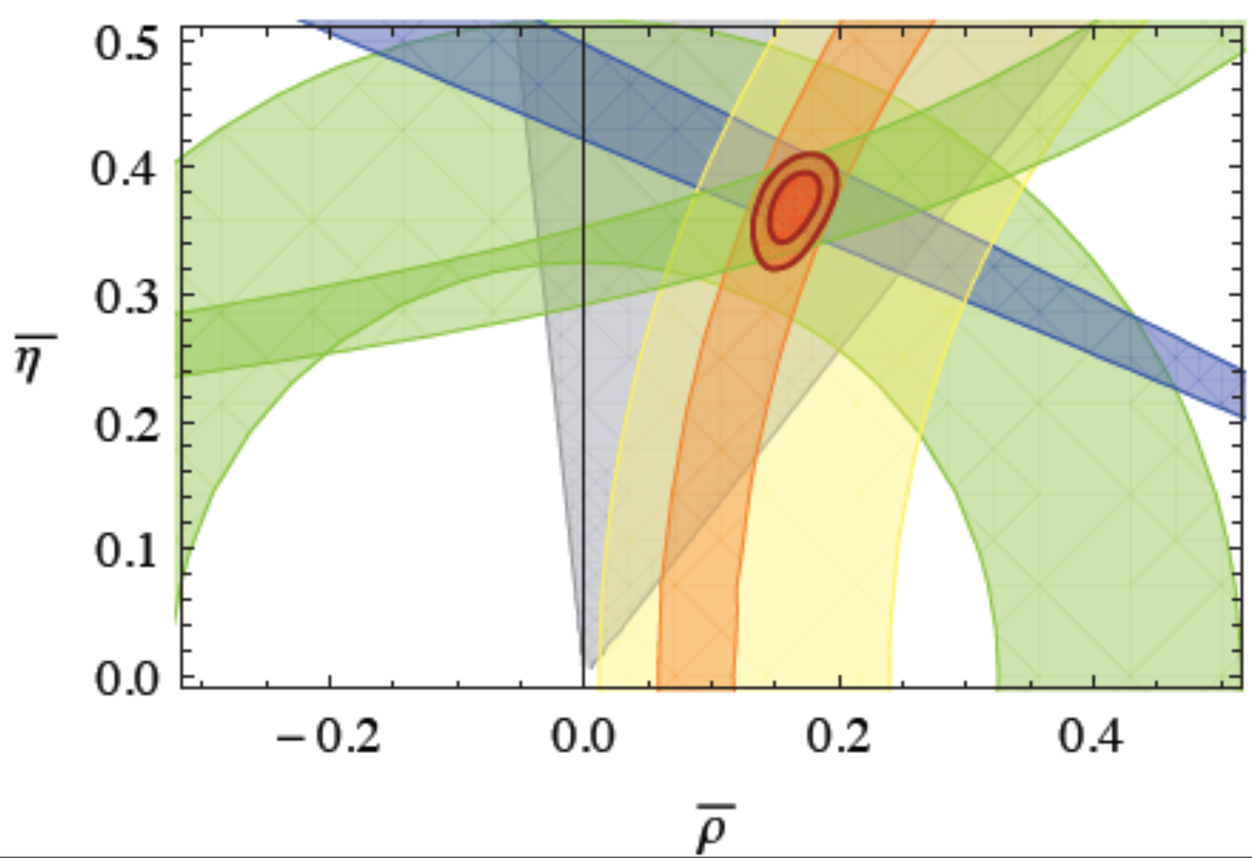
Tree level +

ΔM_d

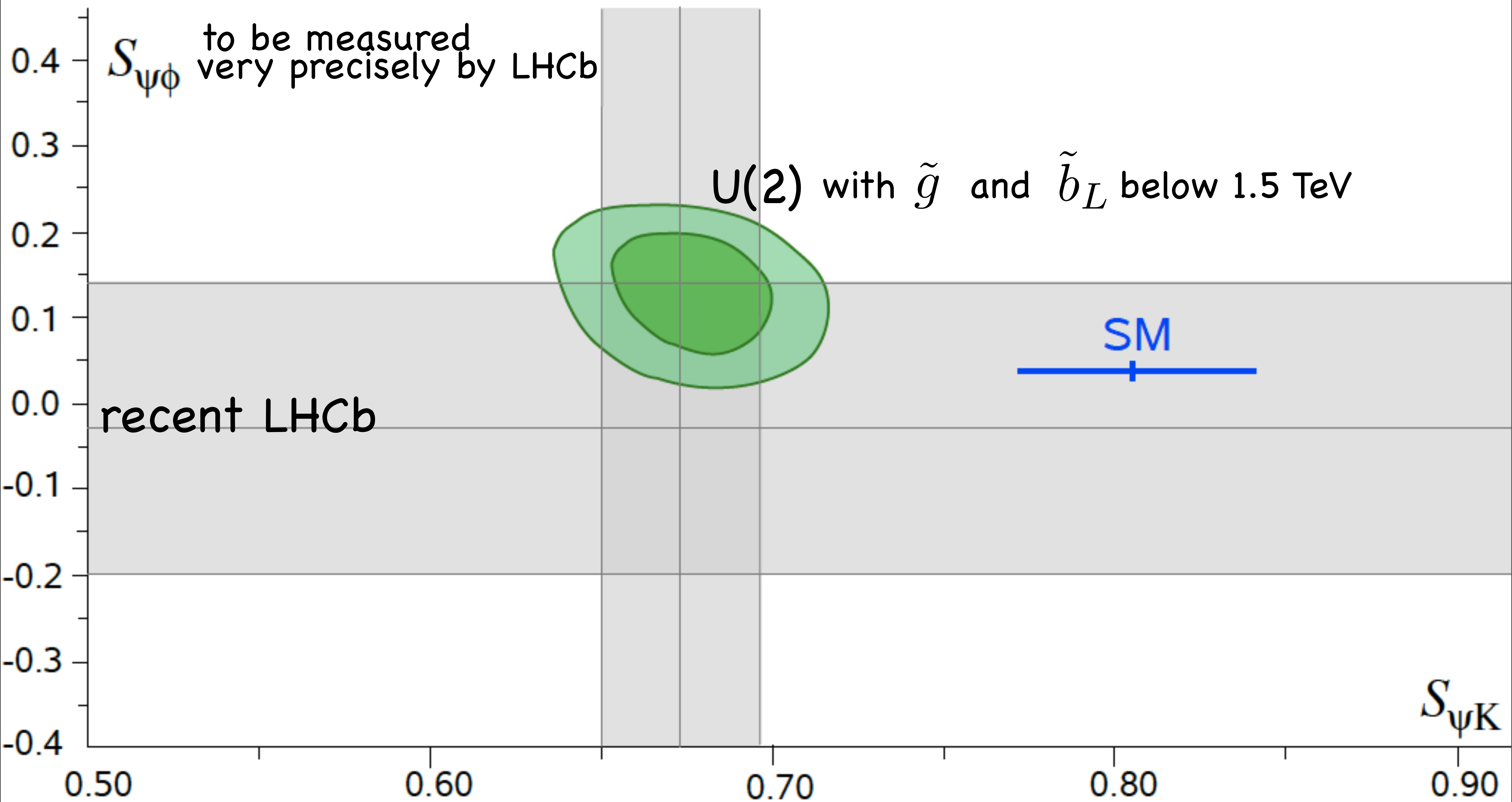
ΔM_s

$S_{B_d \to \Psi K_S}$

ϵ_K



CPV in ΔB = 2



B, Isidori, Jones-Perez, Lodone, Straub

Summary

1. To discover (or to exclude natural) supersymmetry
   focus on $m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}$

2. "Enough" luminosity at LHC1 critical to the Higgs
   boson(s) searches both in the MSSM and in the NMSSM
   $m_h = 110 \div 140\ GeV$ crucial but not exclusive

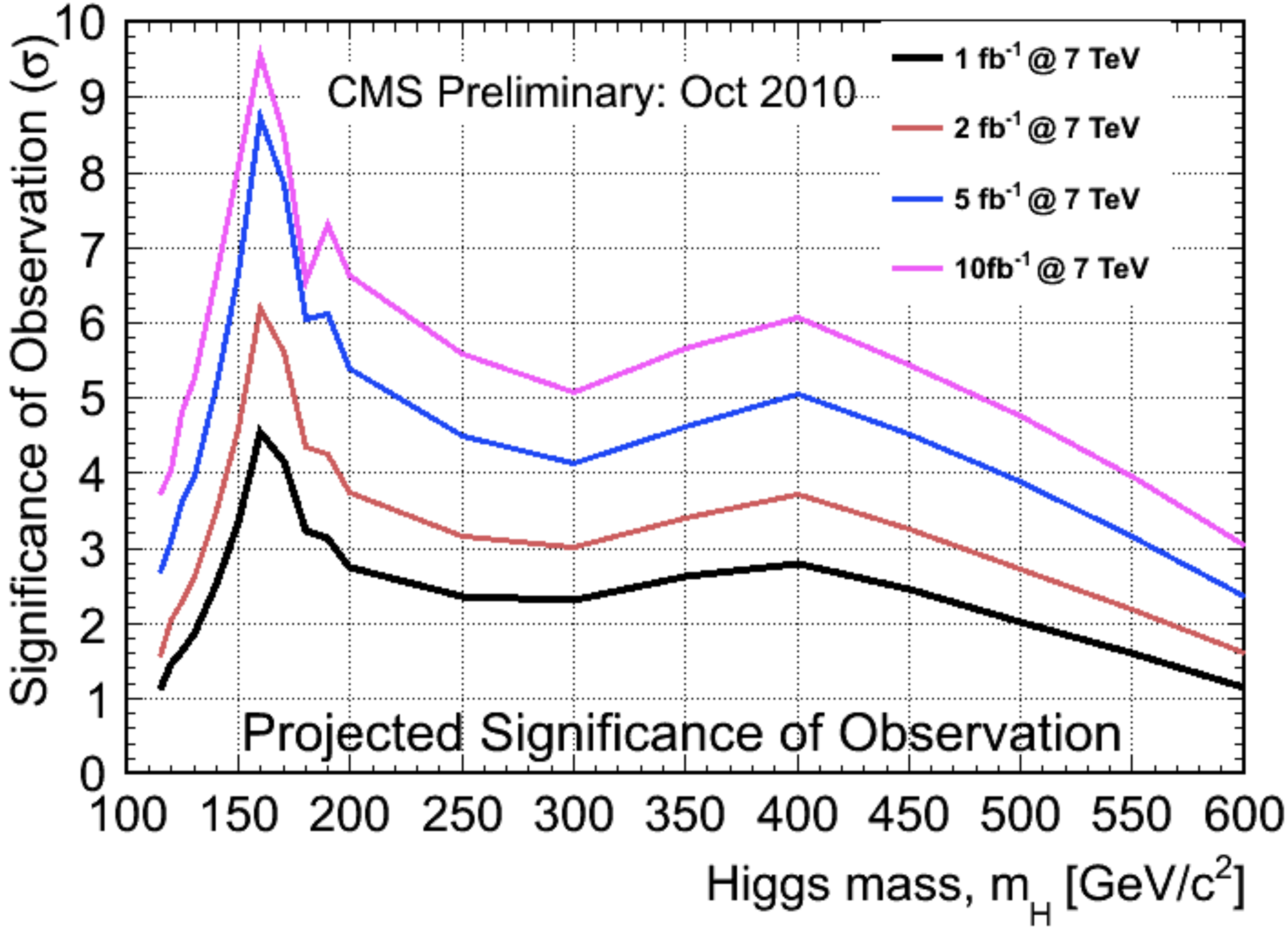
3. Flavour and CPV signals (at low tanβ)

4. Some weakly interacting particles, $\tilde{\chi}^{\pm}, \tilde{\chi}^0_2$
   might start becoming accessible
   (depending on the s-lepton masses)

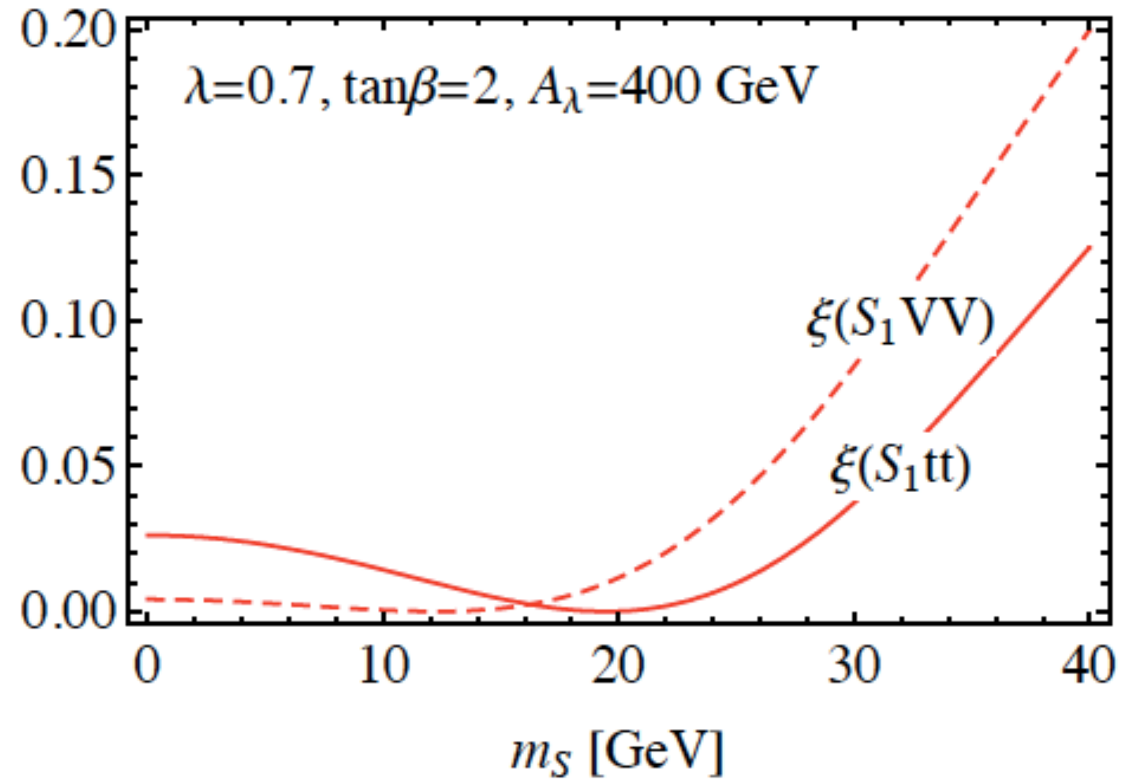
LHC1 with $10 \div 15\ fb^{-1}$ decisive !?!

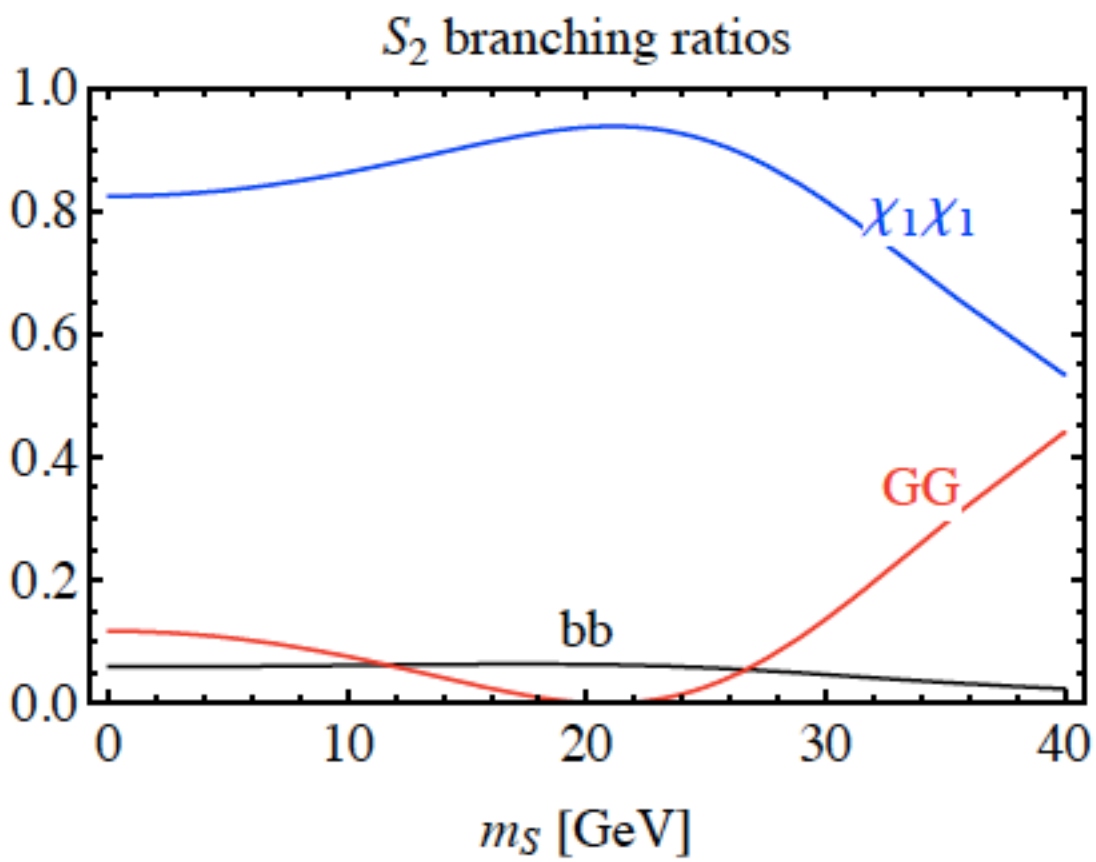
("special" spectra, RPV, hidden sectors, etc.)

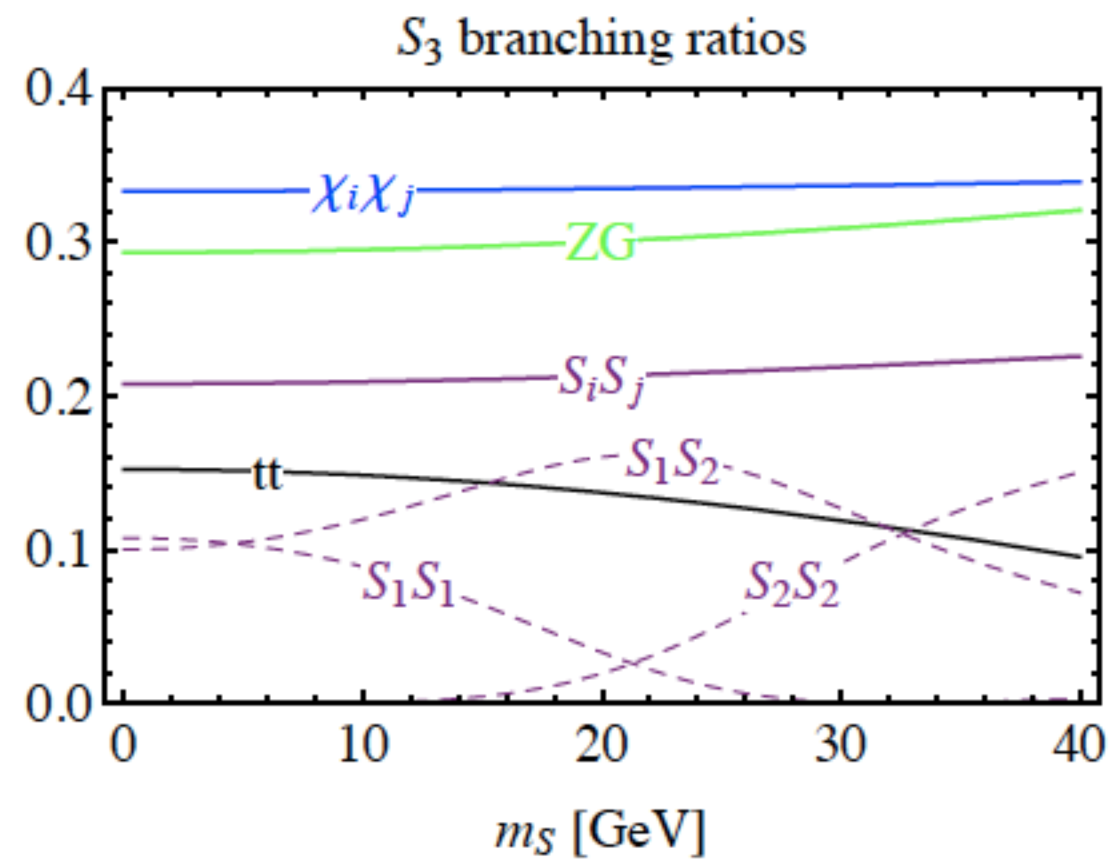
Never mind the exclusions!



PQ SUSY







B, Hall, Pappadopulo, Rychkov, Papaioannou 2007

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

λSUSY

$$m_{S_3} > 500\ GeV > m_{S_2} > m_{S_1}$$

$k=-0.2$	μ (GeV)	m_H (GeV)	m_{s_1} (GeV)	m_{s_2} (GeV)	m_{A_1} (GeV)	$m_{\chi 1}$ (GeV)
a	180	340	252	284	103	130
b	105	180	163	204	95	77
c	130	200	173	243	108	96
$k=-0.6$						
d	105	180	160	194	166	78
e	160	280	232	248	195	120
f	180	370	218	318	168	133

S_1

$k=-0.2$	$\mathrm{BR}_{A_1A_1}$	BR_{ZA_1}	$\mathrm{BR}_{\chi 1\chi 1}$	BR_{WW}	Γ_{tot} (GeV)	$\frac{\sigma\times\mathrm{BR}}{(\sigma\times\mathrm{BR})_{SM}}$
a	0.54	0.01	0	0.31	5.5	0.17
b	0	0	0.8	0.06	0.04	0.04
c	0	0	0	0.79	0.02	0.57
$k=-0.6$						
d	0	0	0.72	0	0.02	3×10^{-4}
e	0	0	0	0.69	0.3	0.04
f	0	0	0	0.71	1.5	0.5

S_2

$k=-0.2$	$\mathrm{BR}_{A_1A_1}$	BR_{ZA_1}	$\mathrm{BR}_{\chi 1\chi 1}$	BR_{WW}	Γ_{tot} (GeV)	$\frac{\sigma\times\mathrm{BR}}{(\sigma\times\mathrm{BR})_{SM}}$
a	0.032	0.324	0.043	0.41	2.55	0.62
b	0.4	0	0.143	0.33	2.8	0.37
c	0.412	0	0.086	0.35	5.45	0.35
$k=-0.6$						
d	0	0	0.189	0.61	1.22	0.8
e	0	0	0.001	0.70	2.7	1.4
f	0	0.21	0.145	0.44	2.4	0.6

$$\frac{\sigma\ BR(WW)}{\sigma\ BR(WW)|_{SM}}$$

or ZZ

Bertuzzo, Farina

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:

$\mu \rightarrow e\gamma$

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

$\tau \rightarrow \mu\gamma$

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

d_e

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

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

Flavour changing interactions

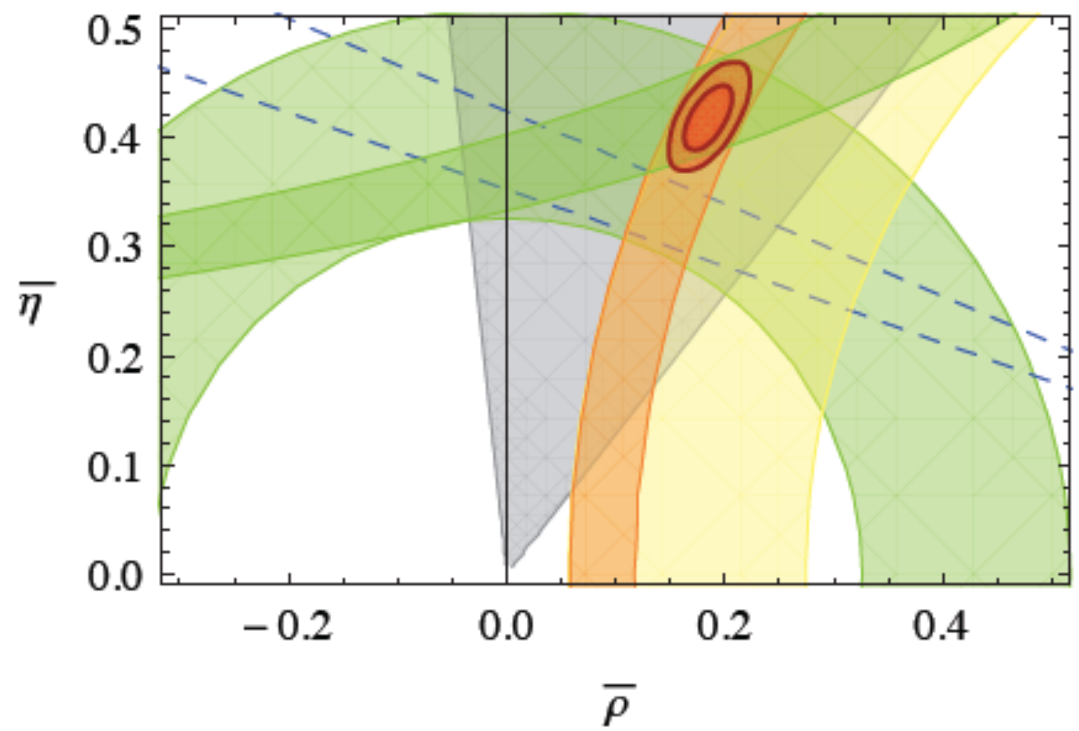
$\Delta F = 2$ - Our own SM fit

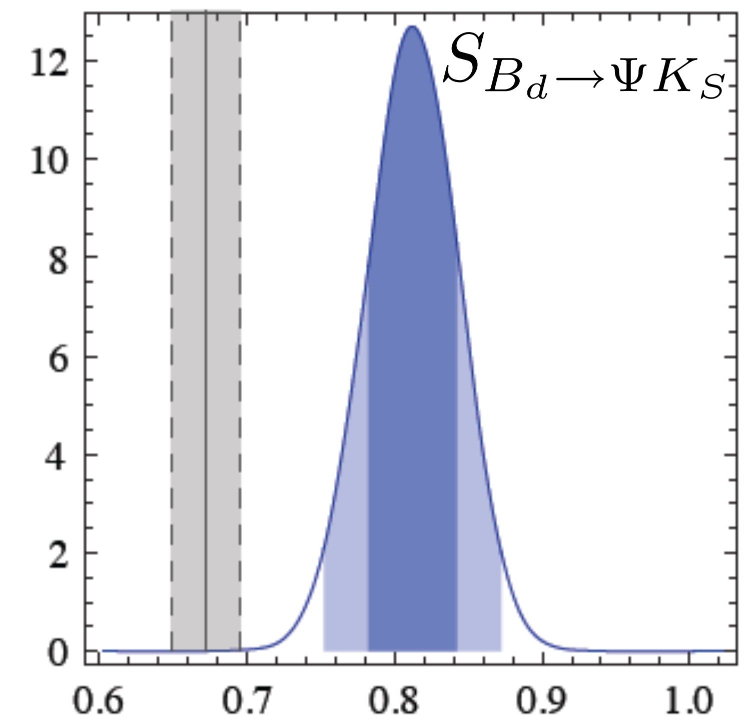
Tree level +

ΔM_d

ΔM_s

ϵ_K



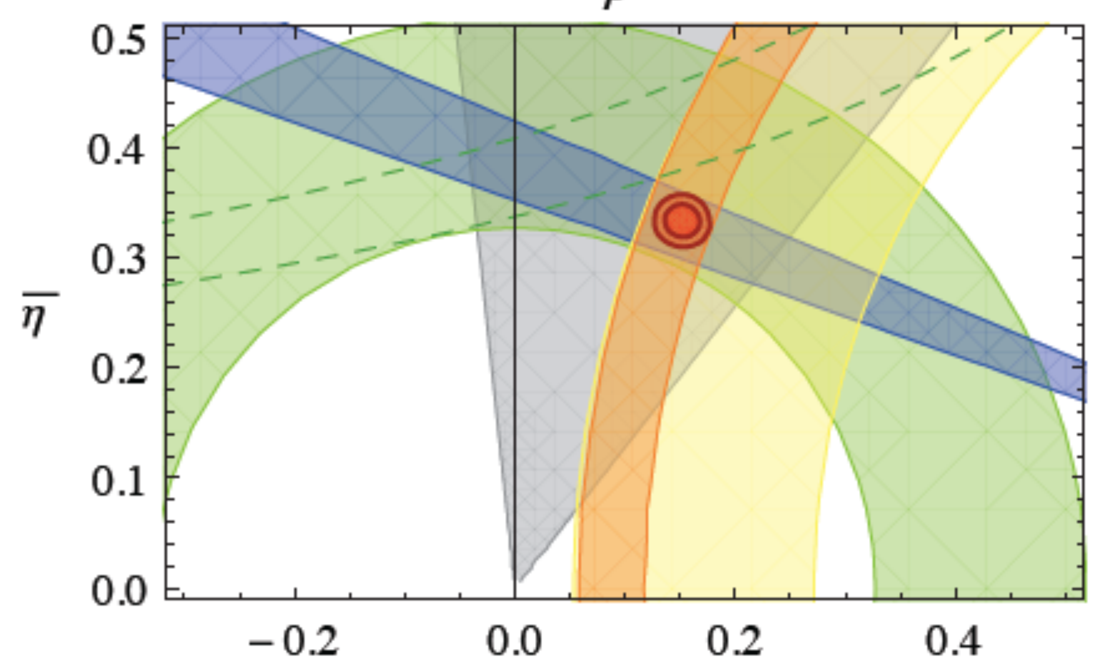


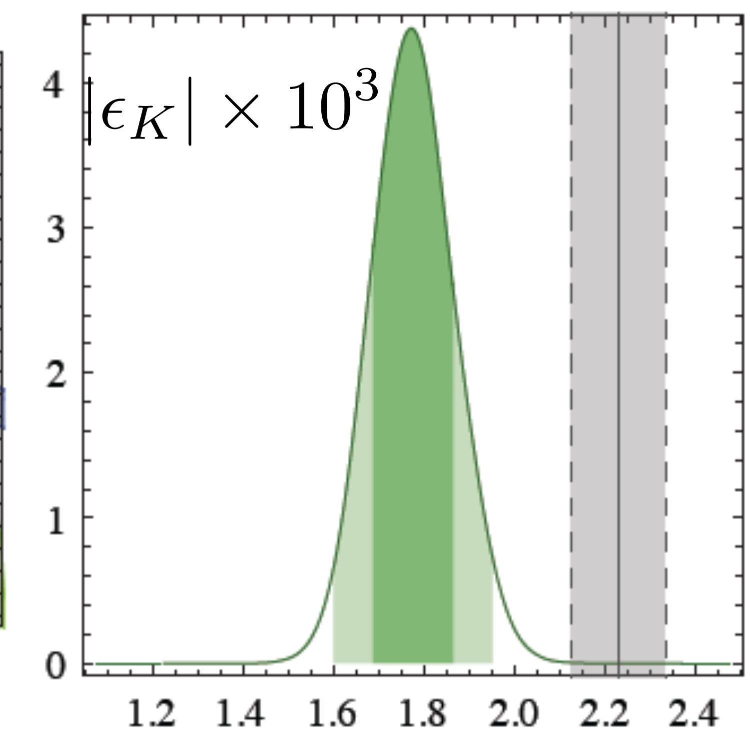
Tree level +

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

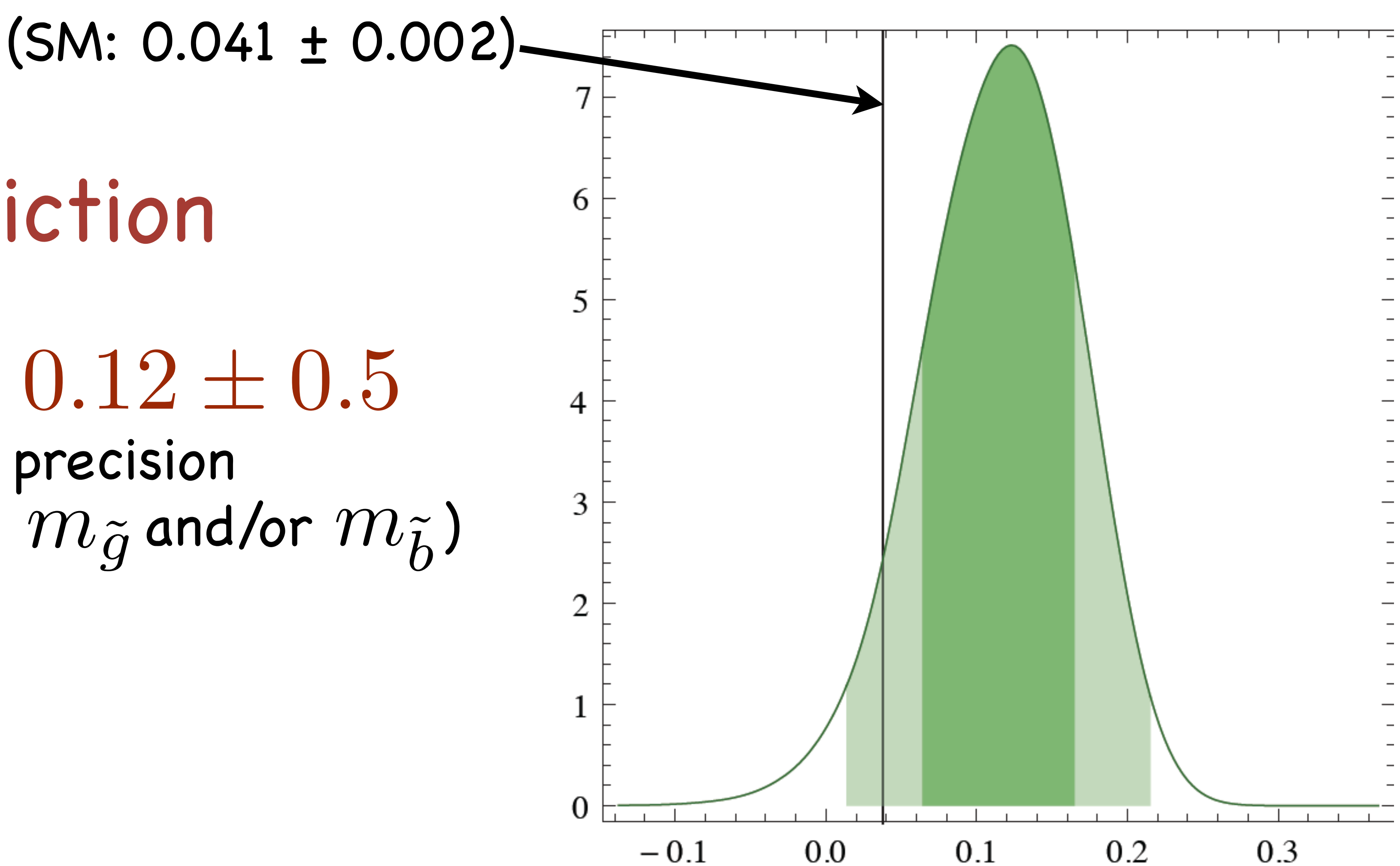
Input data

$\|V_{ud}\|$	$0.97425(22)$	[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]			

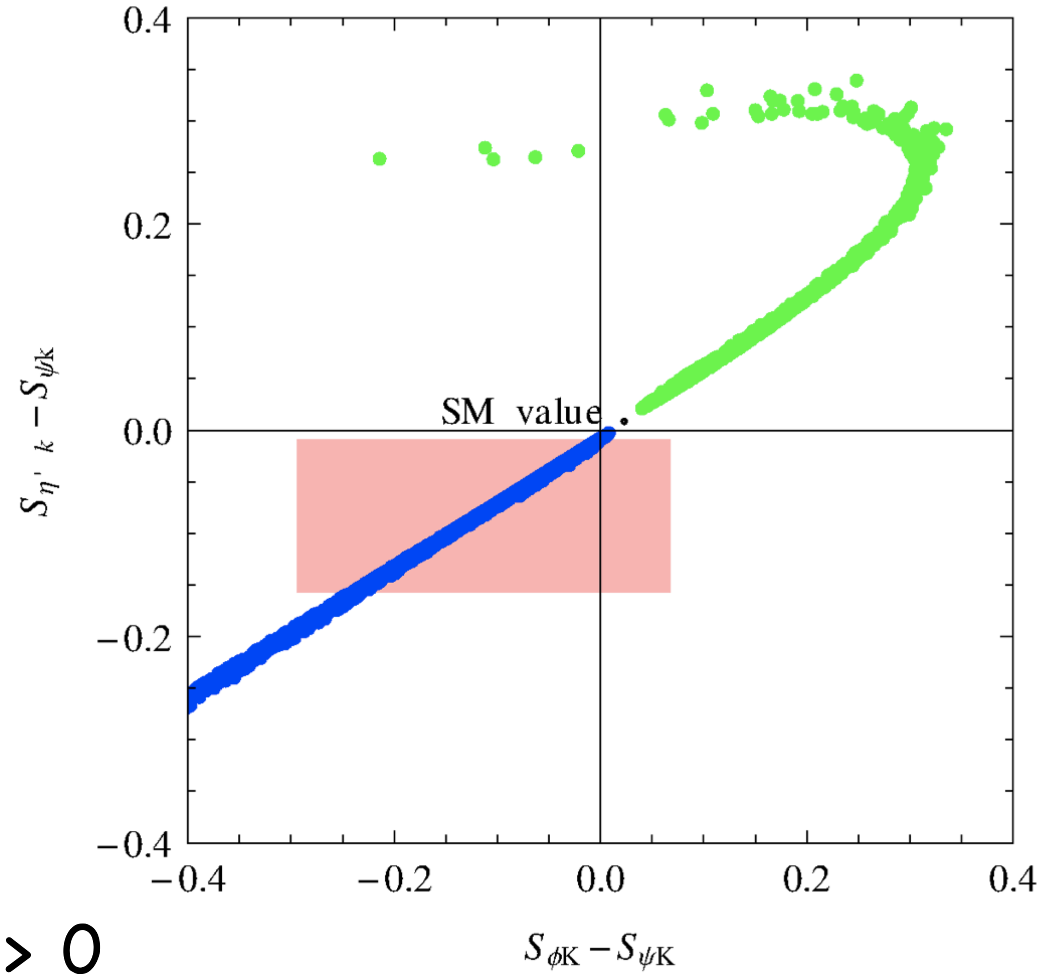
$U(2)^3$ prediction

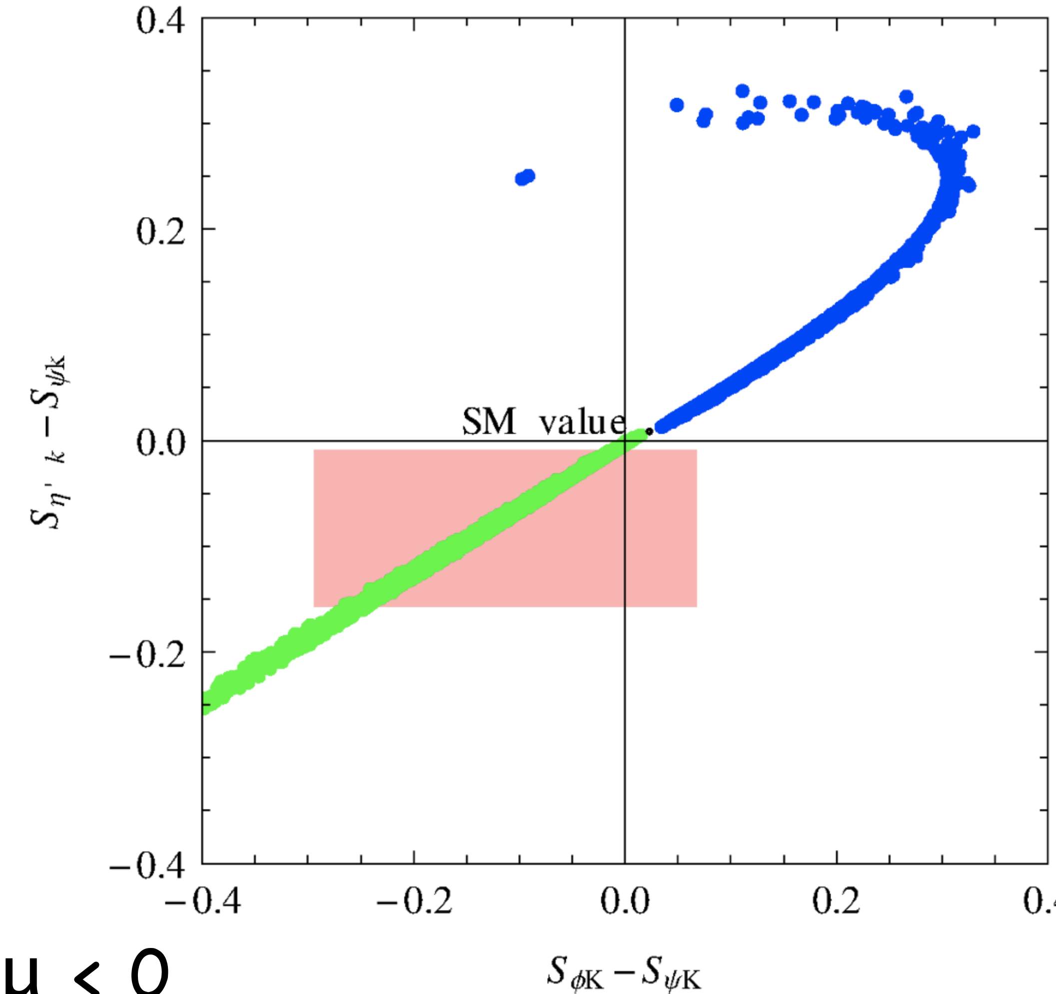
$$S_{B_s \to \Psi\phi} = 0.12 \pm 0.5$$

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



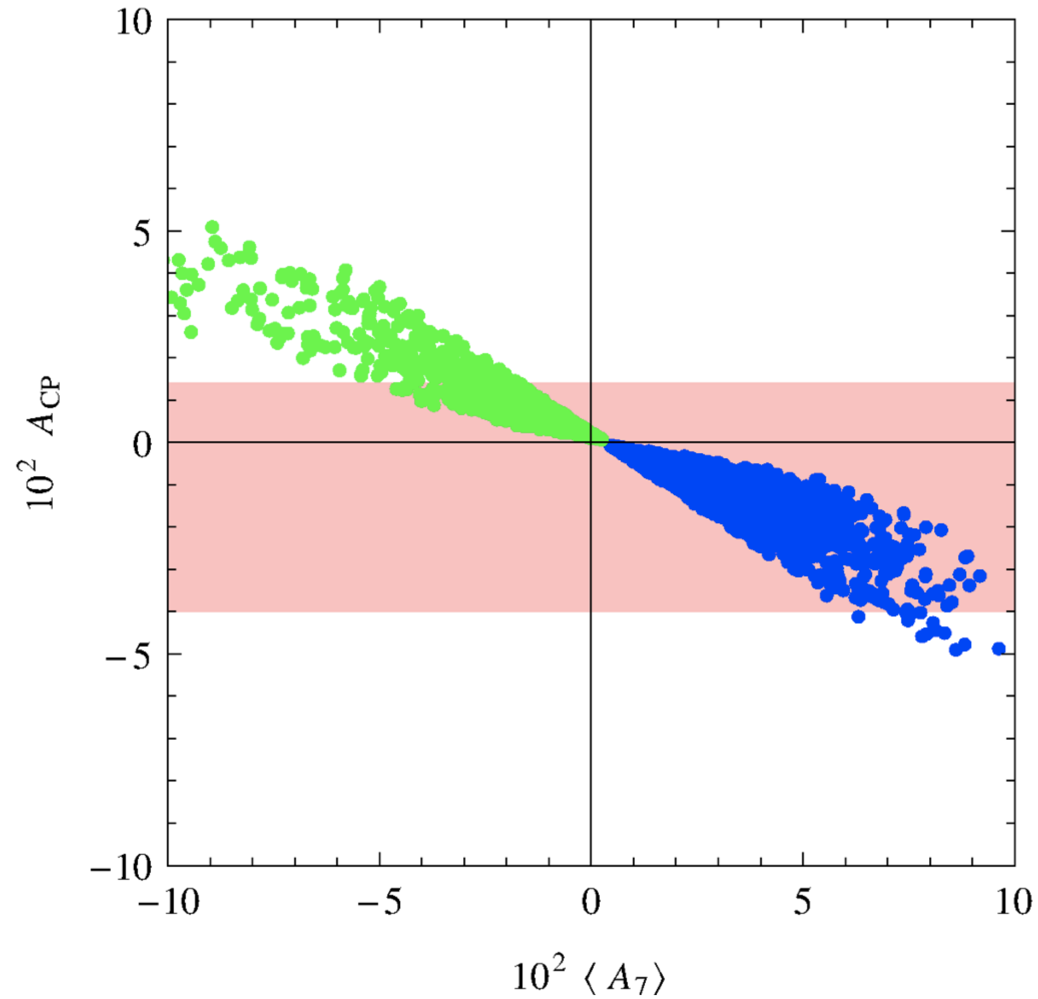
CPV in $\Delta B = 1$

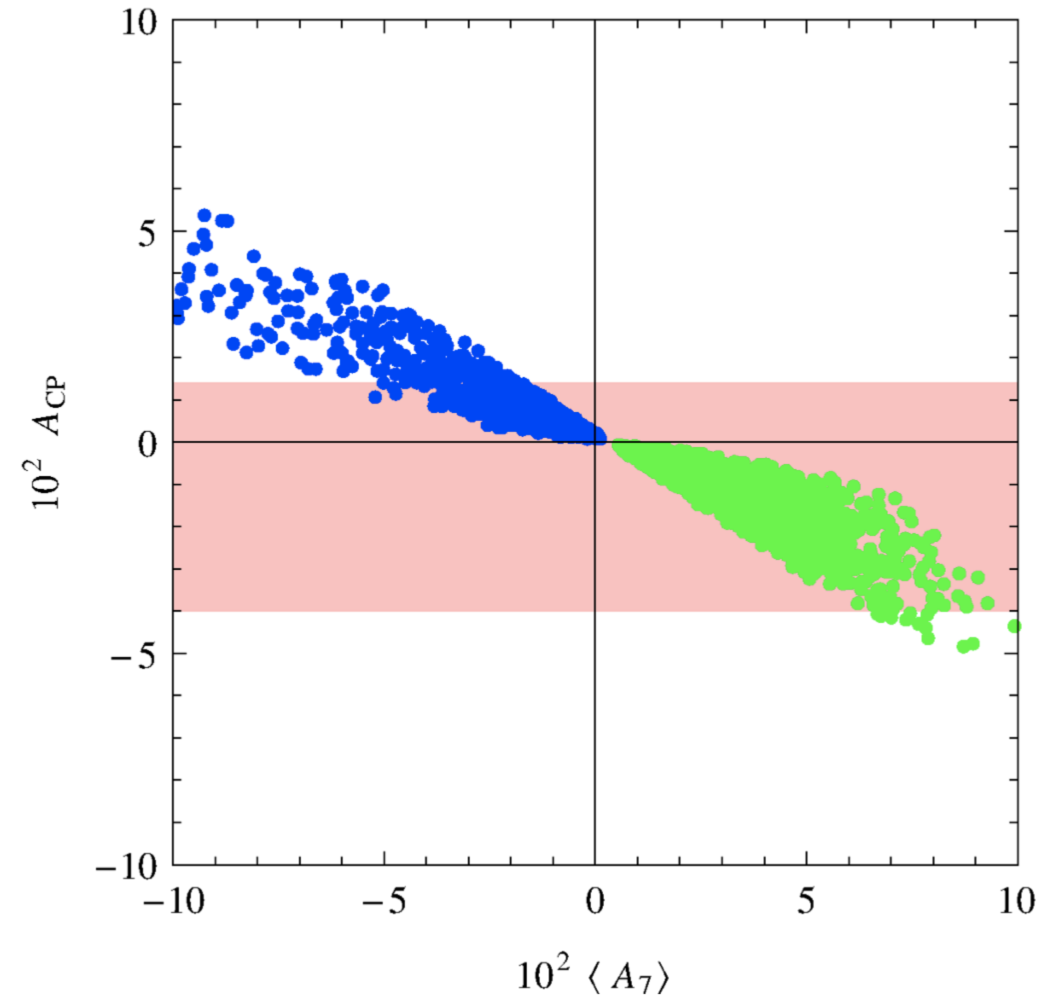




$\mu > 0$

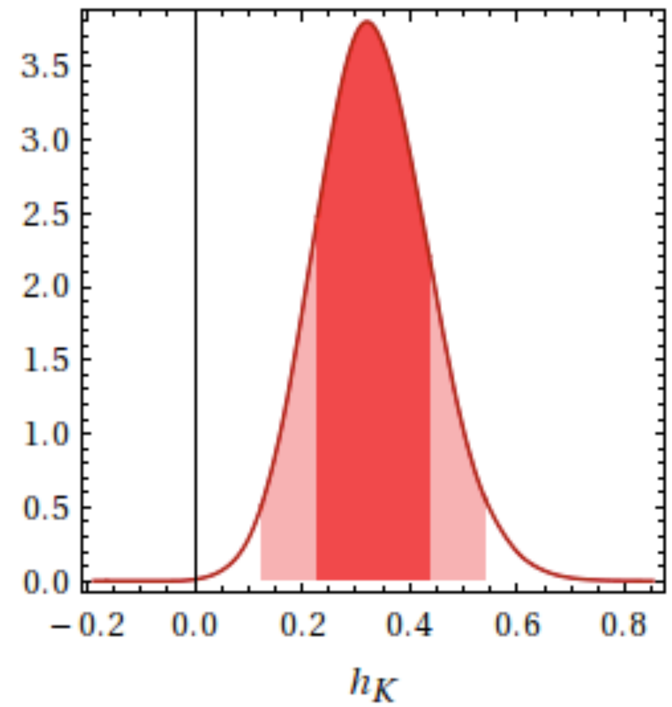
$\mu < 0$

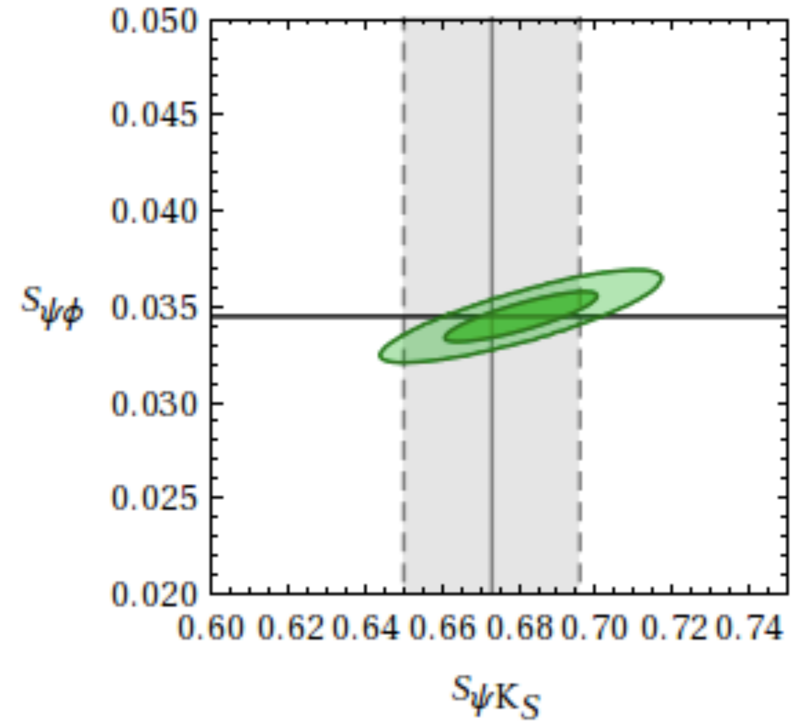




general $U(2)^3$

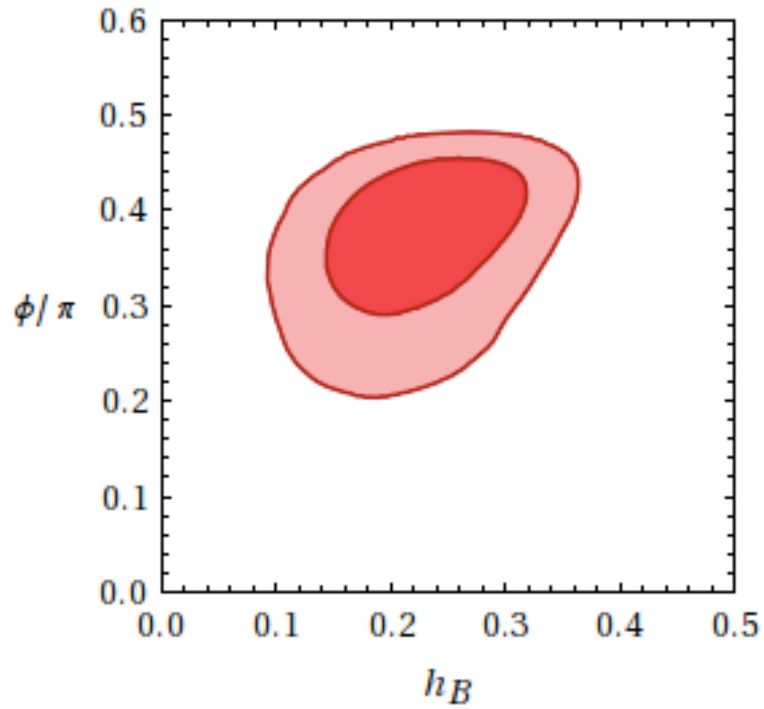
$$\mathcal{M}(K^0 \to \bar{K}^0) = \mathcal{M}^{SM}(K^0 \to \bar{K}^0)(1 + h_K)$$

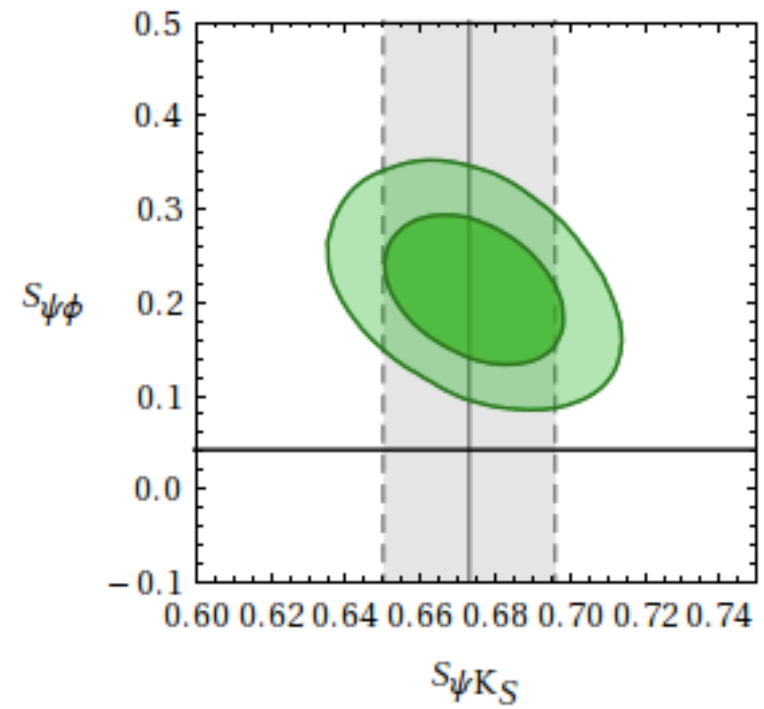




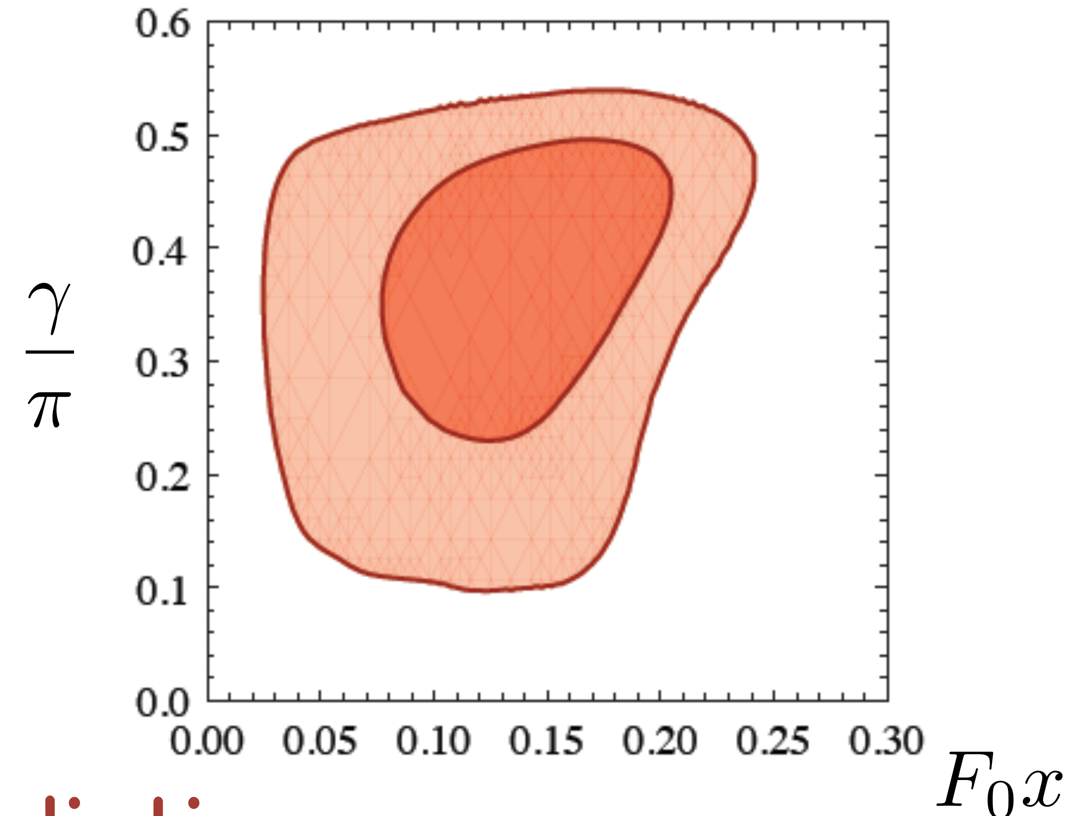
$$\mathcal{M}(B_d \to \bar{B}_d) = \mathcal{M}^{SM}(B_d \to \bar{B}_d)(1 + h_B e^{-2i\gamma})$$

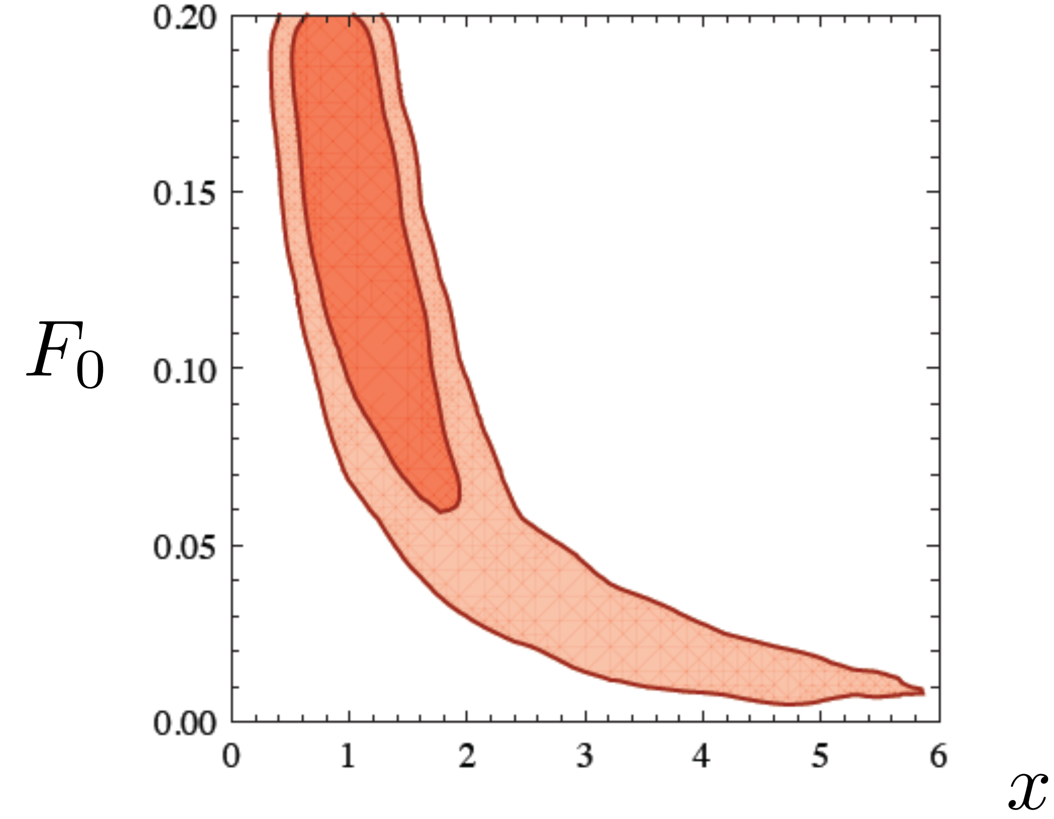
$$\frac{\mathcal{M}_d}{\mathcal{M}_s} = \frac{\mathcal{M}_d^{SM}}{\mathcal{M}_s^{SM}}$$





Constraints on extra parameters:

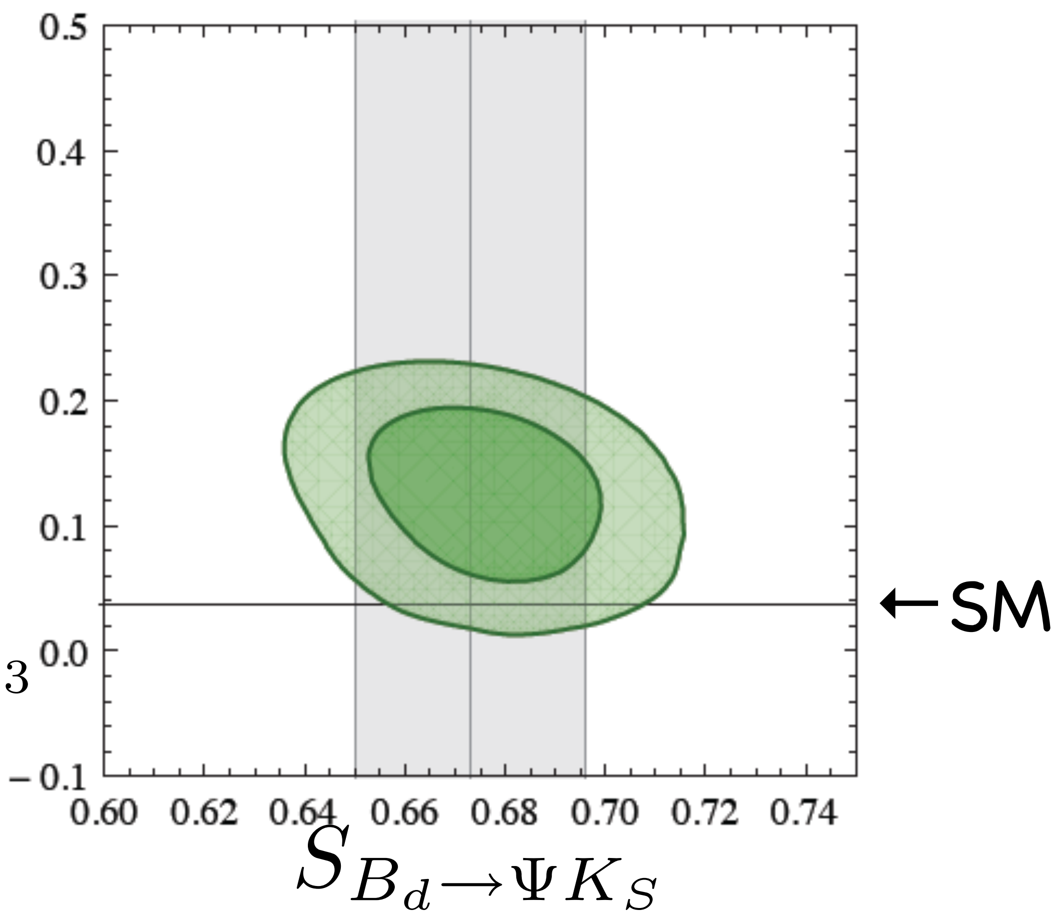


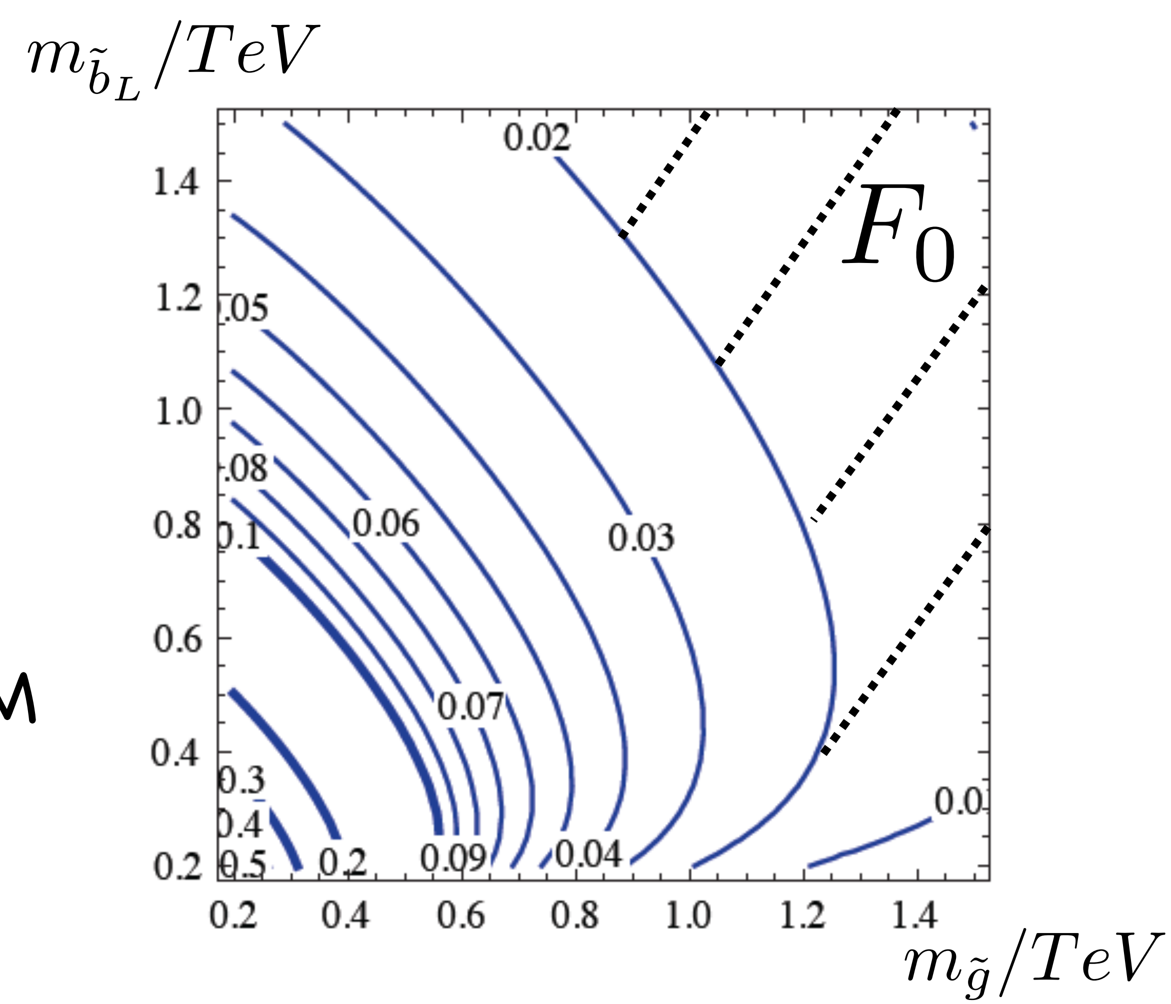


Prediction:

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

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





ElectroWeak Precision Tests in λSUSY

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

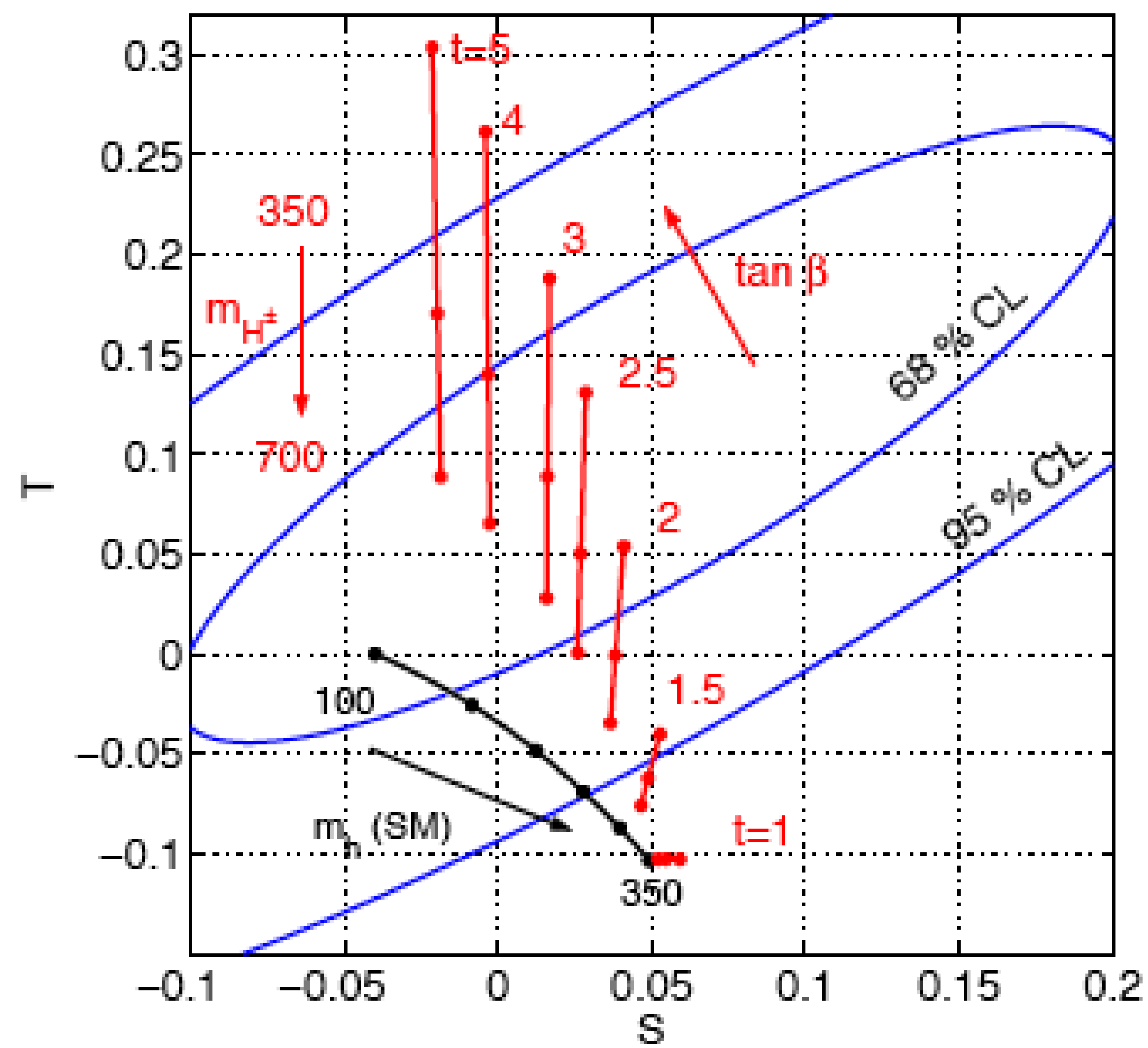
S and T from Higgs's

one loop effects but

$$\Delta T \propto \lambda^4$$

$$\lambda \uparrow \Rightarrow m_h \uparrow$$

compensated by $\Delta T \uparrow$



B, Hall, Nomura, Rychkov

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?

Tevatron bounds on $\tilde{t}$, $\tilde{b}$