EW theory after the first LHC phase

Nobel Symposium on LHC results
Krusenberg, Uppsala, May 13-17, 2013

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SNS and INFN, Pisa

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\,\not{D}\psi$$ The gauge sector 1

$$+|D_\mu h|^2 - V(h)$$ The EWSB sector 2

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$ The flavour sector 3

$$+N_i M_{ij} N_j$$ The ν-mass sector 4
(if Majorana)

(2000: The LEP paradox, the "little hierarchy problem")

2013: The LHC paradox

The discovery of the Higgs boson (hence for 2) and the mounting evidence for the CKM picture of flavour physics (hence for 3)

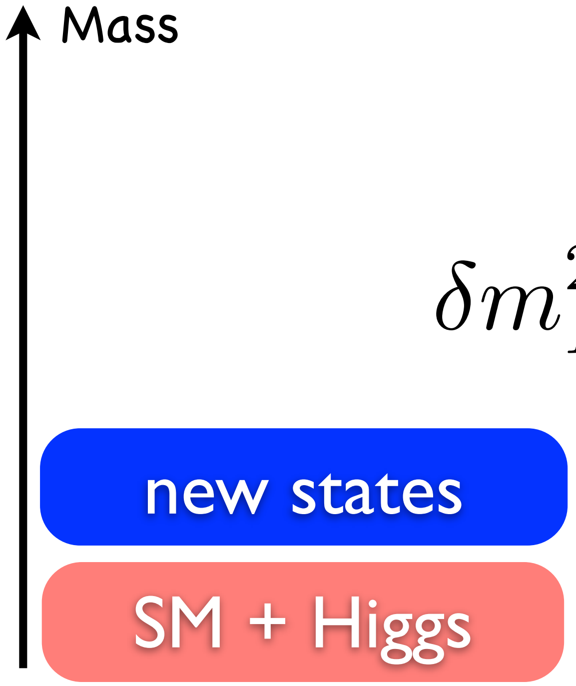
against

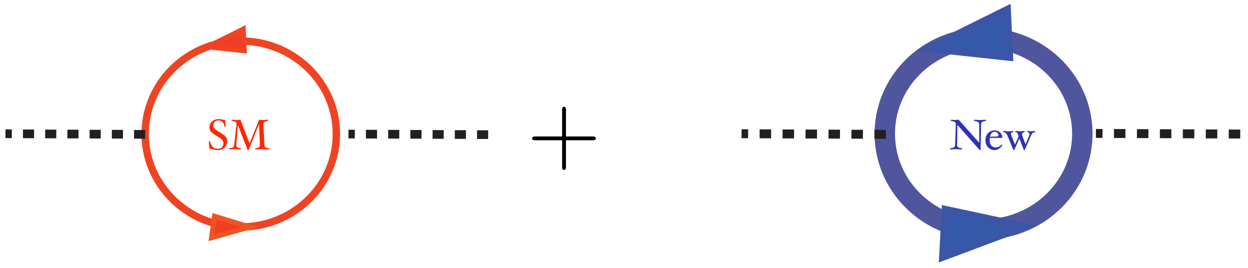
2 and 3 as (to me) still unsatisfactory sectors of the SM

This makes me (prefer to) think that the SM is still incomplete at the TeV scale

(a shortsighted perspective?)
(other directions?)

A "natural", not Fine Tuned Higgs boson





$$\delta m_H^2 = \cdots \quad + \quad \cdots \sim 0$$

by an (approximate) symmetry

relative to any higher physical scale to which the Higgs boson is possibly coupled

If so, explain why the great empirical success of the SM does not depend on unknown short distance physics

My main questions

0. The discovery of the Higgs boson: just the coronation of the SM or a first fundamental step?

1. The Higgs boson(s): one or more?

The pro's for one:
simplicity, 2 phases only, flavour, a single tuning,...?
None compelling

2. Precision EW and Higgs coupling measurements versus direct new physics searches: which comparison?

Might become the key question after 2-3 years of LHC14 if ...

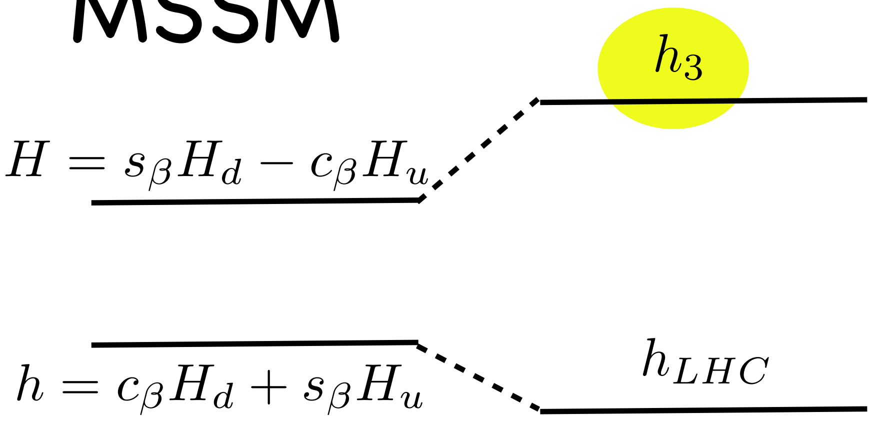
3. What can we expect from (and for) flavour physics?

$m's, V_{CKM} \Leftrightarrow \lambda_{ij}^{Yukawa}$: a great embarrassment,
unlikely to be solved without new key data

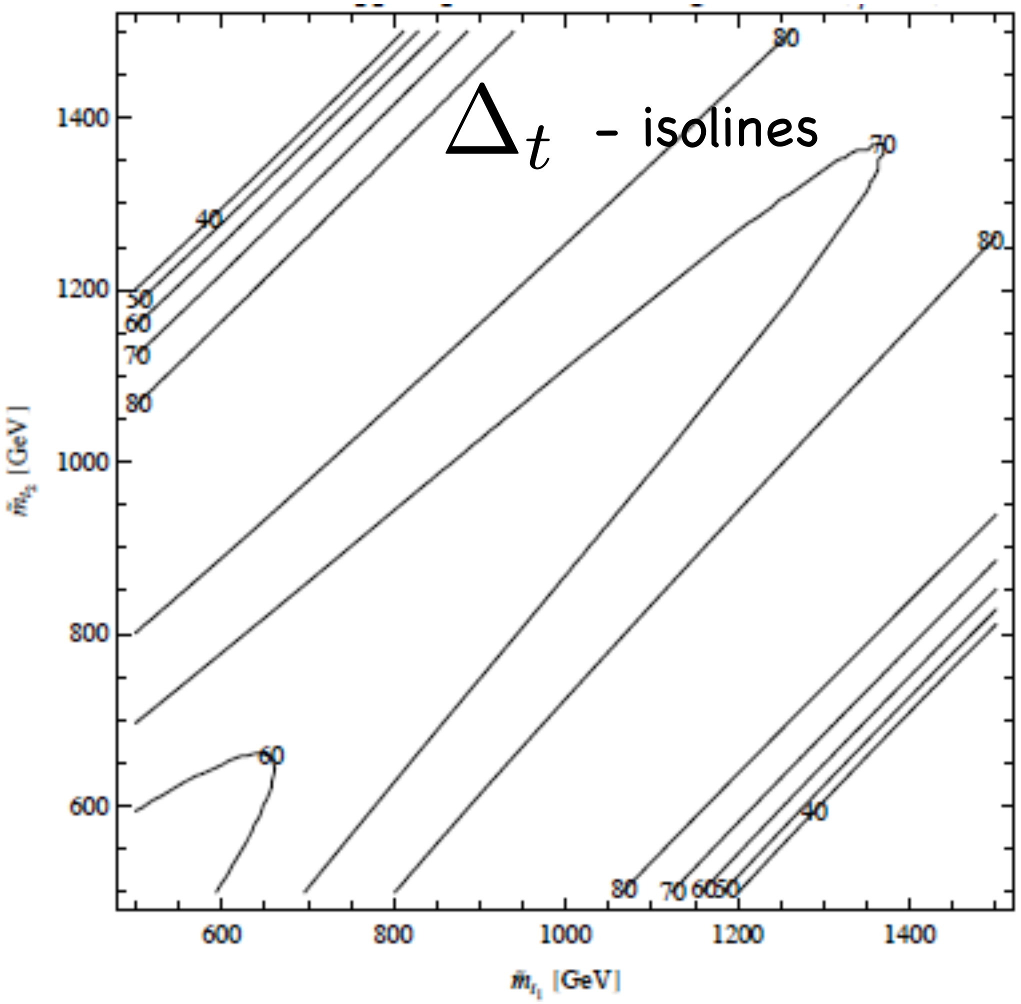
More than one Higgs boson and supersymmetry

(as a relevant example)

MSSM

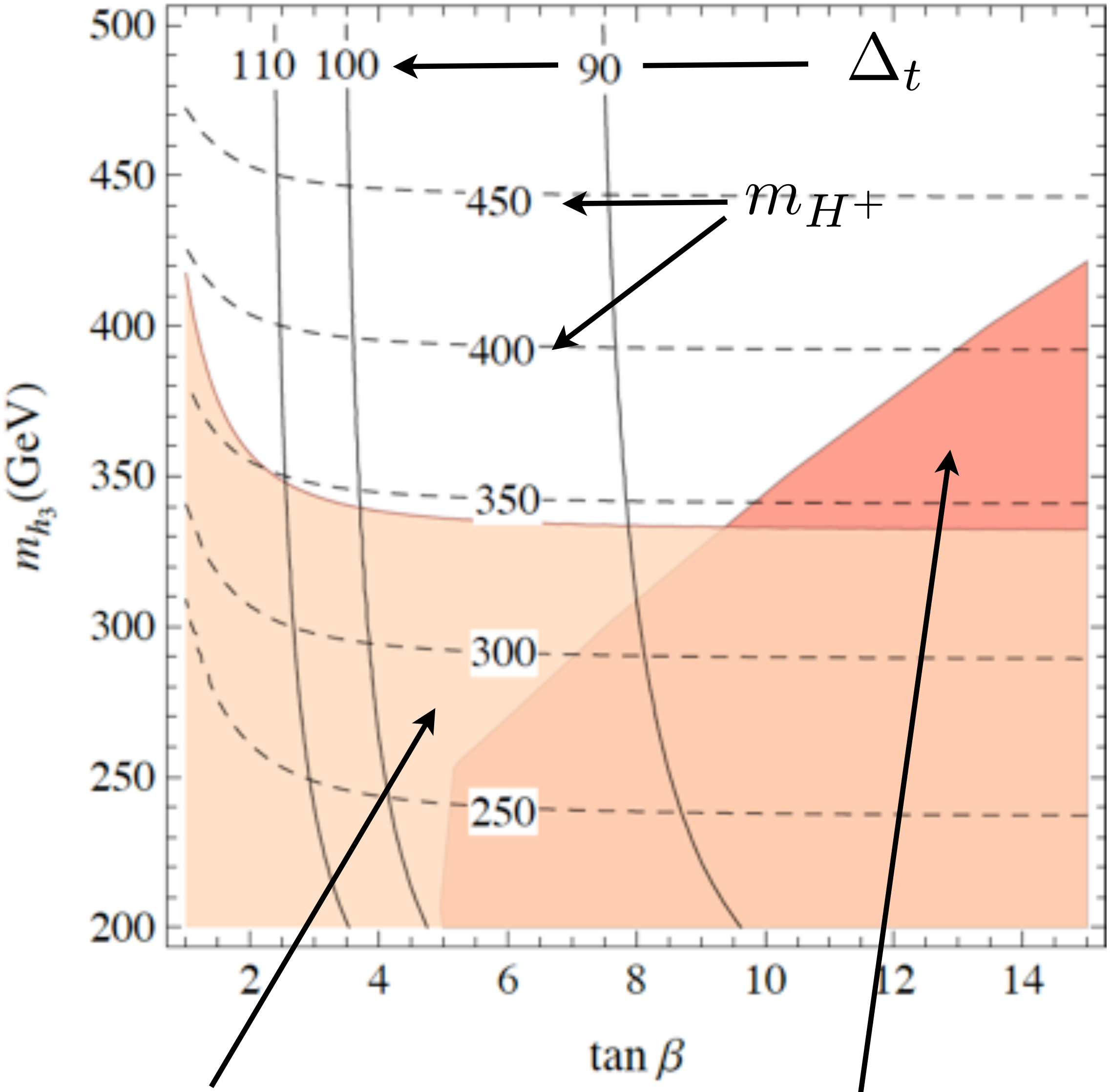


$$m^2_{hh} = m^2_Z c^2_{2\beta} + \Delta^2_t$$



$\theta_t = 45^0$ D-term included $\tan\beta = 4$

(No SUSY loop effect other than Δ_t)
(h_3 only heavier than h_{LHC})



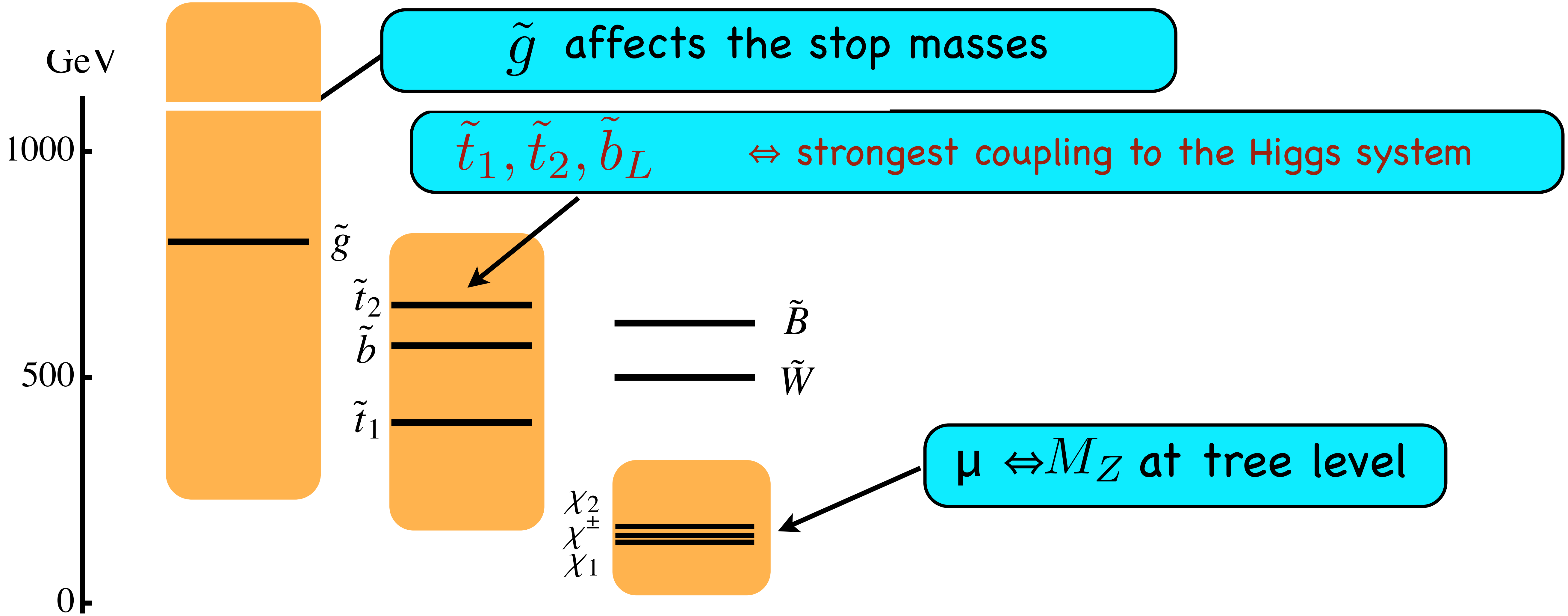
"excluded" by h_{LHC} -signal strenghts

"excluded" by $h_3, A \to \tau\tau$

B, Buttazzo, Kannike, Sala, Tesi 2013
D'Agnolo, Kuflik, Zanetti 2012

The “crucial” configuration of supersymmetry

“s-particles at their naturalness limit”



$\tilde{g}$ affects the stop masses

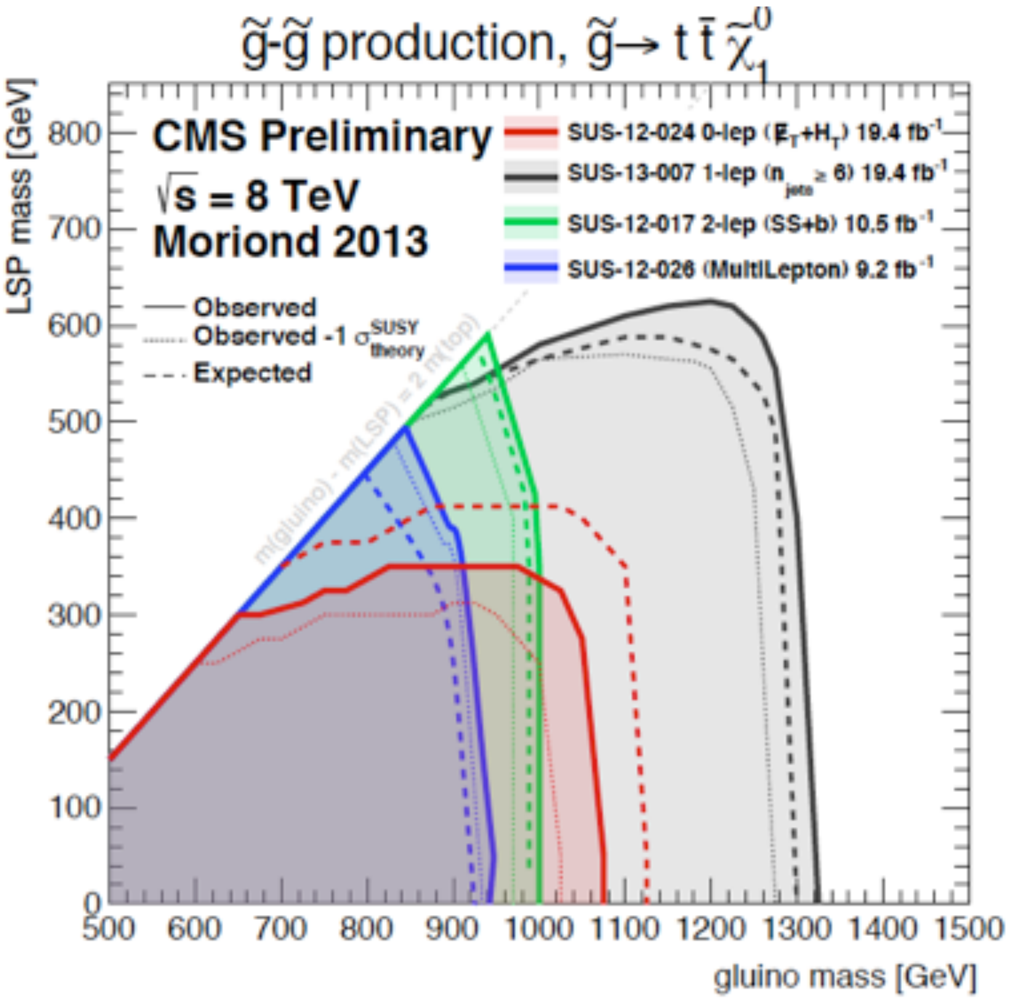
$\tilde{t}_1, \tilde{t}_2, \tilde{b}_L$ ⇔ strongest coupling to the Higgs system

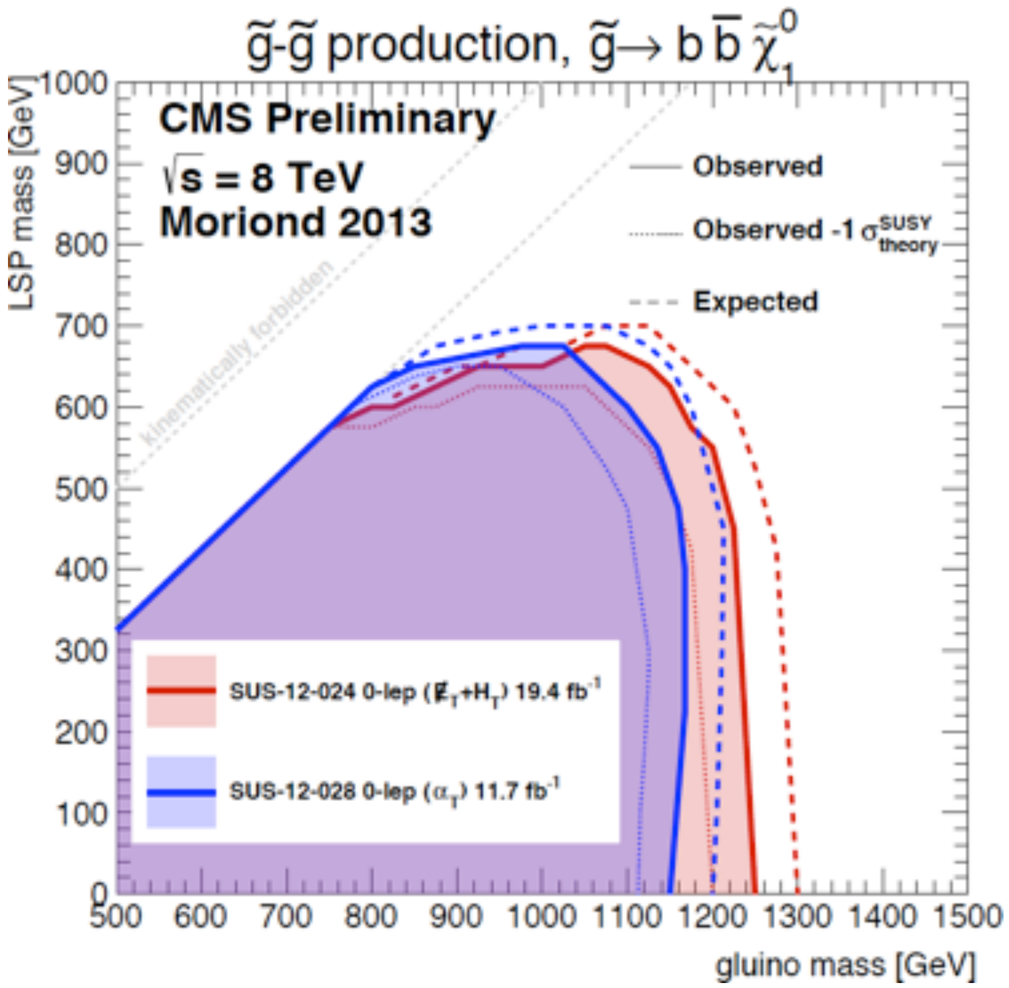
μ ⇔ M_Z at tree level

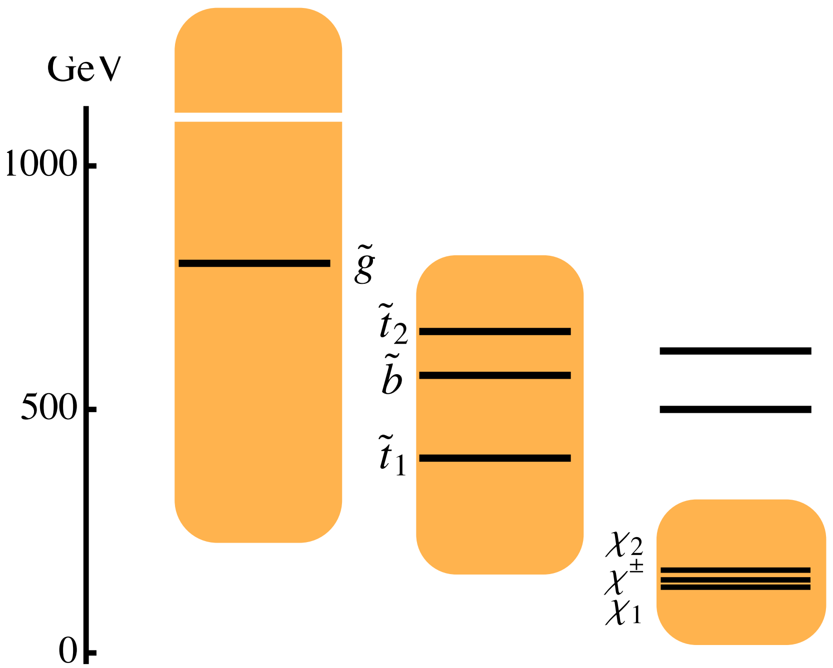
orange areas indicative and dependent
on how the Higgs boson gets its mass

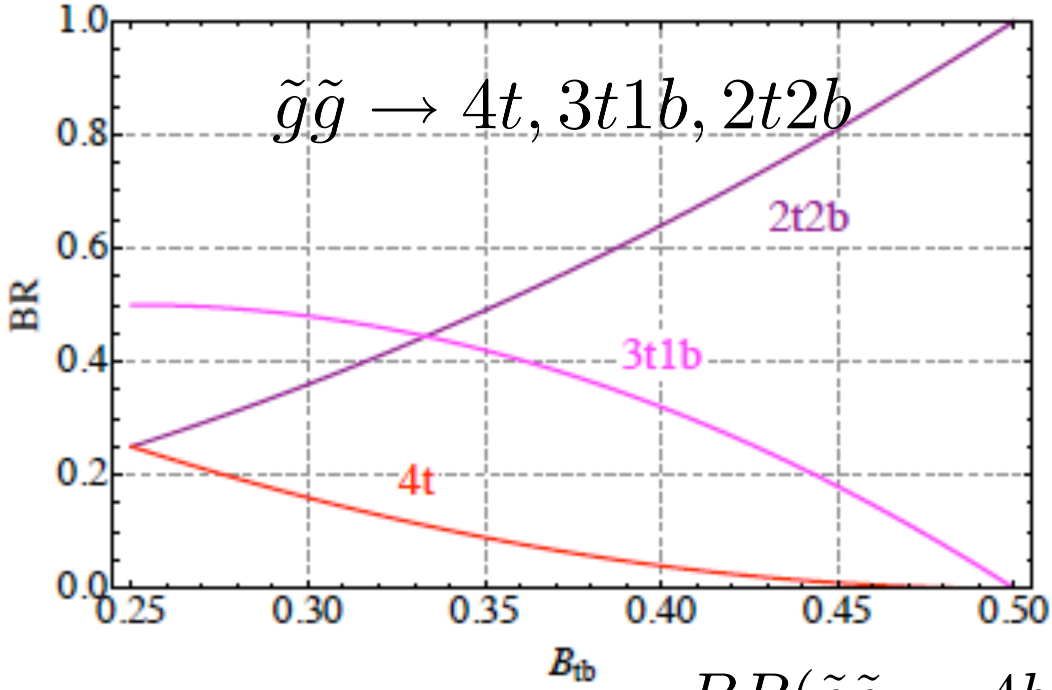
$\tilde{B}, \tilde{W}$ not much constrained but expected below $m_{\tilde{g}}$

Dimopoulos, Giudice 1995
Cohen, Kaplan, Nelson 1996







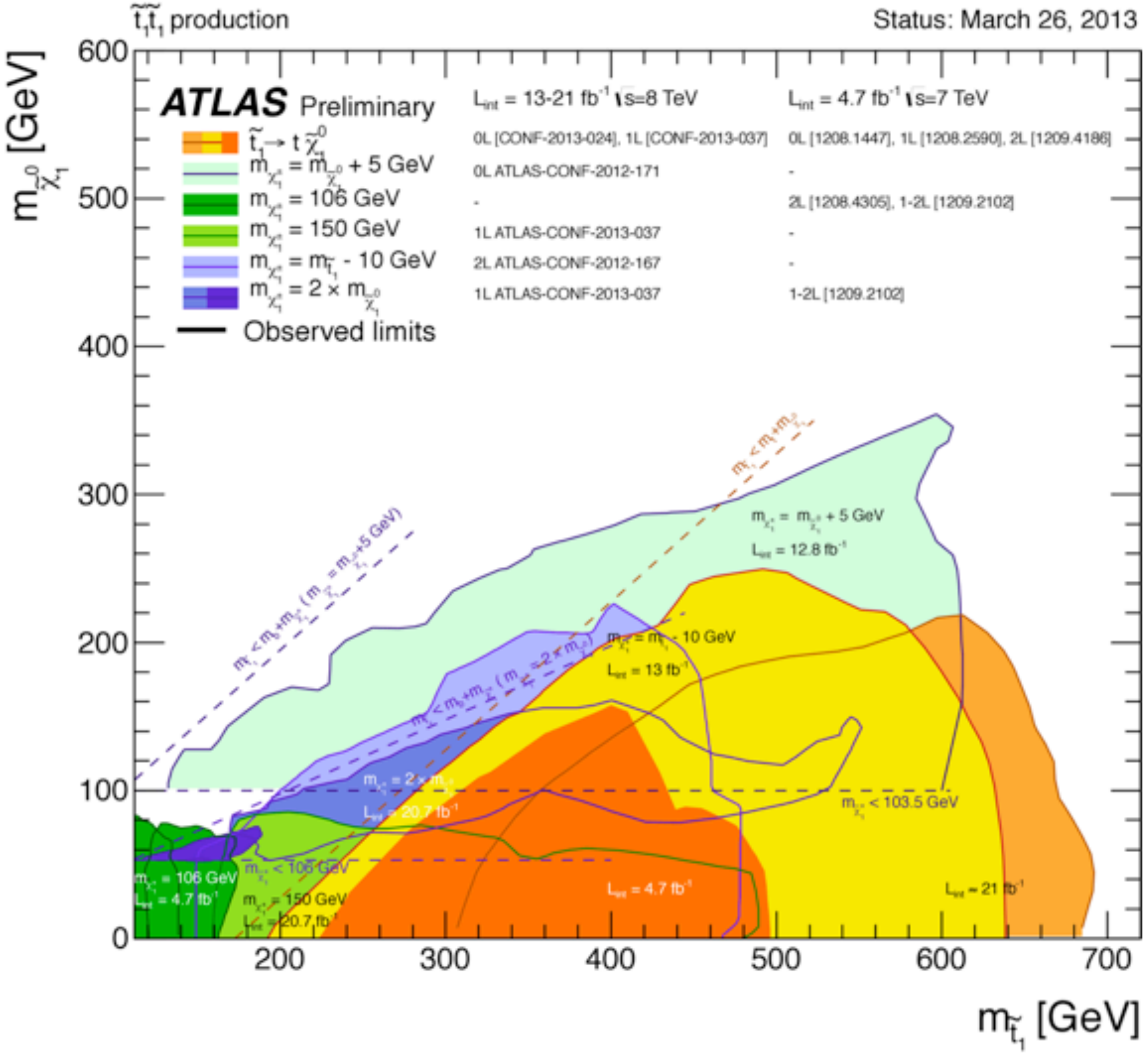


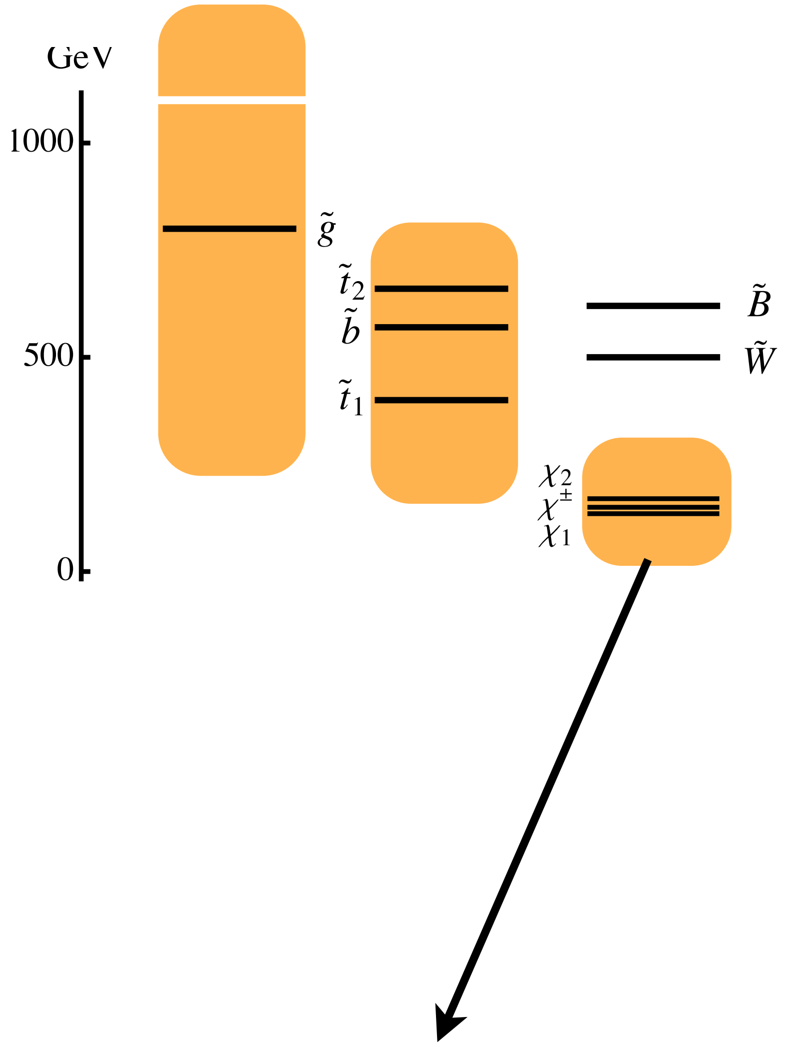
$$BR(\tilde{g}\tilde{g}\to 4b)\lesssim 4\%$$
$$(\tan\beta\lesssim 10)$$

B, Pappadopulo 2009

“optimistically” $m_{\tilde{g}}\gtrsim 1300\ GeV$

“conservatively” $m_{\tilde{g}}\gtrsim 1000\ GeV$





$$m_{\chi_2} \approx m_{\chi^\pm} \approx m_{\chi_1}$$

“optimistically” $m_{\tilde{t}_1} \gtrsim 700\ GeV$

“conservatively” $m_{\tilde{t}_1} \gtrsim 200 \div 300\ GeV$ (with $m_\chi = 150 \div 250\ GeV$)

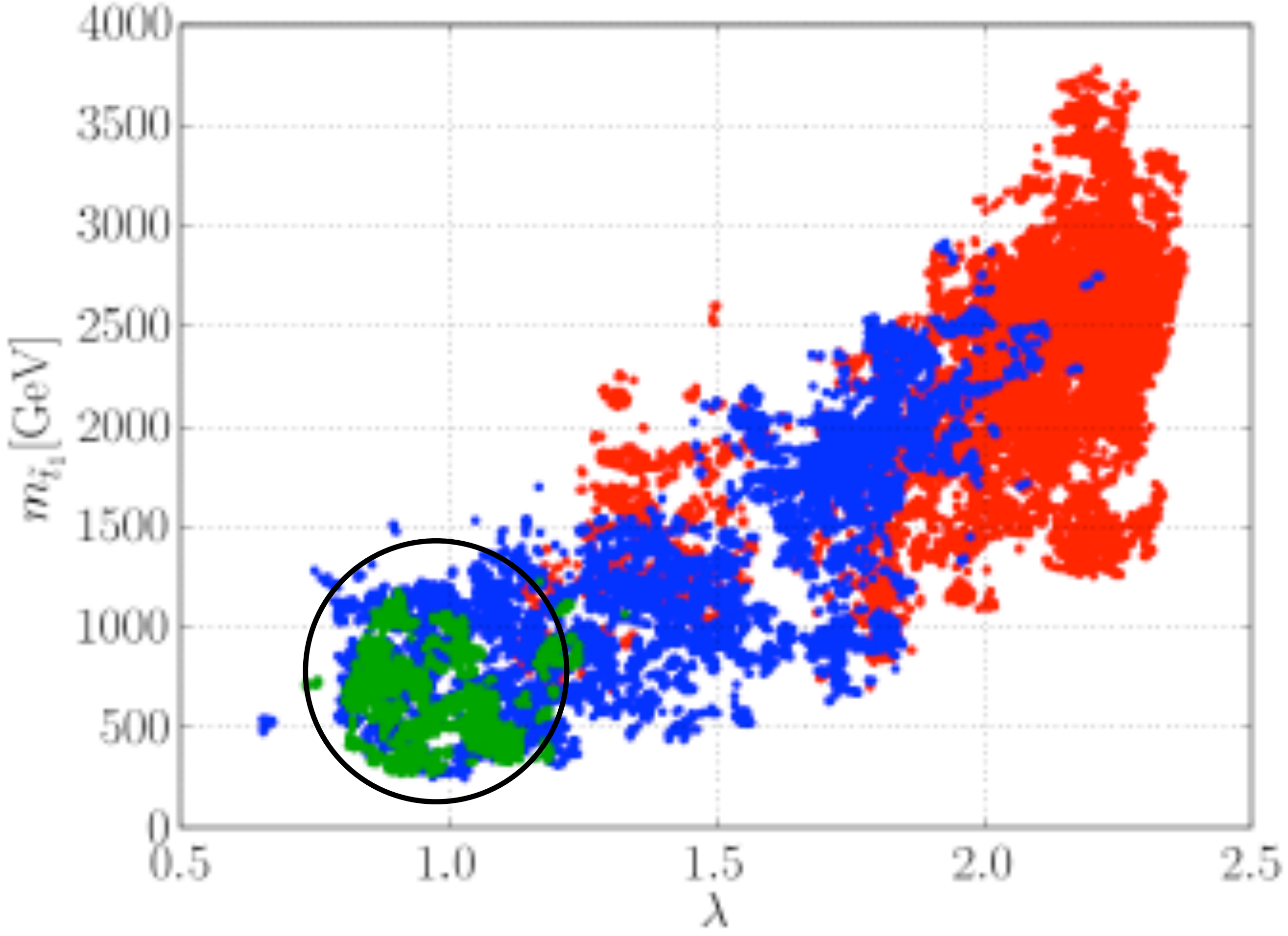
NMSSM $\Delta f = \lambda H_u H_d$

Fayet 1975

Two independent reasons to consider it:

1. Add an extra contribution to $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$ thus allowing for lighter stops
2. Alleviates fine tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{\kappa}{\lambda^3}\cot 2\beta \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$



green points have better than 5% "combined" fine-tuning and $\Lambda_{mess} = 20\ TeV$ in the scale invariant NMSSM

$$m_{\tilde{t}_1} < 1.2\ TeV$$

$$m_{\tilde{g}} < 3\ TeV$$

Gherghetta et al 2012

Can the extra Higgs bosons of the NMSSM be the lightest new particles around?

⇒ Assume a negligibly small CPV in the Higgs sector

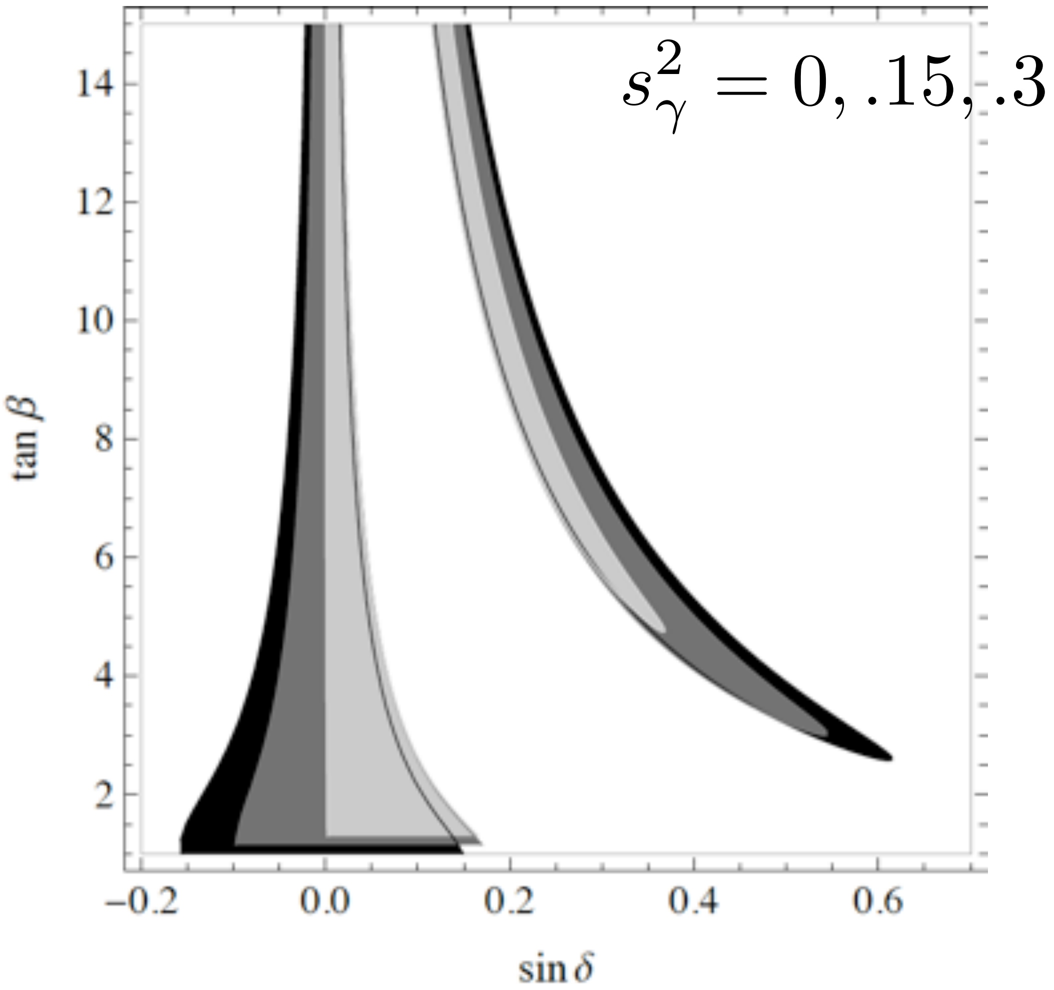
$$\mathcal{H} \equiv (H_d, H_u, S)^T = R_\alpha^{12} R_\gamma^{23} R_\sigma^{13} (h_3, h_1, h_2)^T \equiv R\, \mathcal{H}_{\rm ph}$$

⇒ Take $h_1 = h_{LHC}$ with $m_{h_1} > m_{h_2}, m_{h_3}$

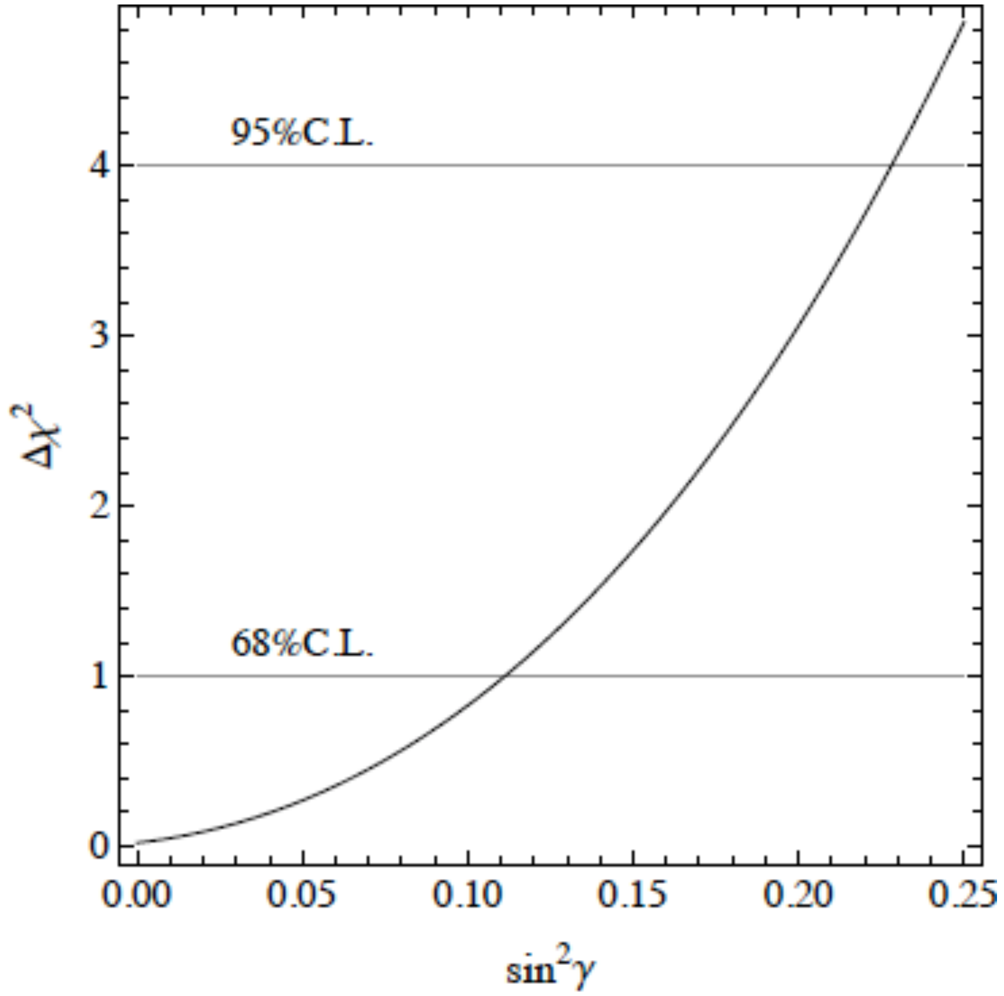
$$h_1 = c_\gamma(-s_\alpha H_d + c_\alpha H_u) + s_\gamma S$$

⇒ No susy loops nor invisible decays, like $h_1 \to \chi\chi$

95%CL on $\delta = \alpha - \beta + \pi/2$


$s_\gamma^2 = 0, .15, .3$

95%CL on γ $(\delta = 0)$



How to deal with the pletora of parameters of the general NMSSM?

(without scatter plots or benchmark points)

MSSM

$$\tan 2\alpha = \tan 2\beta \frac{m_A^2 - m_Z^2}{m_A^2 + m_Z^2}$$

(up to Δ_t corrections)

$$m_A^2 = m_{h_3}^2 + m_{h_1}^2 - m_Z^2 \qquad m_{H+}^2 = m_A^2 + m_W^2$$

general NMSSM

$$\mathcal{M}^2 = R \, \mathrm{diag}(m_{h_3}^2, m_{h_1}^2, m_{h_2}^2) \; R^T$$

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & \left(2v^2\lambda^2 - m_A^2 - m_Z^2\right) c_\beta s_\beta & vM_1 \\ \left(2v^2\lambda^2 - m_A^2 - m_Z^2\right) c_\beta s_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 + \Delta_t^2/s_\beta^2 & vM_2 \\ vM_1 & vM_2 & M_3^2 \end{pmatrix}$$

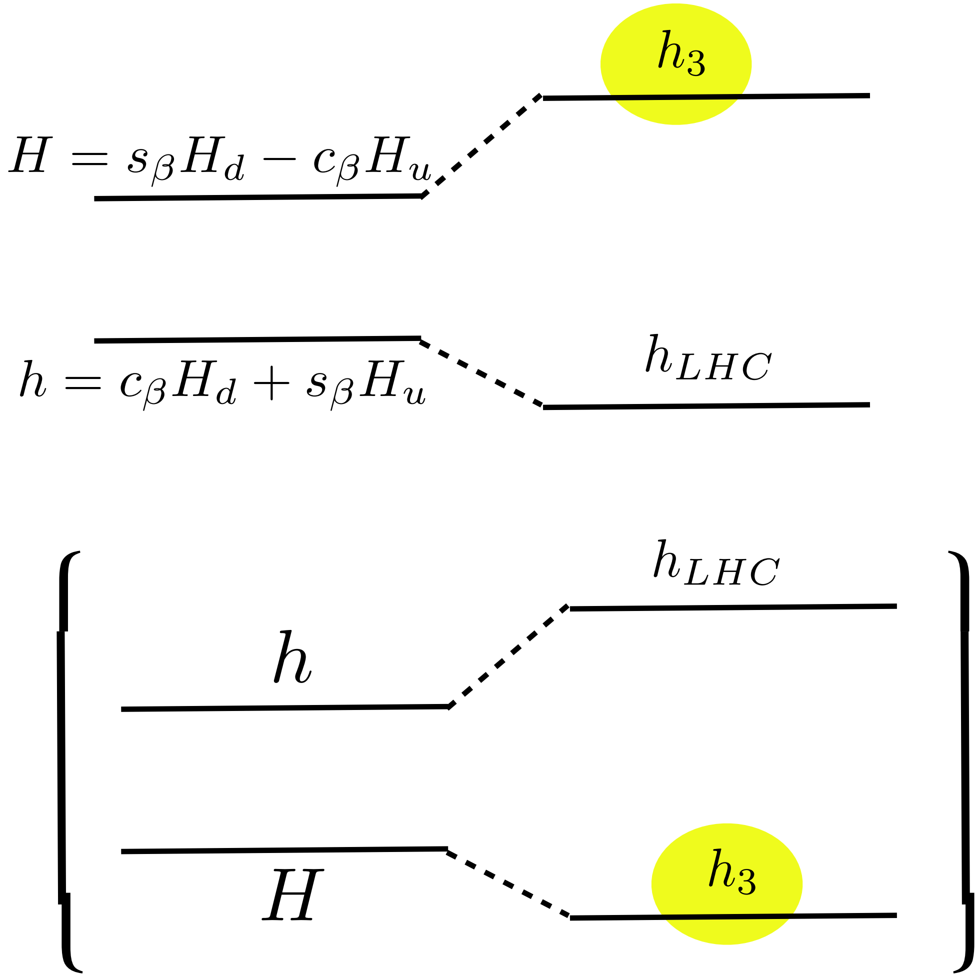
$$m_A^2 = m_{H+}^2 - m_W^2 + \lambda^2 v^2$$

$$\Rightarrow \;\; \alpha, \delta, \gamma = \alpha, \delta, \gamma(m_i^2, m_{H+}^2; \tan\beta, \lambda, \Delta_t)$$

Two (4) simplified cases

S-decoupled

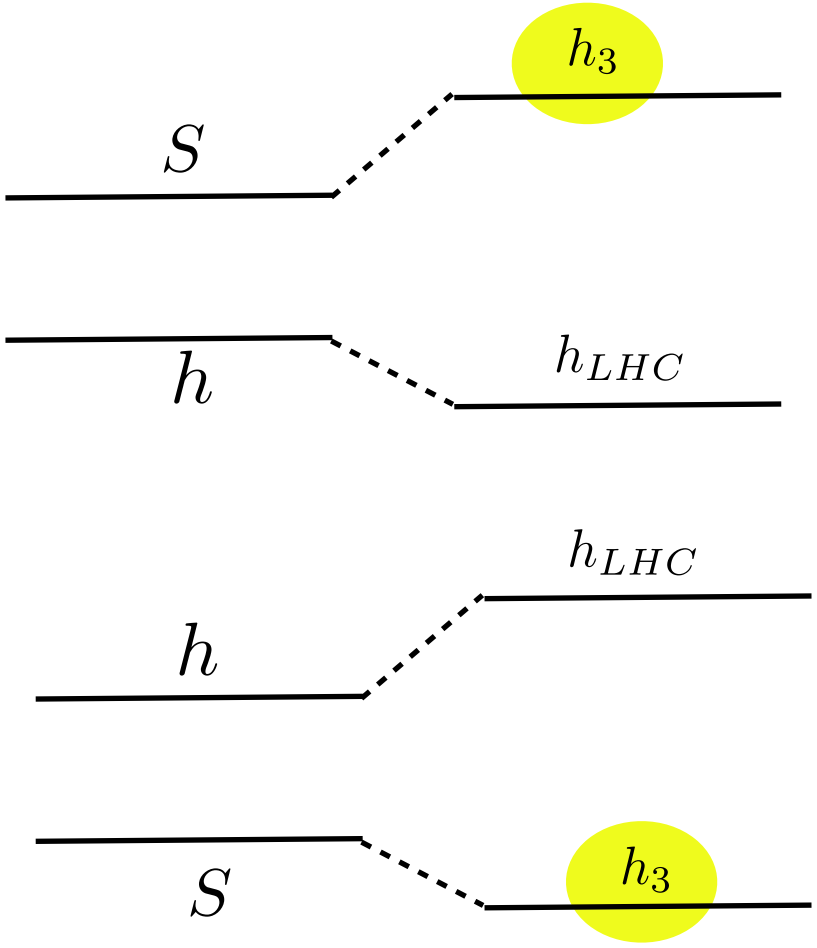
both in the MSSM and in the NMSSM



(unlikely, too light H^+)

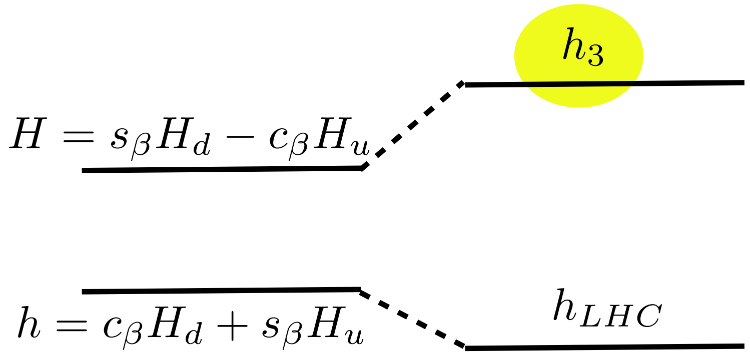
H-decoupled

only in the NMSSM

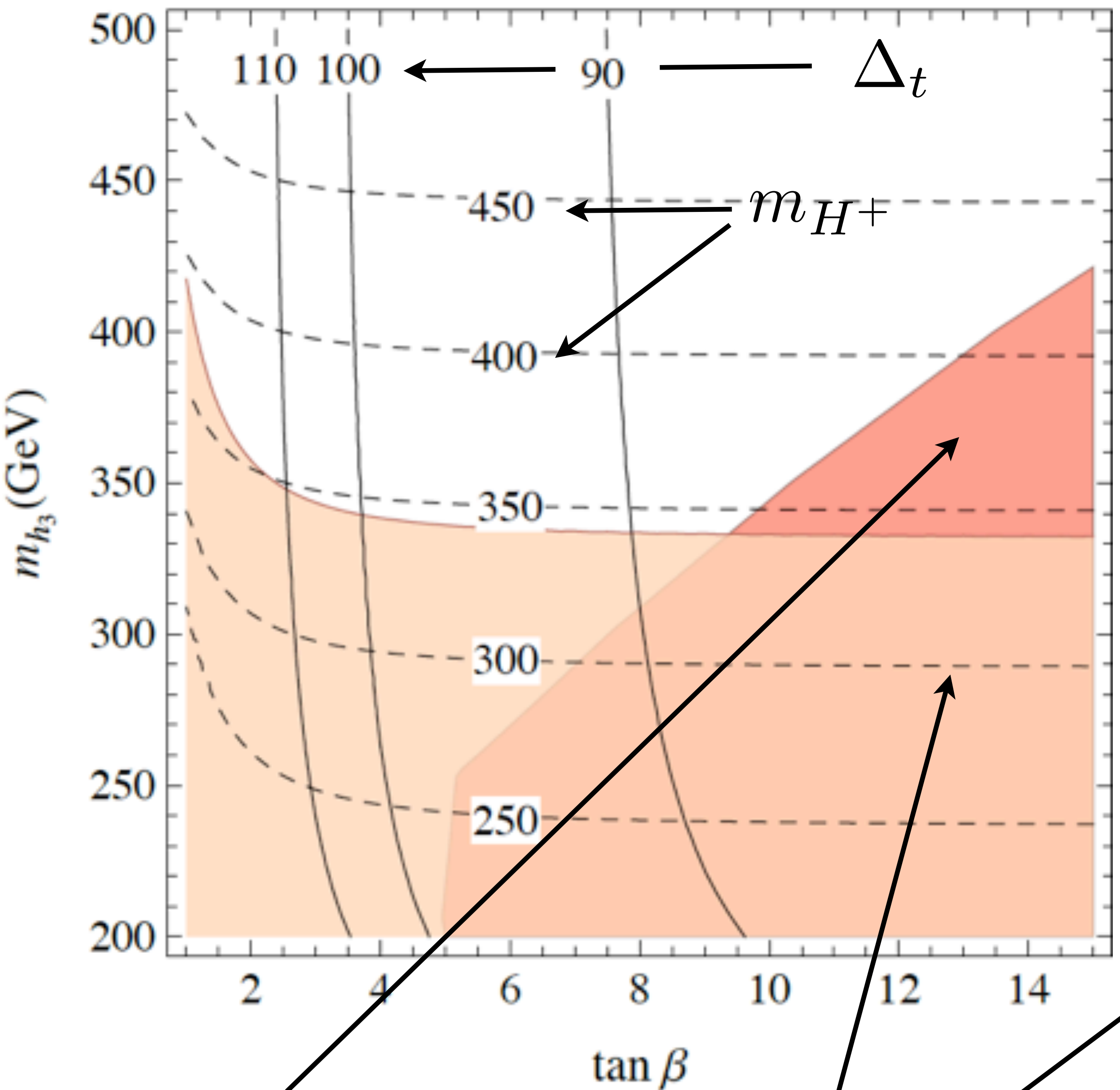


(In the NMSSM a triple mixing can also occur)

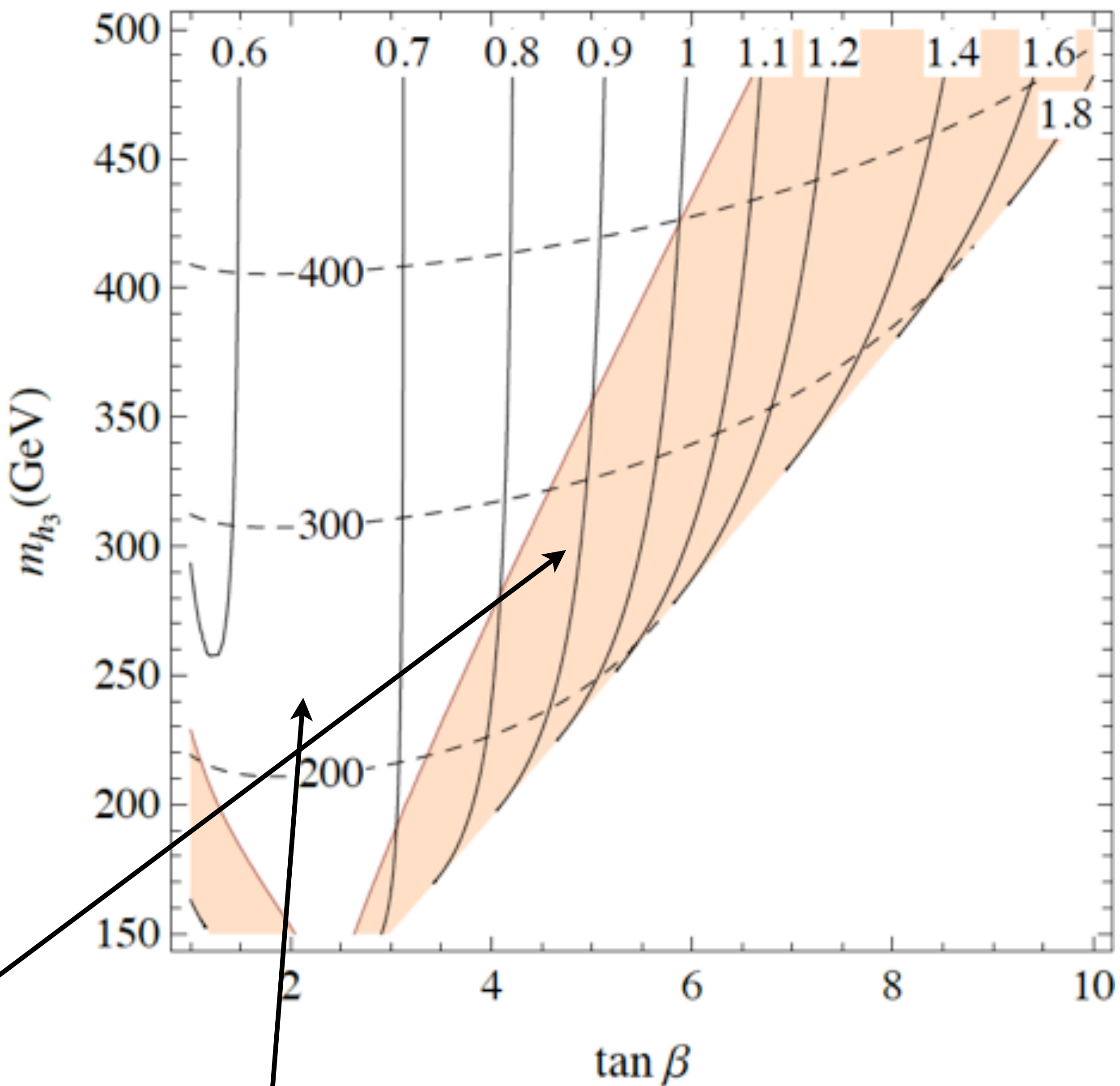
S-decoupled



MSSM at variable Δ_t



NMSSM at variable λ



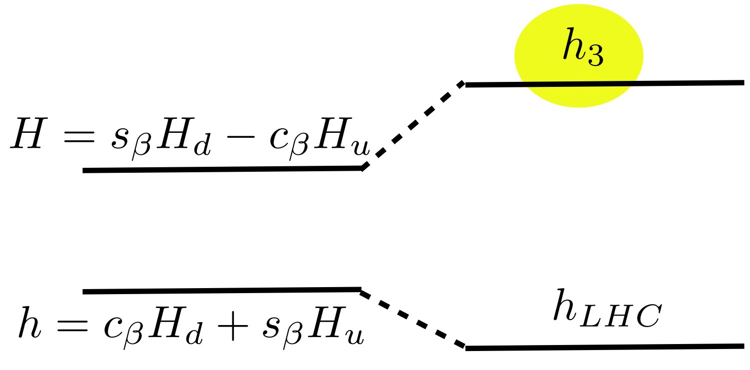
"excluded" by $h_3, A \to \tau\tau$

"excluded" by h_{LHC} -signal strenghts

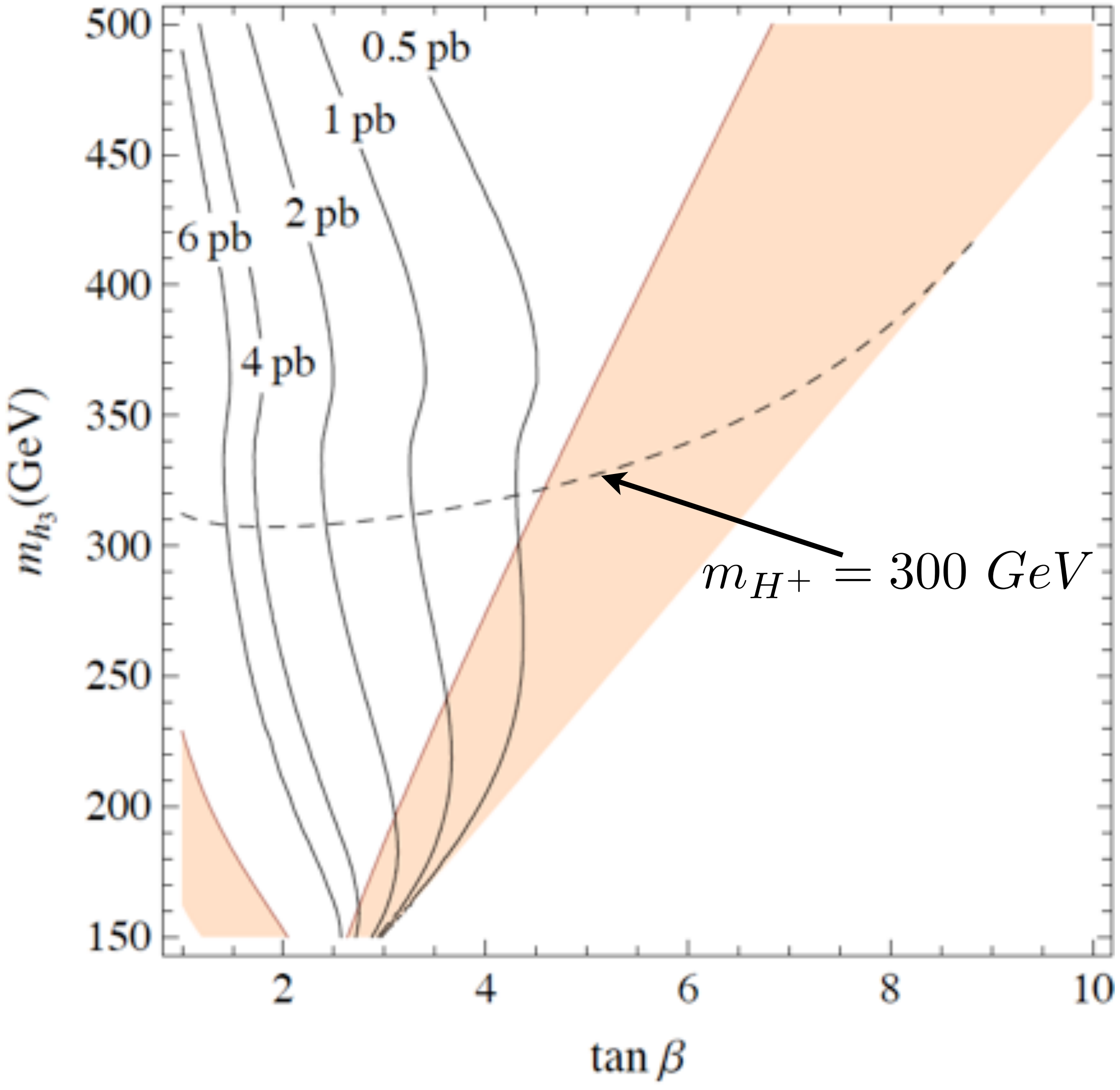
$\Delta_t \leq 75\ GeV$ almost irrelevant

might be closed by $h_3 \to \tau\bar{\tau}$
already with current data?

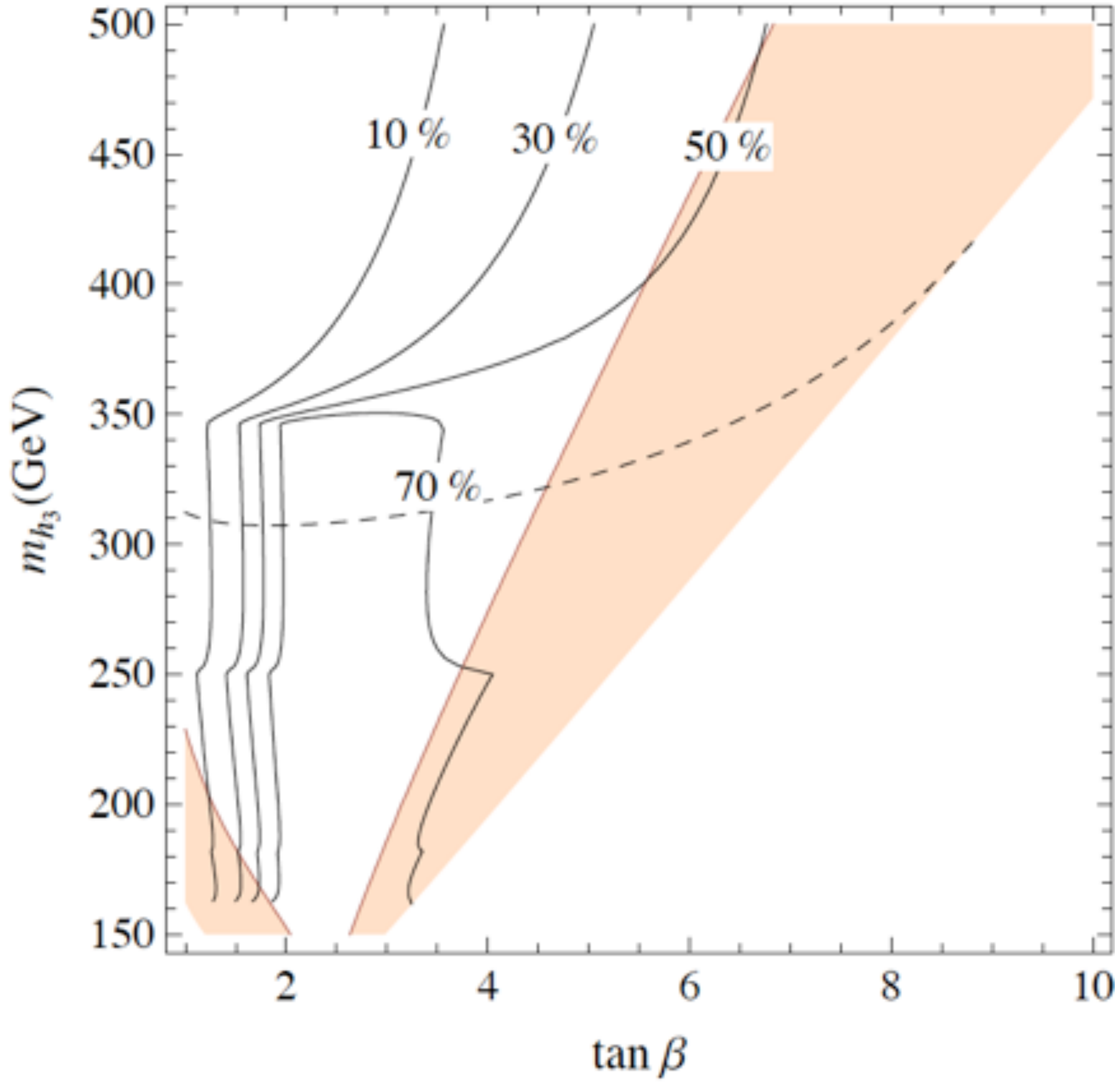
S-decoupled at LHC14



$\sigma(gg \to h_3)$

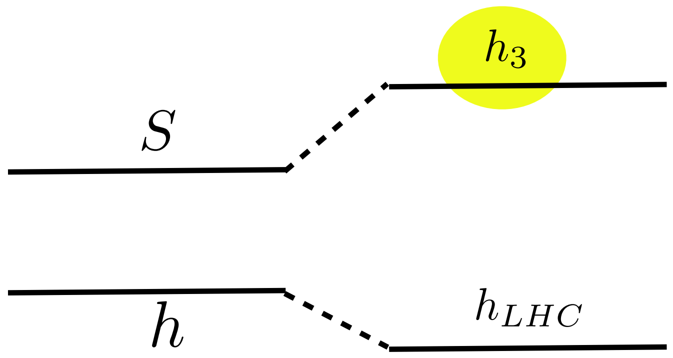


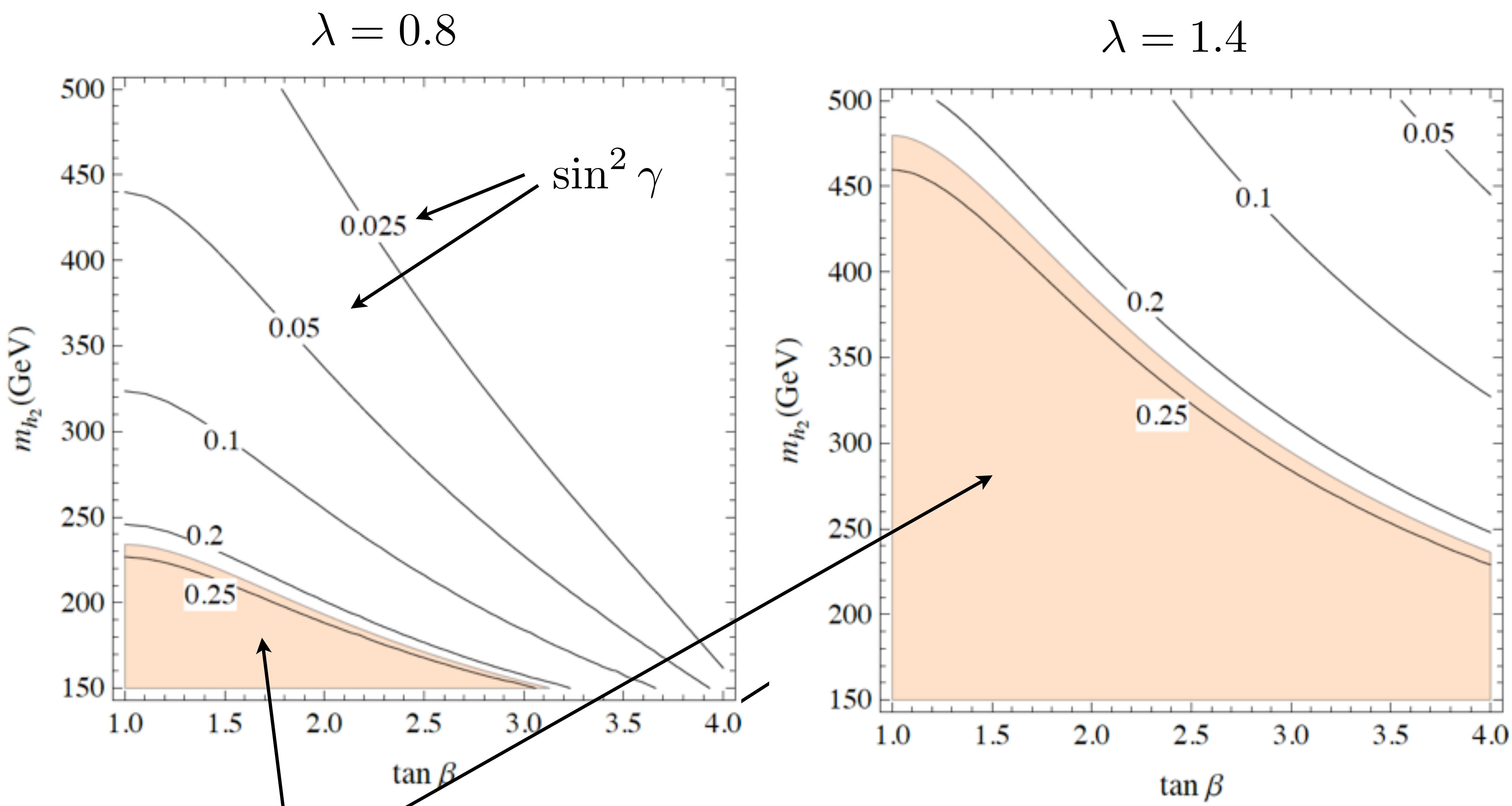
$BR(h_3 \to b\bar{b})$



(and correspondingly $\tau\bar{\tau}$)

H-decoupled

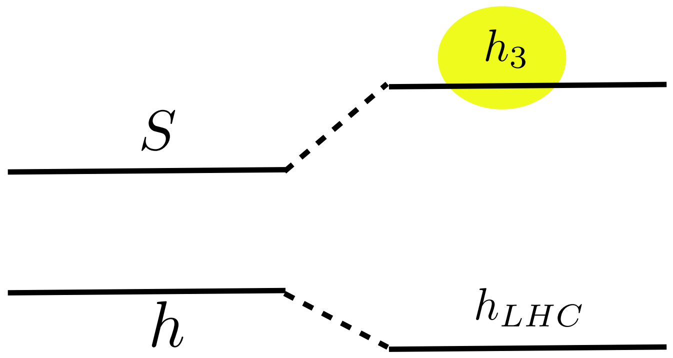




$\Delta_t \leq 75\ GeV$ almost irrelevant

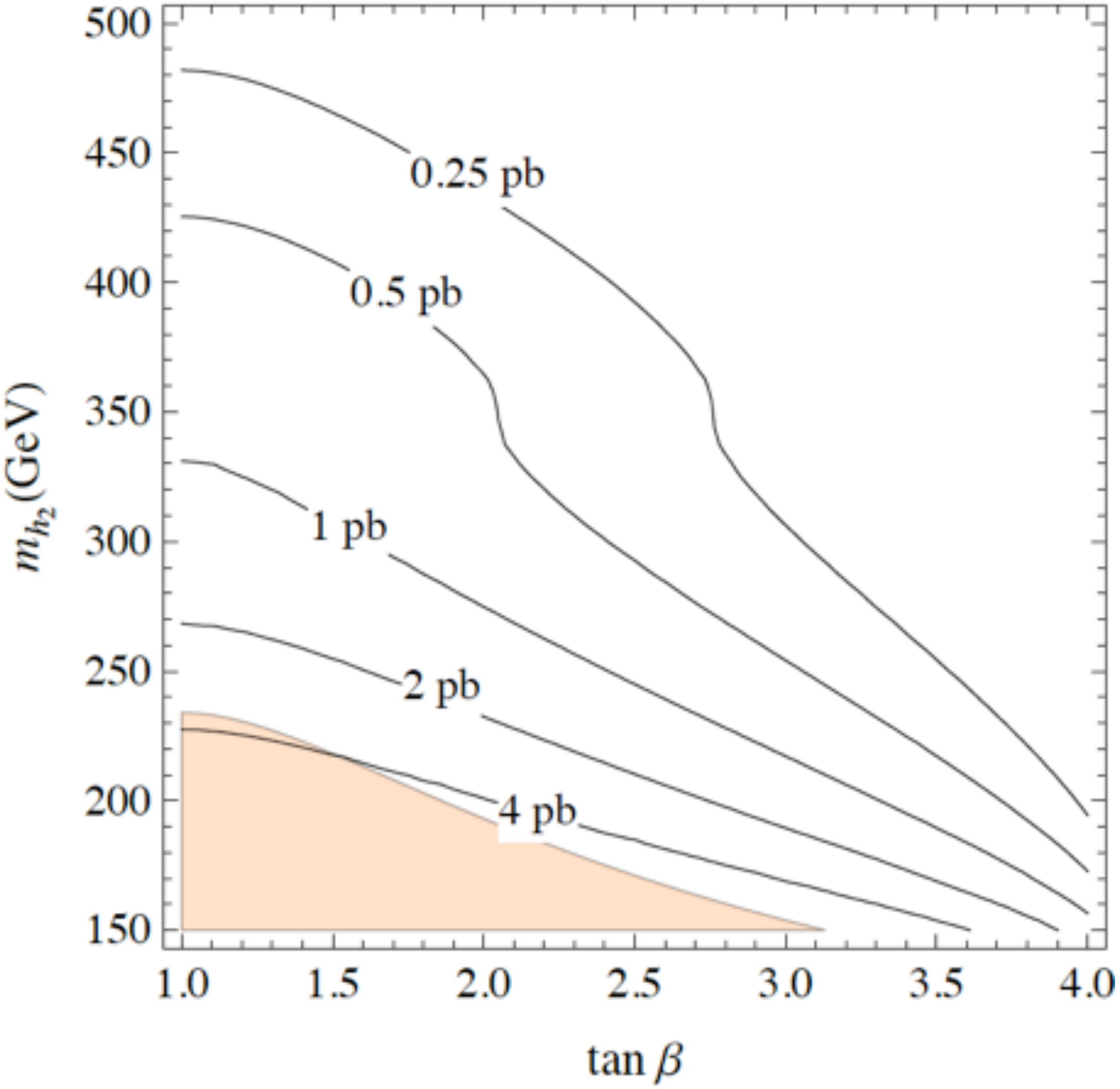
"excluded" by h_{LHC} -signal strenghts

H-decoupled at LHC14



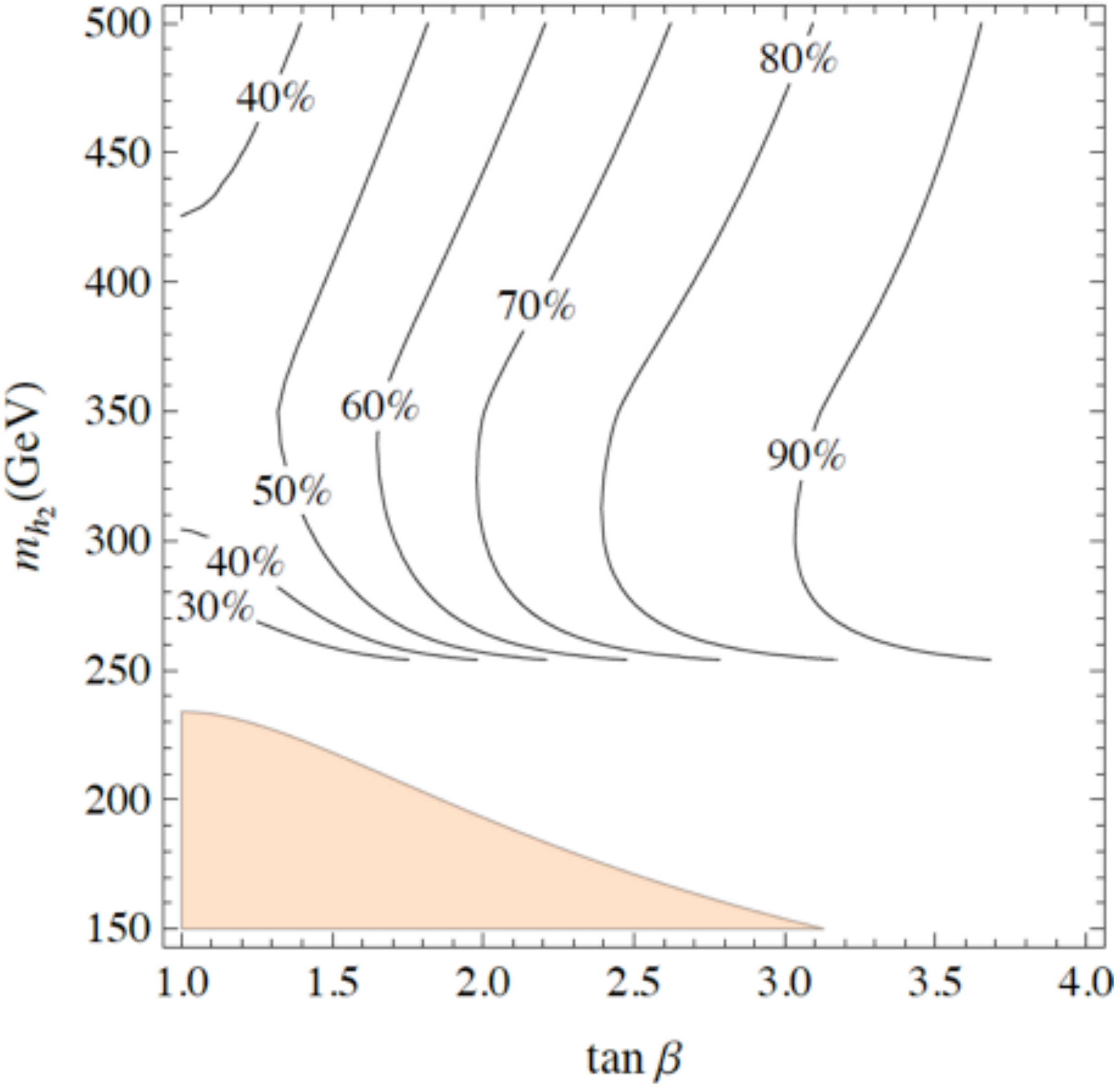
$\lambda = 0.8$

$\sigma(gg \to h_2)$



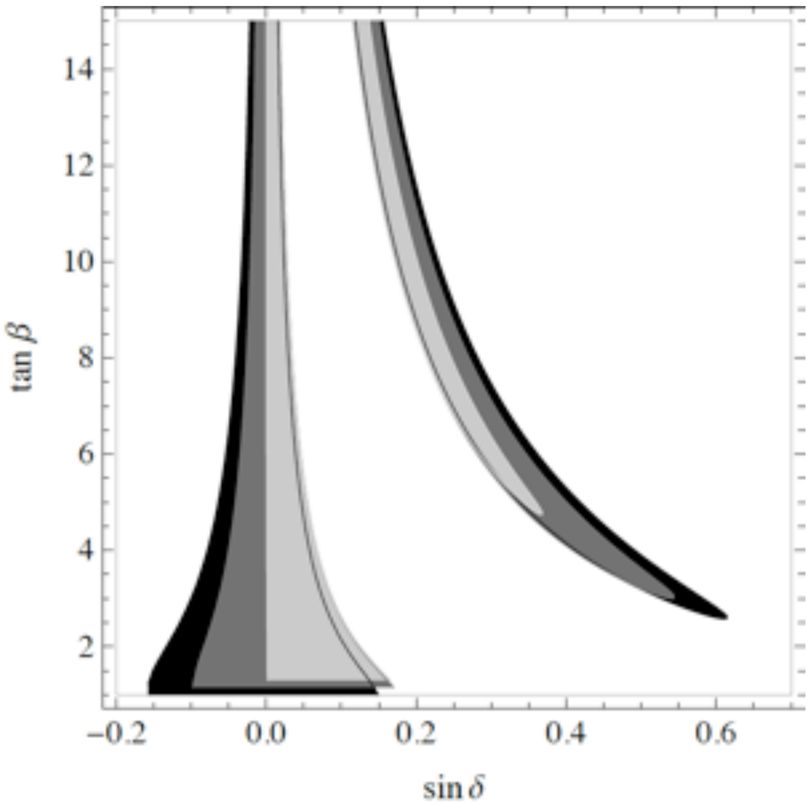
(with all cross sections relative to gluon fusion as in the SM)

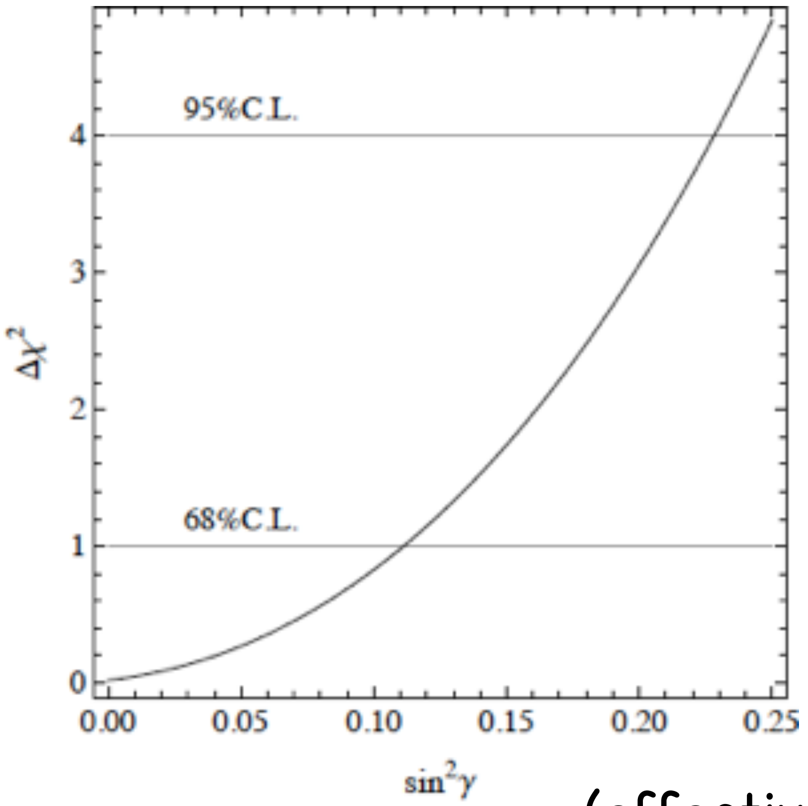
$BR(h_2 \to h_1 h_1)$



A projection from the measurements of the signal strenghts (ATLAS and CMS preliminary) on the mixing angles

Now



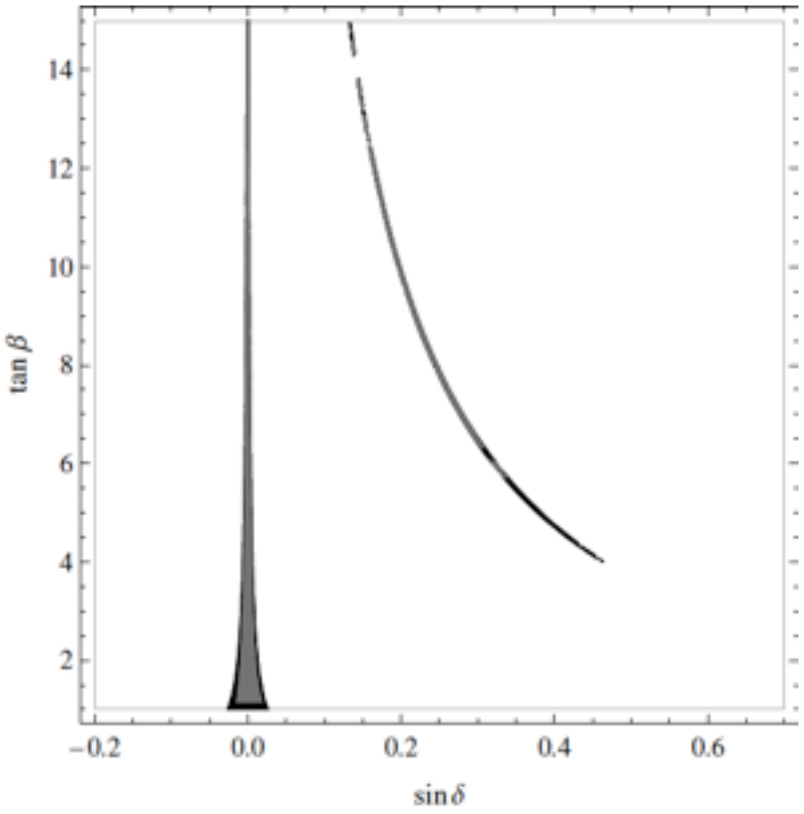


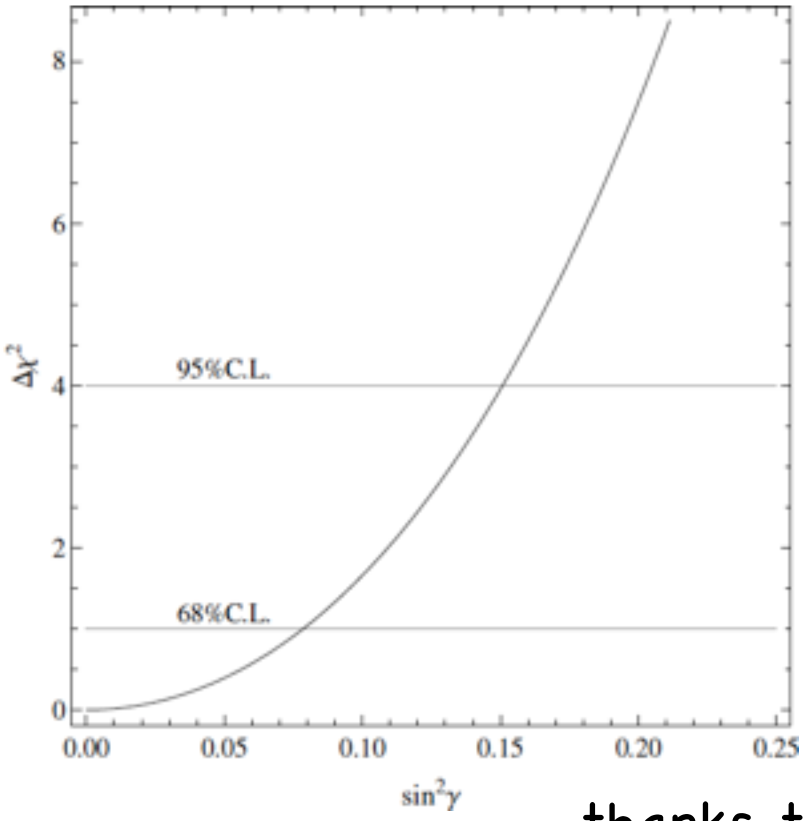
(effective BR_{inv})

LHC14

at $300 fb^{-1}$

(central values as in the SM)



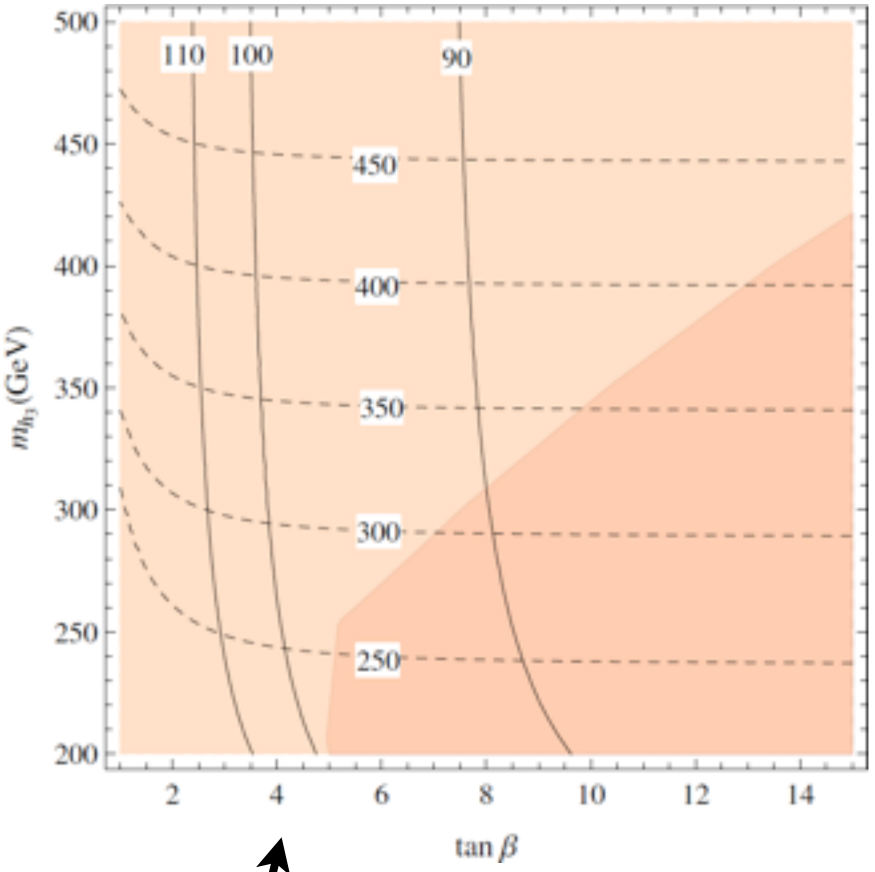


thanks to Kannike

A projection from the measurements of the signal strenghts

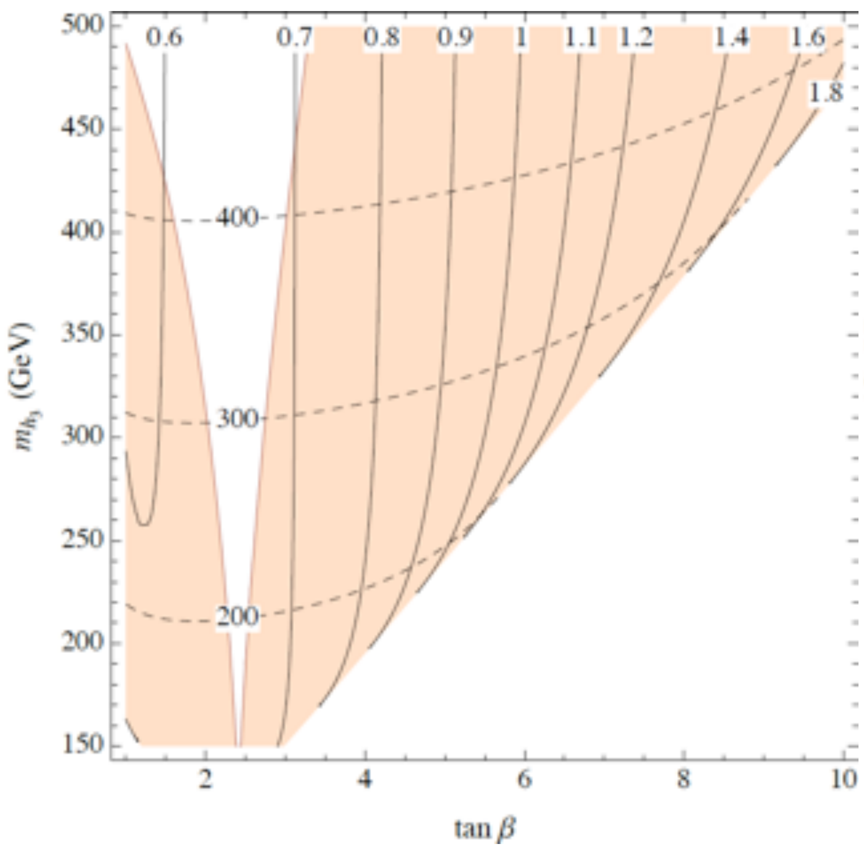
LHC14 at $300fb^{-1}$

(Preliminary)

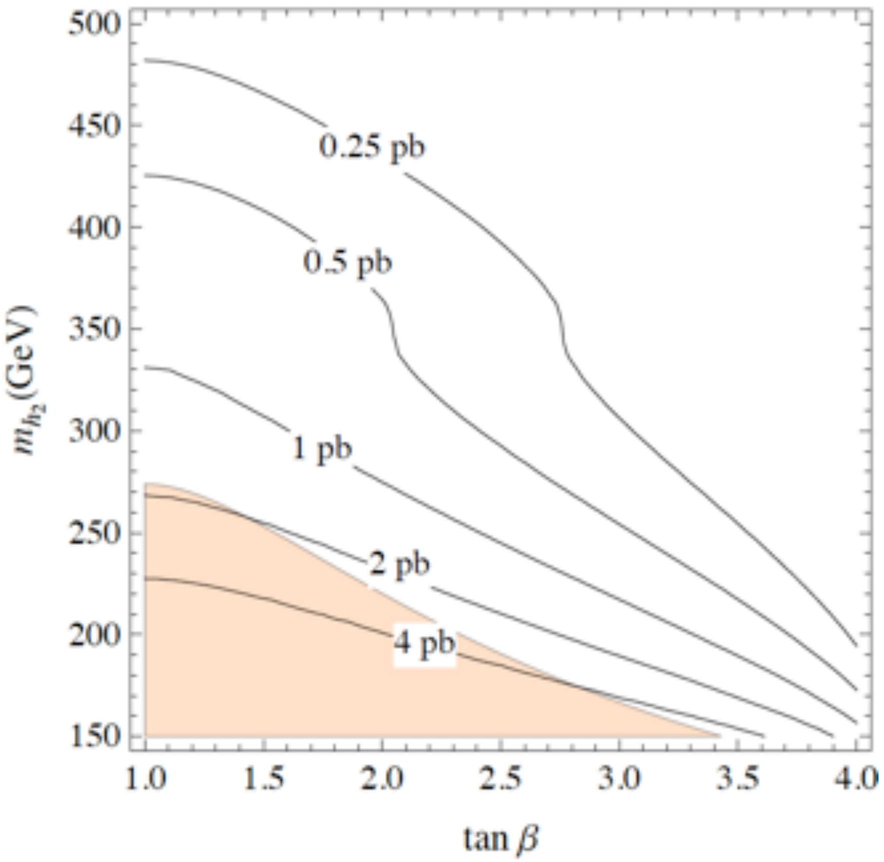


MSSM

The sensitivity region extends up to about 1 TeV for m_{h_2}

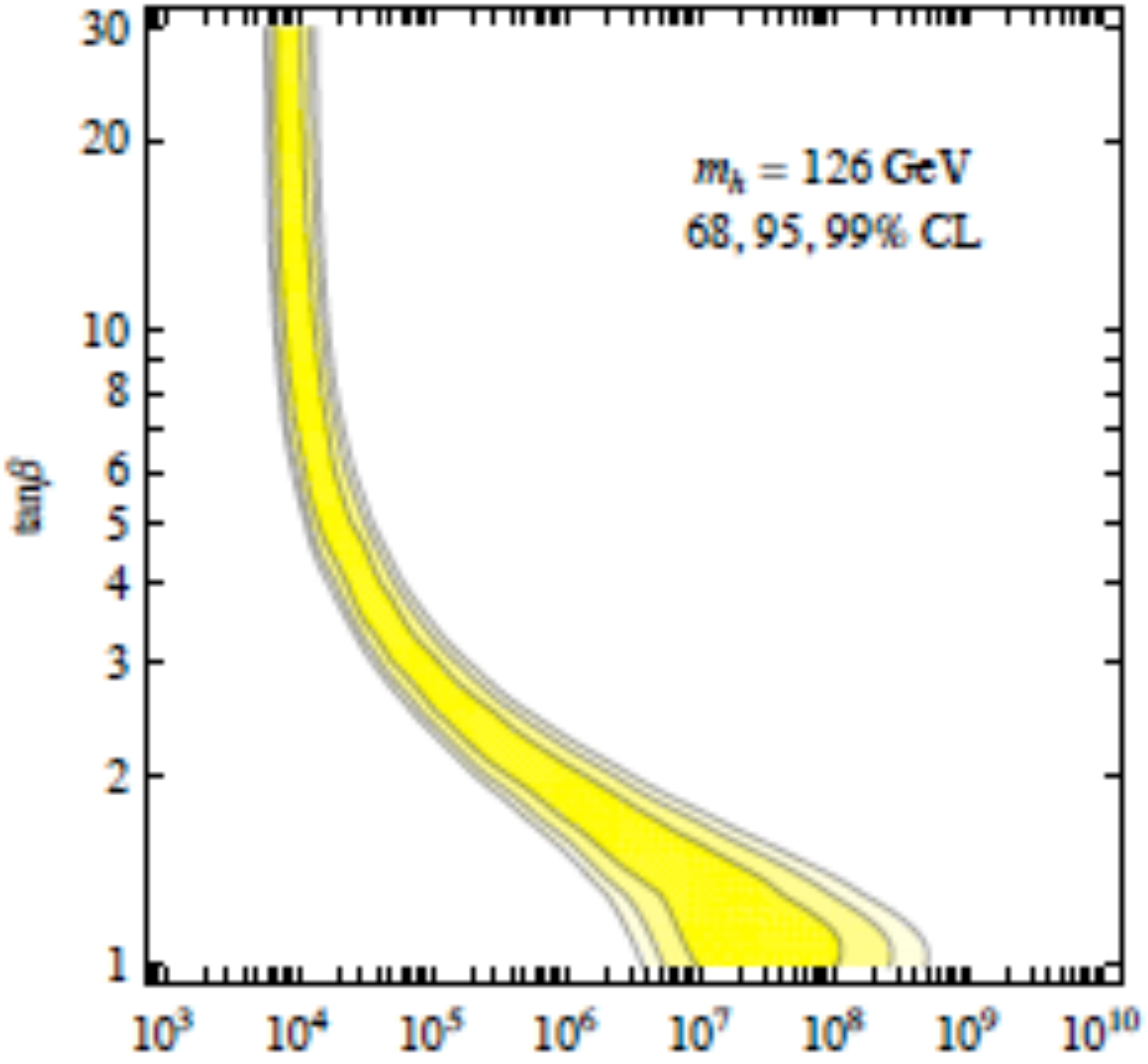


NMSSM, S-decoupled

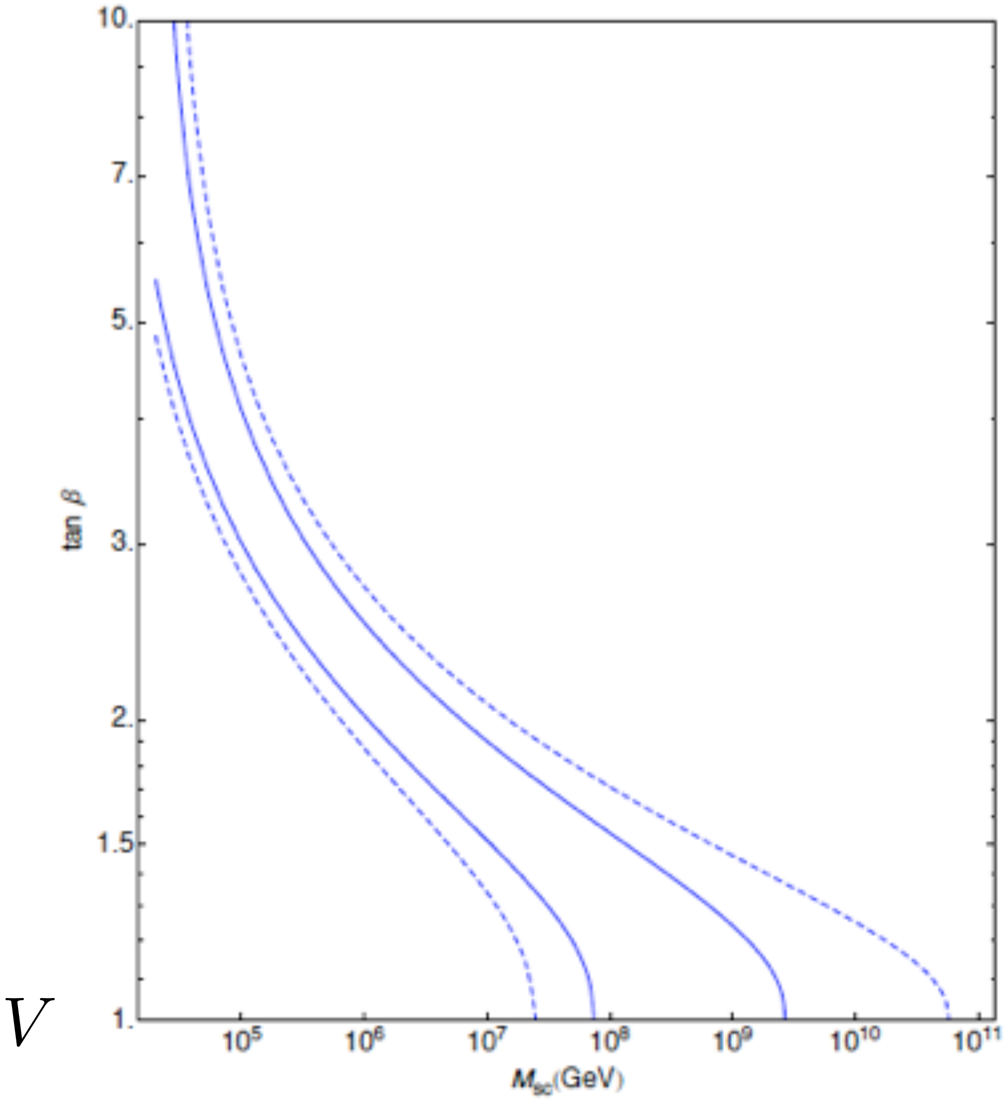


NMSSM, H-decoupled

An alternative supersymmetric view



m_S/GeV



SUSY scalars at m_S
SUSY fermions at ~TeV

gauginos only at ~ TeV

Arkani-Hamed, Dimopoulos 2004
Giudice, Strumia 2011
Arkani-Hamed et al 2012

[If $m_S < T_R$, not to overclose the universe by a stable LSP, $m_S < 10 \div 100\ TeV$]

Hall et al, 2013

A less motivated (?) but simpler (?) picture

What can we expect from (and for) flavour physics?

Breaking of flavour symmetries embedded in few basic parameters

$$U(3)_Q \times U(3)_u \times U(3)_d \equiv U(3)^3$$

$$Y_u = (3, \bar{3}, 1) \qquad Y_d = (3, 1, \bar{3}) \qquad \text{(MFV)}$$

Chivukula, Georgi 1987 (TC)
Hall, Randall 1990 (SUSY)
D'Ambrosio et al 2002 (general)

$$U(2)_Q \times U(2)_u \times U(2)_d \equiv U(2)^3$$

B, Isidori et al 2011 (general)

Y_u, Y_d split under $U(2)^3$ - representations

$$Y_u = \lambda_t \begin{bmatrix} \Delta_u & V_Q \\ V_u^T & 1 \end{bmatrix} \qquad Y_d = \lambda_b \begin{bmatrix} \Delta_d & V'_Q \\ V_d^T & 1 \end{bmatrix}$$

Requiring a small breaking of $U(2)^3$: $V = V_Q \propto V'_Q \quad ||V|| = O(V_{cb})$
and, by consistency with flavour data, $||V_u||, ||V_d|| << ||V||$

$\Big\{$ $U(3)^3$ at large $\tan\beta$ → $U(2)^3$ Feldmann, Mannel 2008
Kagan et al 2009 $\Big\}$

The $\Delta F = 2$ case

$U(3)^3$

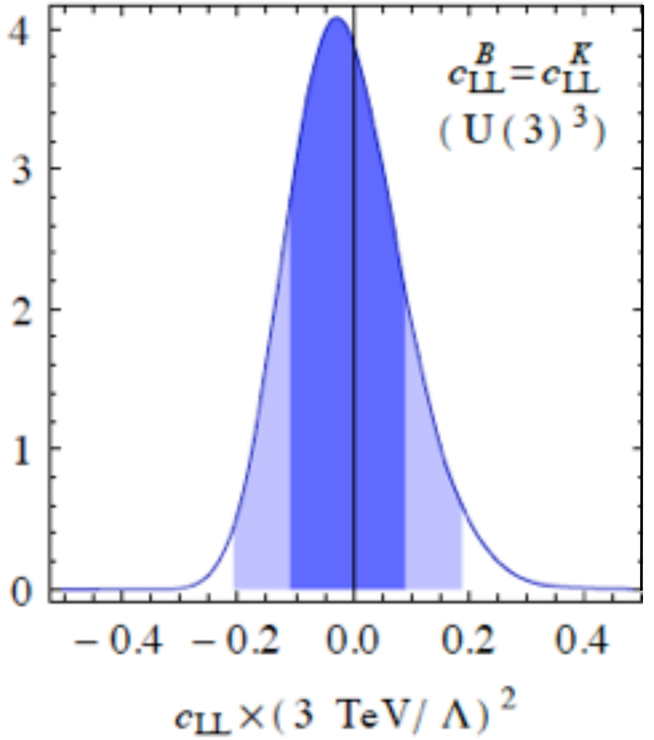
$U(2)^3$

$$\frac{c_{LL}}{\Lambda^2}\xi_{ij}^2\frac{1}{2}(\bar{d}_{Li}\gamma_\mu d_{Lj})^2$$

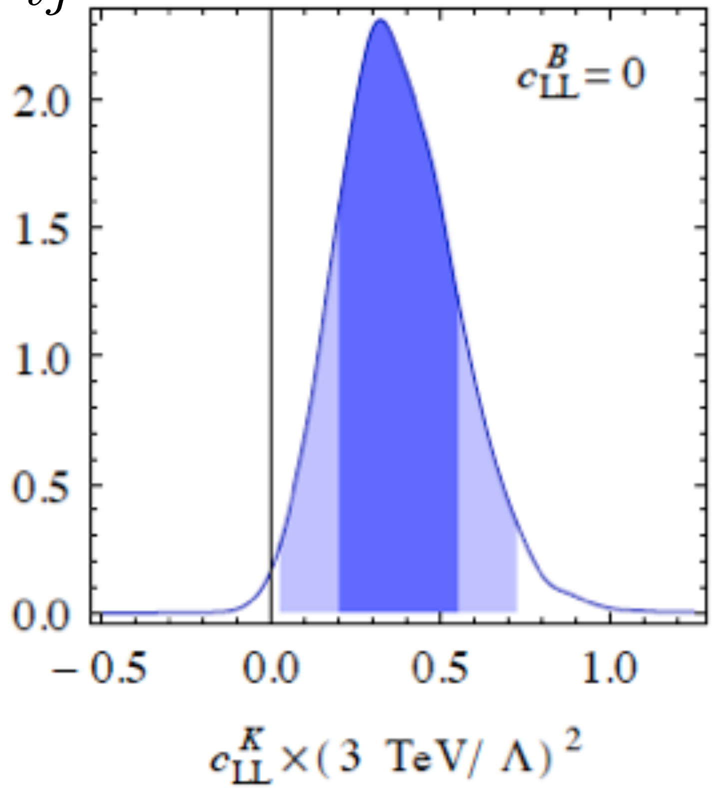
$$\xi_{ij} = V_{ti}V_{tj}^*$$

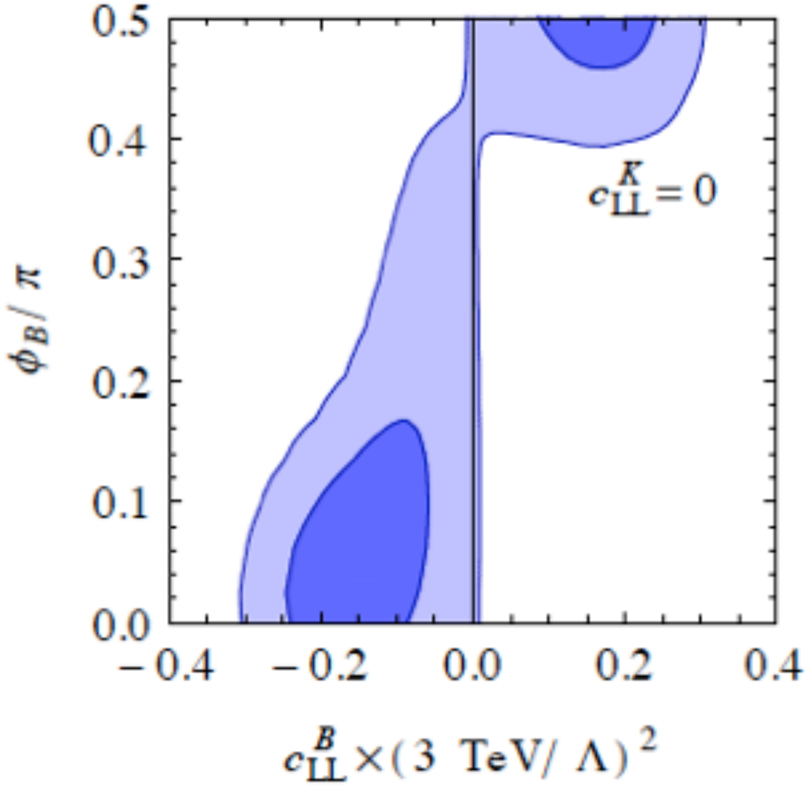
$$\frac{c^K_{LL}}{\Lambda^2}\xi_{ds}^2\frac{1}{2}(\bar{d}_L\gamma_\mu s_L)^2$$

$$\frac{c^B_{LL}e^{i\phi_B}}{\Lambda^2}\xi_{ib}^2\frac{1}{2}(\bar{d}_{Li}\gamma_\mu b_L)^2$$



(cannot fit the "discrepancy")





B, Buttazzo et al 2012

Flavour tests
versus direct searches
(cum grano salis)

for $c = 1$ $\quad \Lambda \approx 4\pi(m, f)$

E.g. $c \cdot (3\ TeV/\Lambda)^2 \approx 0.1$ means $m, f \approx 0.8\ TeV$

$\Delta F = 1$ Summary

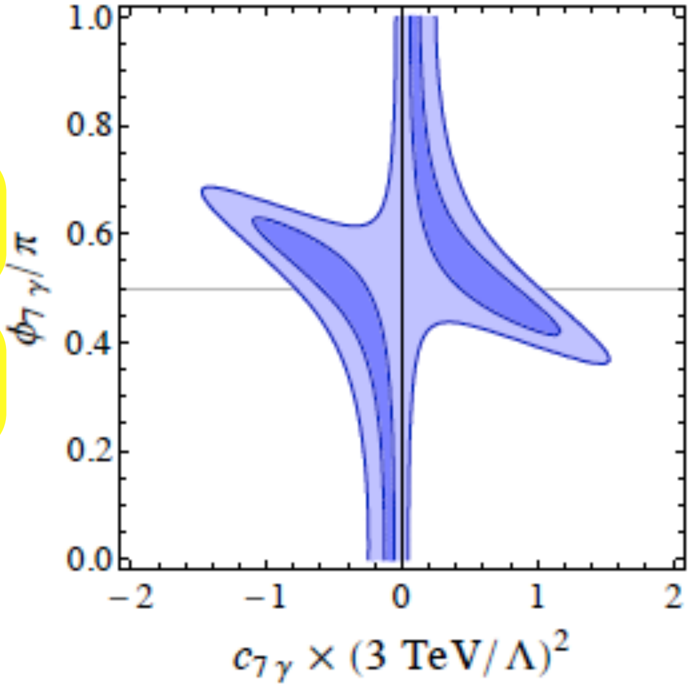
Chirality breaking
(cromo-)magnetic operators

$B \to X_{(s,d)}\gamma$

$B \to K(\pi)\mu\mu$

$U(3)^3$

$U(2)^3$



Chirality conserving op.s

$B \to X_{(s,d)}\gamma$

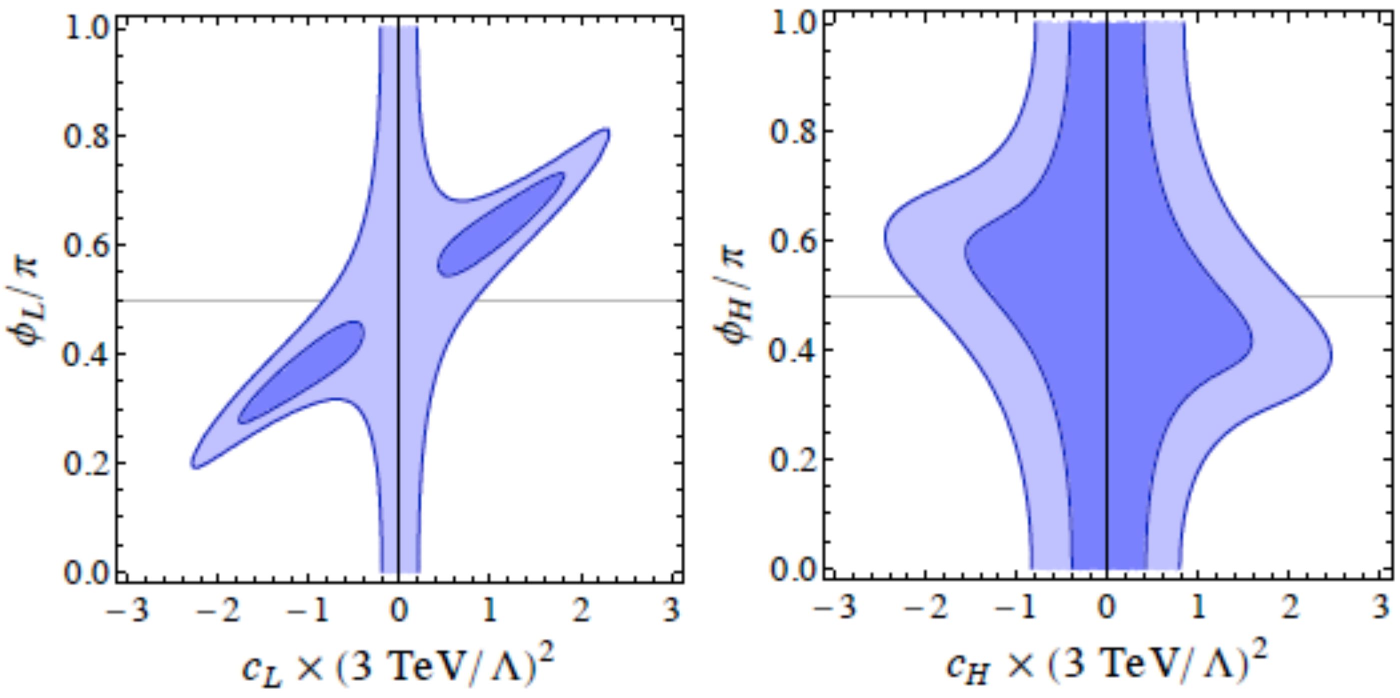
$B \to K(\pi)\mu\mu$

$B_s \to \mu\mu$

$[K \to \pi\nu\nu]$

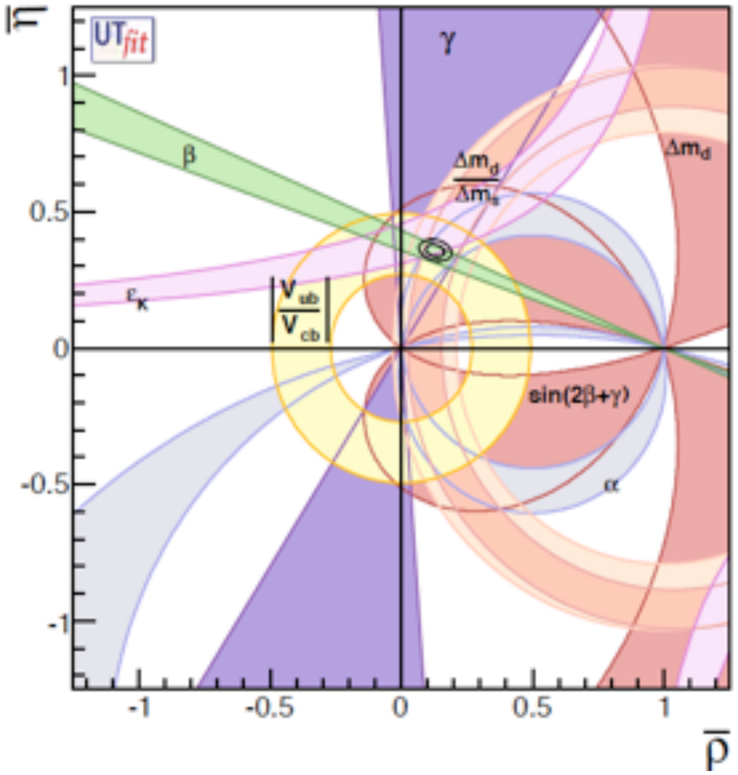
correlated

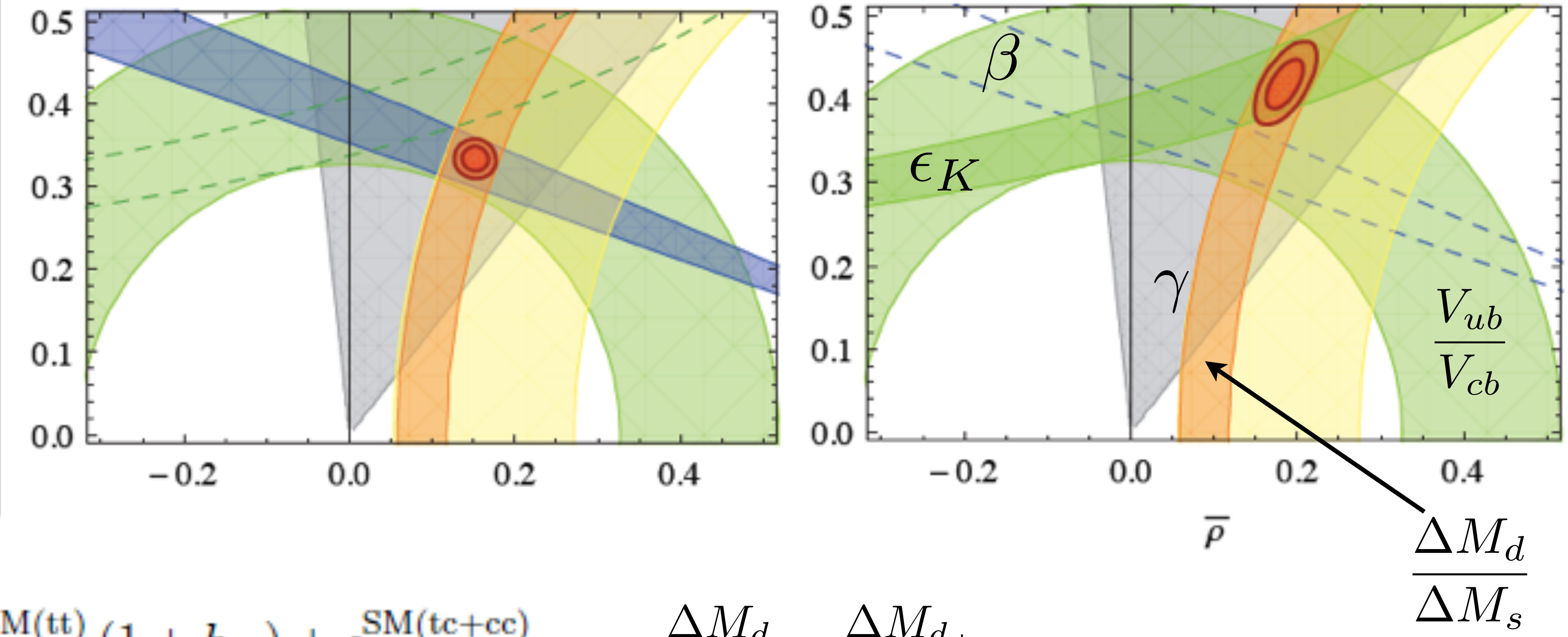
$U(2)^3$



no phase in $U(3)^3$

$\Delta F = 2$ key measurements





$U(2)^3$

$$\epsilon_K = \epsilon_K^{\rm SM(tt)}\left(1+h_K\right)+\epsilon_K^{\rm SM(tc+cc)},$$

$$S_{\psi K_S} = \sin\left(2\beta+\arg\left(1+h_B e^{i\phi_B}\right)\right),$$

$$S_{\psi\phi} = \sin\left(2|\beta_s|-\arg\left(1+h_B e^{i\phi_B}\right)\right)$$

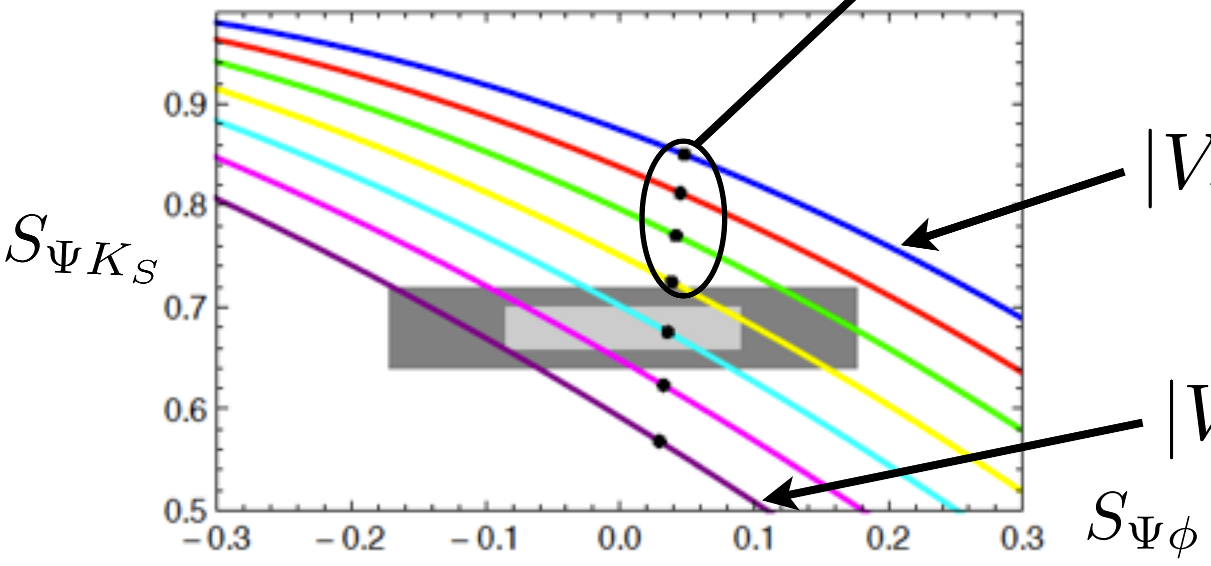
$$\Delta M_d = \Delta M_d^{\rm SM}\left|1+h_B e^{i\phi_B}\right|,$$

$$\frac{\Delta M_d}{\Delta M_s} = \frac{\Delta M_d}{\Delta M_s}|_{SM} = 34.5 \pm 3.0$$

$$\frac{\Delta M_d}{\Delta M_s}|_{exp} = 35.0 \pm 0.3$$

$$\Rightarrow \boxed{\gamma \approx 70^0}$$

The key role of V_{ub} and $S_{\Psi\phi}$ as well as of $F_{B_{d,s}}(B_{d,s})^{1/2}$ from the lattice



SM centered on ϵ_K

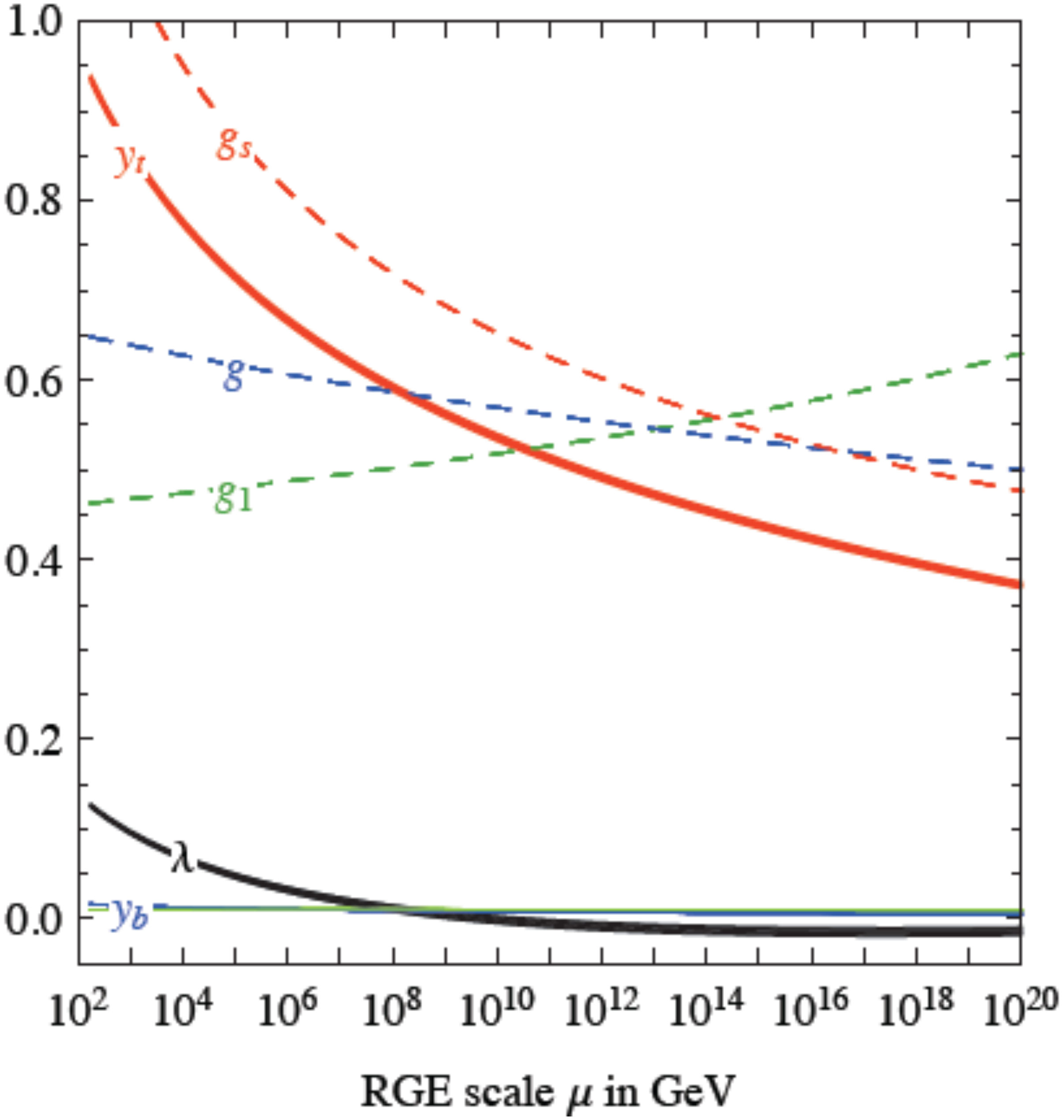
$|V_{ub}| = 0.0046$

$|V_{ub}| = 0.0028$

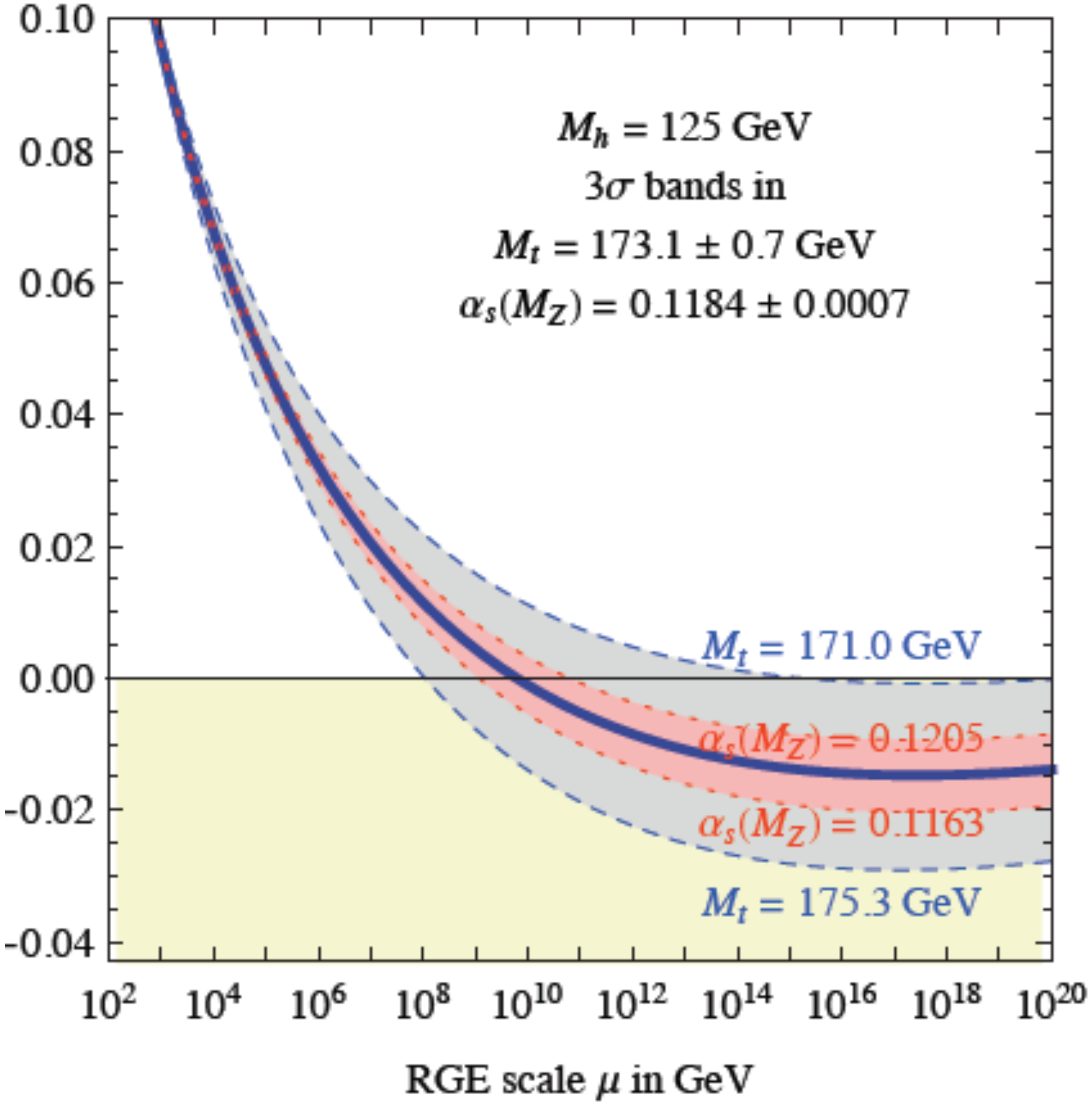
Buras, Girbach 2012

What if the Higgs boson likes to be unnatural and the SM is unchanged up to very high energies?

largest couplings



Higgs self-coupling

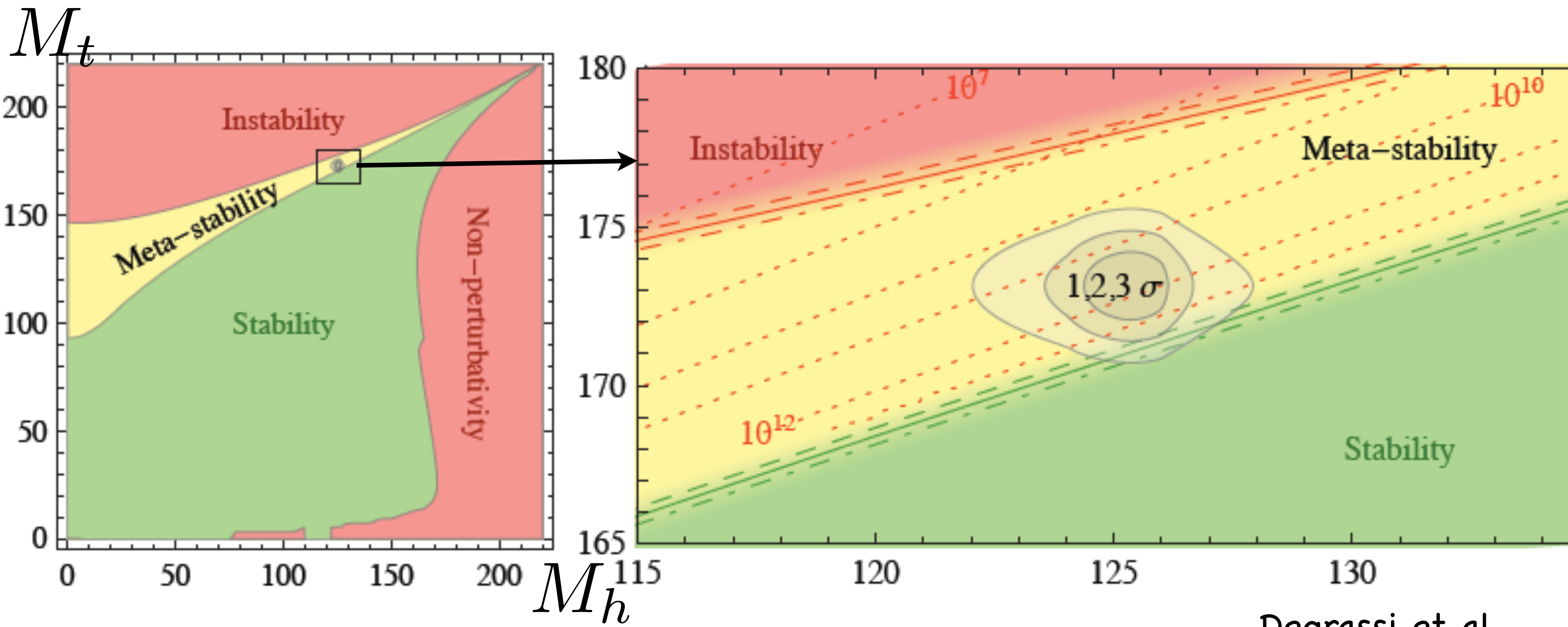


Degrassi et al 2012
Chetyrkin, Zoller 2005
Bezrukov et al 2005

A special meaning for $\lambda\approx0$ at M_{Pl}?

Nielsen et al 1988
Shaposhnikov et al 2009

Assume SM unchanged up to M_{Pl}

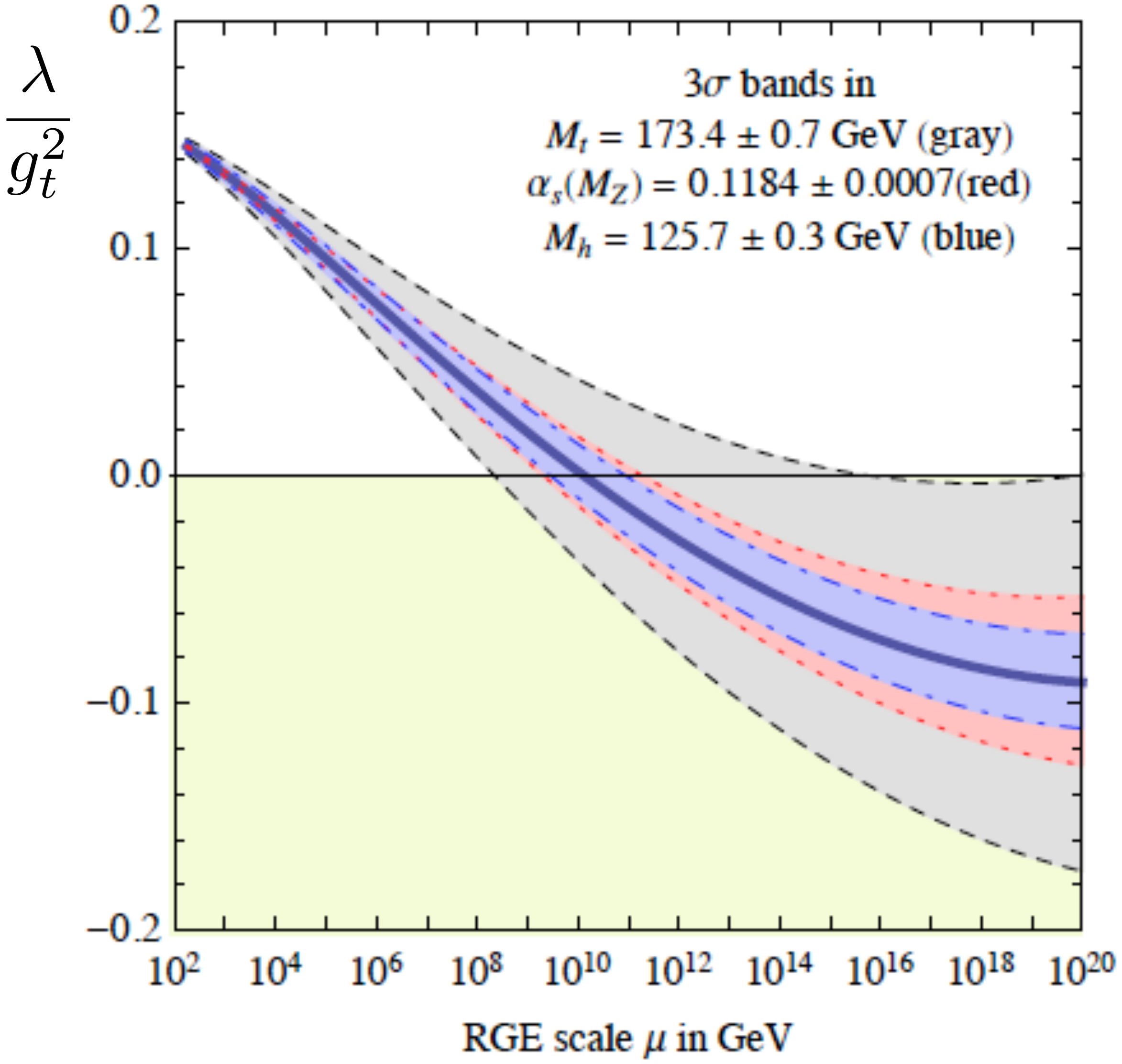


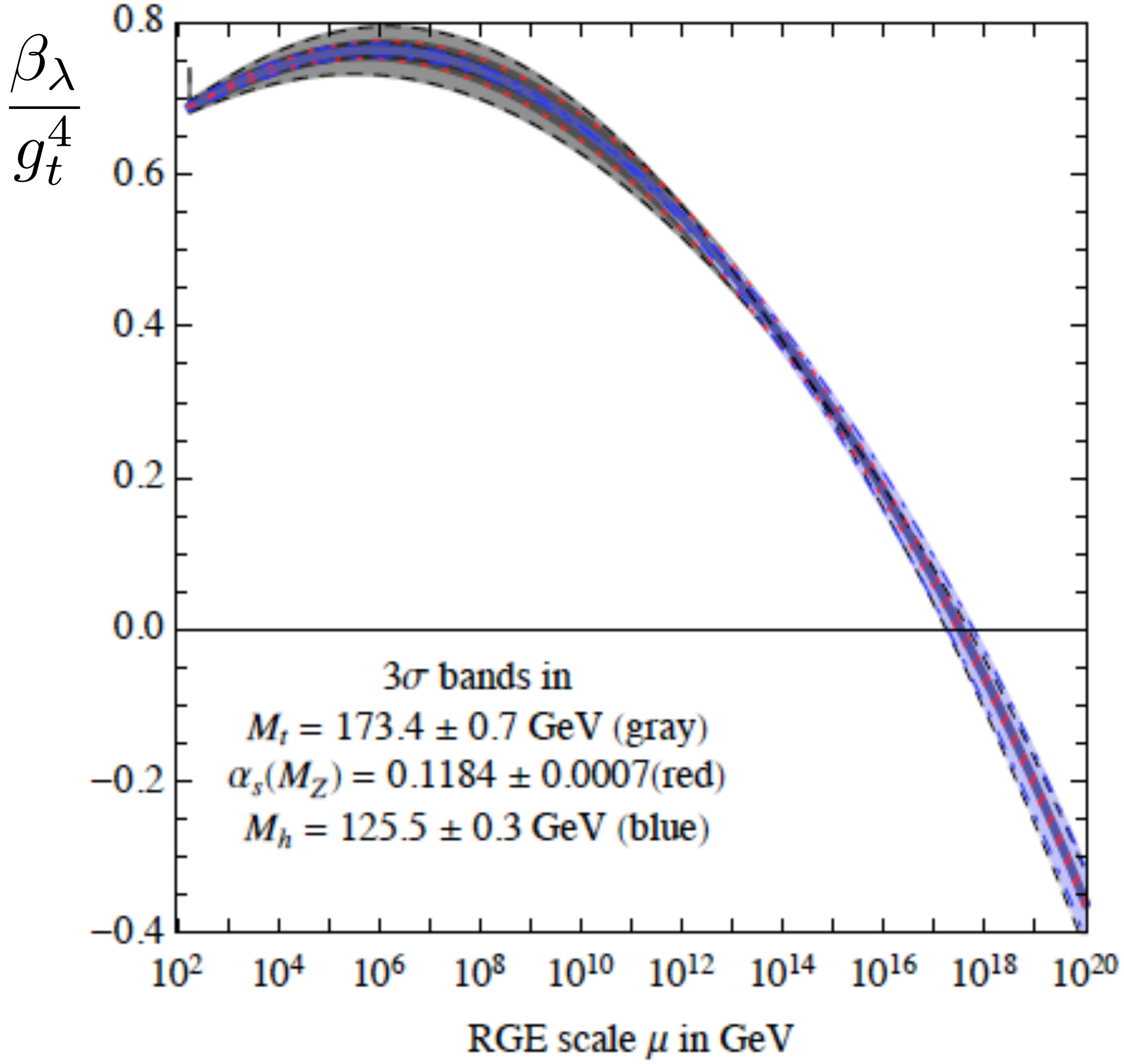
Degrassi et al

Absolute stability at $M_{Pl}(\lambda(M_{Pl})\gtrsim 0)$ not quite achieved for current "best" values of M_t and M_h

Speculations about possible meaning of all this not lacking (anthropic pressure, …)

What's the real evidence for $\lambda(M_{Pl}) \approx \beta_\lambda(M_{Pl}) = 0$?





Even if this improved (g_t, etc) how shall we know that it is not a coincidence?

Thanks to Rattazzi and Strumia

My main questions

0. The discovery of the Higgs boson: just the coronation of the SM or a first fundamental step?

1. The Higgs boson(s): one or more?

The pro's for one:
simplicity, 2 phases only, flavour, a single tuning,...?
None compelling

2. Precision EW and Higgs coupling measurements versus direct new physics searches: which comparison?

Might become the key question after 2-3 years of LHC14 if ...

3. What can we expect from (and for) flavour physics?

$m's, V_{CKM} \Leftrightarrow \lambda_{ij}^{Yukawa}$: a great embarrassment,
unlikely to be solved without new key data