SUSY phenomenology, including Susy Higgs

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2011HCP, Paris, Nov 14/18, 2011

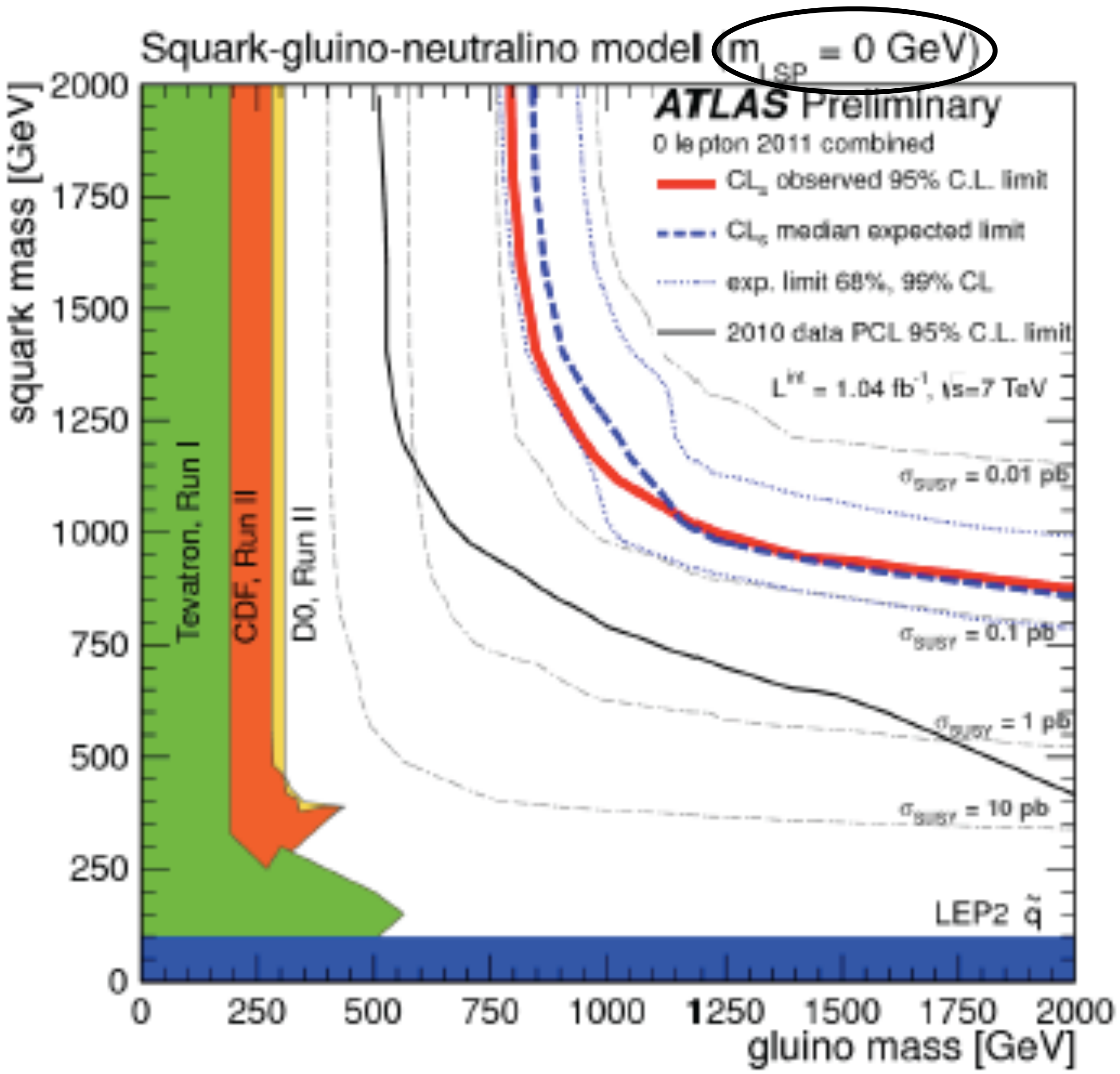
(No introduction)

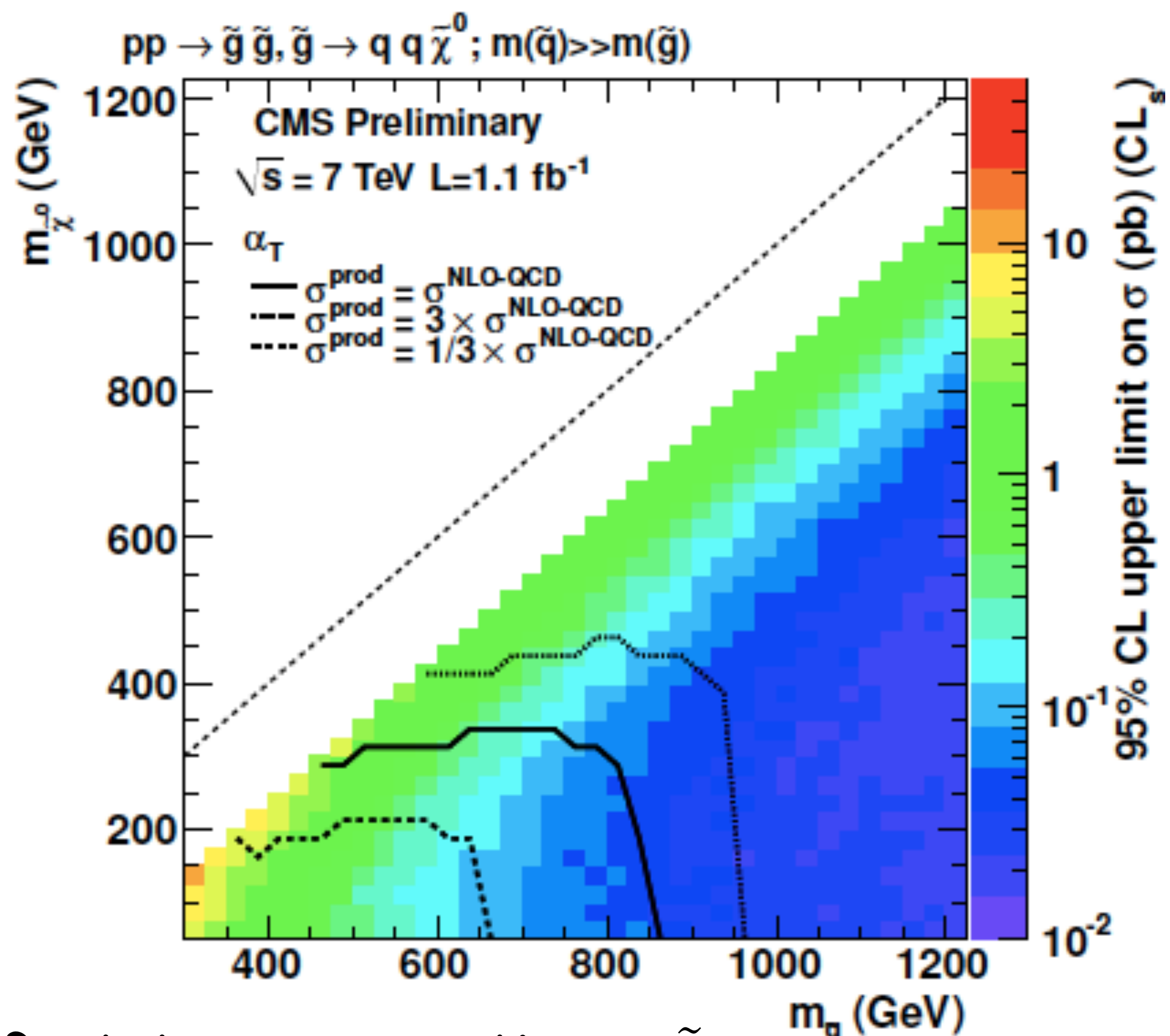
1. Which implications of the (negative) searches so far?
2. What new searches to lead to first discoveries?
3. What's needed to discover a Higgs boson in the MSSM?
4. What about the Higgs system in the NMSSM?

(on 3 and 4 see also Gunion's talk)

A remarkable new constraint from LHC

the missing energy signal

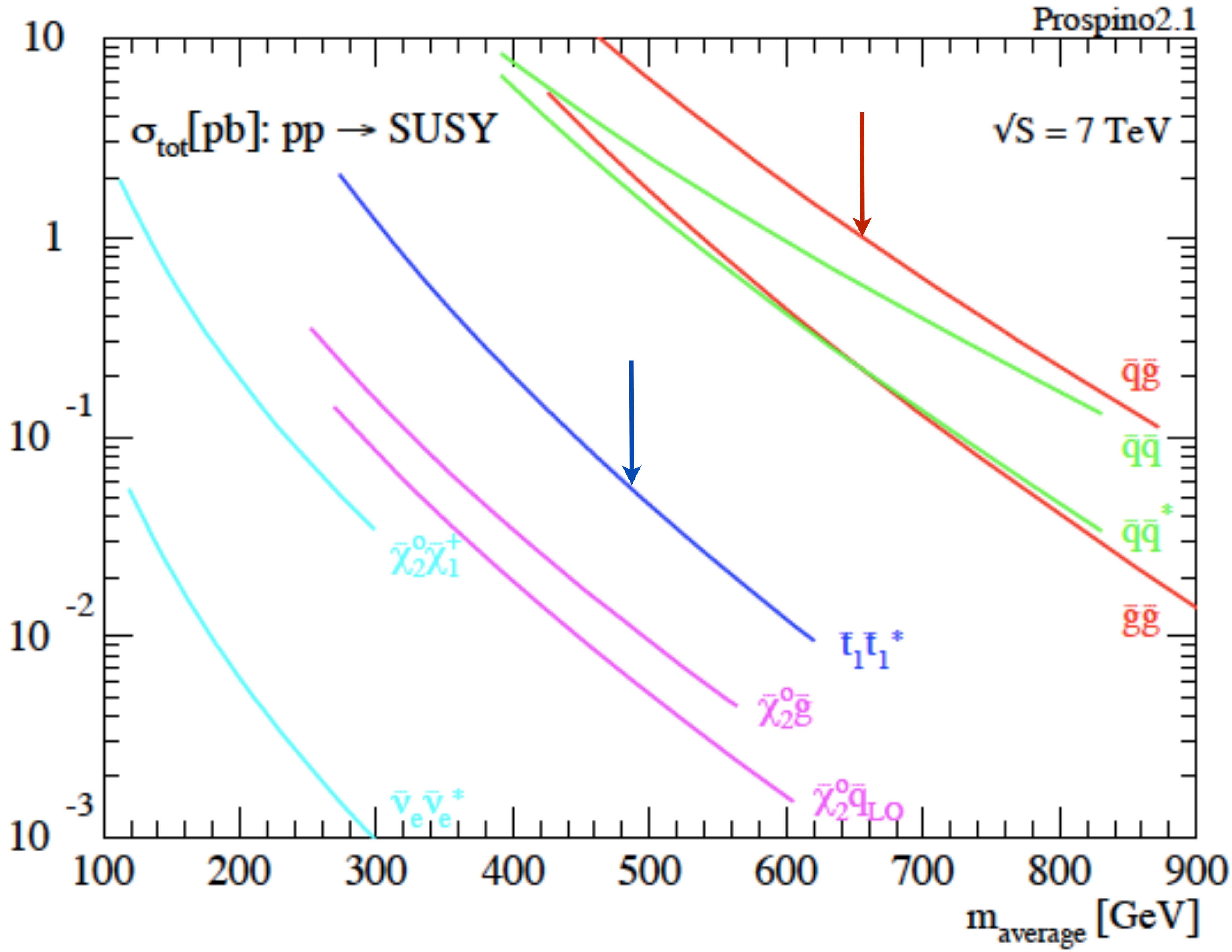




for degenerate squarks of the first two generations $\tilde{q}_{1,2}$
and $\chi^0, \tilde{g}$ not too close in mass $\Rightarrow m_{\tilde{g}}, m_{\tilde{q}_{1,2}} \gtrsim 1\ TeV$

$$g\ q \to \tilde{g}\ \tilde{q}$$
$$q\ q \to \tilde{q}\ \tilde{q}$$
$$q\ \bar{q} \to \tilde{q}\ \tilde{q}^*$$

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



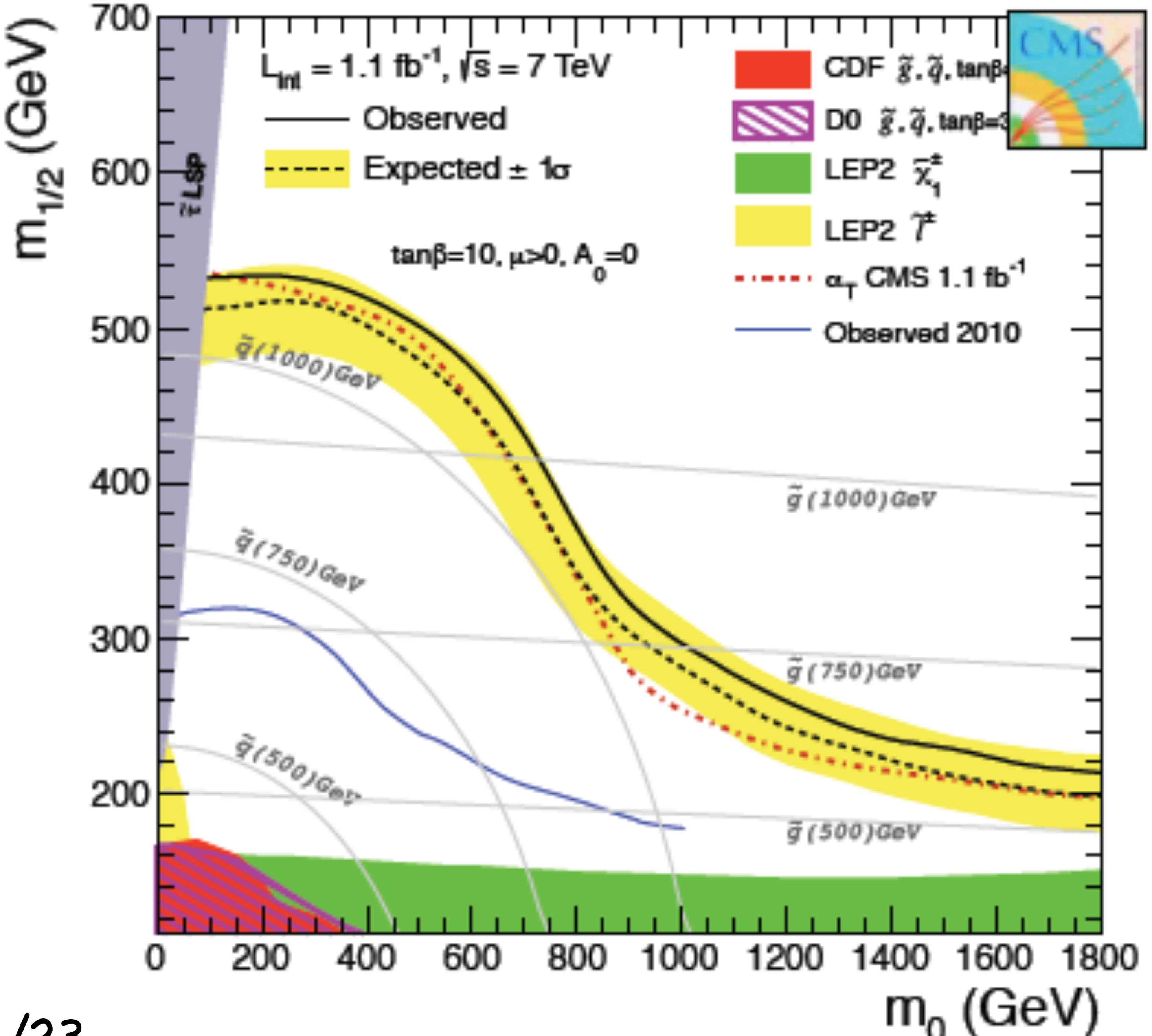
Prospino2.1
σ_tot[pb]: pp → SUSY
√S = 7 TeV
10
1
10^-1
10^-2
10^-3
100
200
300
400
500
600
700
800
900
m_average [GeV]
q̄g̅
q̄q̄
q̄q̄*
g̅g̅
t̄₁t̄₁*
χ̃₂°g̃
χ̃₂°q̃_LO
χ̃₂°χ̃₁⁺
ṽ_e ṽ_e*

Which implications?

Take a simple prototype theory **mSUGRA**

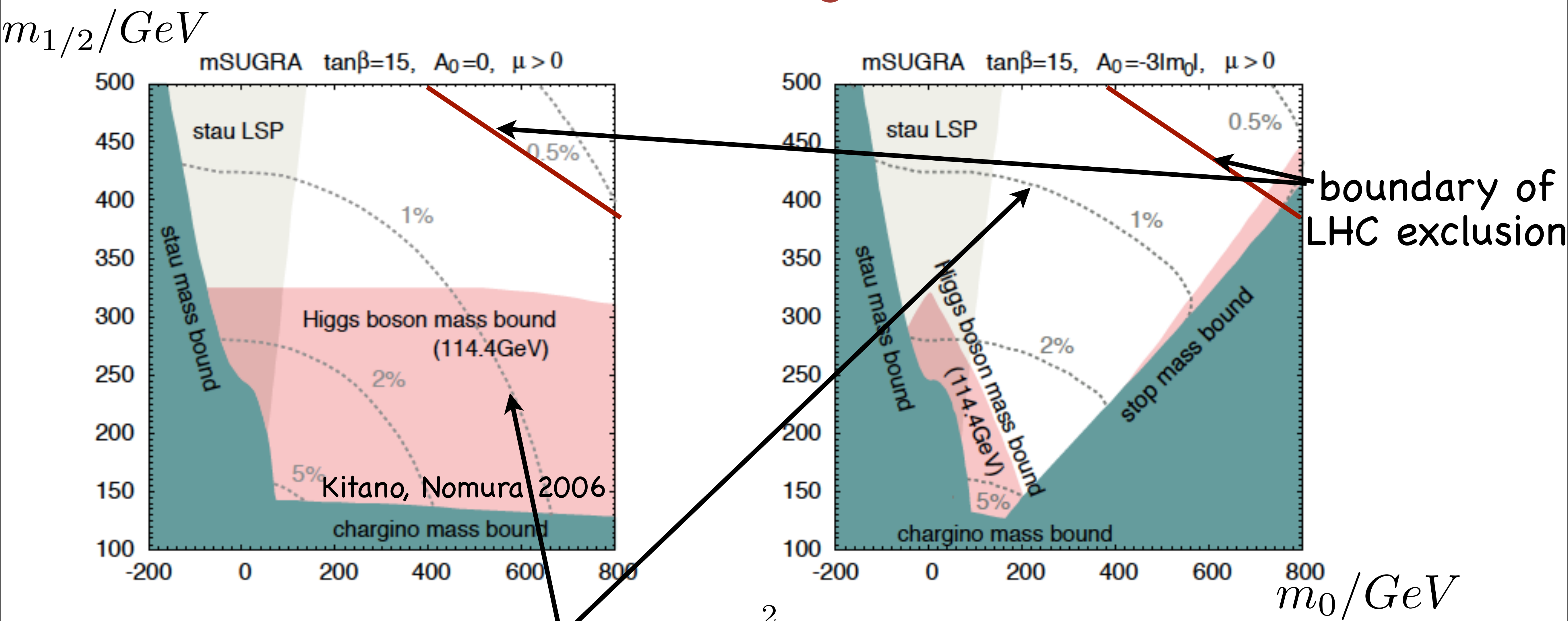
Input parameters at high scale: $m_0, m_{1/2}, A, B, \mu$

a common mass for all scalars



How significant is this?

Naturalness/fine-tuning of the Fermi scale



Amount of cancellation in $\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2$

Should one care about ft?

YES

1. The very reason for SUSY at the weak scale
2. If ft< 1% accepted, why not less than 1 ppm? But then...

SUSY still well alive,

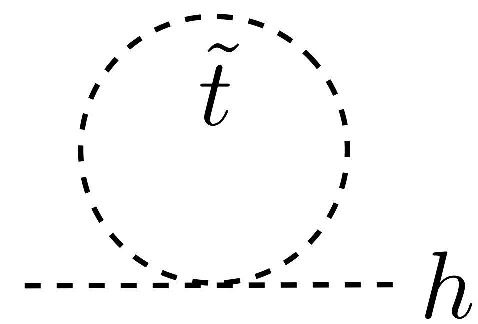
since no hard info, yet, on the crucial configuration

The key equations:

$m_{\tilde{h}}$

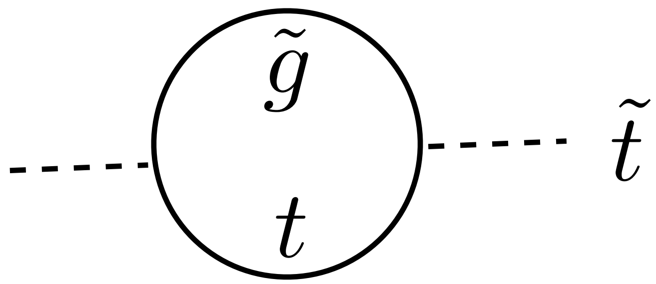
$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2$$

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



$m_{\tilde{b}_L}$

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



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

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

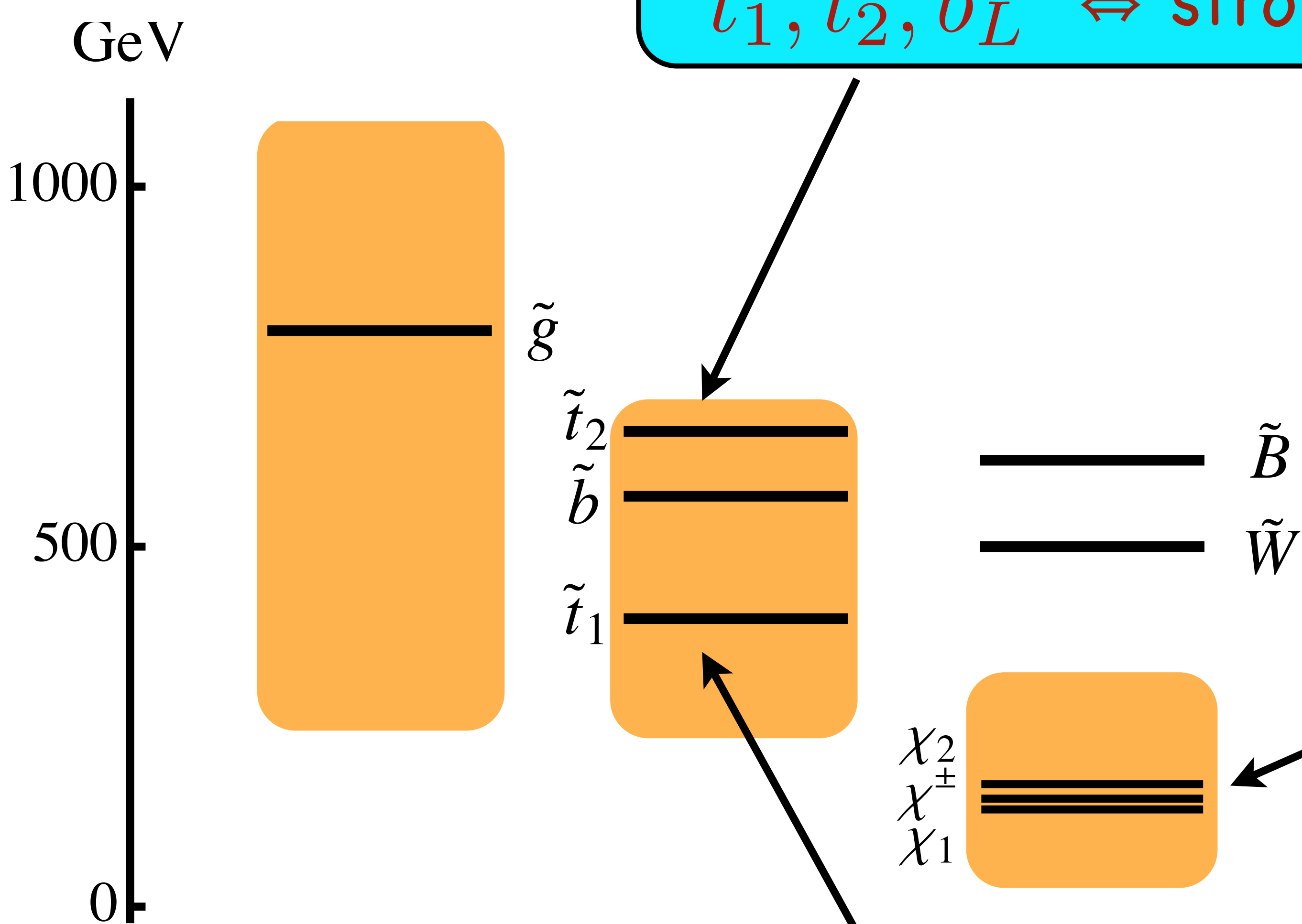
All s-particles other than $\tilde{g}, \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{h}$ weakly constrained

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: μ, $\tan\beta$
m_{Q_3}, m_{u_3}, A_t
M_3

(μ ⇔ M_Z at tree level)

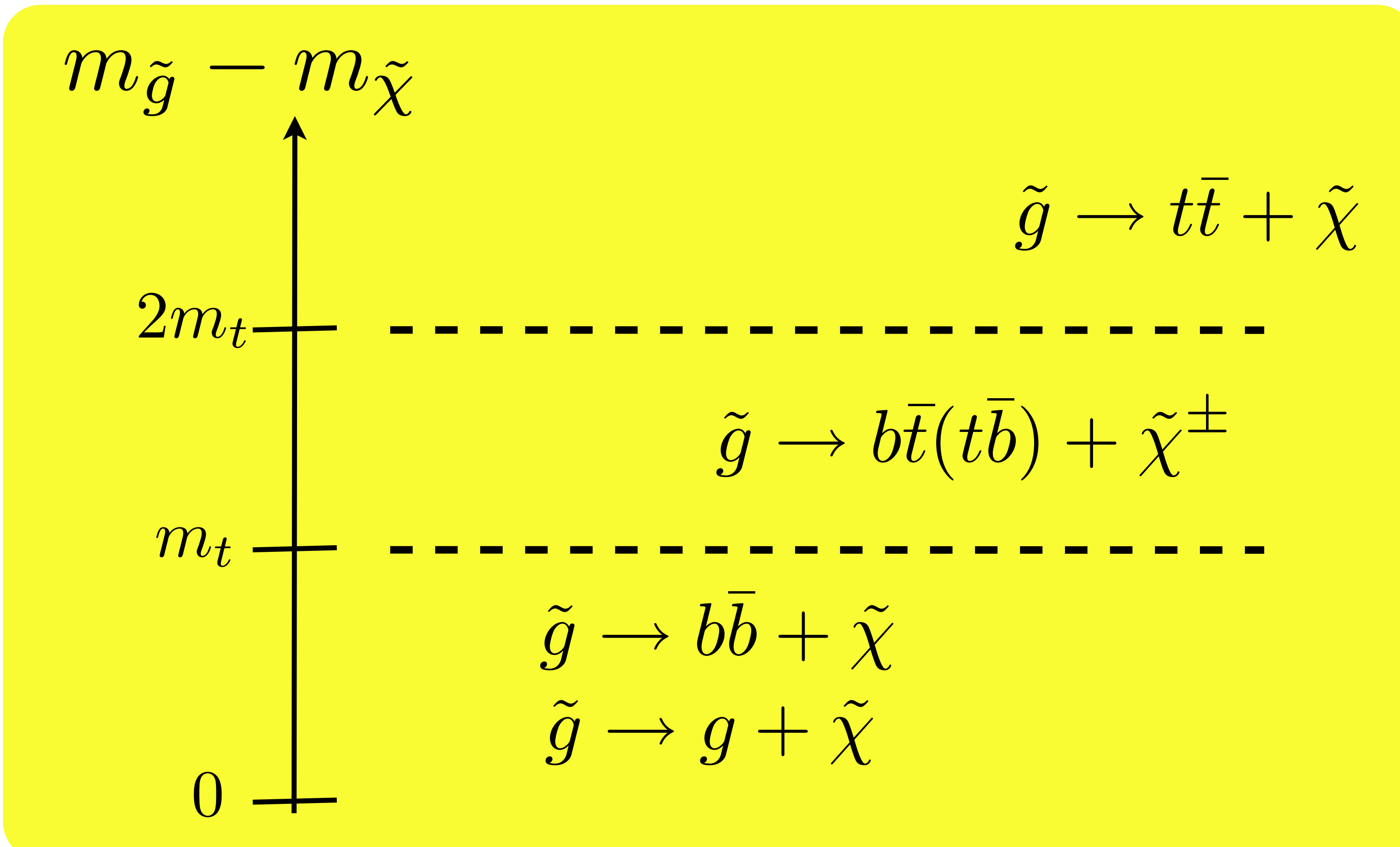
$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ heavy enough (≥ $\tilde{g}$) to be ~ irrelevant

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

$pp \to \tilde{g}\tilde{g}$ dominant over $pp \to \tilde{t}\tilde{t}^* \ (\tilde{b}\tilde{b}^*)$



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

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

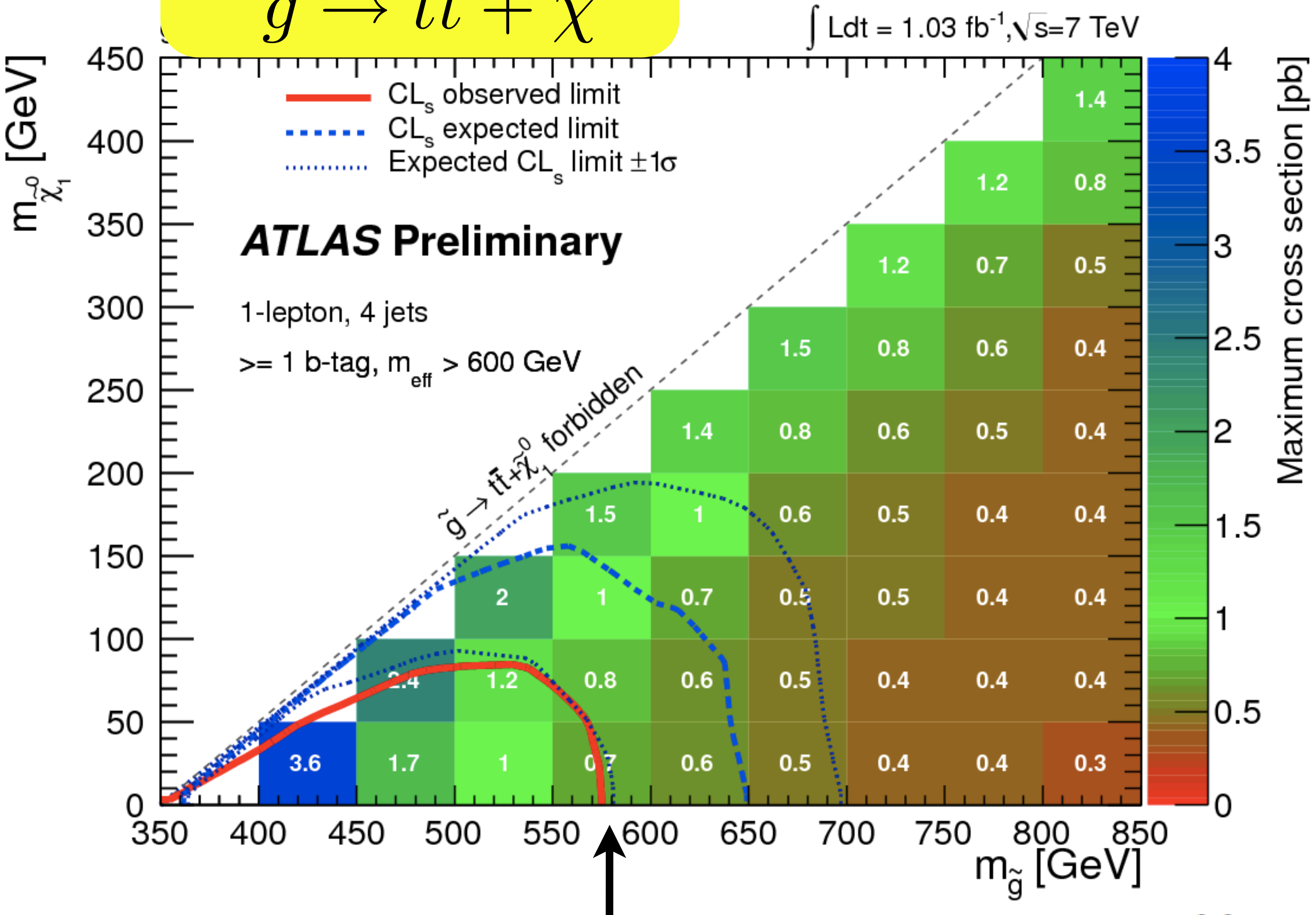
3 body final states either by cascade or direct
($m_{\tilde{t}}, m_{\tilde{b}}$ almost don't matter)

When phase space opens up, $\tilde{g} \to b\bar{b}\chi$ suppressed

If $\mu < M_1, M_2$ then $\chi^{\pm}, \chi^0$ close in mass

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

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



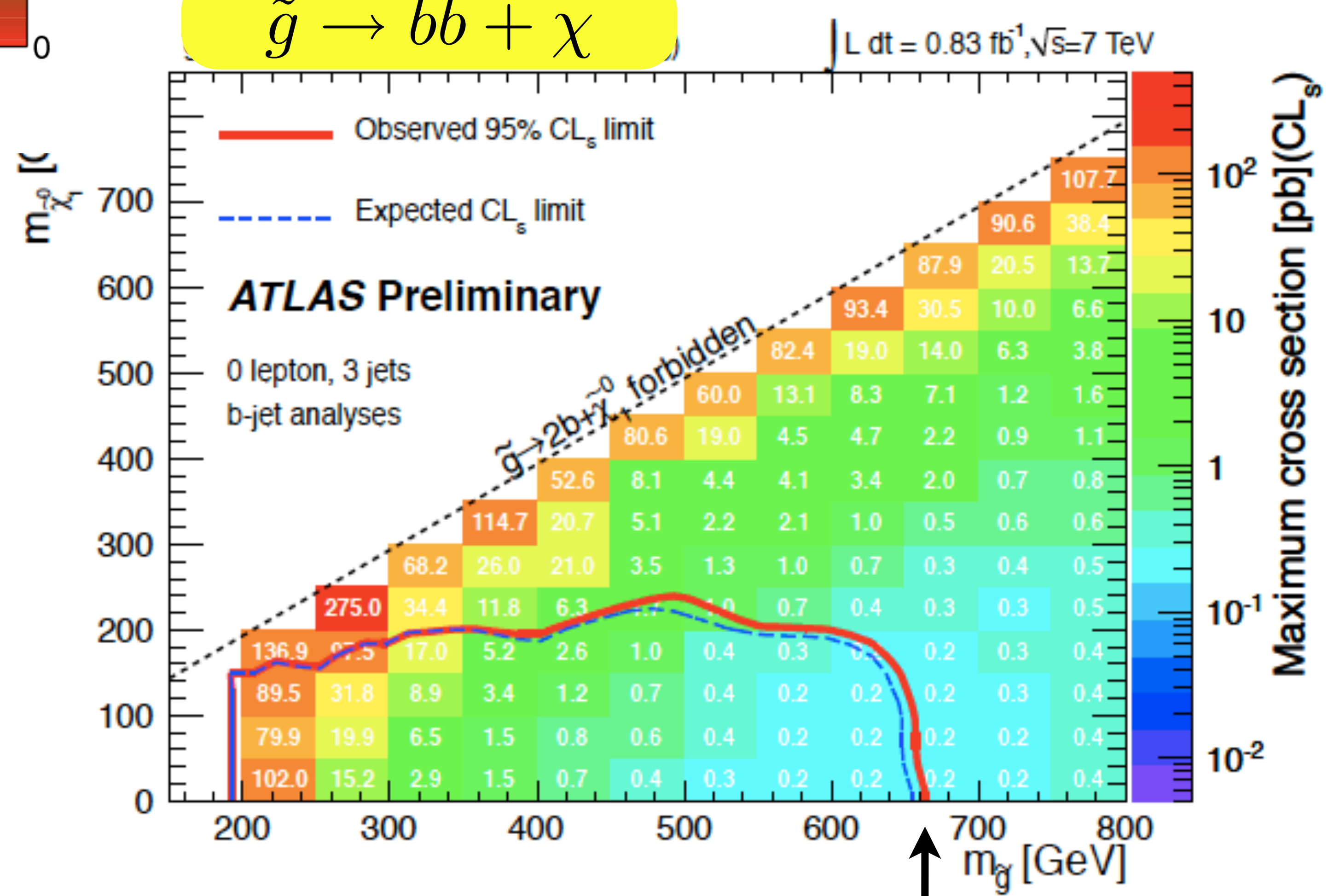
My rough guess:

$m_{\tilde{g}} \gtrsim 600\ GeV$

$m_{\tilde{t}}, m_{\tilde{b}} \gtrsim 200\ GeV$

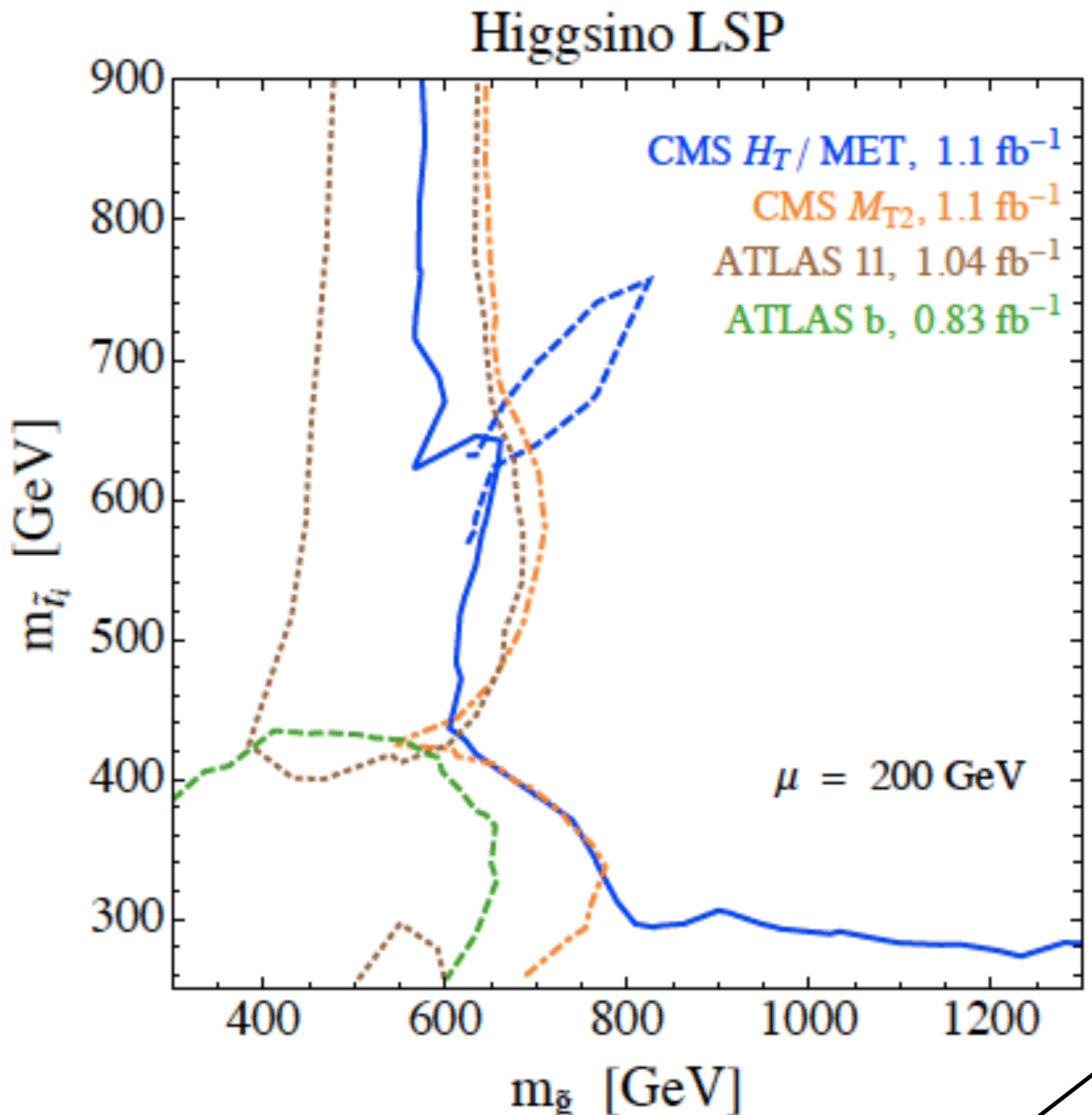
(from direct $\tilde{t}, \tilde{b}$ production)

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

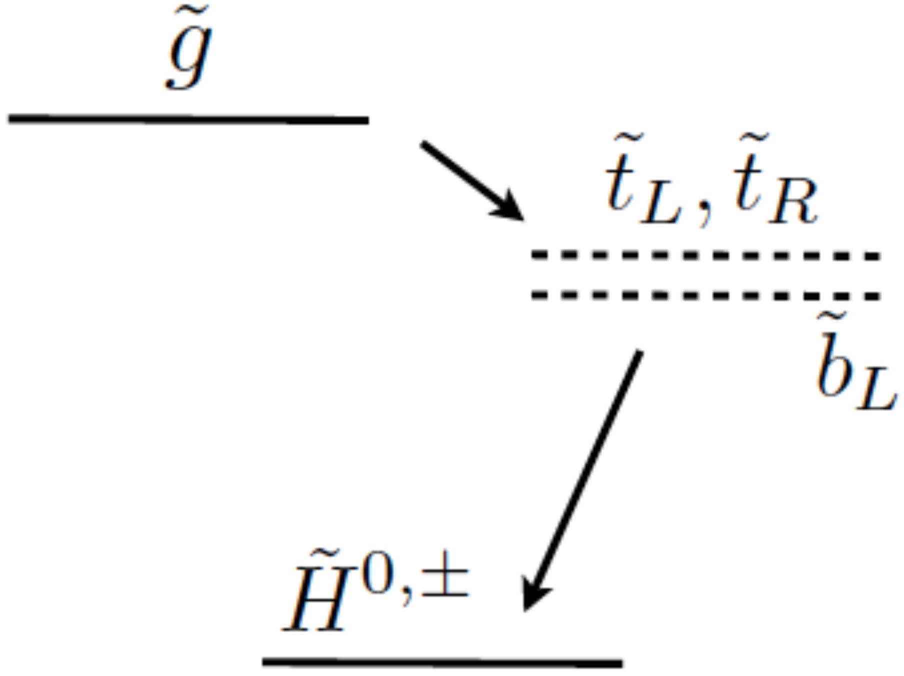


Which sensitivity with 10xmore data?

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



Papucci, Ruderman, Weiler 2011



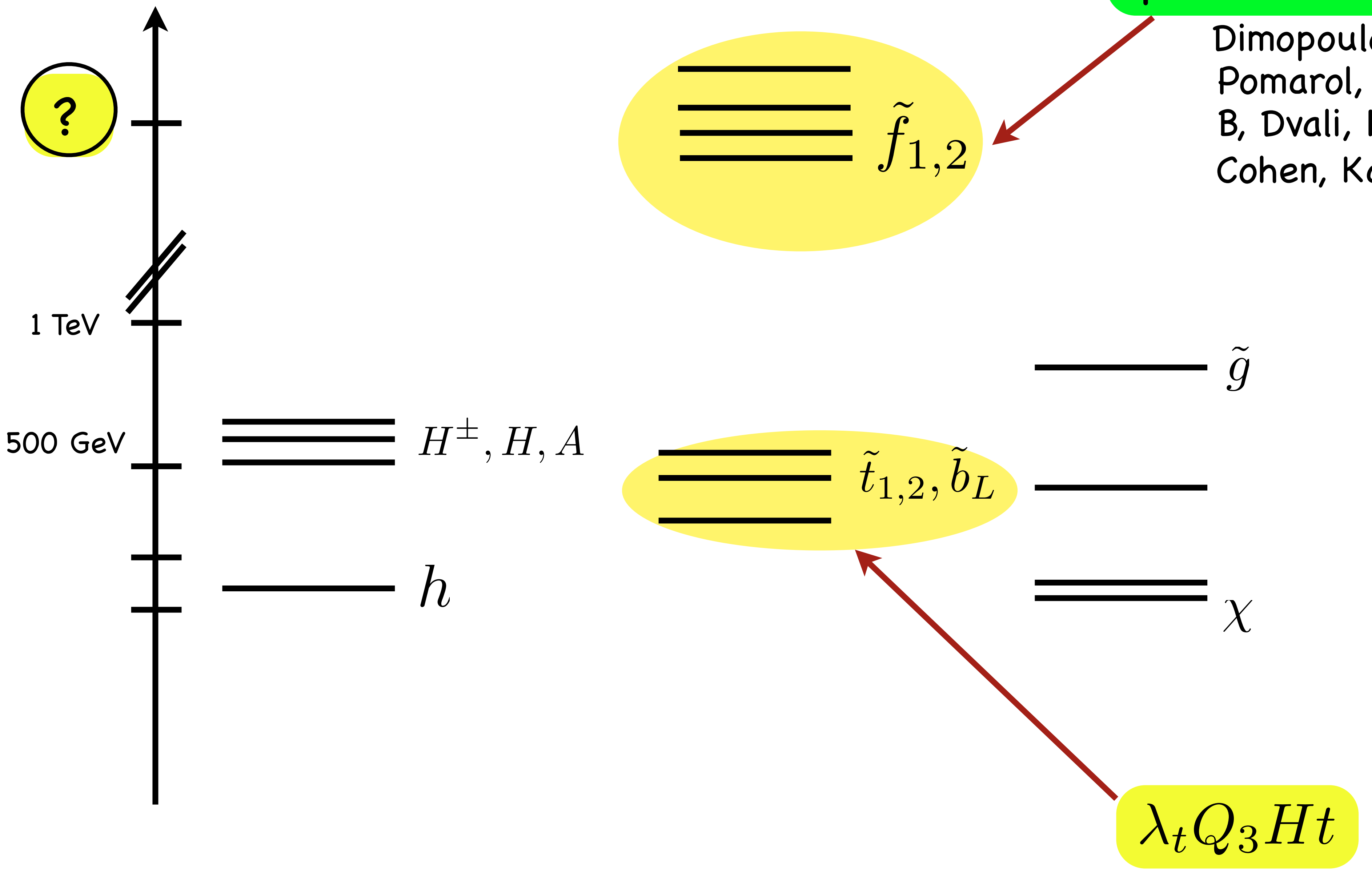
with some caveats for special mass configurations

“Beyond mSUGRA”

(minimal natural spectrum is 15 years old)

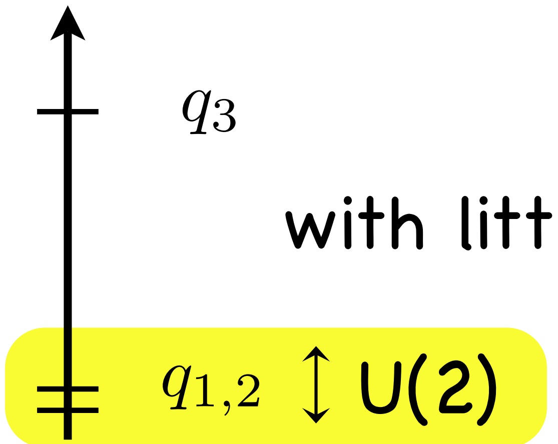
Flavour and CP problems improved

Dimopoulos, Giudice 1995
Pomarol, Tommasini 1995
B, Dvali, Hall 1995
Cohen, Kaplan, Nelson 1996



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

Tomassini, Pomarol 1995
B, Dvali, Hall 1995



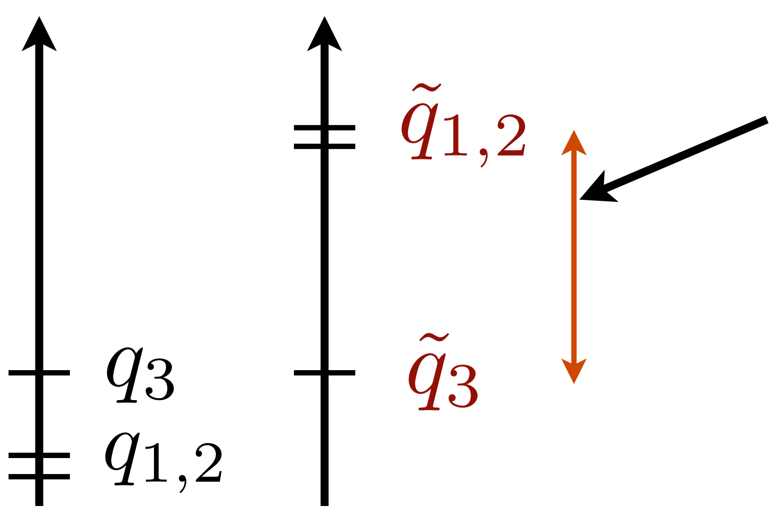
with little communication between $q_{1,2}$ and q_3

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

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

and perhaps also in the SUSY non-data

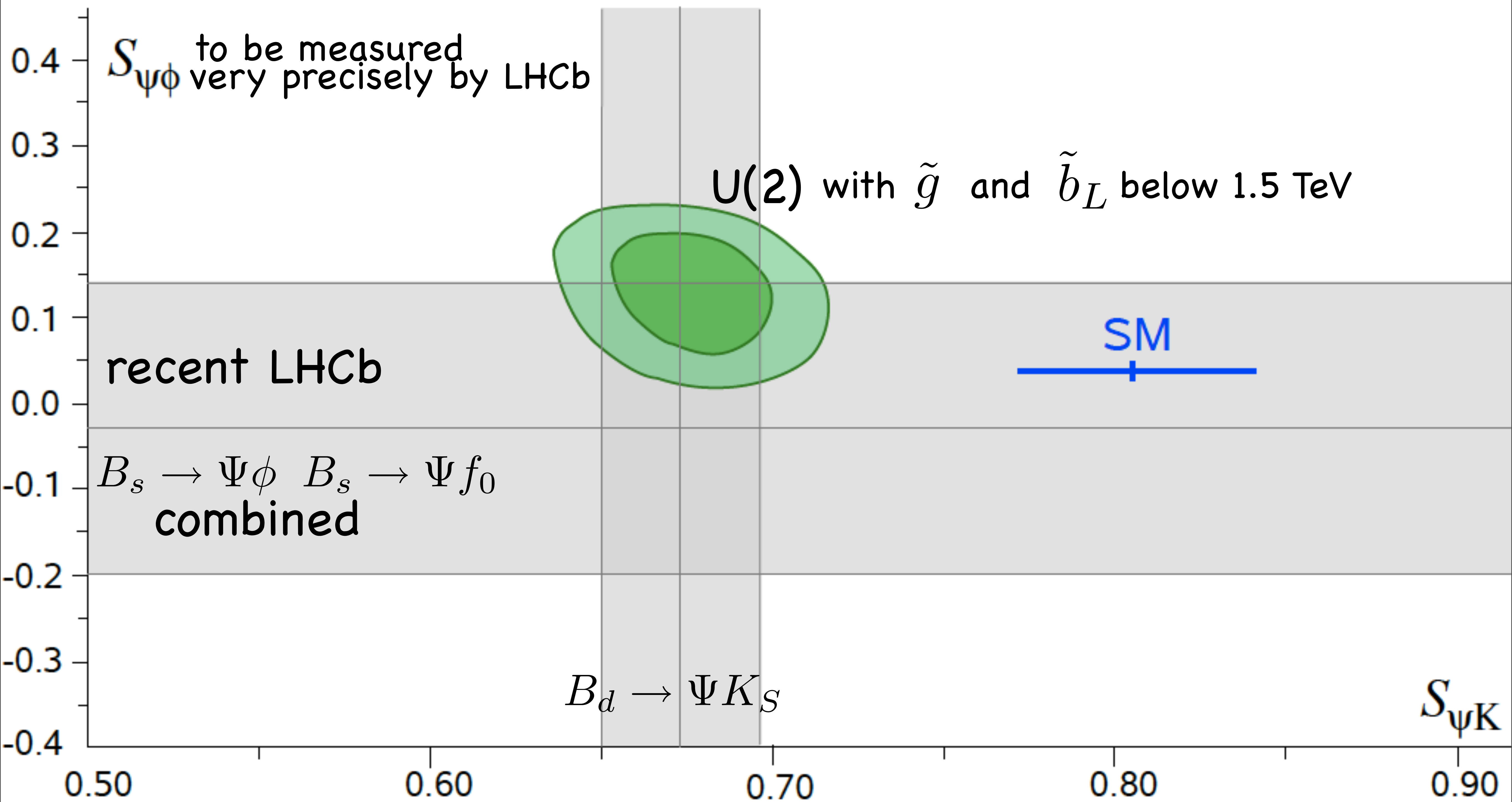
flavour, EDMs, direct s-particle searches



An inverted spectrum

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

CPV in $\Delta B = 2$

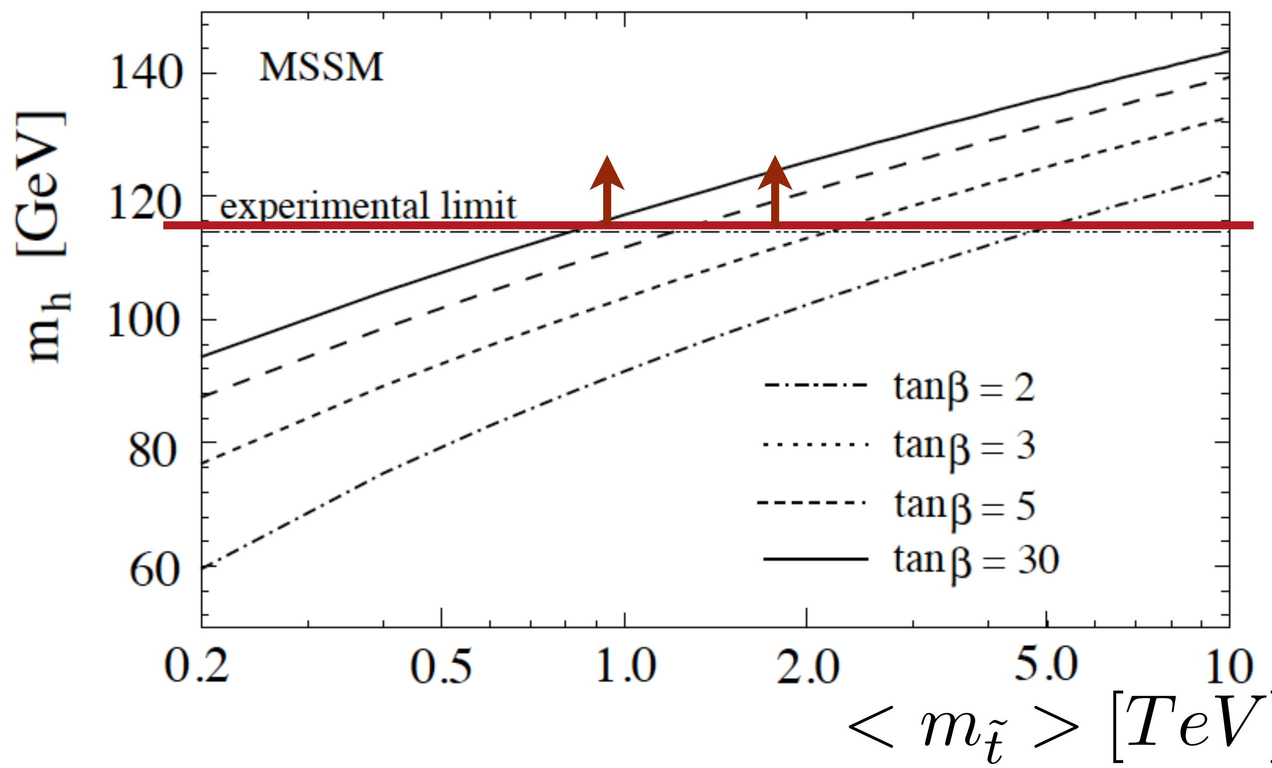


B, Isidori, Jones-Perez, Lodone, Straub 2011

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 largish $m_{\tilde{t}}, A_t$ but swallow, e.g. in mSUGRA, a large contribution to M_Z , to be fine-tuned away

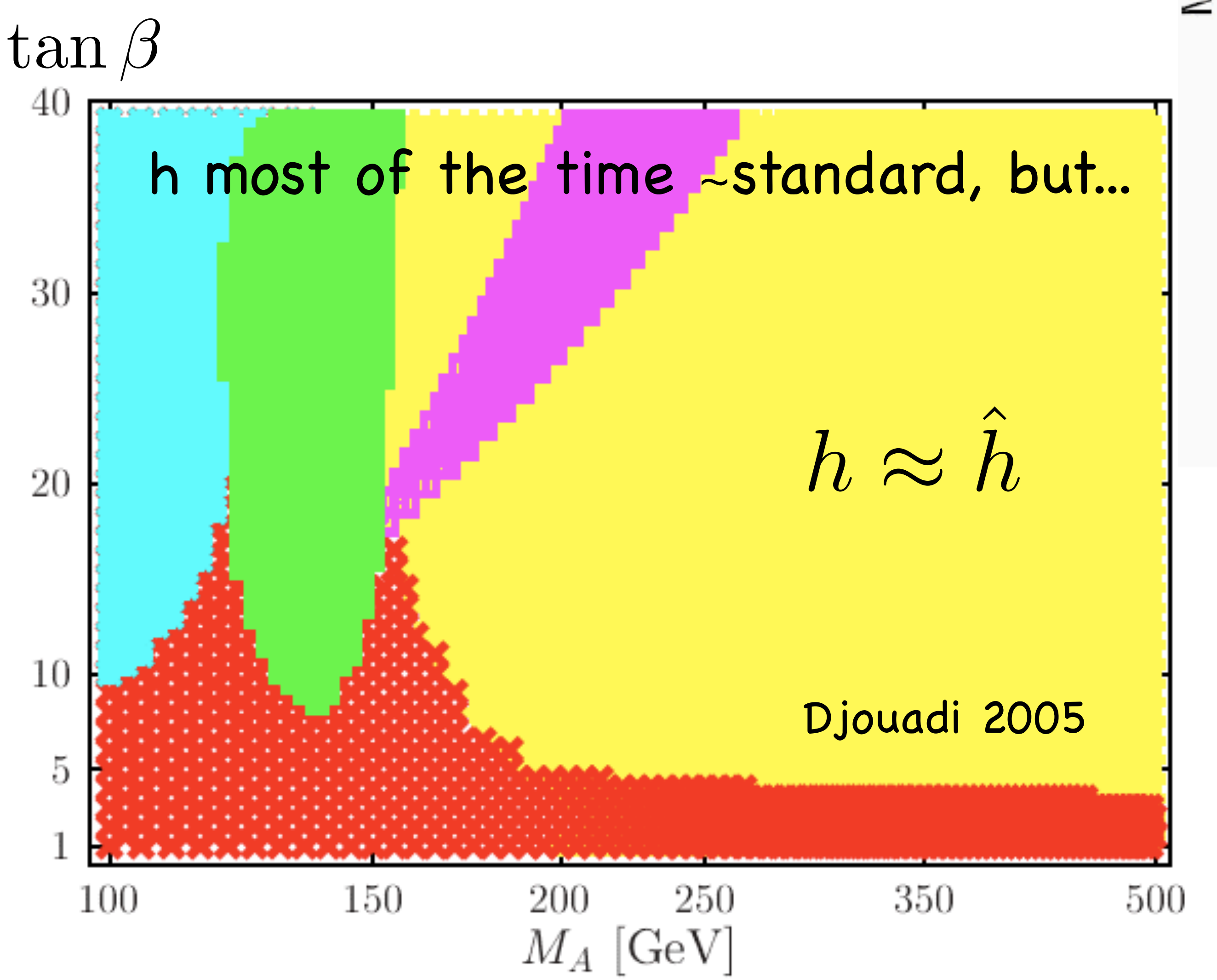
Never mind the ft for a while:

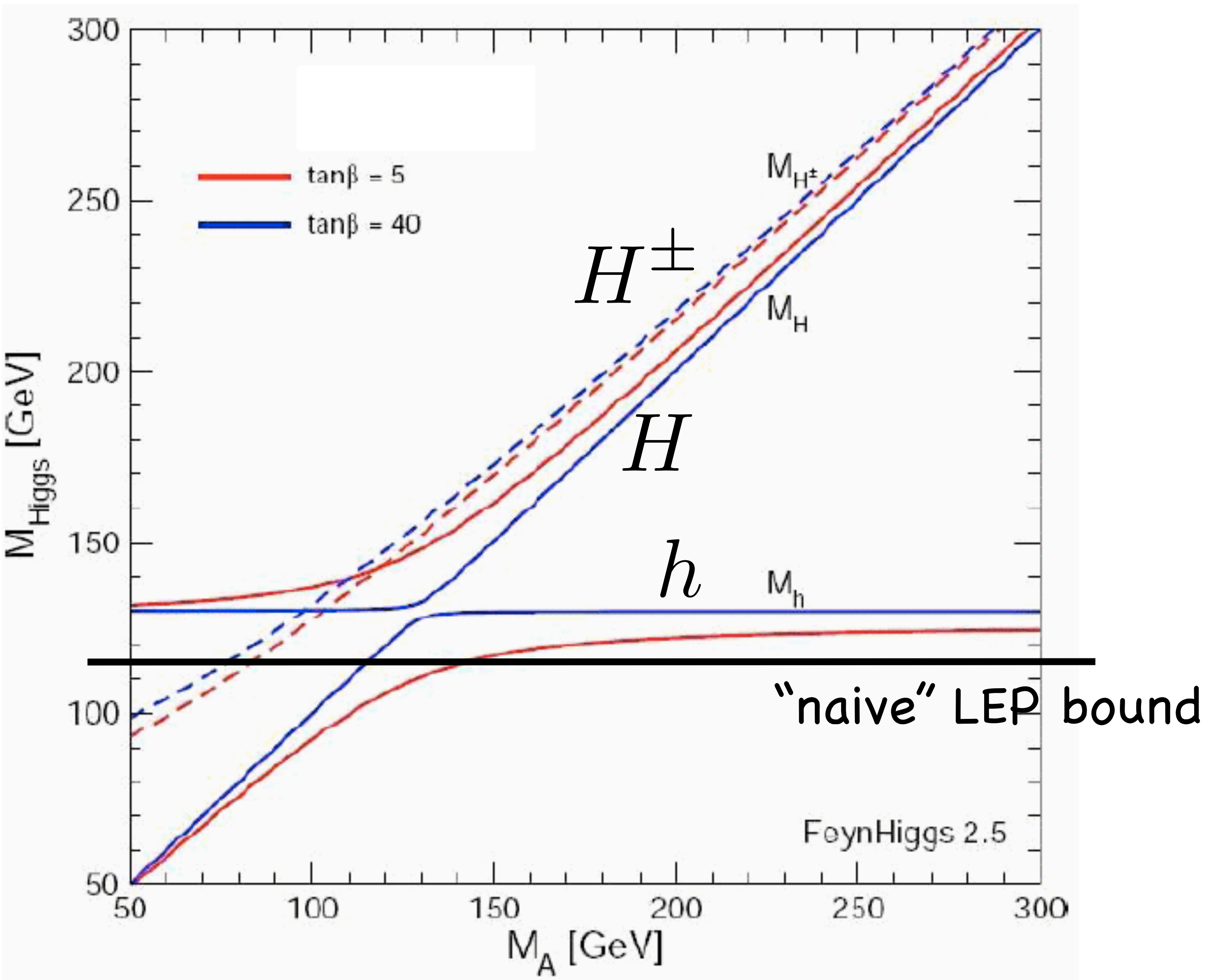
What's needed to discover a Higgs boson in the MSSM, no matter what the fine-tuning is?

(or to disprove the MSSM at all)

The Higgs system in the MSSM

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





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

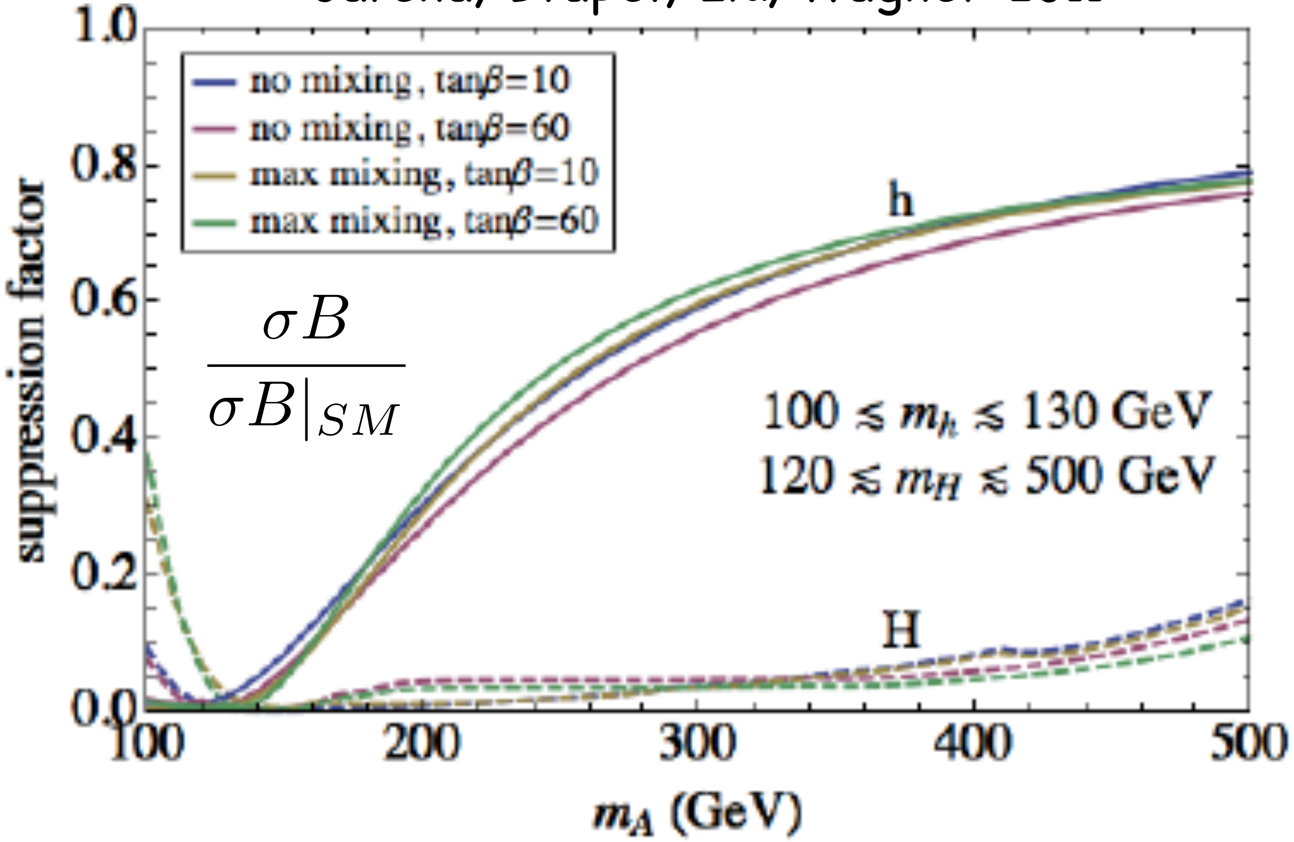
$$g_{\hat{H}t\bar{t}} = 1/\tan\beta$$
$$g_{\hat{H}b\bar{b}} = \tan\beta$$

3 ways to deplete σB(γγ) (or WW)

(with a bit of work in the parameter space)

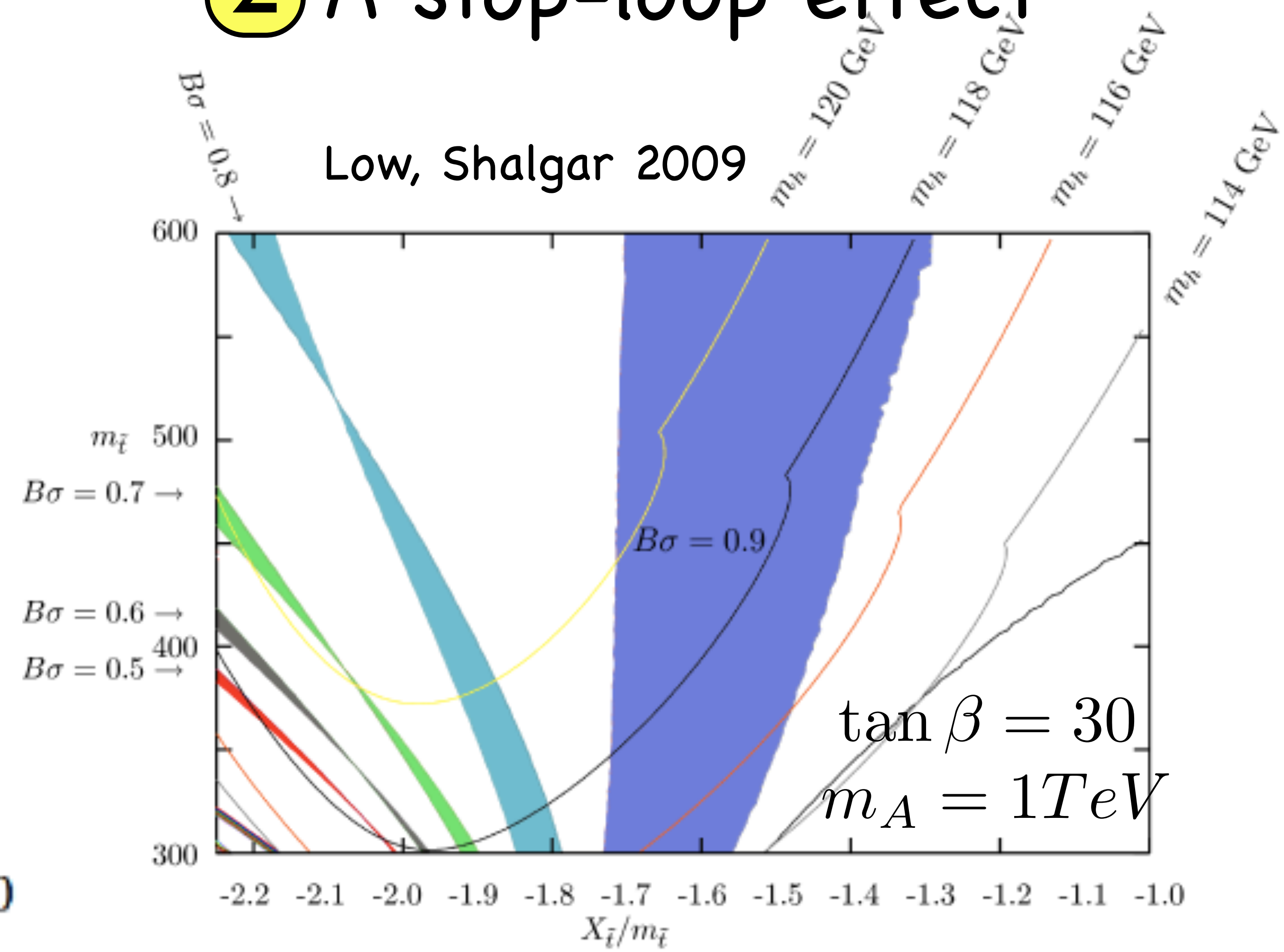
1 A $\hat{h}, \hat{H}$ mixing effect

Carena, Draper, Liu, Wagner 2011



2 A stop-loop effect

Low, Shalgar 2009



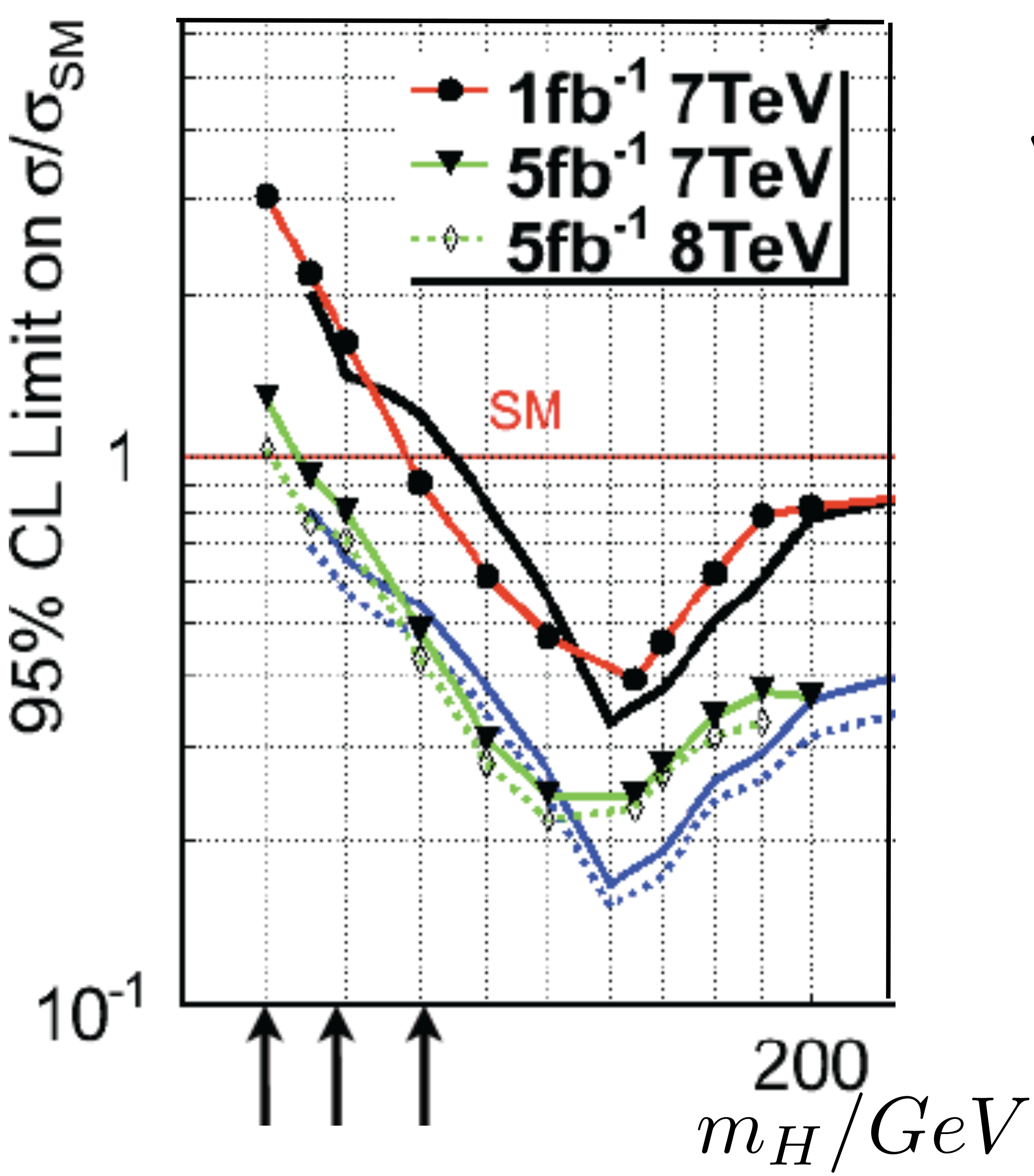
Shaded regions from varying μ

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

What's needed to discover a Higgs boson in the MSSM, no matter what the fine-tuning is?

(or to disprove the MSSM at all)

ATLAS and CMS projections



With suitable reinforcement

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

$$VBF,\ Wh,\ t\bar{t}h$$

$$h/H/A \rightarrow \tau\bar{\tau}$$

it should be possible

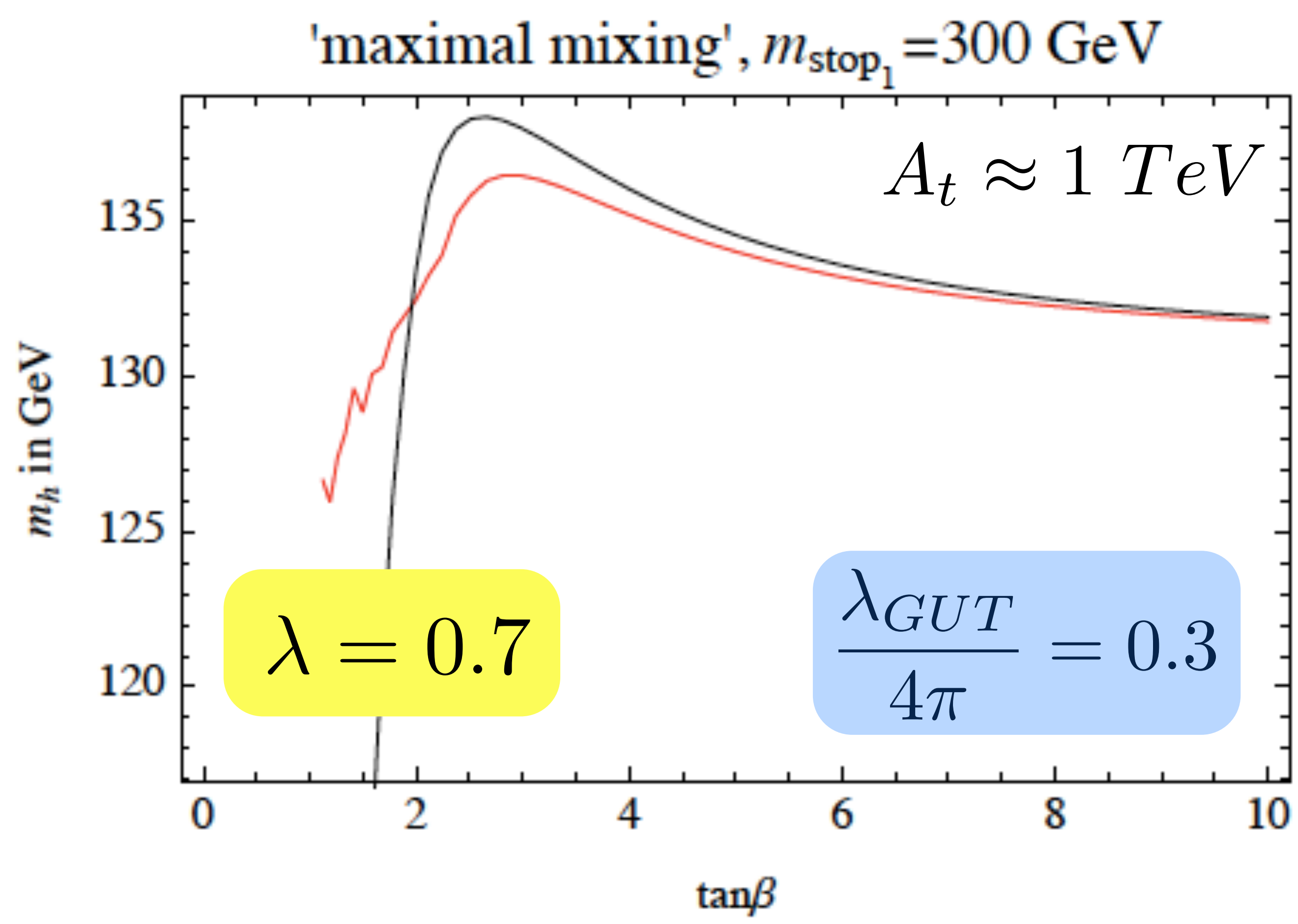
The easiest way to raise the Higgs mass

(if needed by the ft again)

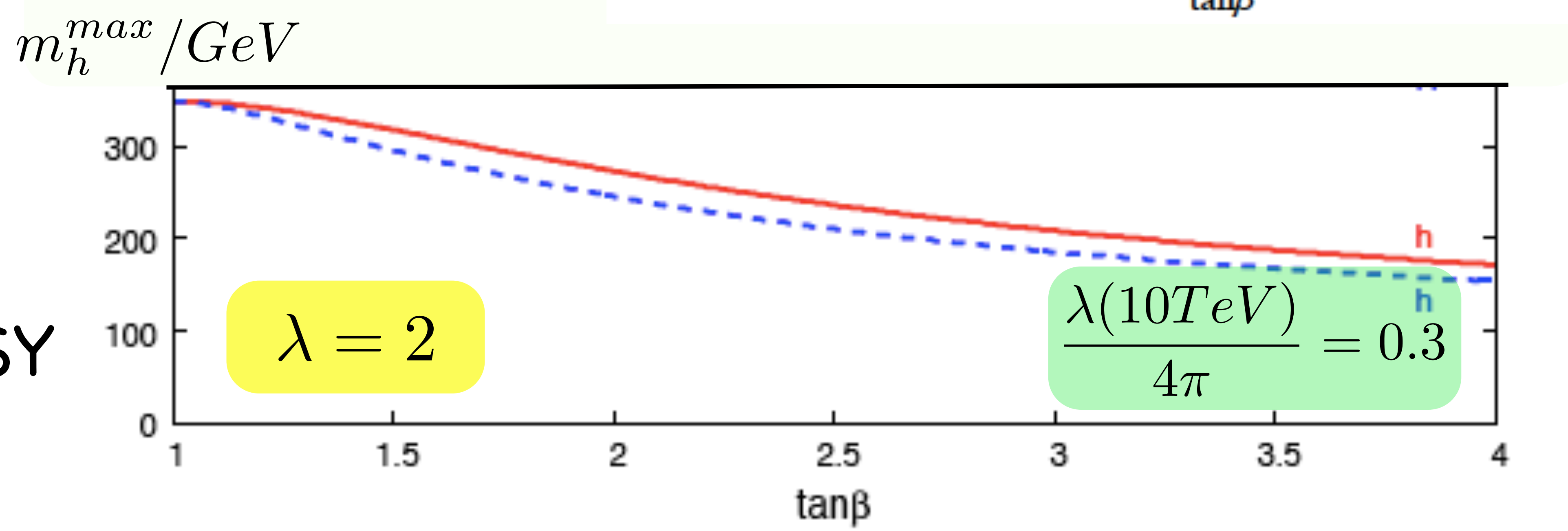
$$\Delta f = \lambda S H_u H_d$$

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

standard NMSSM

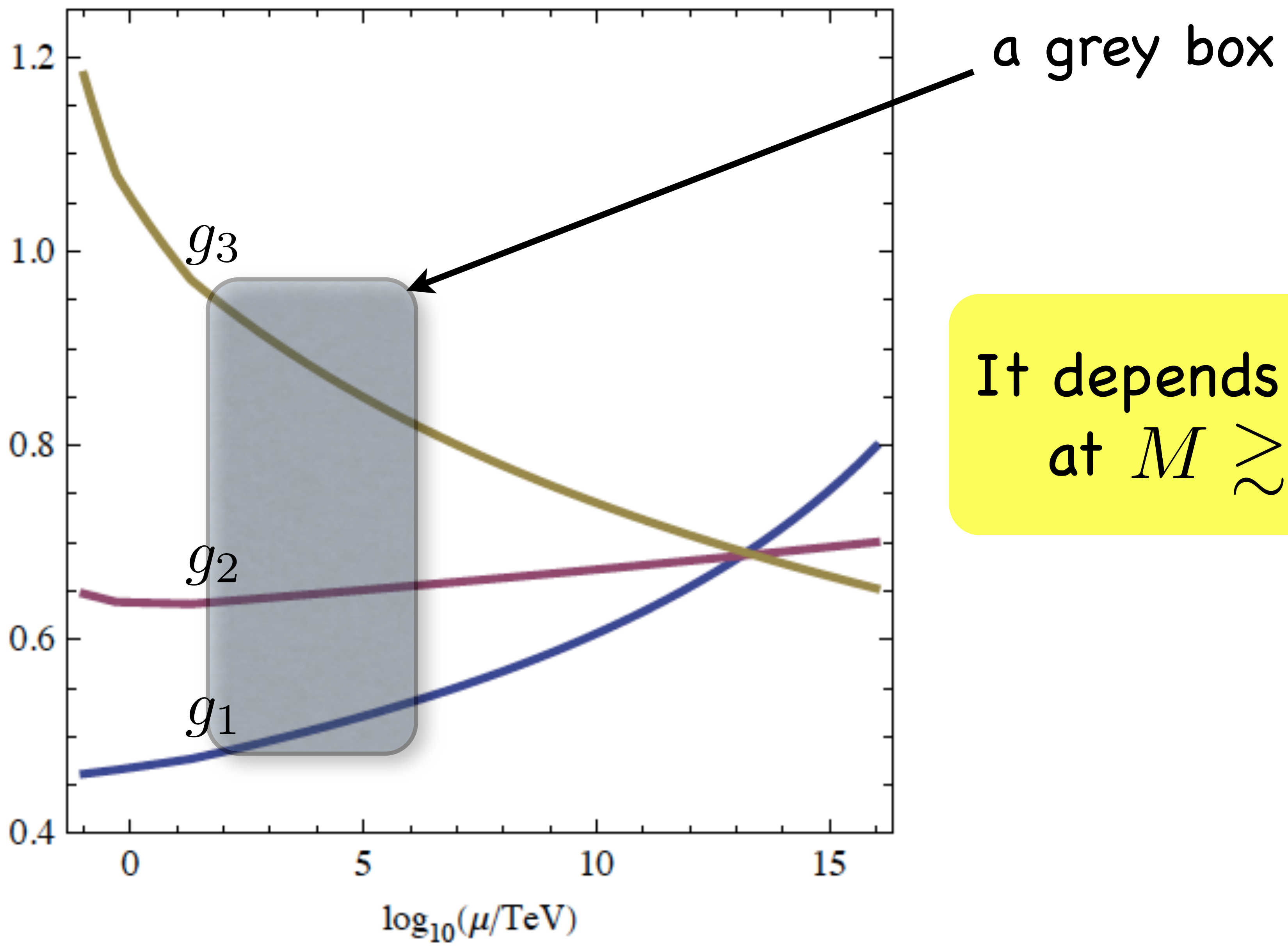


λSUSY



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

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

$\lambda = 0.7$

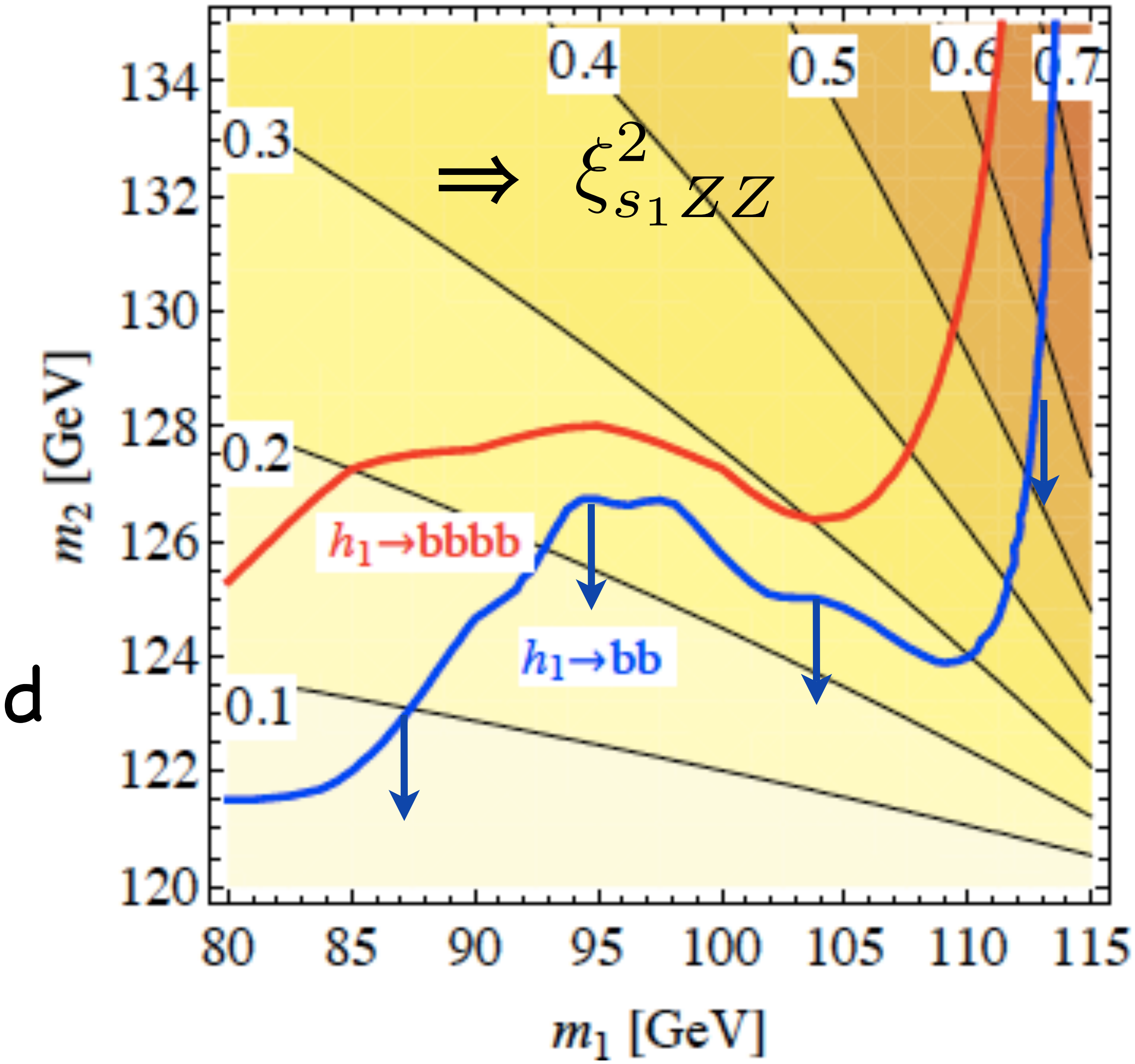
An illustrative 2x2 mixing model: $\hat{h}, \hat{s}$

Take:

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

m_{s_1}, m_{s_2} as shown

below the blue line allowed
by current data (LEP)



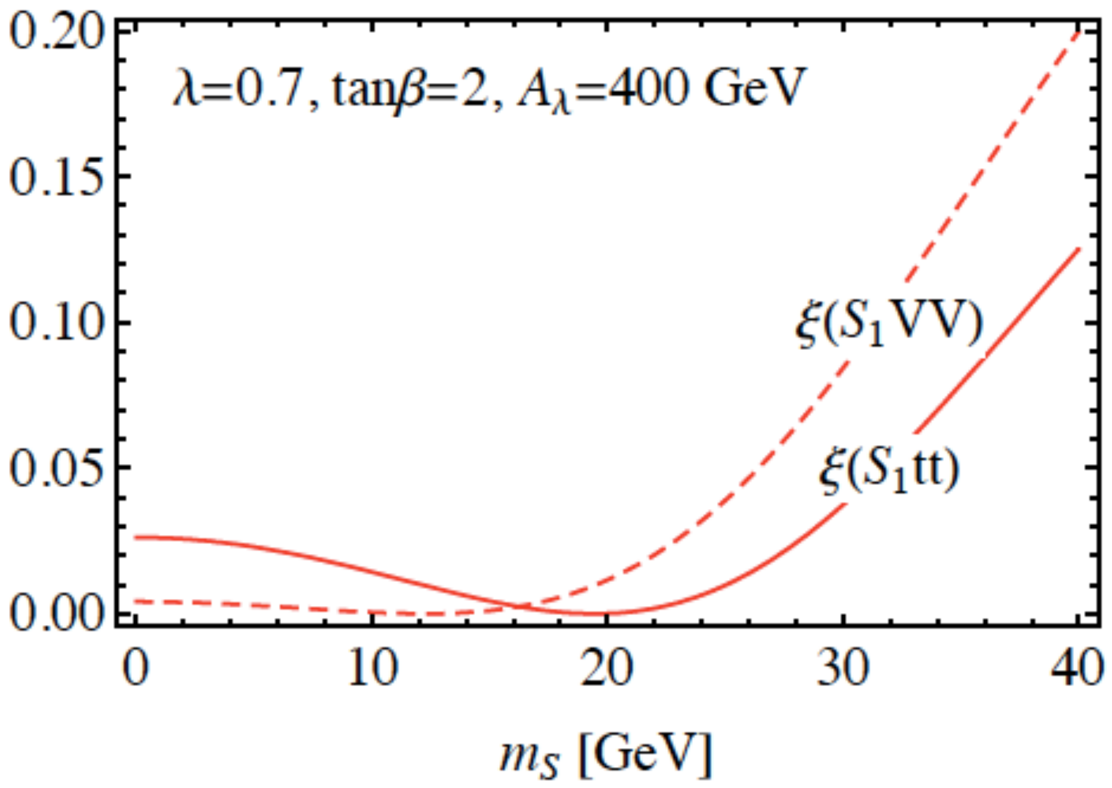
B, Hall, Pappadopulo, Rychkov, Papaioannou 2007

$\lambda = 0.7$

PQ SUSY (a particular NMSSM)

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

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



B, Hall, Pappadopulo, Rychkov, Papaioannou 2007

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

$$S_2 \to GG \to b\bar{b}\ b\bar{b}, \quad S_2 \to \chi_1\chi_1$$

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

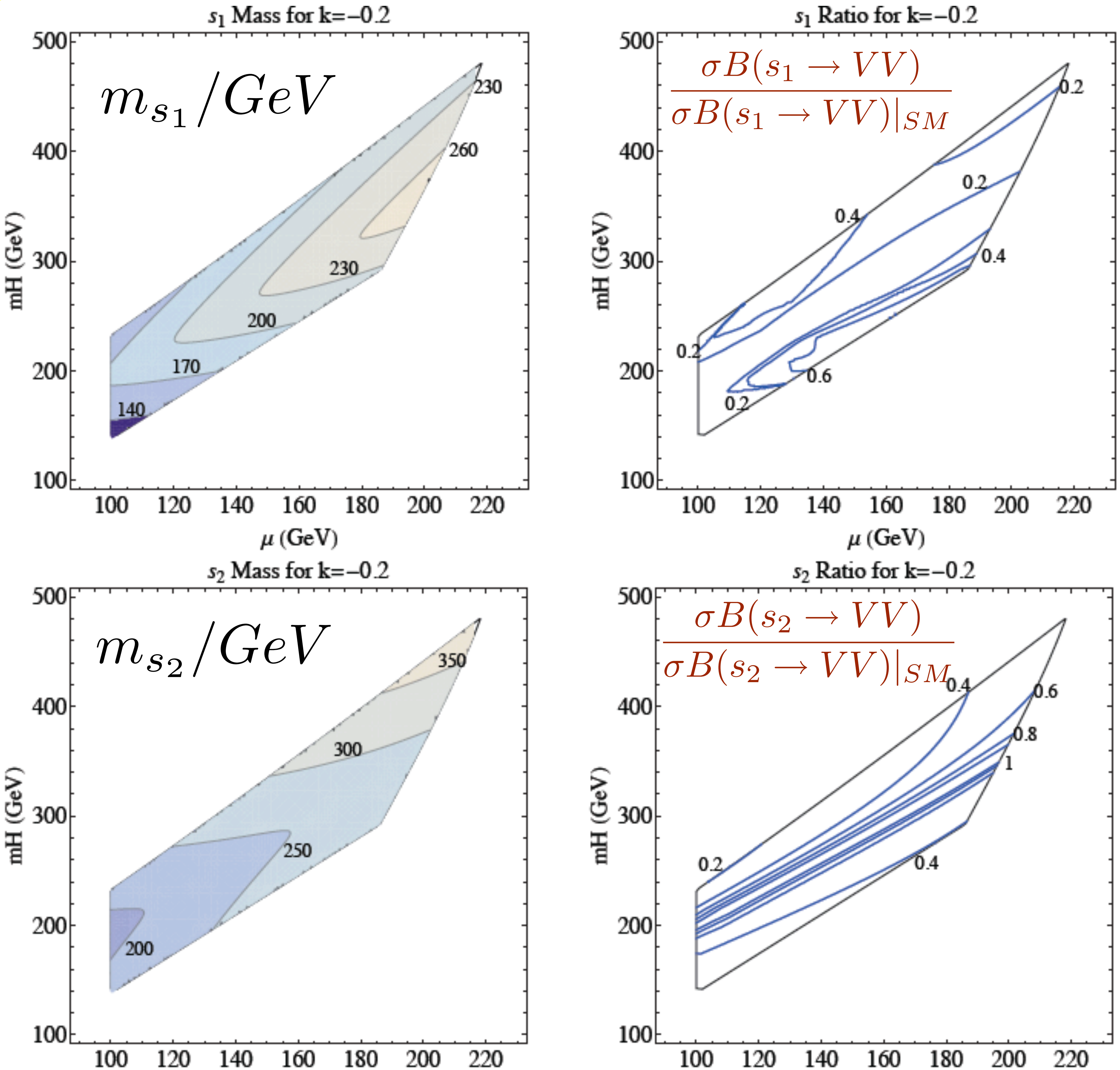
$\Leftarrow$!?!

G = a CP-odd pseudoGoldstone

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

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

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



s_2 visible in ZZ with enough lumi

Bertuzzo, Farina 2011

Summary

(mostly with an end-of-2012 perspective)

1. Some simple theories less interesting than before LHC
   (although certainly not excluded)

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

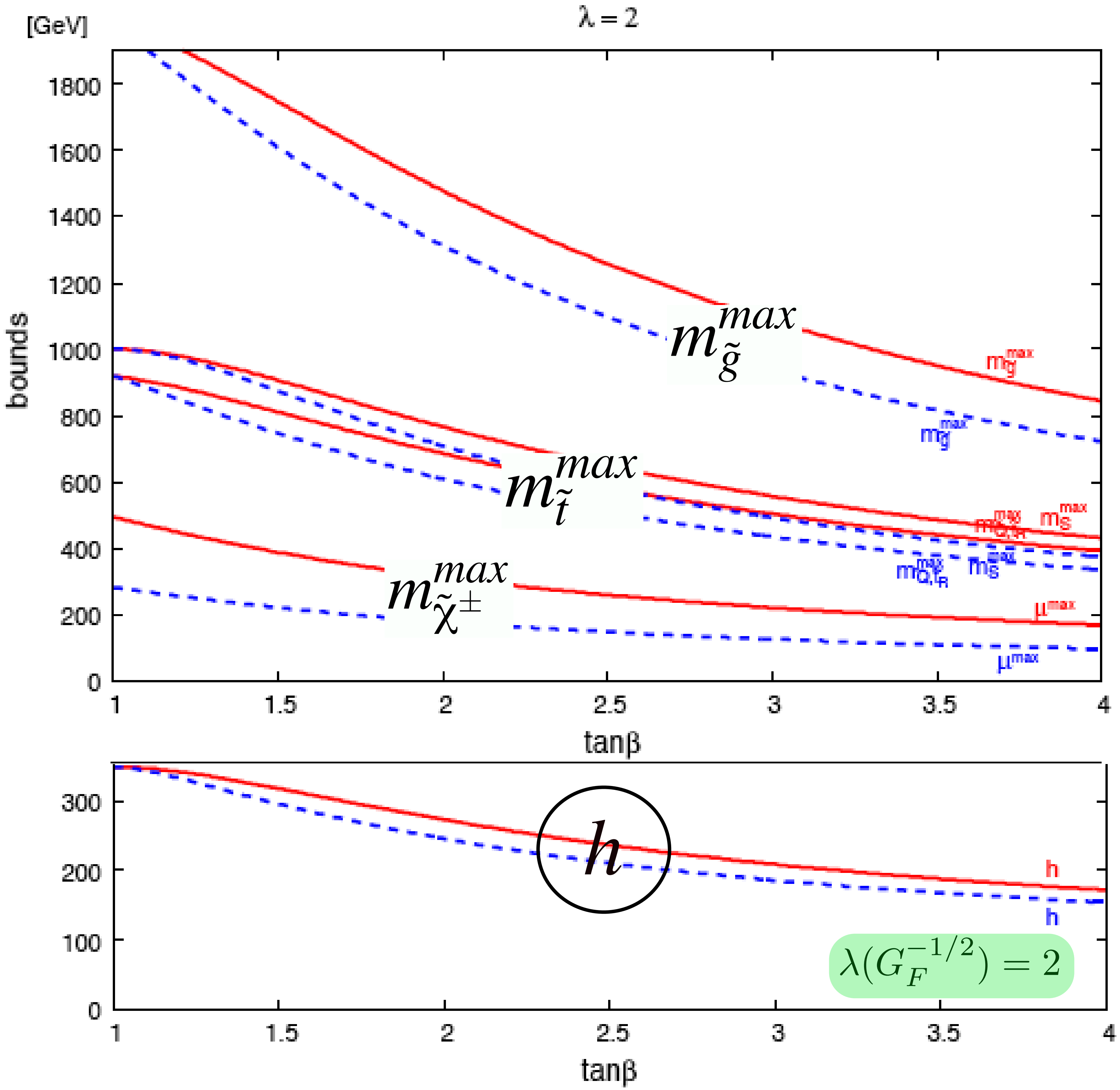
3. $10 \div 15 fb^{-1}$ at 7 TeV + extended searches likely enough to discover a Higgs boson in the MSSM
   (or to disprove the MSSM at all)

4. The Higgs system of the NMSSM:
   $\lambda \lesssim 0.8: \; h_1, h_2, h_3$ may all escape by non standard modes
   $0.8 < \lambda < 2: h_1$ or h_2 visible with enough luminosity

5. Beware of flavour and CPV signals (at low tanβ)

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

Particle spectrum (naturalness bounds)



$\lambda = 2$

$\Lambda_{mess} = 100\ TeV$

with up to 20% tuning

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

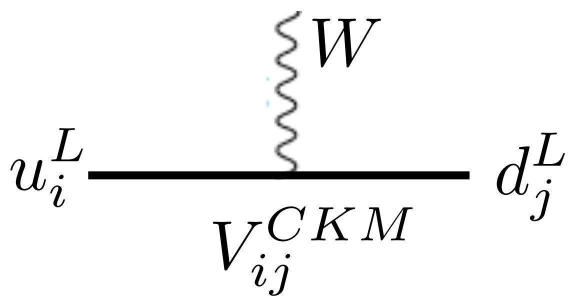
$$(m^{max} \propto \sqrt{\Delta/5})$$
$$\Delta = \frac{1}{20\%} = 5$$

B, Hall, Nomura, Rychkov 2006

Consequences of $U(2)^3$

Flavour changing interactions

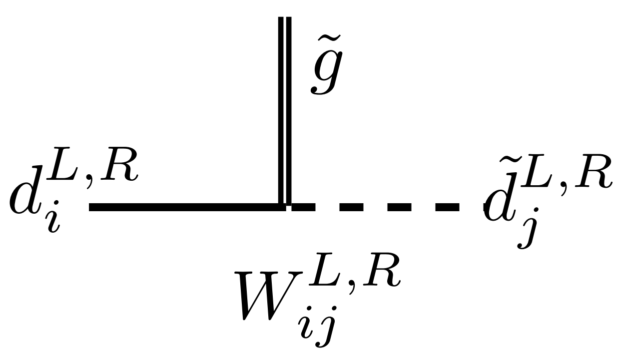
standard, in non standard parametrization



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

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

$$s_d = -0.22 \pm 0.01$$
$$(\sqrt{m_d/m_s} = 0.220 \pm 0.015)$$
$$s_u = 0.086 \pm 0.003$$
$$(\sqrt{m_u/m_c} = 0.055 \pm 0.015)$$
$$s = 0.0411 \pm 0.0005$$
$$\phi = (-97 \pm 9)^\circ$$



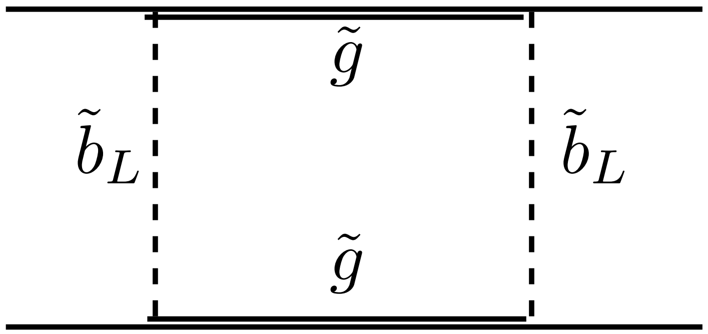
$$W^L = \begin{pmatrix} c_d & s_d e^{-i(\delta+\phi)} & -s_d s_L e^{i\gamma} e^{-i(\delta+\phi)} \\ -s_d e^{i(\delta+\phi)} & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

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

1 new angle s_L and 1 new phase γ

Supersymmetric flavour fit

including:



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

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

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

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

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

B, Isidori, Jones-Perez, Lodone, Straub 2011

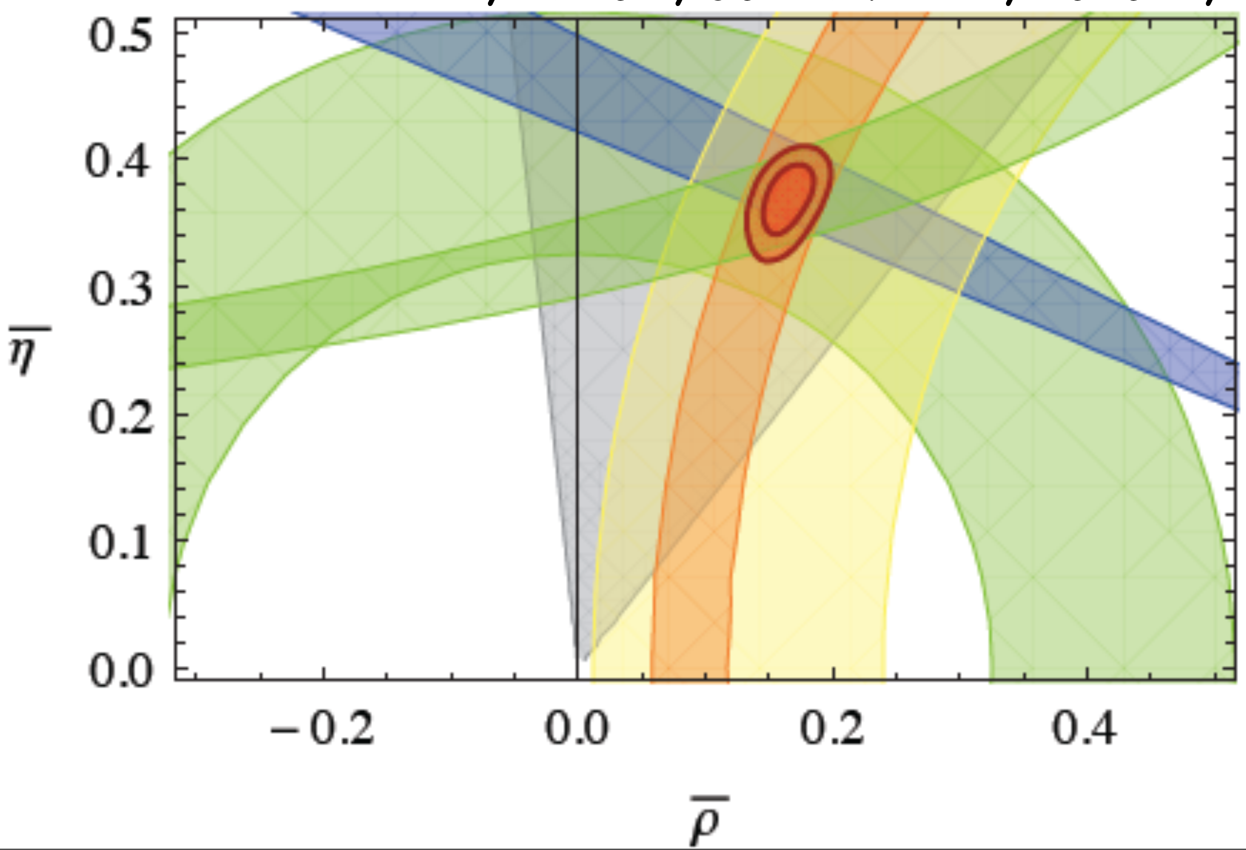
Tree level +

ΔM_d

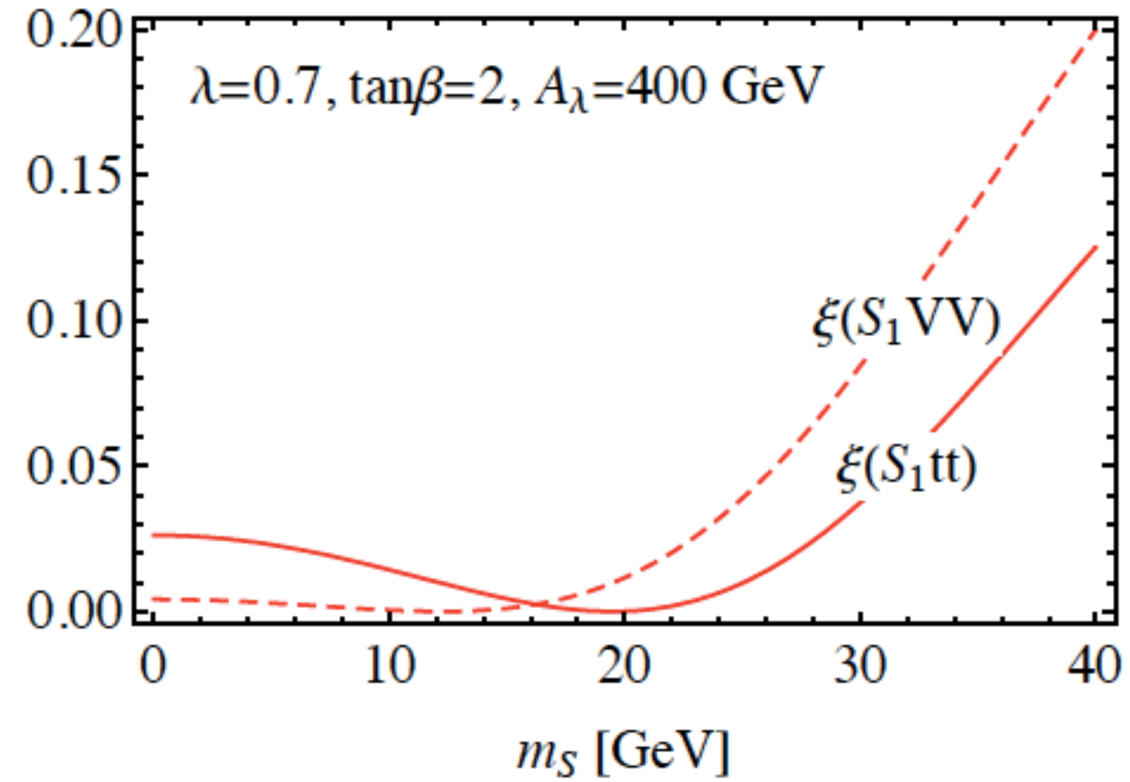
ΔM_s

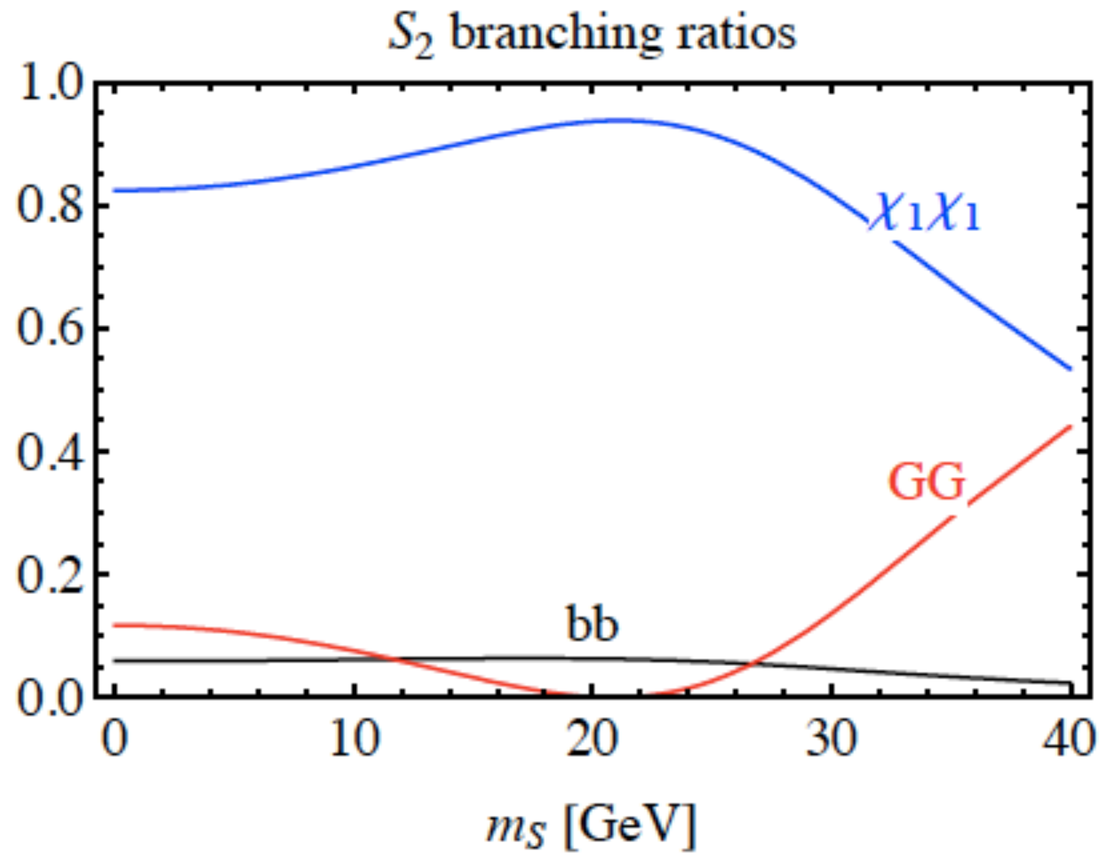
$S_{B_d \to \Psi K_S}$

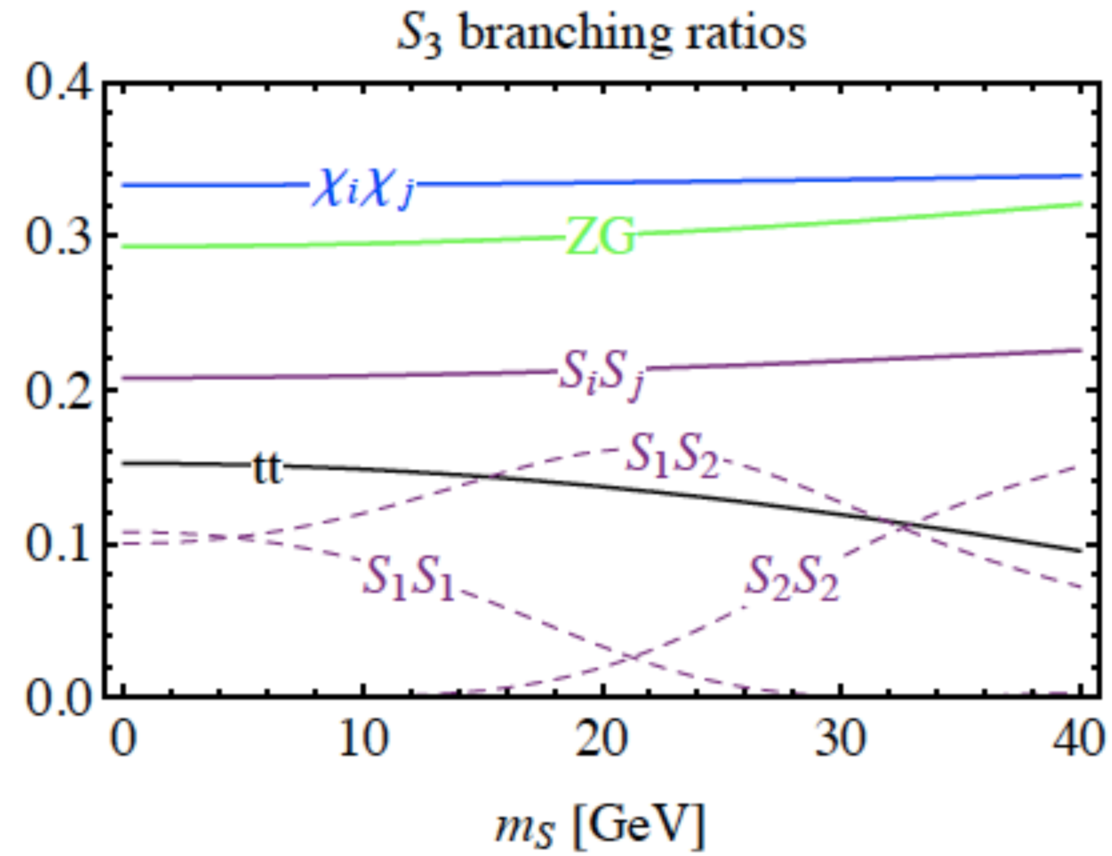
ϵ_K



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

$k=-0.2$	$BR_{A_1A_1}$	BR_{ZA_1}	$BR_{\chi 1 \chi 1}$	BR_{WW}	Γ_{tot} (GeV)	$\frac{\sigma\times BR}{(\sigma\times BR)_{SM}}$
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

$k=-0.2$	$BR_{A_1A_1}$	BR_{ZA_1}	$BR_{\chi 1 \chi 1}$	BR_{WW}	Γ_{tot} (GeV)	$\frac{\sigma\times BR}{(\sigma\times BR)_{SM}}$
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 changing interactions

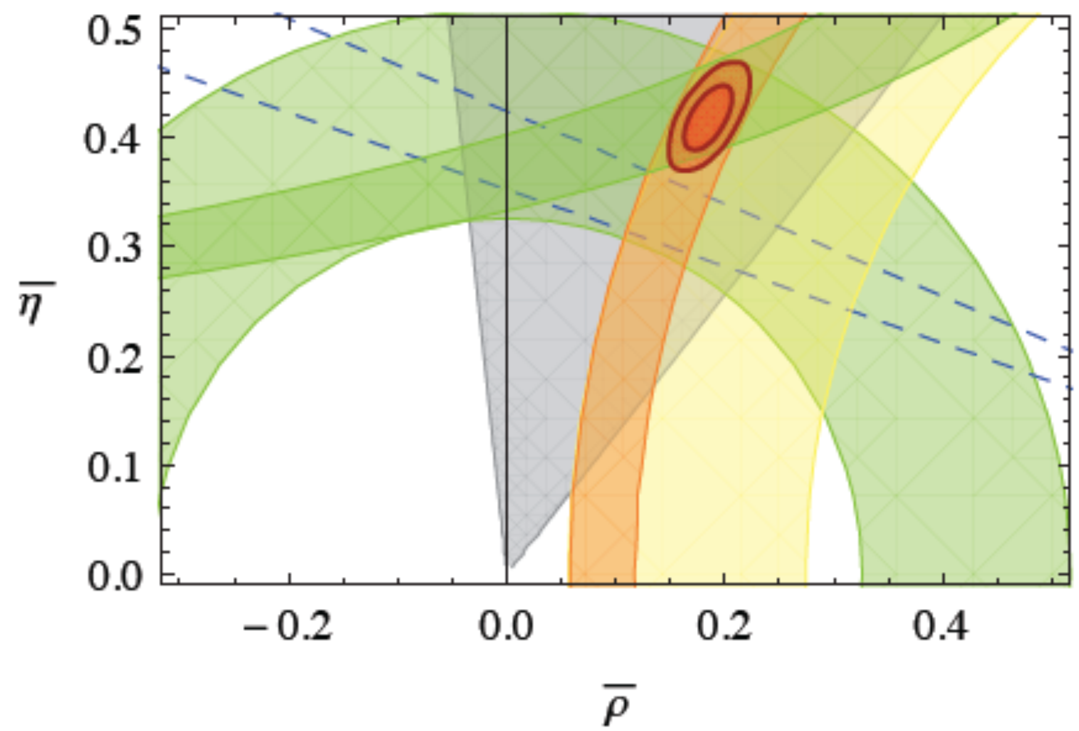
ΔF = 2 - Our own SM fit

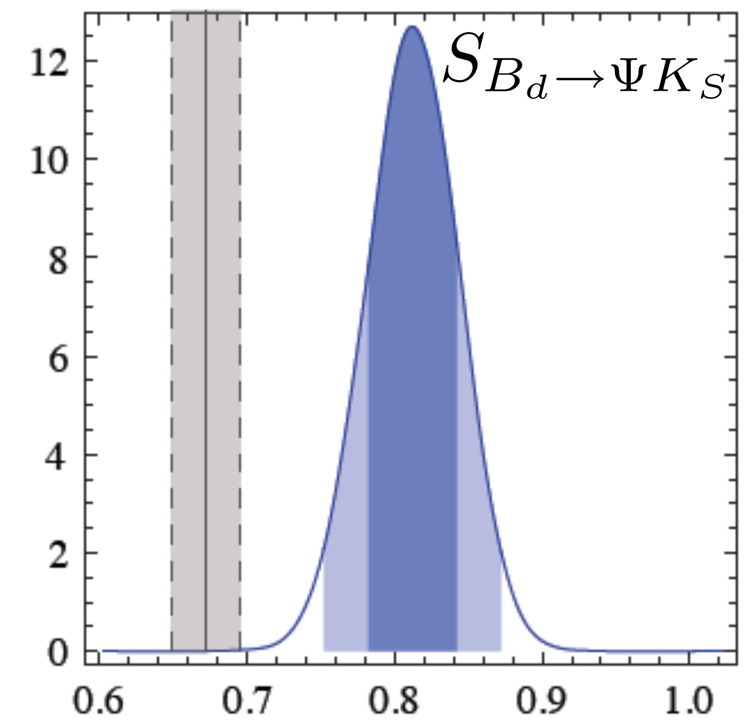
Tree level +

ΔM_d

ΔM_s

ϵ_K



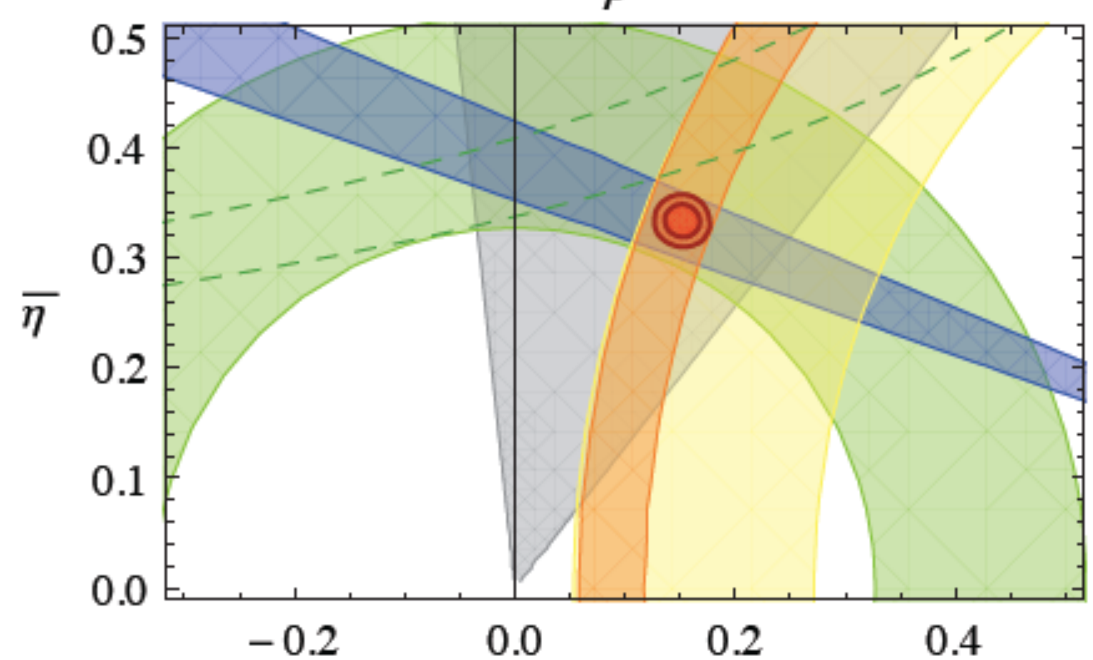


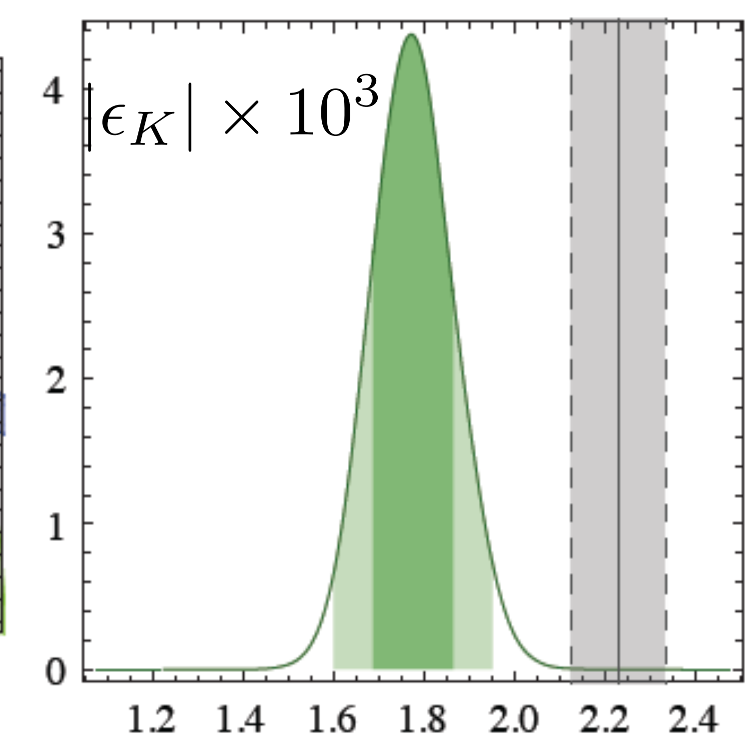
Tree level +

ΔM_d

ΔM_s

$S_{B_d \to \Psi K_S}$





details subject to discussion

a hint of a potential problem for the SM

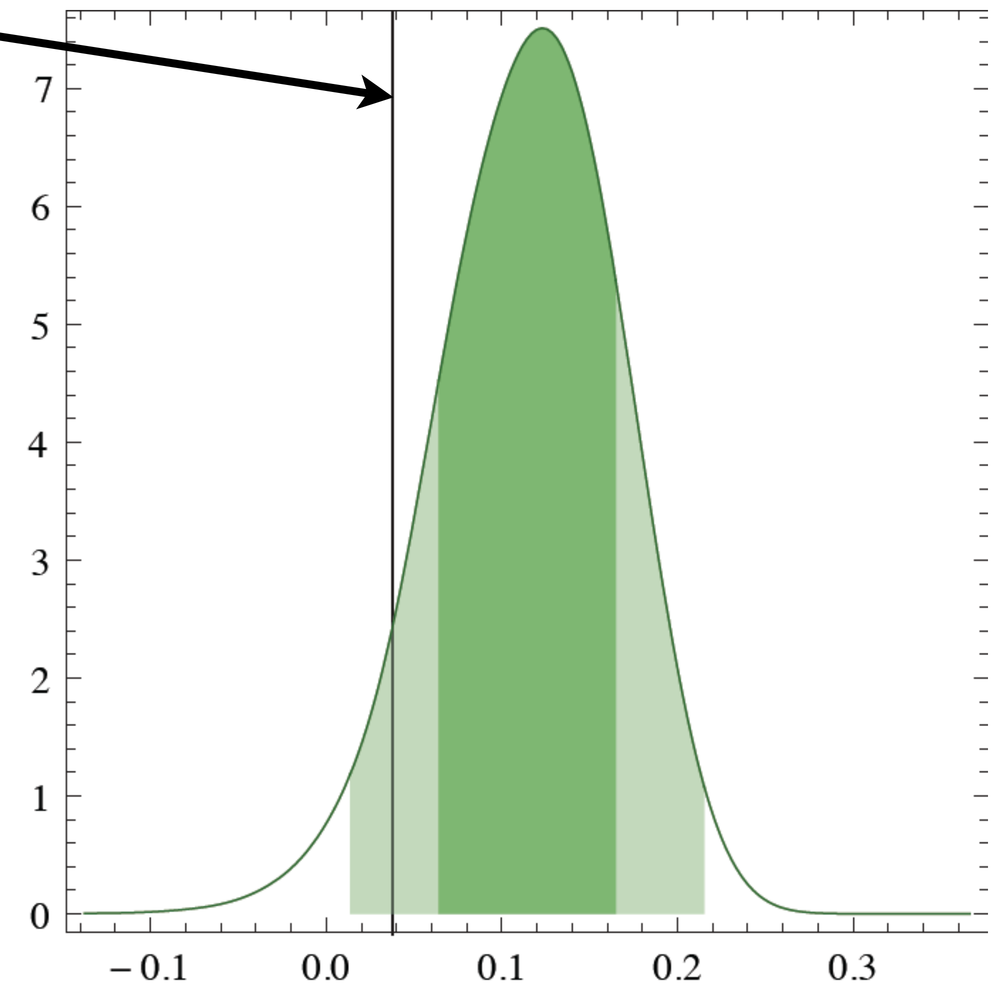
Lunghi, Soni
Buras, Guadagnoli
UT fit, CKM fit

Input data

$\lvert V_{ud}\rvert$	$0.97425(22)$	[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	$(0.507 \pm 0.004)\,\text{ps}^{-1}$	[22]			
ΔM_s	$(17.77 \pm 0.12)\,\text{ps}^{-1}$	[23]			

B, Isidori, Jones-Perez, Lodone, Straub 2011

(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 $m_{\tilde{b}}$)

$\lambda = 0.7$

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

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

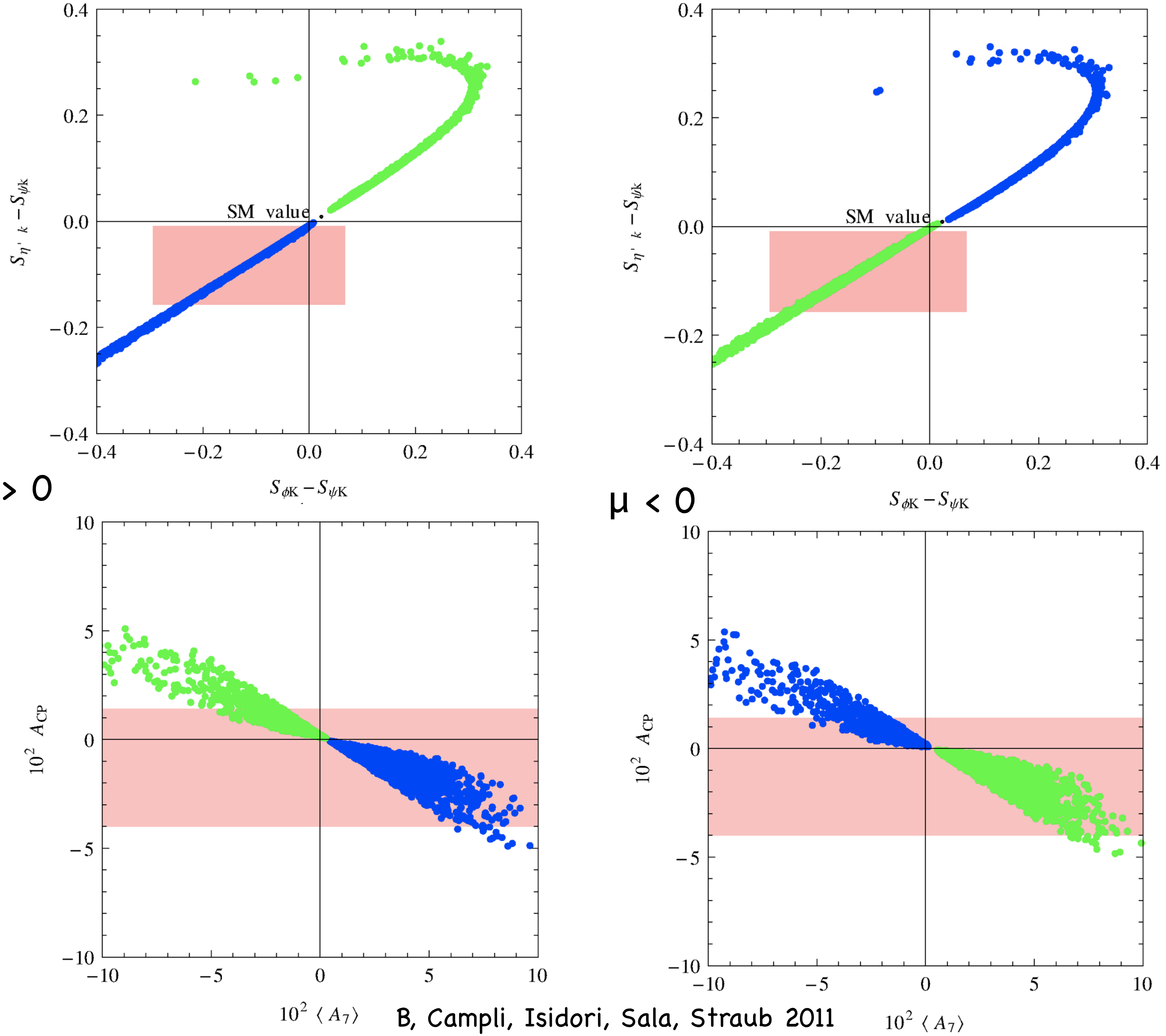
$$S_2 \to \begin{cases} GG \to b\bar{b}\ b\bar{b} \\ \chi_1\chi_1 \end{cases}$$

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

$\Leftarrow$!?!

B, Hall, Pappadopulo, Rychkov, Papaioannou 2007

CPV in ΔB = 1



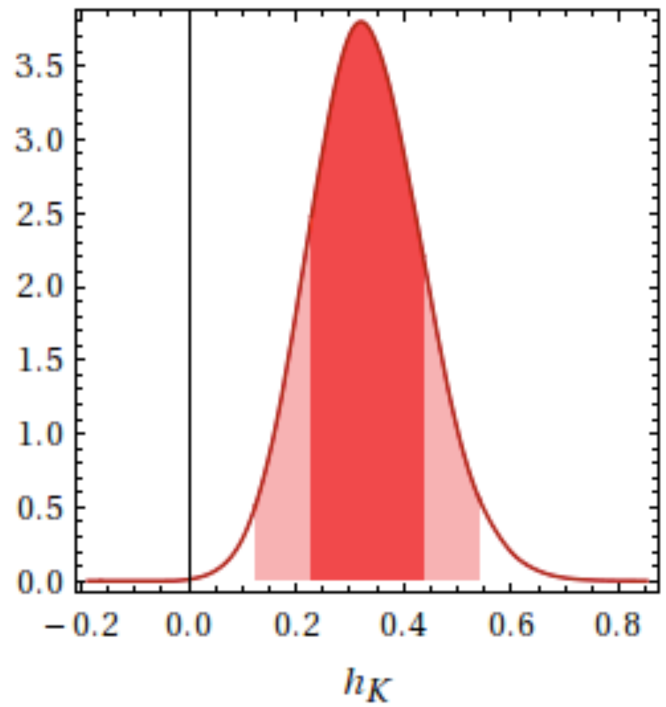
μ > 0

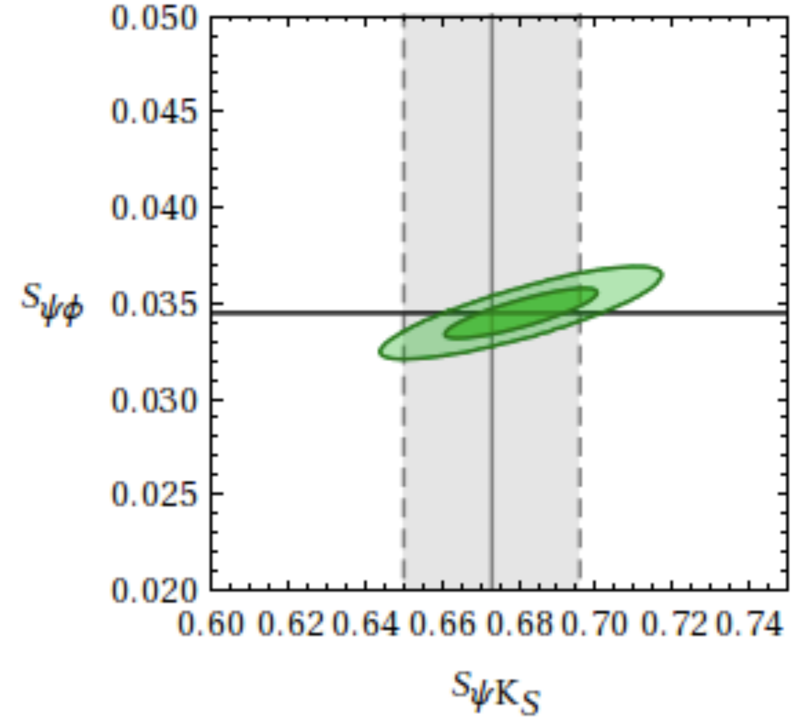
μ < 0

B, Campli, Isidori, Sala, Straub 2011

general $U(2)^3$

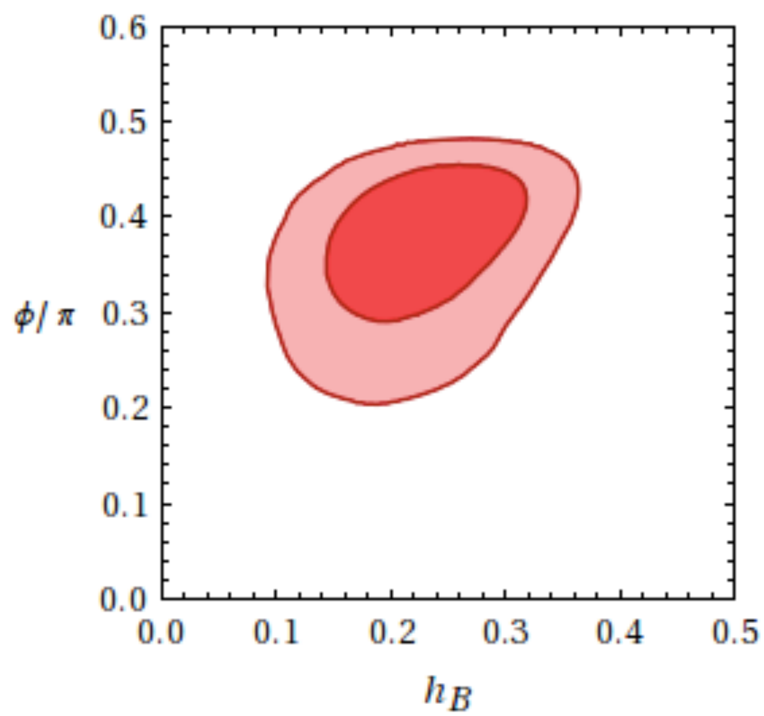
$$\mathcal{M}(K^0 \to \bar{K}^0) = \mathcal{M}^{SM}(K^0 \to \bar{K}^0)(1 + h_K)$$

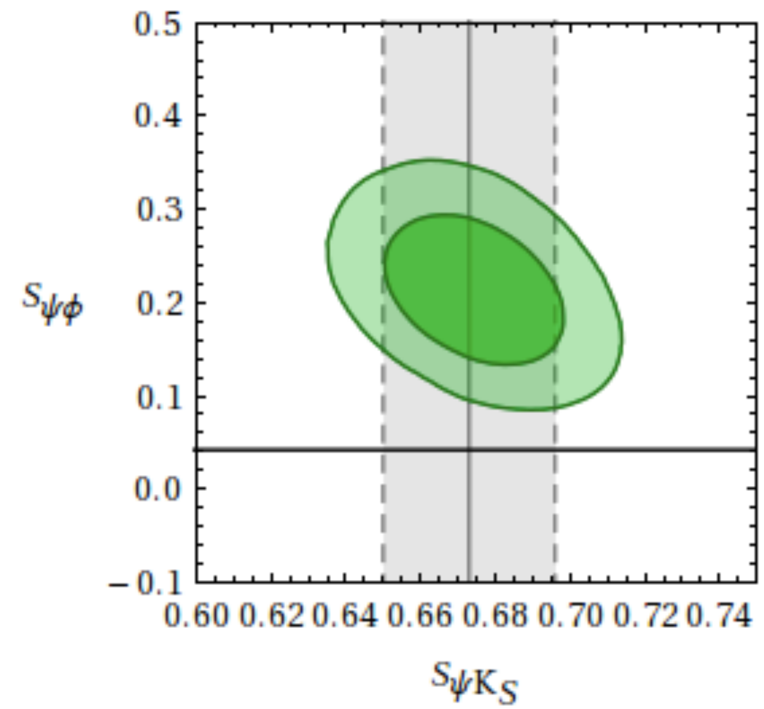




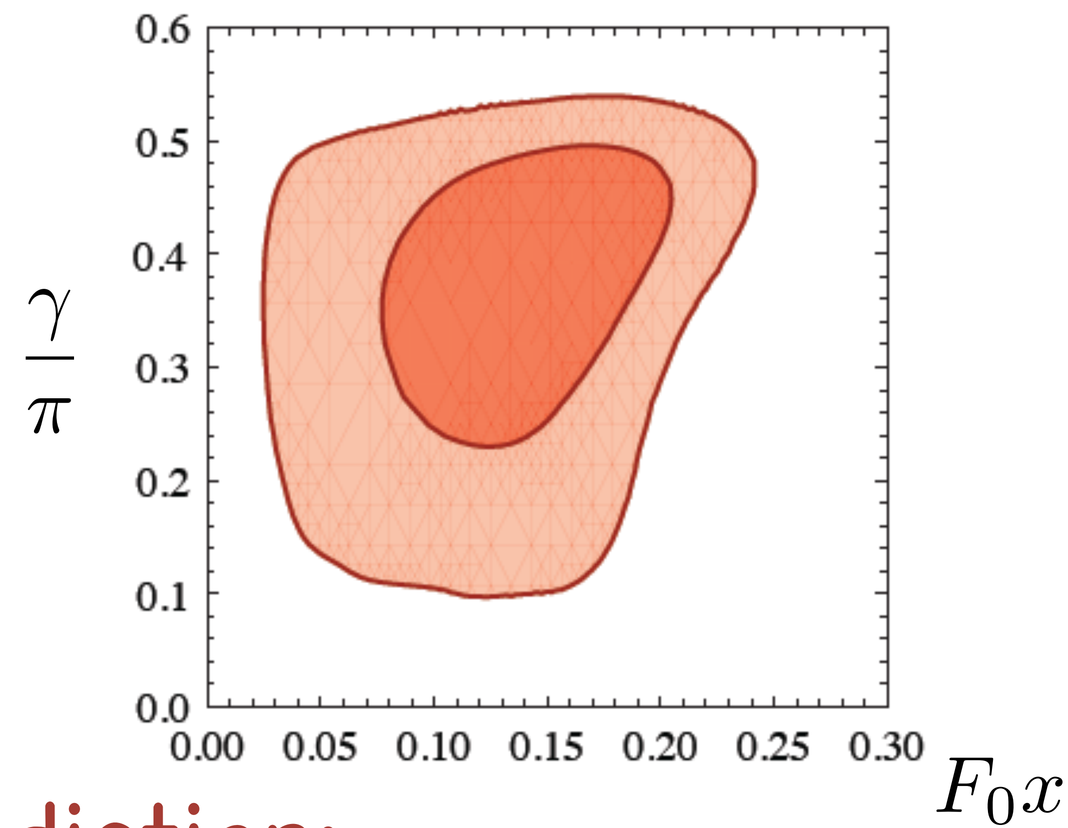
$$\mathcal{M}(B_d \to \bar{B}_d) = \mathcal{M}^{SM}(B_d \to \bar{B}_d)(1 + h_B e^{-2i\gamma})$$

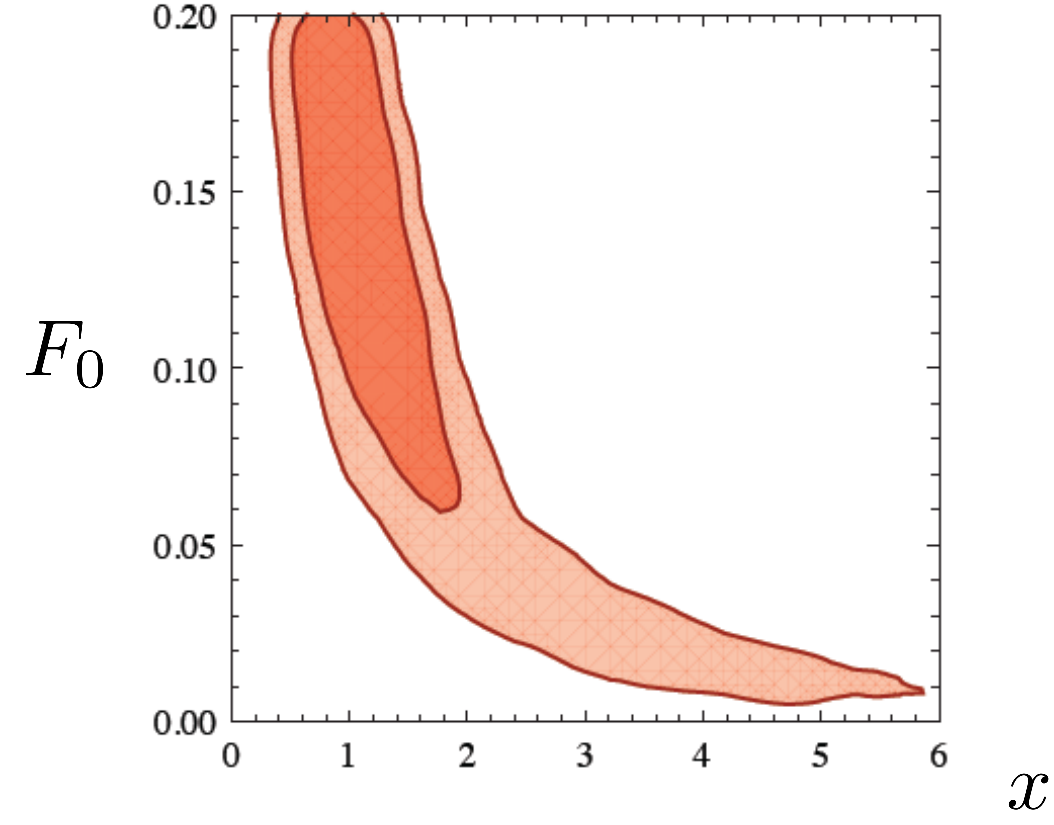
$$\frac{\mathcal{M}_d}{\mathcal{M}_s} = \frac{\mathcal{M}_d^{SM}}{\mathcal{M}_s^{SM}}$$





Constraints on extra parameters:

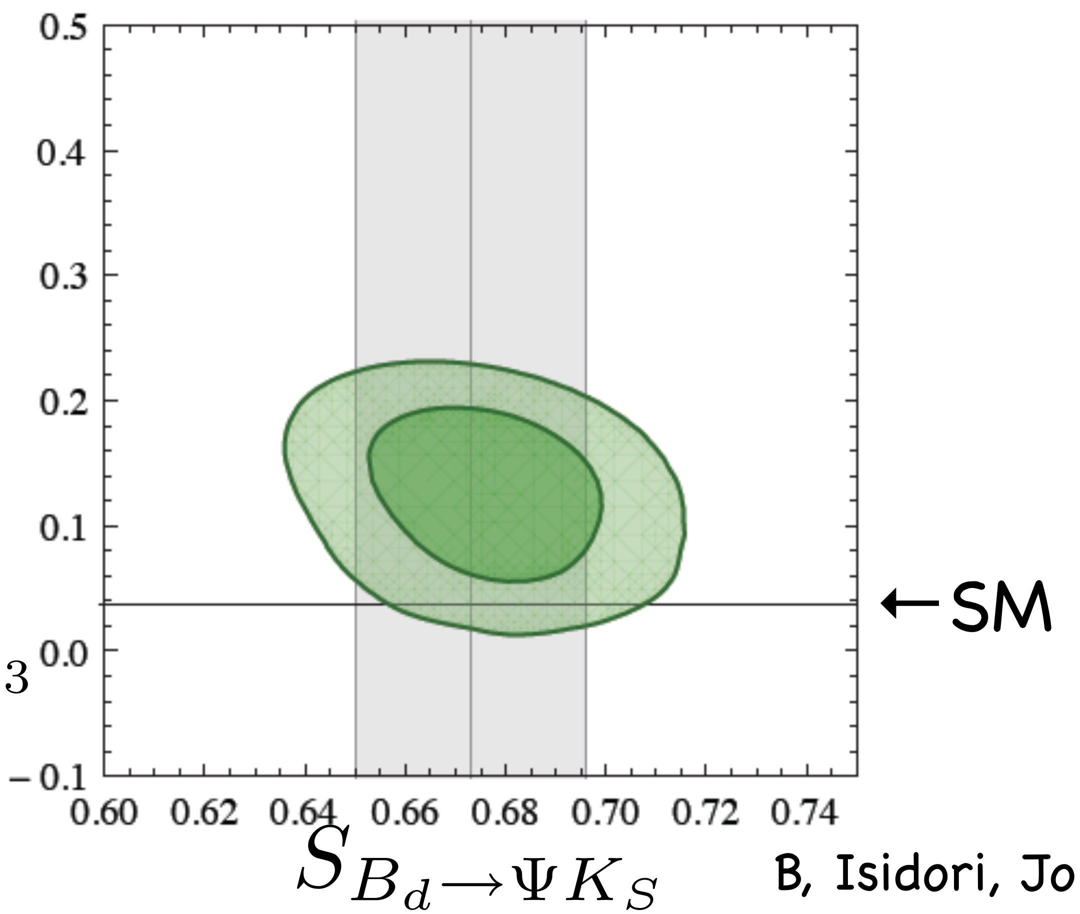


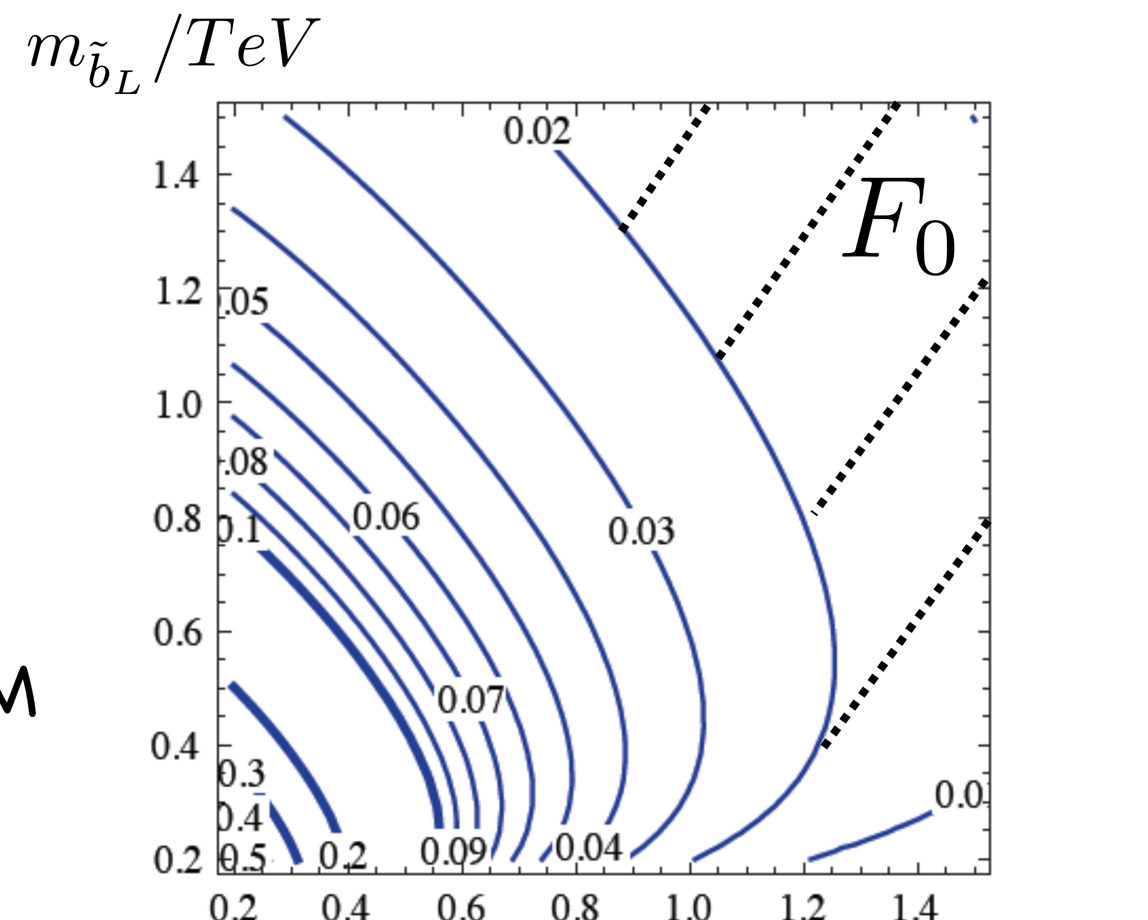


Prediction:

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

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





B, Isidori, Jones-Perez, Lodone, Straub 2011

ElectroWeak Precision Tests in λSUSY

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

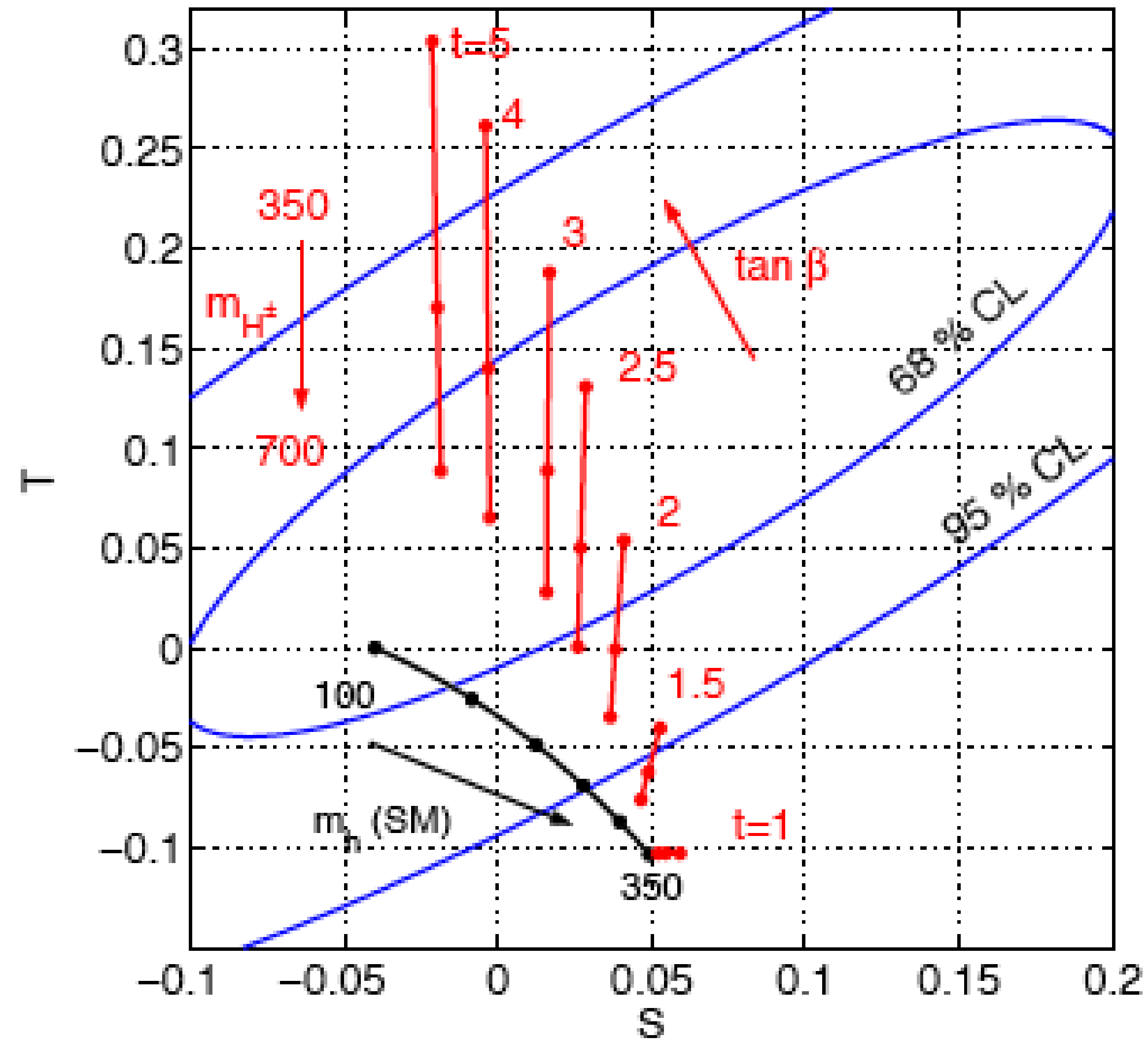
S and T from Higgs's

one loop effects but

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

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

compensated by $\Delta T \uparrow$



B, Hall, Nomura, Rychkov 2006

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