Natural scalars in the NMSSM

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based on 1304.3670 and 1307.4937 with R. Barbieri, K. Kannike, F. Sala and A. Tesi

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IAS TUM Institute for Advanced Study

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One or more scalar bosons?

1. Is the observed 125 GeV boson alone, or is it a member of an extended scalar sector?

2. May the extra scalar bosons be the lightest new particles?

3. Sketch a search strategy for the extra states

   - Direct searches: $pp \to h_{\cancel{LHC}} + X$

     → decay products

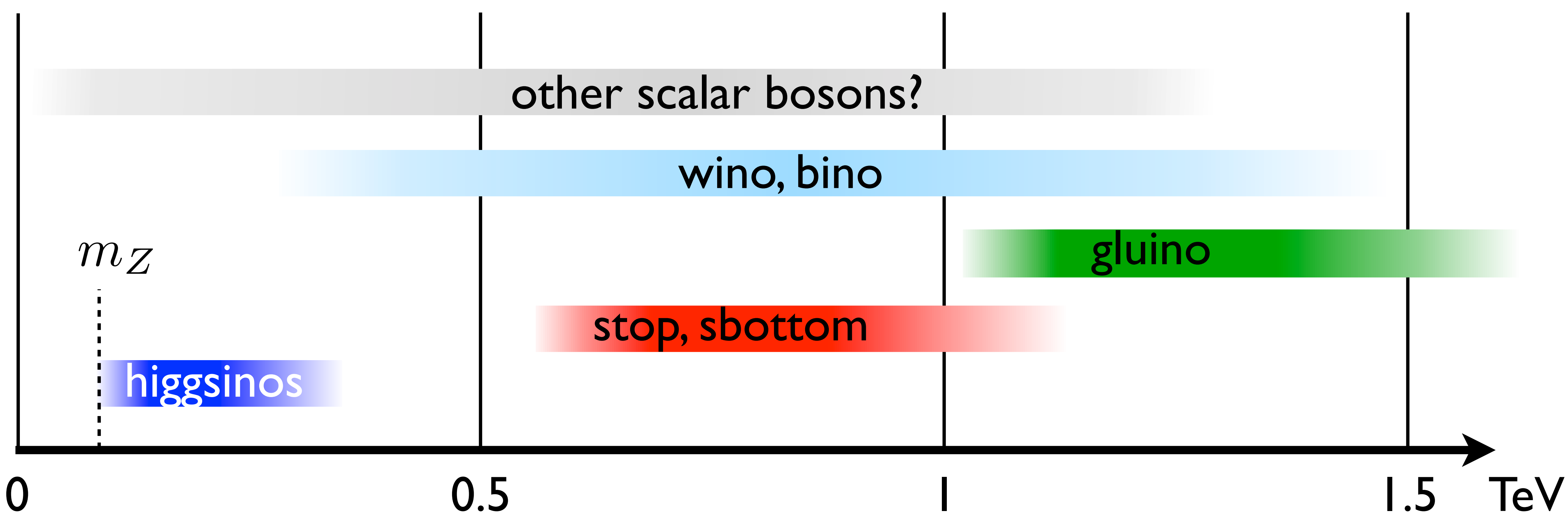
   - Precision measurements of the couplings of the 125 GeV (standard-like) boson h_{LHC}

7. Supersymmetry: at least 2 doublets H_u, H_d.

A natural supersymmetric spectrum

Softly broken SUSY: quadratic UV corrections to the scalar mass cancel, only logarithmic above the s-particle scale.

- Is a "natural" supersymmetric spectrum still allowed?

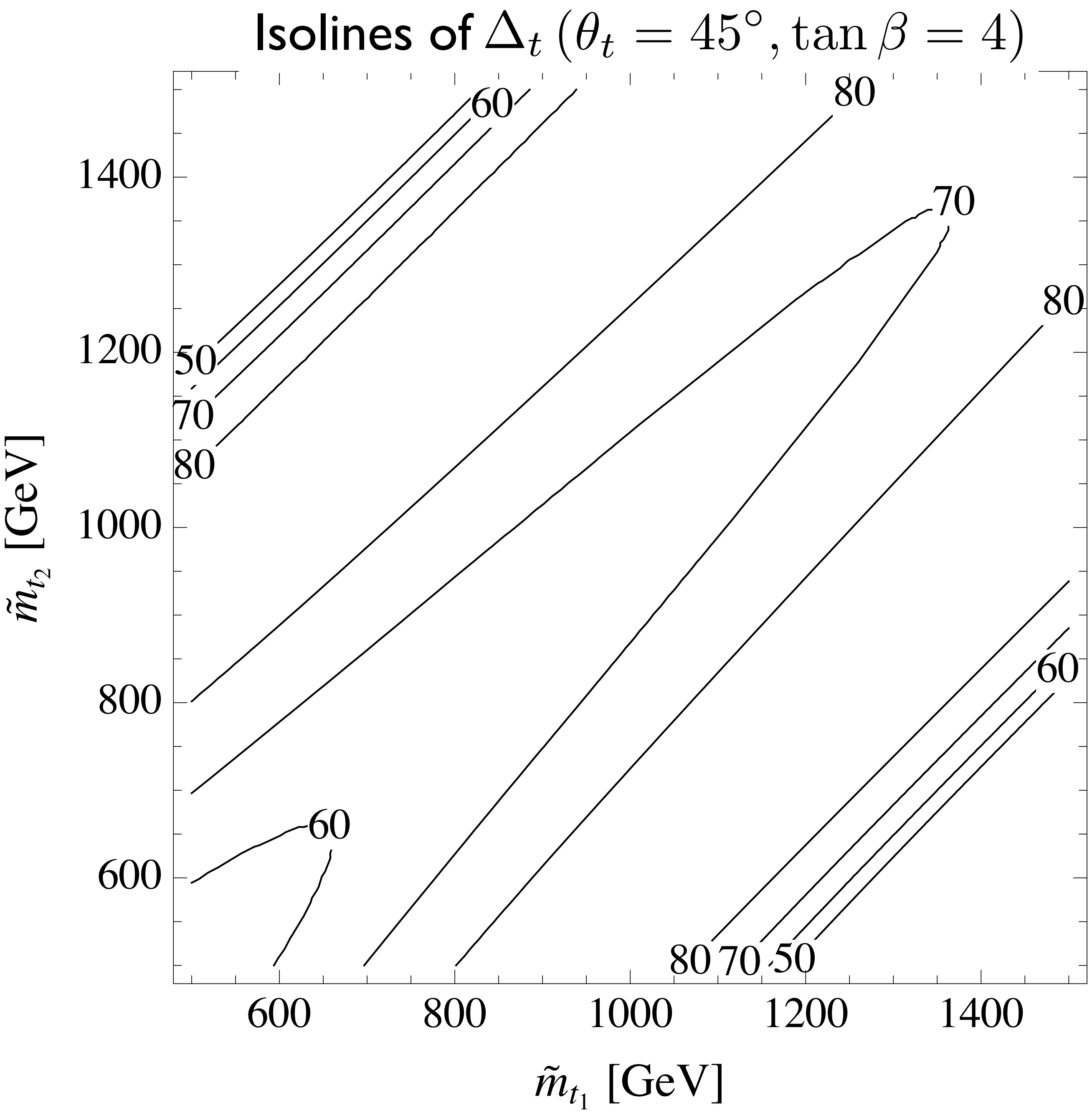


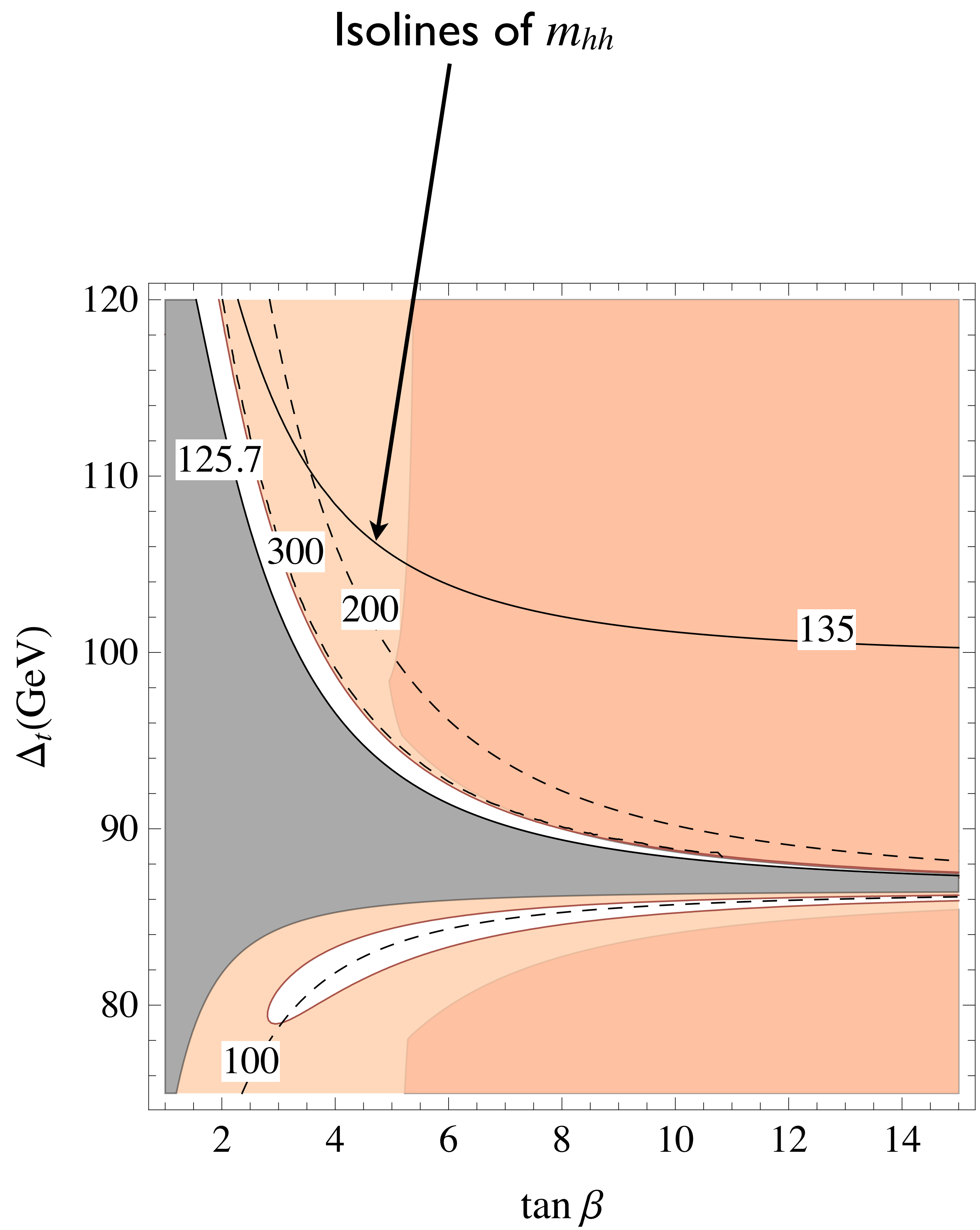
Natural spectrum: $\tilde{t}_{L,R}, \tilde{g}, \tilde{H}_{u,d}$ light!

Scalar masses in the MSSM

$$m_h^2 < m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2$$

Δ_t is the top-stop contribution to m_h





Scalar masses in the MSSM

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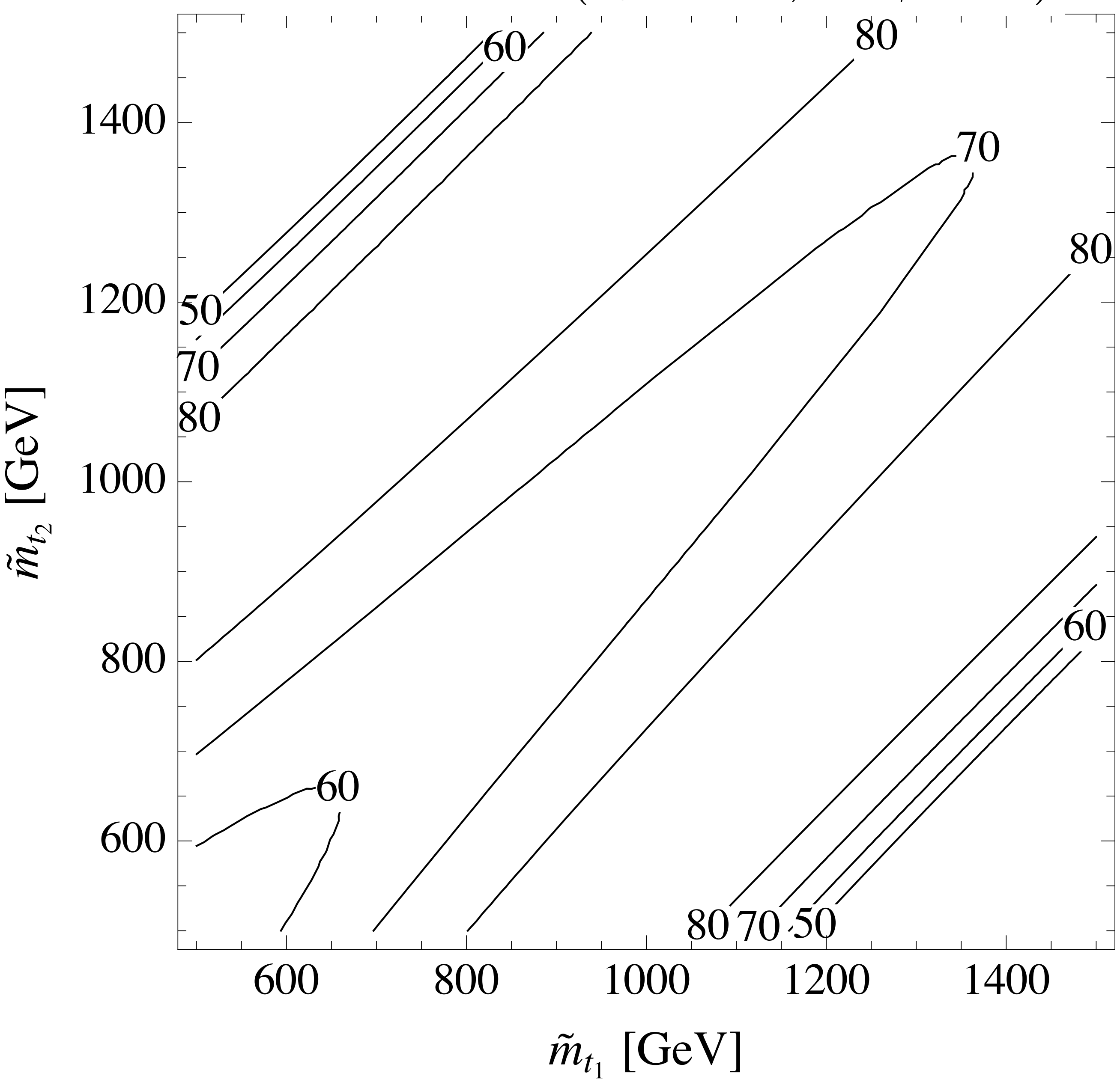
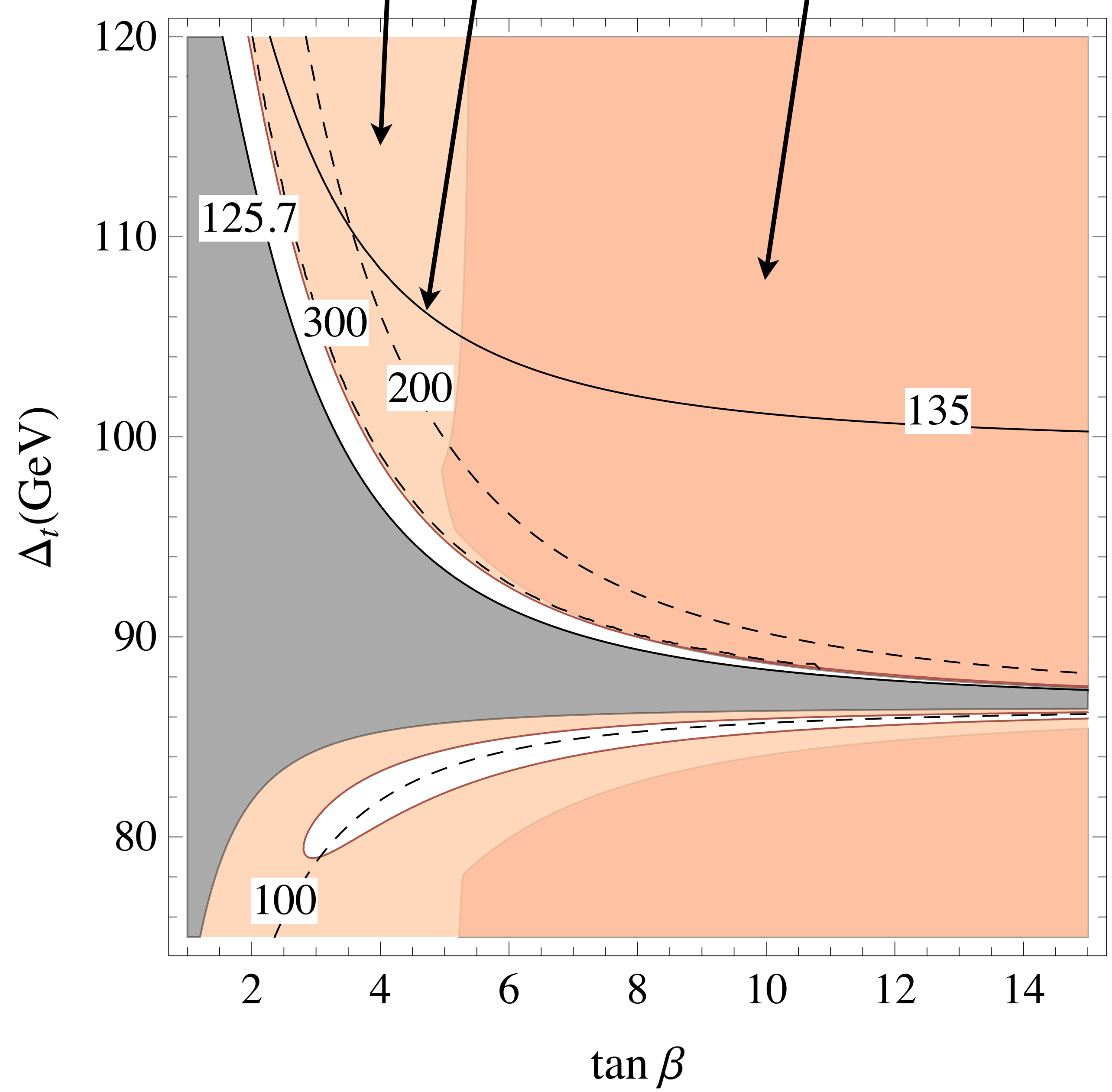
Isolines of Δ_t $(\theta_t = 45°, \tan\beta = 4)$



Isolines of m_{hh}

Excluded by h_{LHC} signal strengths

Excluded by $h_3 \to \tau\tau$



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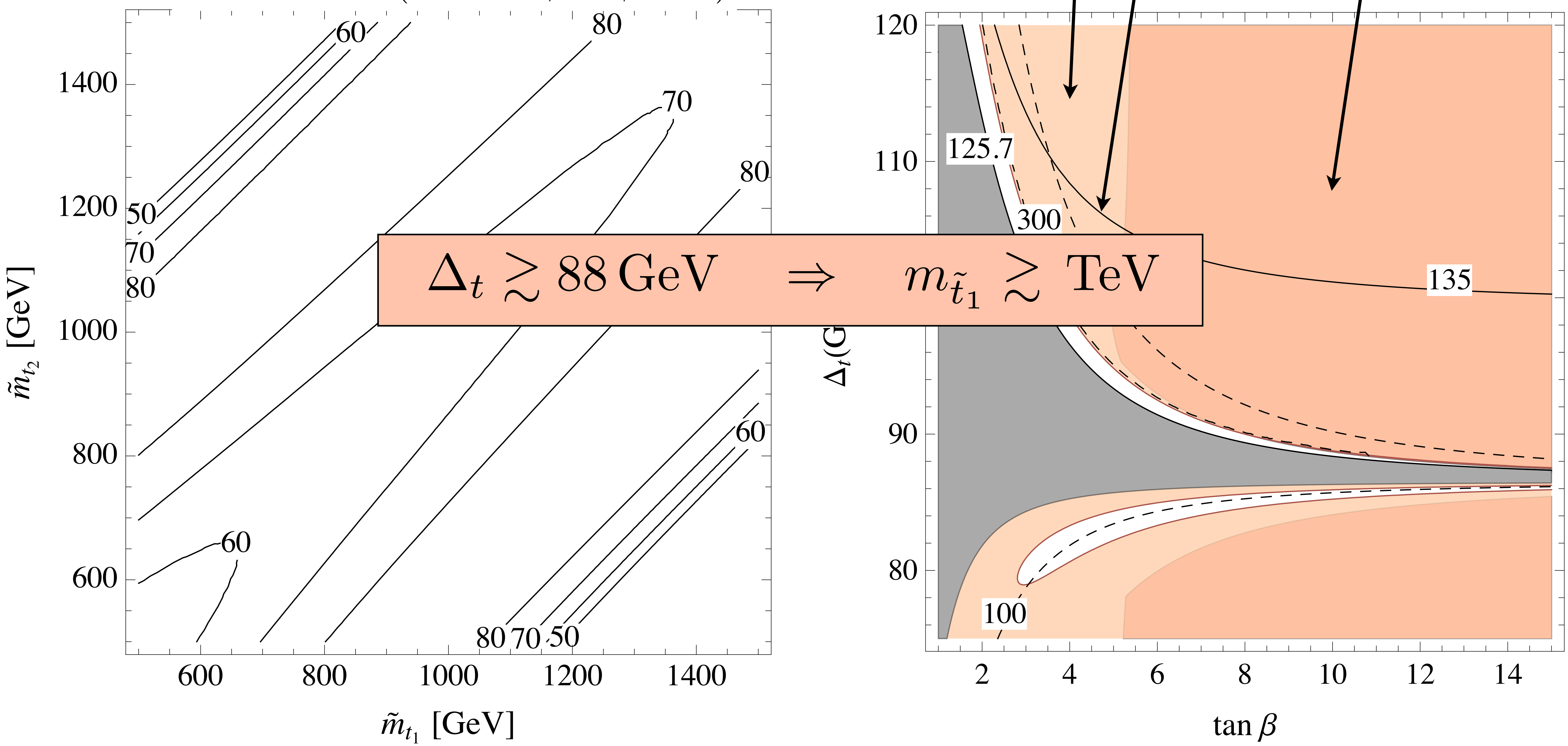


$$\Delta_t \gtrsim 88\,\mathrm{GeV} \quad \Rightarrow \quad m_{\tilde{t}_1} \gtrsim \mathrm{TeV}$$

NMSSM: $W \supset \lambda S H_u H_d$

Fayet '75
...

- Adds an extra contribution to the tree-level scalar mass $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2 \Rightarrow$ allows for lighter stops
- Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$:

$$\left.\frac{dv^2}{dm_{H_u}^2}\right|_{NMSSM} \simeq \frac{\kappa}{\lambda^3}\cot 2\beta, \qquad \left.\frac{dv^2}{dm_{H_u}^2}\right|_{MSSM} \simeq \frac{4}{g^2}$$

coefficient of quadratic correction to v

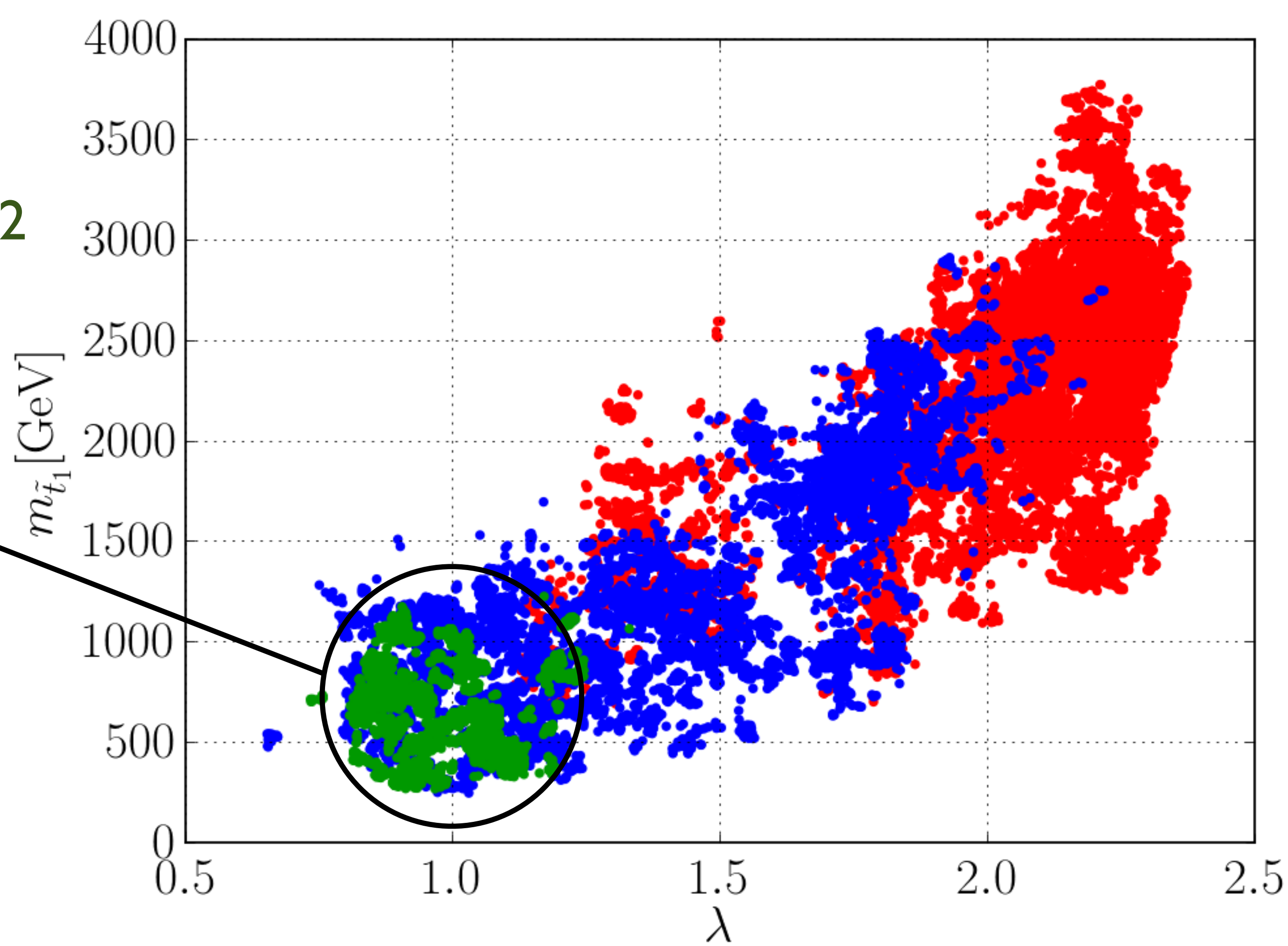
Hall et al.'11

Example:

Gherghetta et al.'12

better than 5% combined fine-tuning and $\Lambda_{\rm mess} \approx 20\,\mathrm{TeV}$ in the scale-invariant NMSSM

$$m_{\tilde{t}_1} \lesssim 1.2\,\mathrm{TeV}$$
$$m_{\tilde{g}} \lesssim 3\,\mathrm{TeV}$$



Parameter space in a general NMSSM

Assume:

- No CPV in the scalar sector
- Neglect loop effects from sparticles other than Δ_t

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

$$\mathcal{M} = R \cdot {\rm diag}(m_{h_3}, m_{h_1}, m_{h_2}) \cdot R^T$$

$$\mathcal{M} = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & (2\lambda^2 v^2 - m_A^2 - m_Z^2) s_\beta c_\beta & v M_1 \\ (2\lambda^2 v^2 - m_A^2 - m_Z^2) s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 + \Delta_t^2 / s_\beta^2 & v M_2 \\ v M_1 & v M_2 & M_3^2 \end{pmatrix}$$

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3 unknown parameters

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

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3 relations

$$(\alpha, \gamma, \sigma) = \alpha, \gamma, \sigma(m_i^2, m_{H^\pm}^2, \lambda, \tan\beta, \Delta_t)$$

3 mixing angles

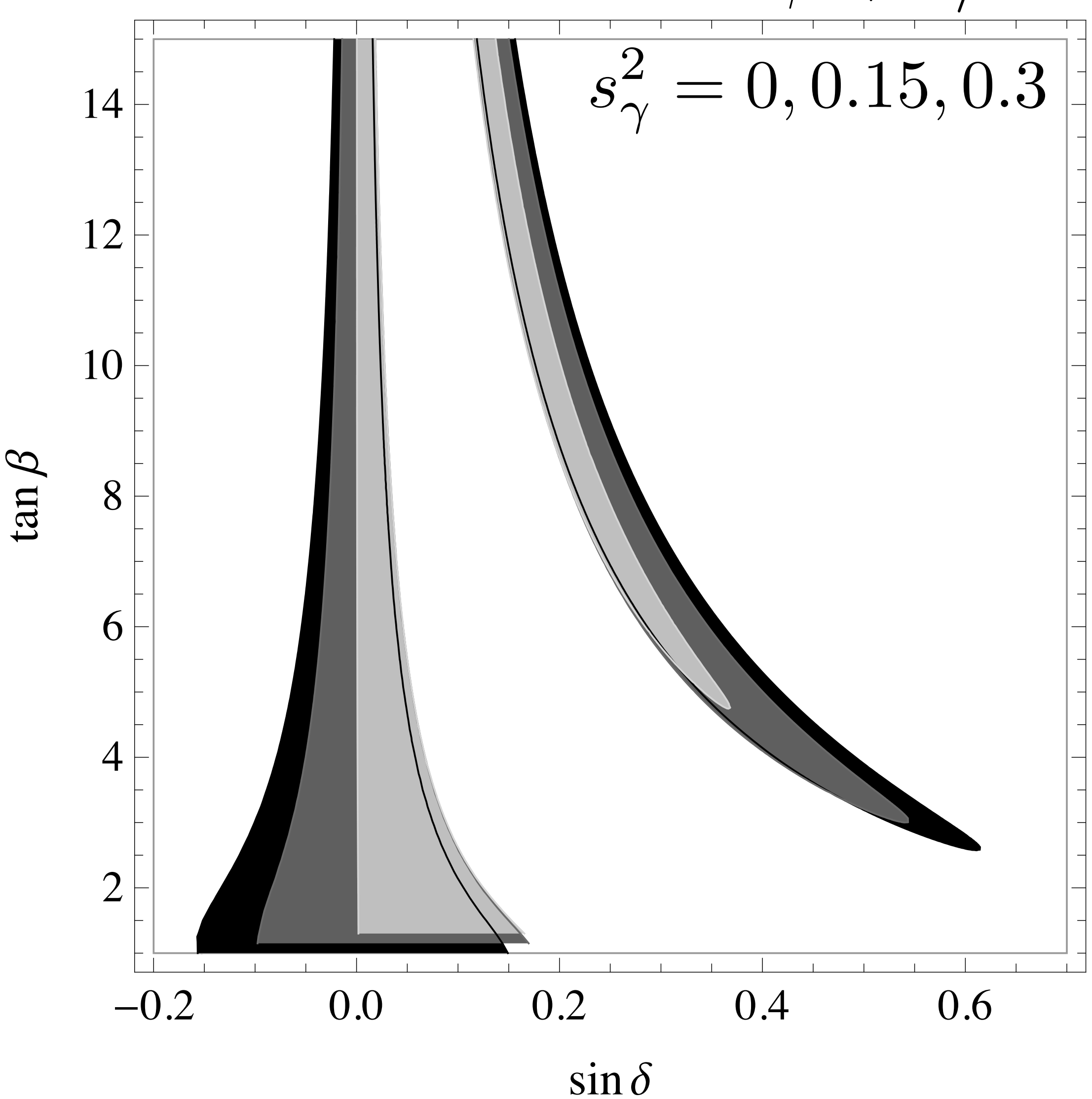
6 independent parameters

Modified scalar couplings

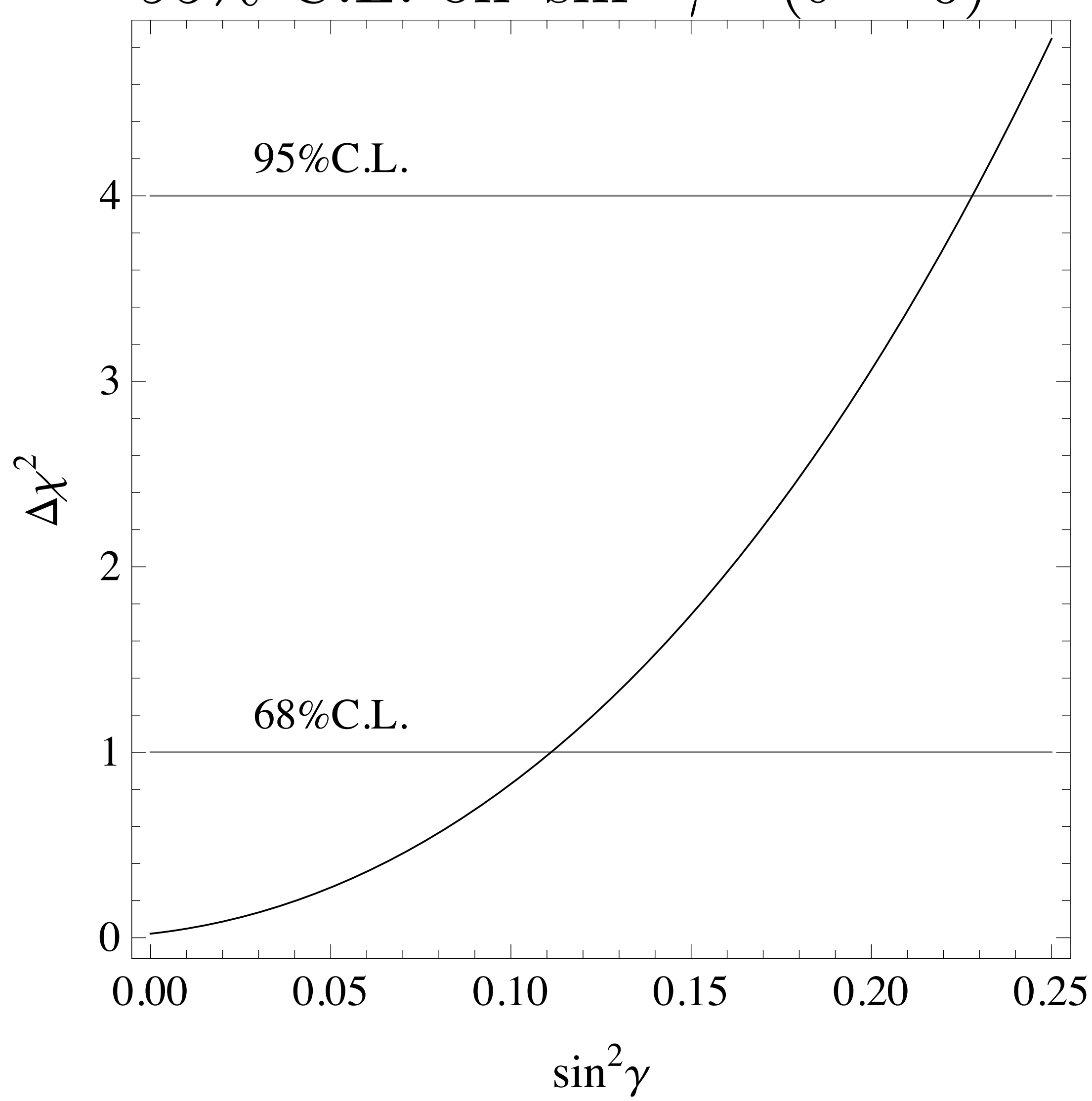
- Take $h_1 = c_\gamma(-s_\alpha H_d + c_\alpha H_u) + s_\gamma S \equiv h_{\rm LHC}$
- No SUSY loops or invisible decays, e.g. $h_1 \to \chi\chi$

$$\frac{g_{h_1 tt}}{g^{\rm SM}_{htt}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{h_1 bb}}{g^{\rm SM}_{hbb}} = c_\gamma\left(c_\delta - s_\delta\tan\beta\right), \qquad \frac{g_{h_1 VV}}{g^{\rm SM}_{hVV}} = c_\gamma c_\delta$$

95% C.L. on $\delta = \alpha - \beta + \pi/2$



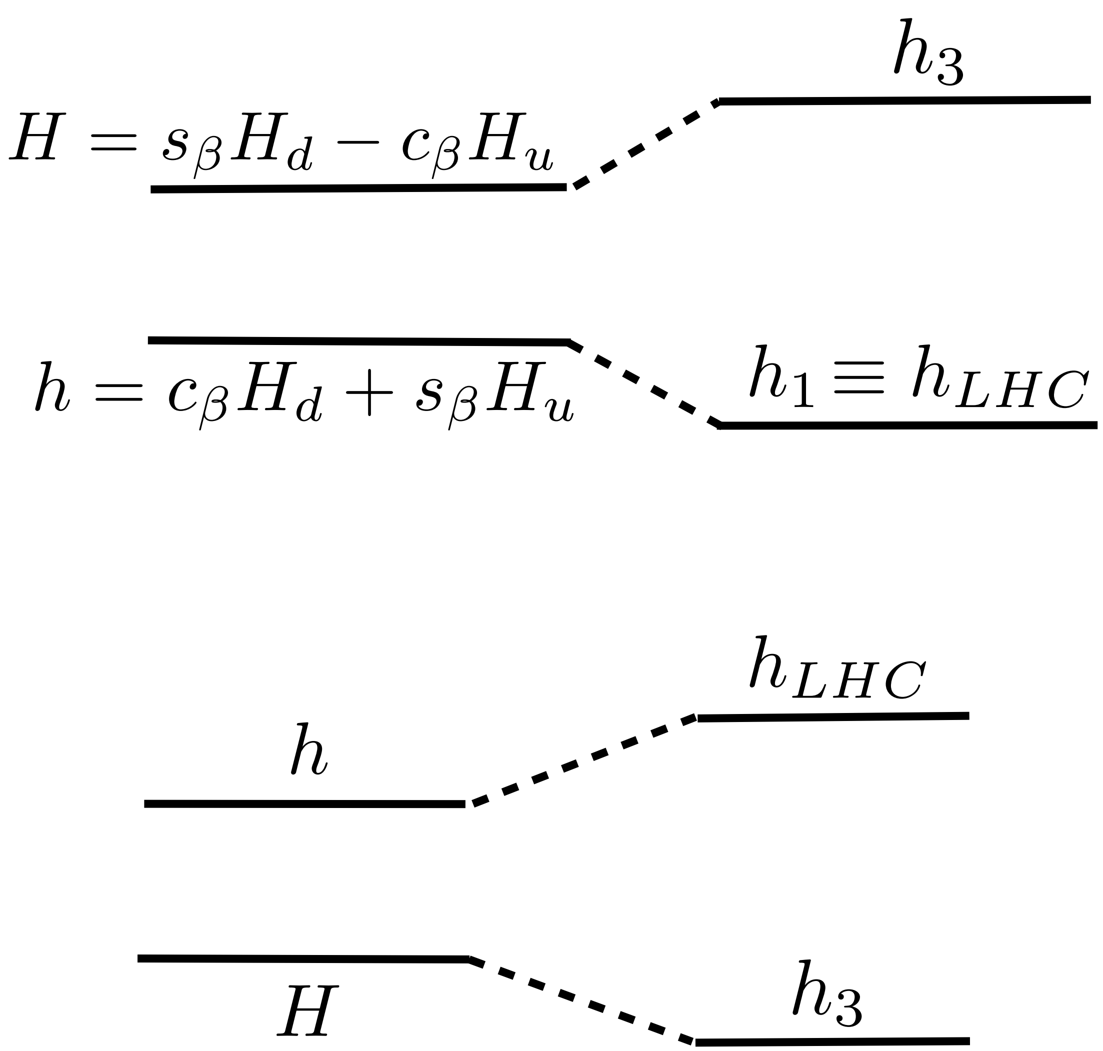
95% C.L. on $\sin^2\gamma \quad (\delta = 0)$



Two limiting cases

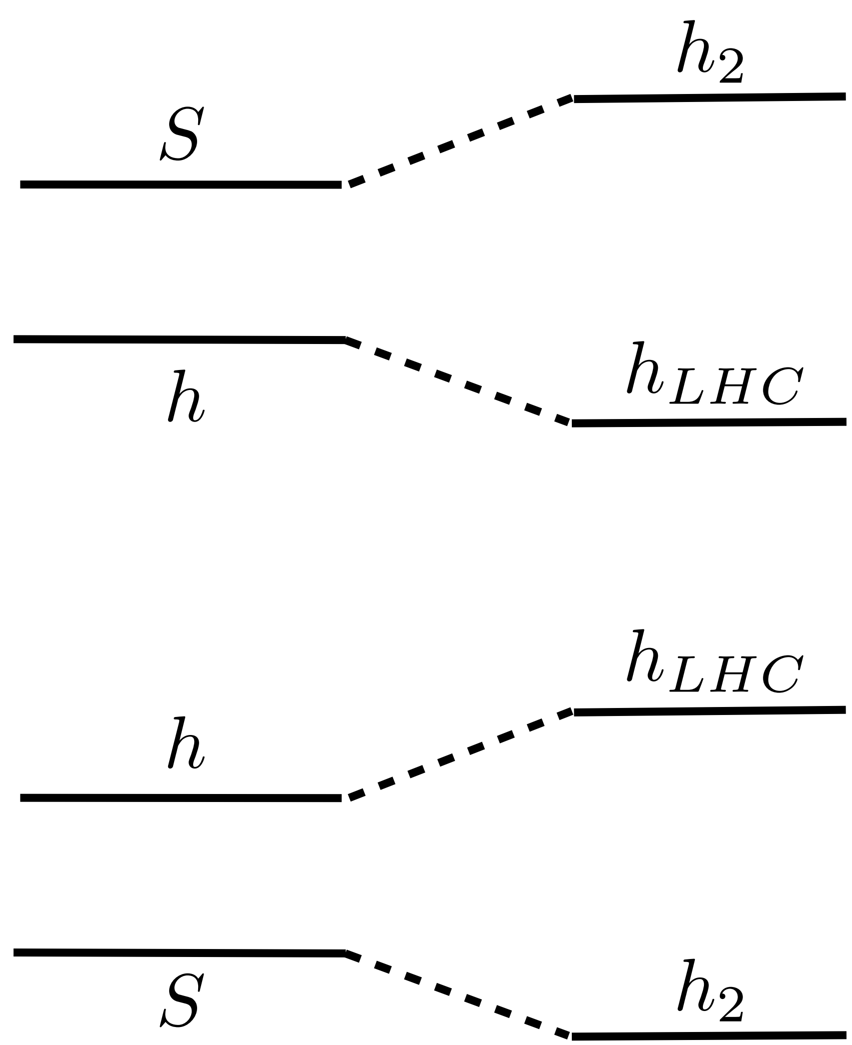
S decoupled

(both MSSM and NMSSM)



H decoupled

(NMSSM only)



Two limiting cases

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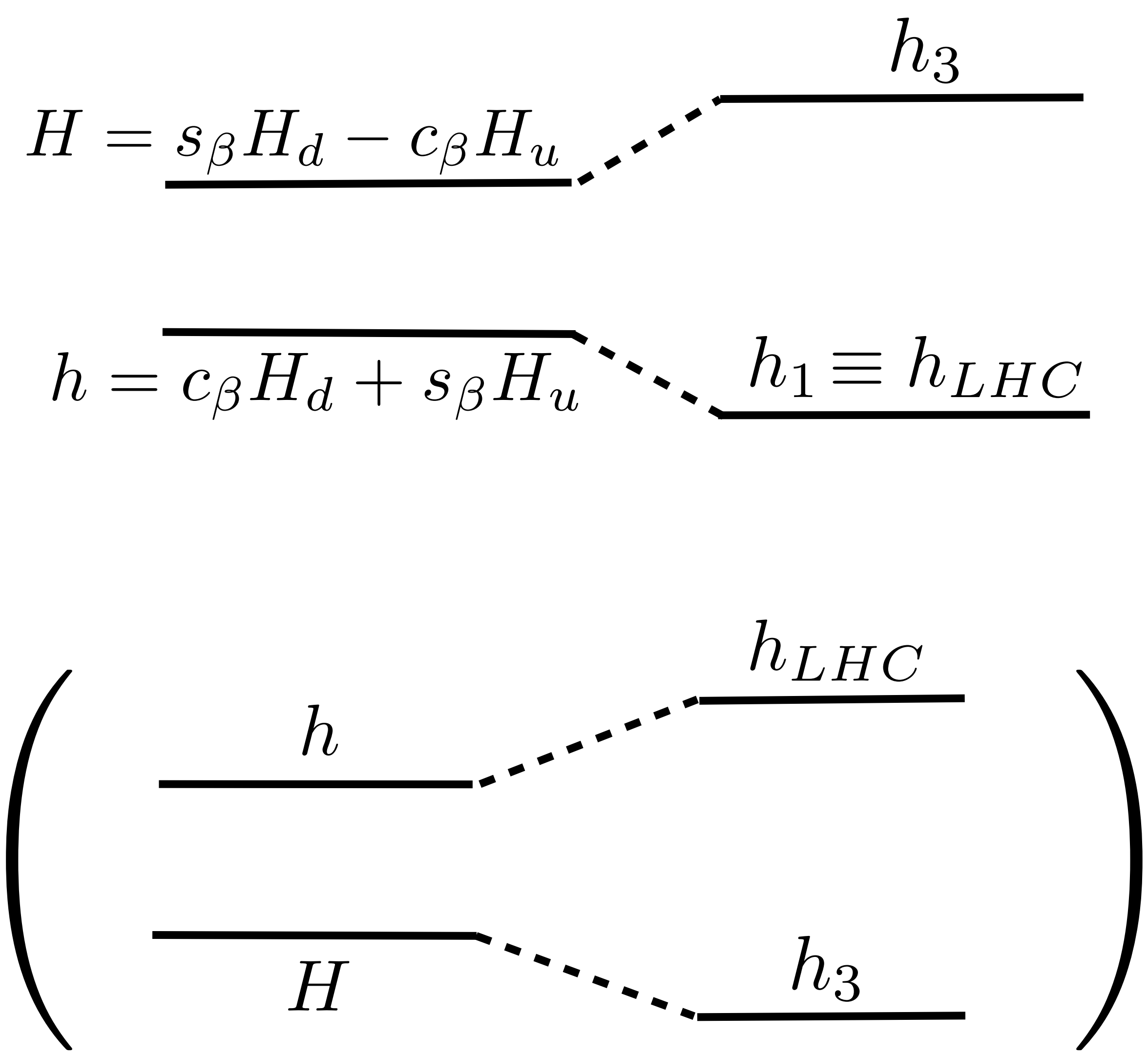
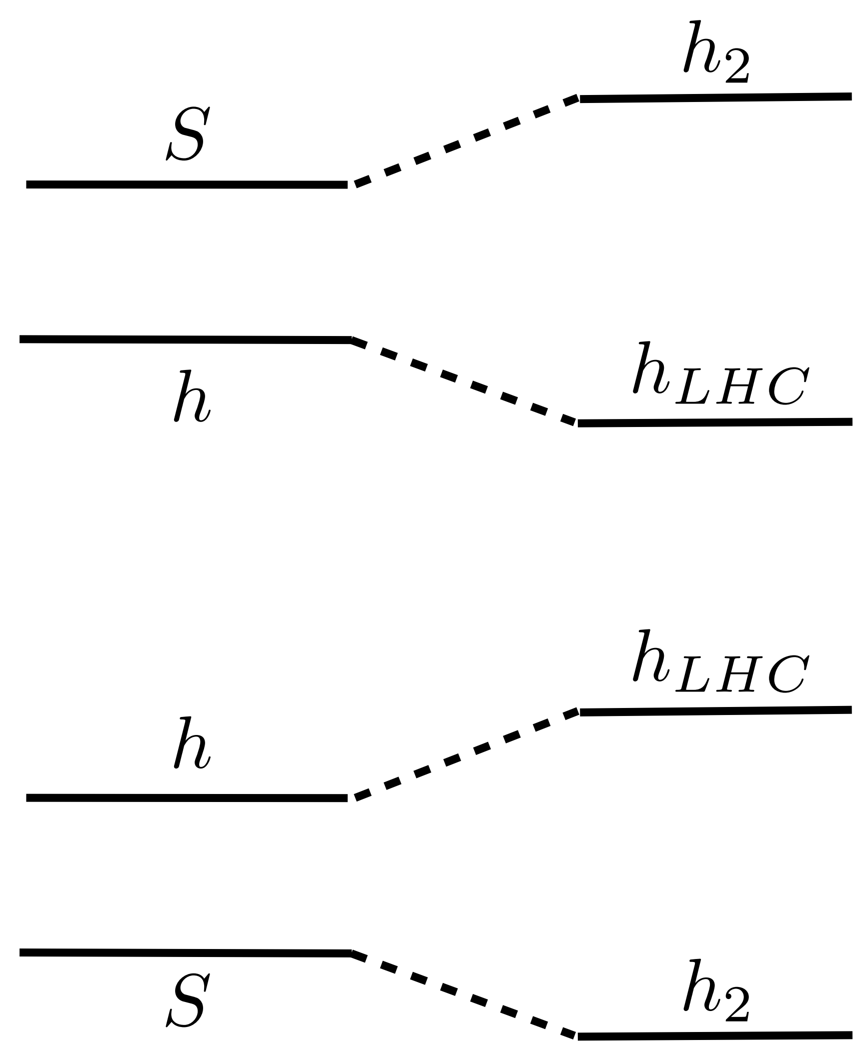


(unlikely: $H^\pm$ too light)

H decoupled

(NMSSM only)



Singlet decoupled

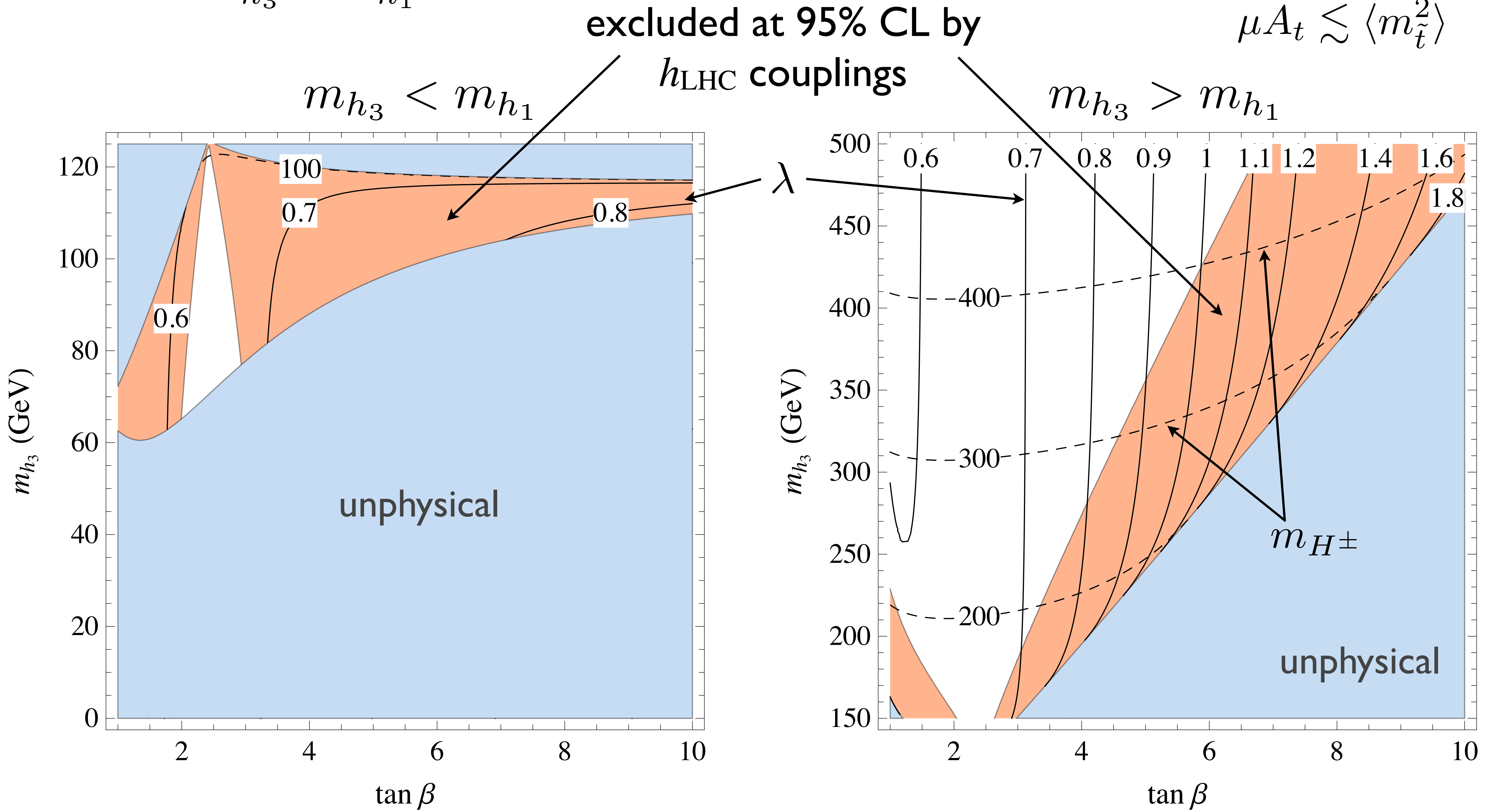
$M_3^2 \gg M_{1,2} v$ and $\gamma, \sigma \to 0$

Only δ nonzero $\Rightarrow$ 3 independent parameters: $\delta, \lambda, m_{H^\pm} (m_{h_3}, \tan\beta, \Delta_t)$

$$\sin^2\delta = \frac{m_{hh}^2 - m_{h_1}^2}{m_{h_3}^2 - m_{h_1}^2}$$ where $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + v^2\lambda^2$

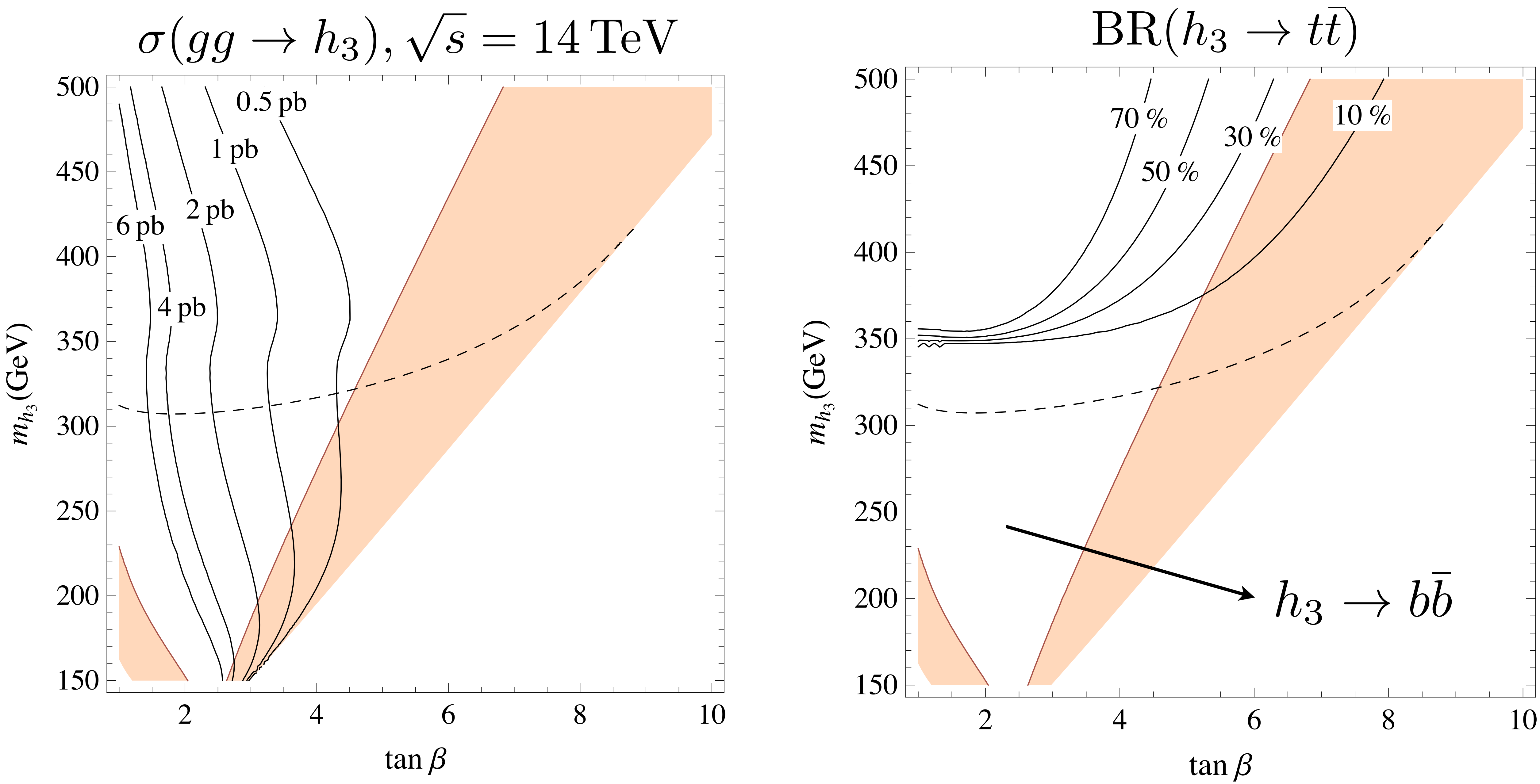
$\Delta_t \approx 75\,\mathrm{GeV}$

$\mu A_t \lesssim \langle m_{\tilde{t}}^2 \rangle$



S decoupled: h_3 production and decays

$m_{h_3} > m_{h_1}$

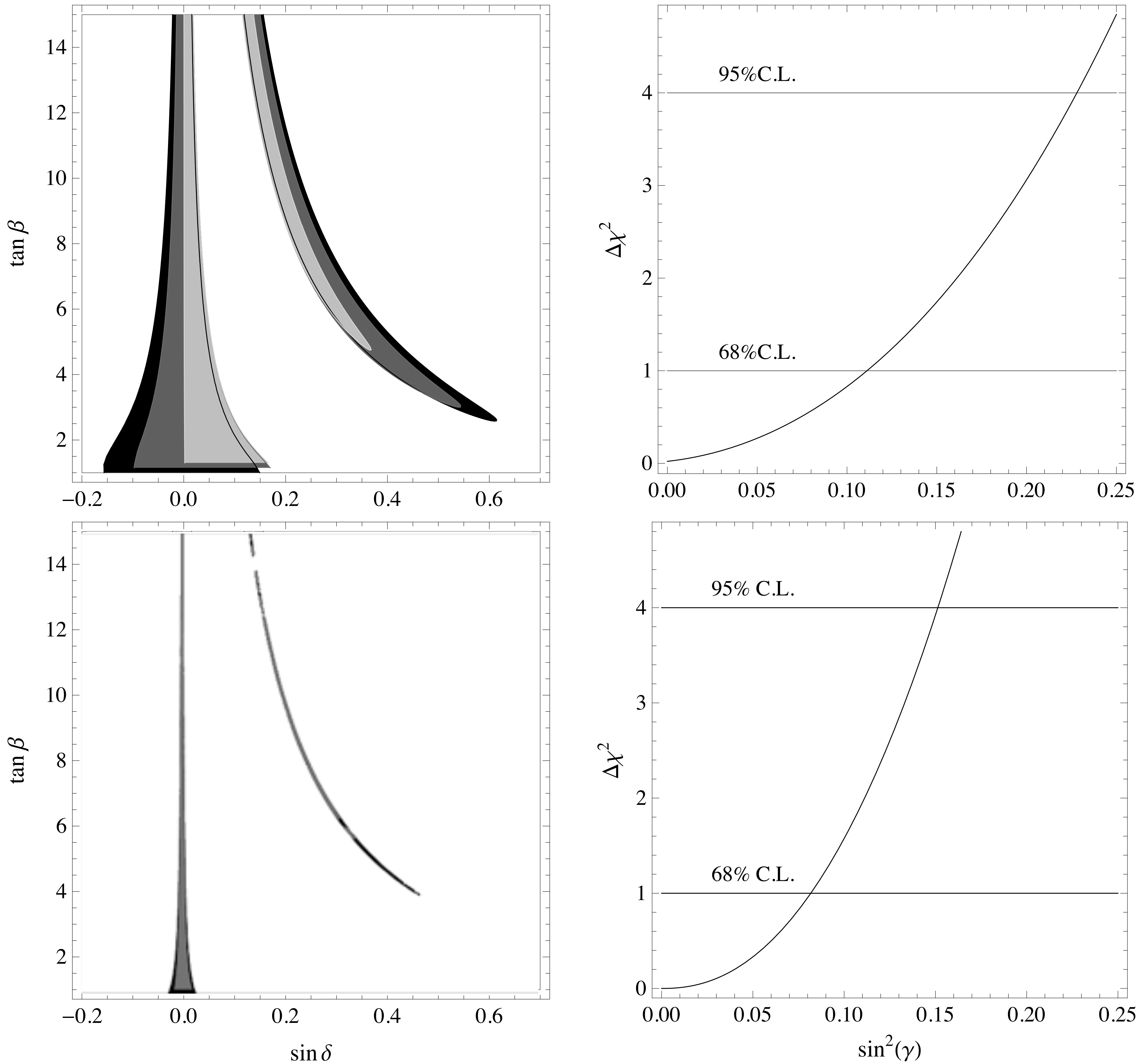


- Small values of λ: h_3 decays mainly into fermions $(b\bar{b}, \tau\bar{\tau}, t\bar{t})$ ~ MSSM

A projection from the measurements of the signal strengths of h_{LHC}

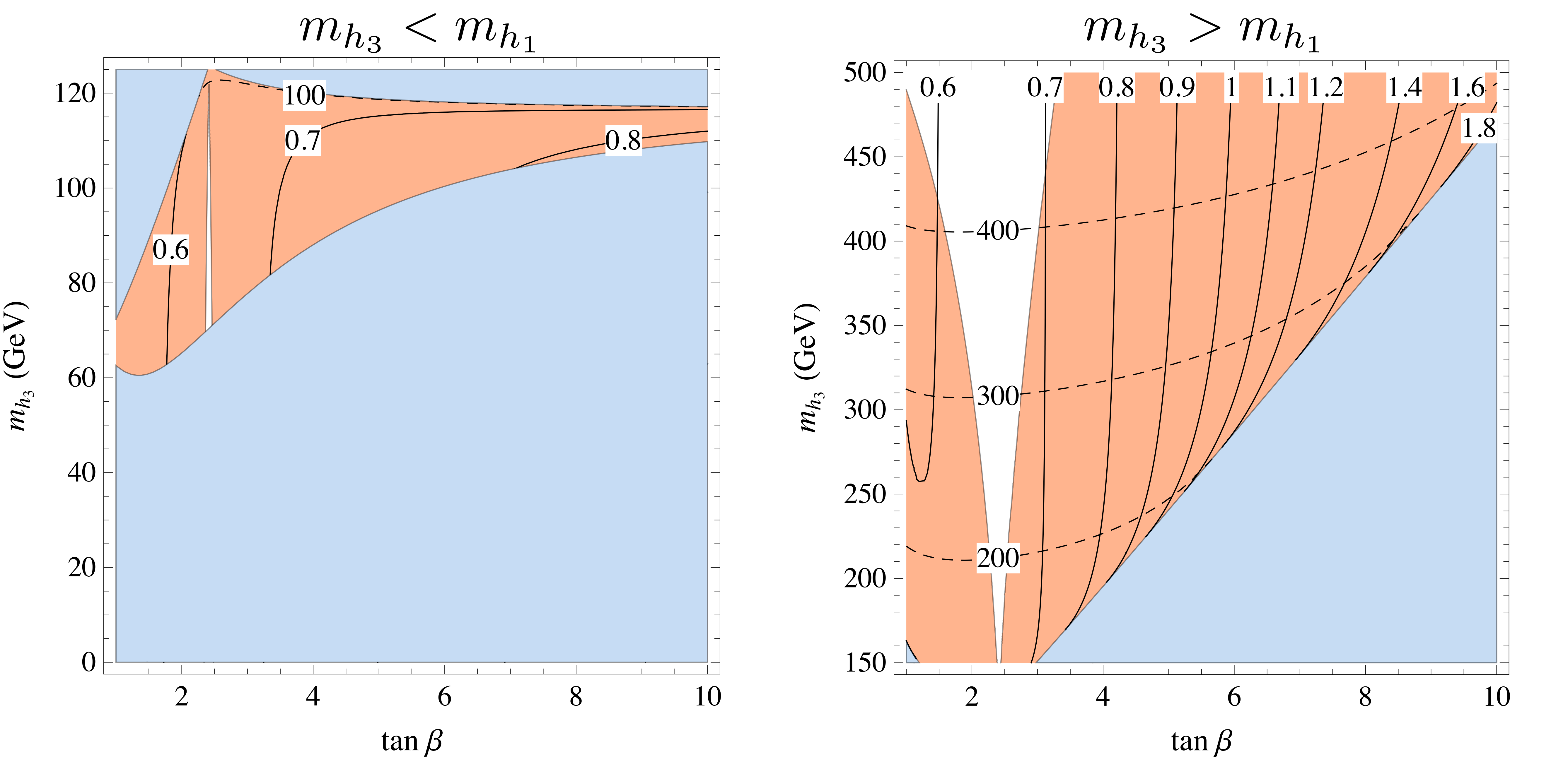
Now (LHC8 with 20 fb^{-1})

LHC14 with 300 fb^{-1} (central values as in the SM)



A projection from the measurements of the signal strengths of h_{LHC}

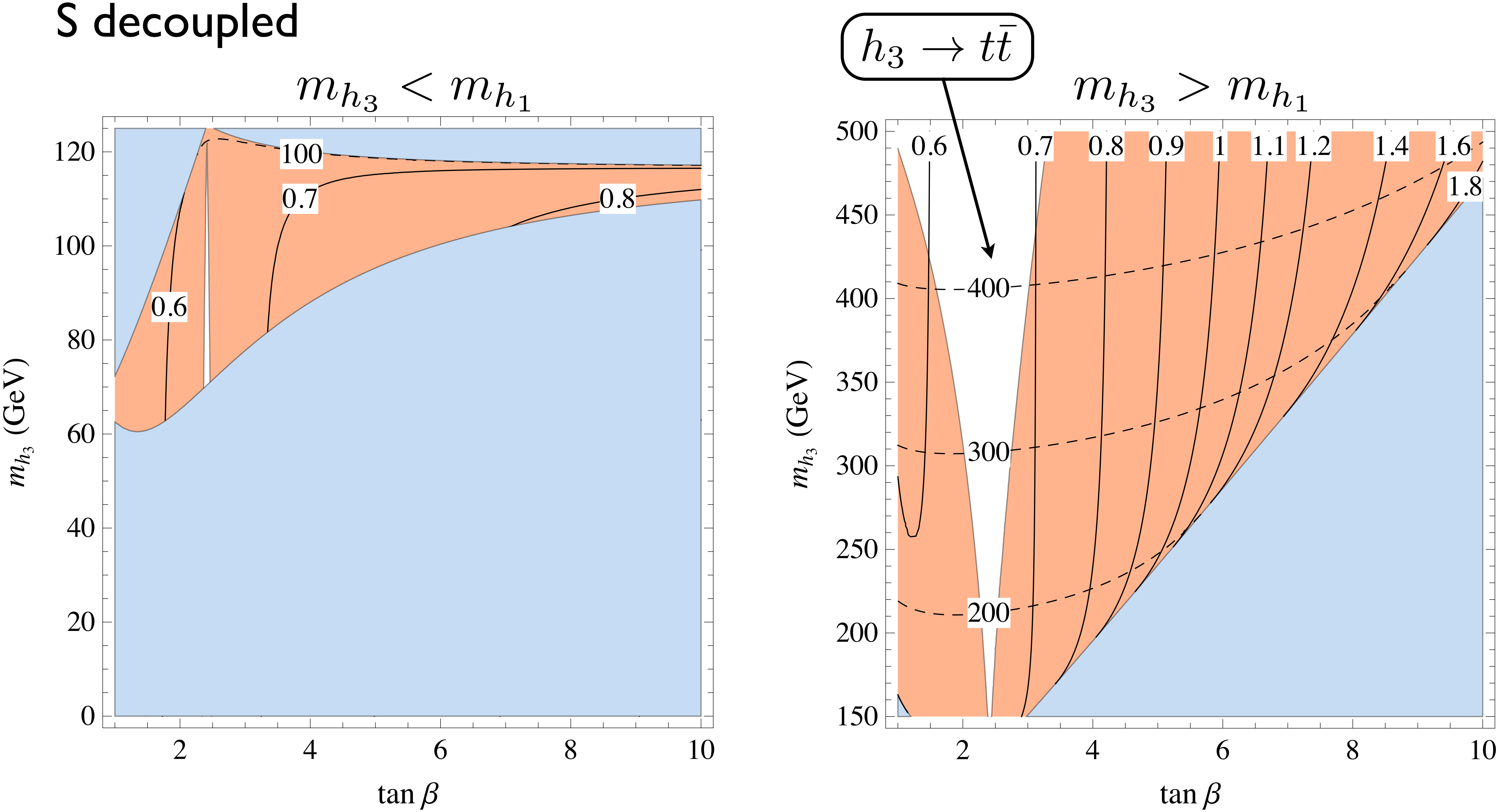
S decoupled



LHC14 at 300 fb^{-1} with ATLAS/CMS projected errors
(assuming SM central values)

A projection from the measurements of the signal strengths of h_{LHC}

S decoupled



LHC14 at 300 fb^{-1} with ATLAS/CMS projected errors
(assuming SM central values)

The MSSM for comparison

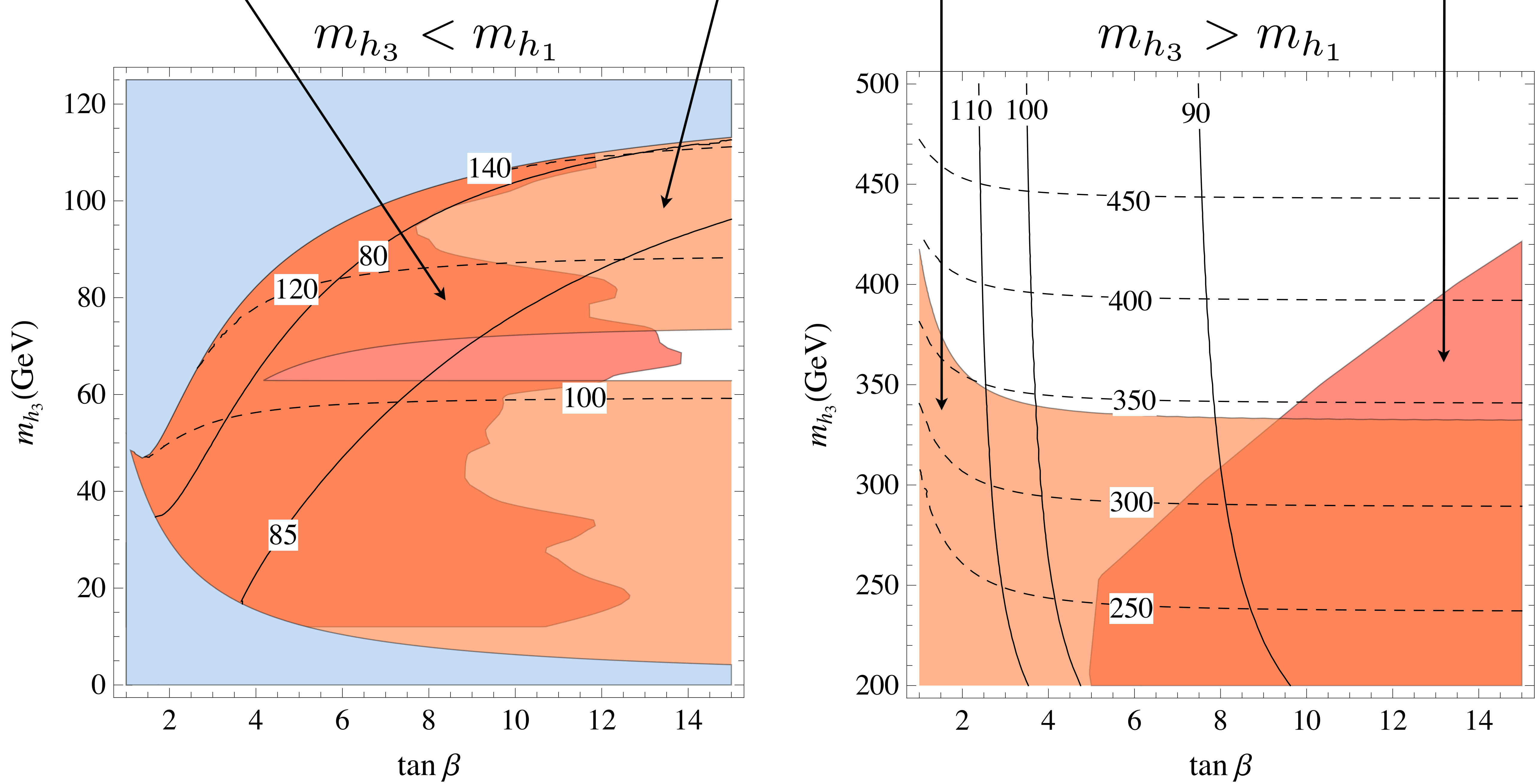
LHC8

Limit $\lambda \to 0$ with S decoupled

excluded by LEP searches for $h_3 \to b\bar{b}$

excluded at 95% CL by h_{LHC} couplings

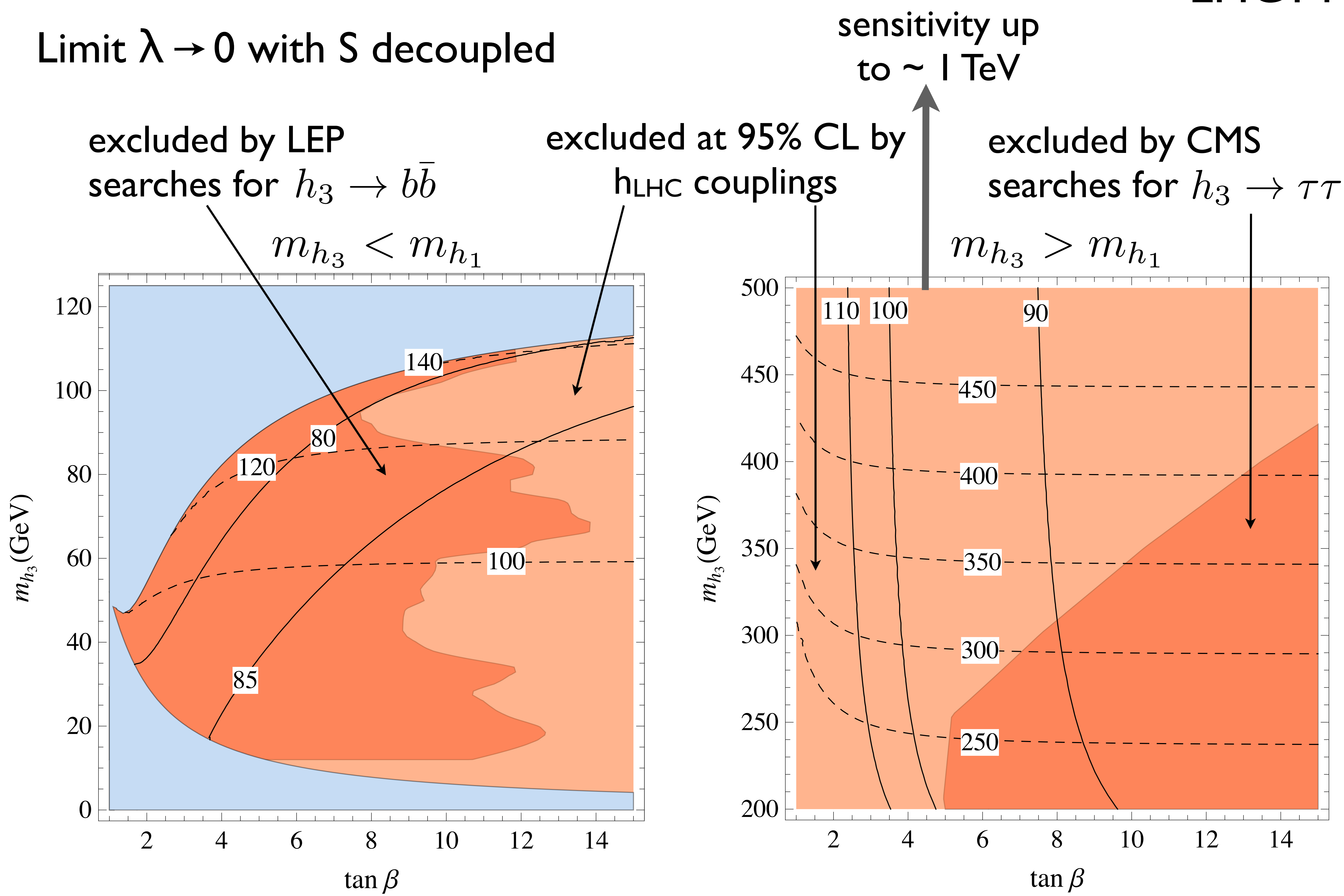
excluded by CMS searches for $h_3 \to \tau\tau$



The MSSM for comparison

LHC14

Limit λ → 0 with S decoupled

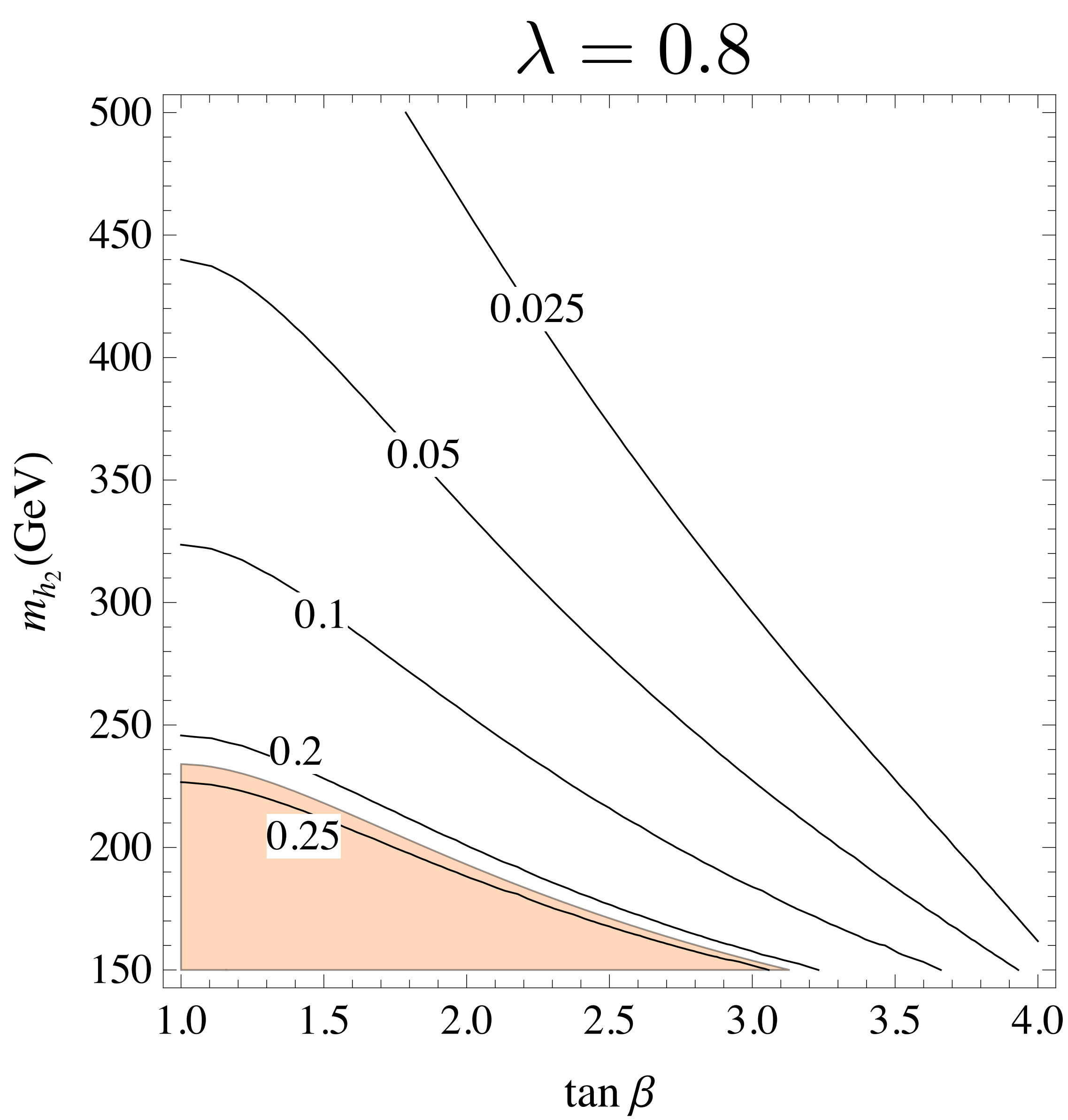


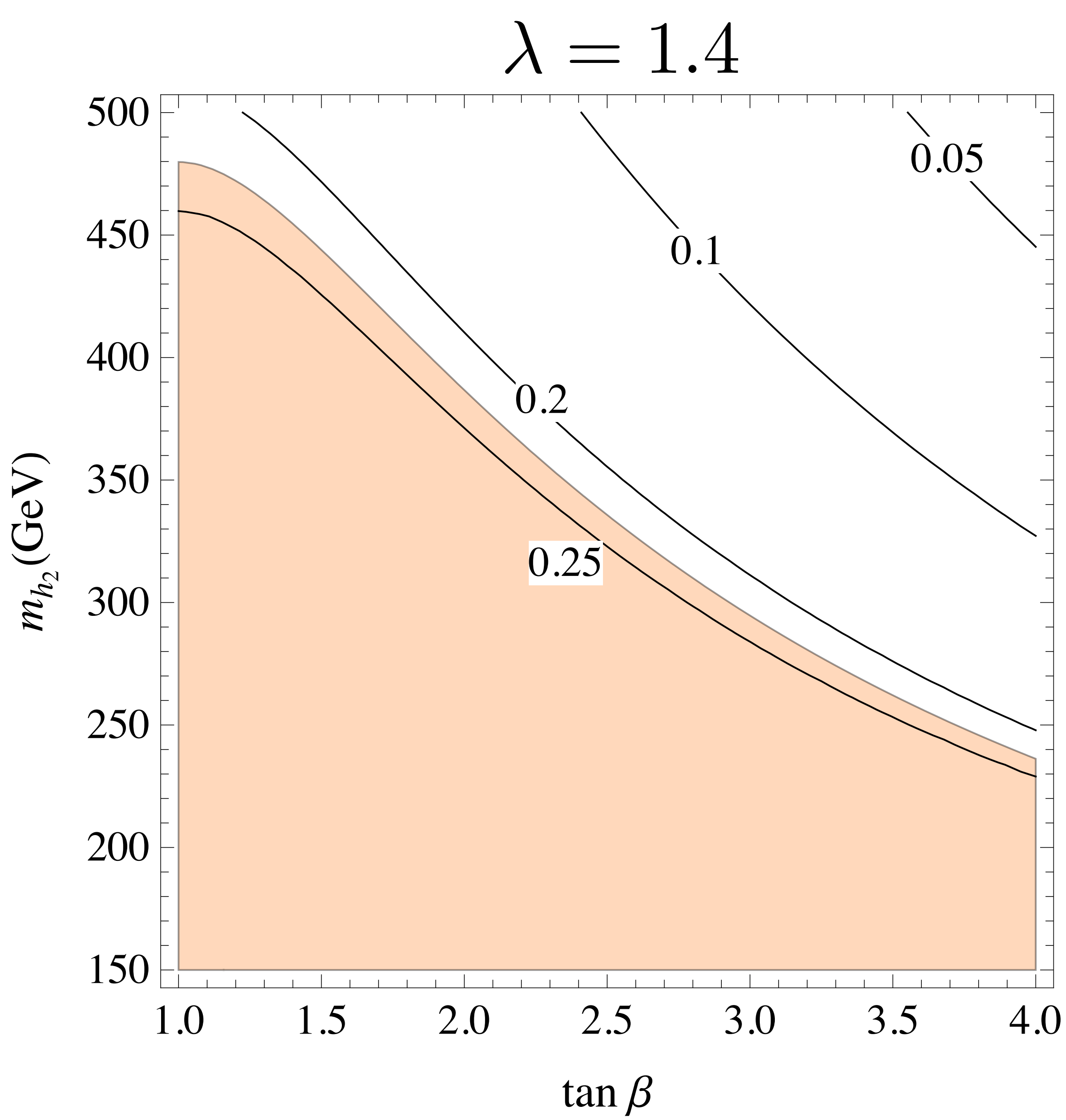
Doublet decoupled $m_A^2 \gg \lambda^2 v^2$ and $\delta, \sigma \to 0$

$$\sin^2\gamma = \frac{m_{hh}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_1}^2} \quad \text{where } m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + v^2\lambda^2$$

One relation less w.r.t. S decoupled case: one more free parameter.

$\gamma, m_{H^\pm} = \gamma, m_{H^\pm}(m_{h_2}, \lambda, \tan\beta, \Delta_t)$ $\Delta_t \approx 75\,\text{GeV}$ $m_{h_1} < m_{h_2}$



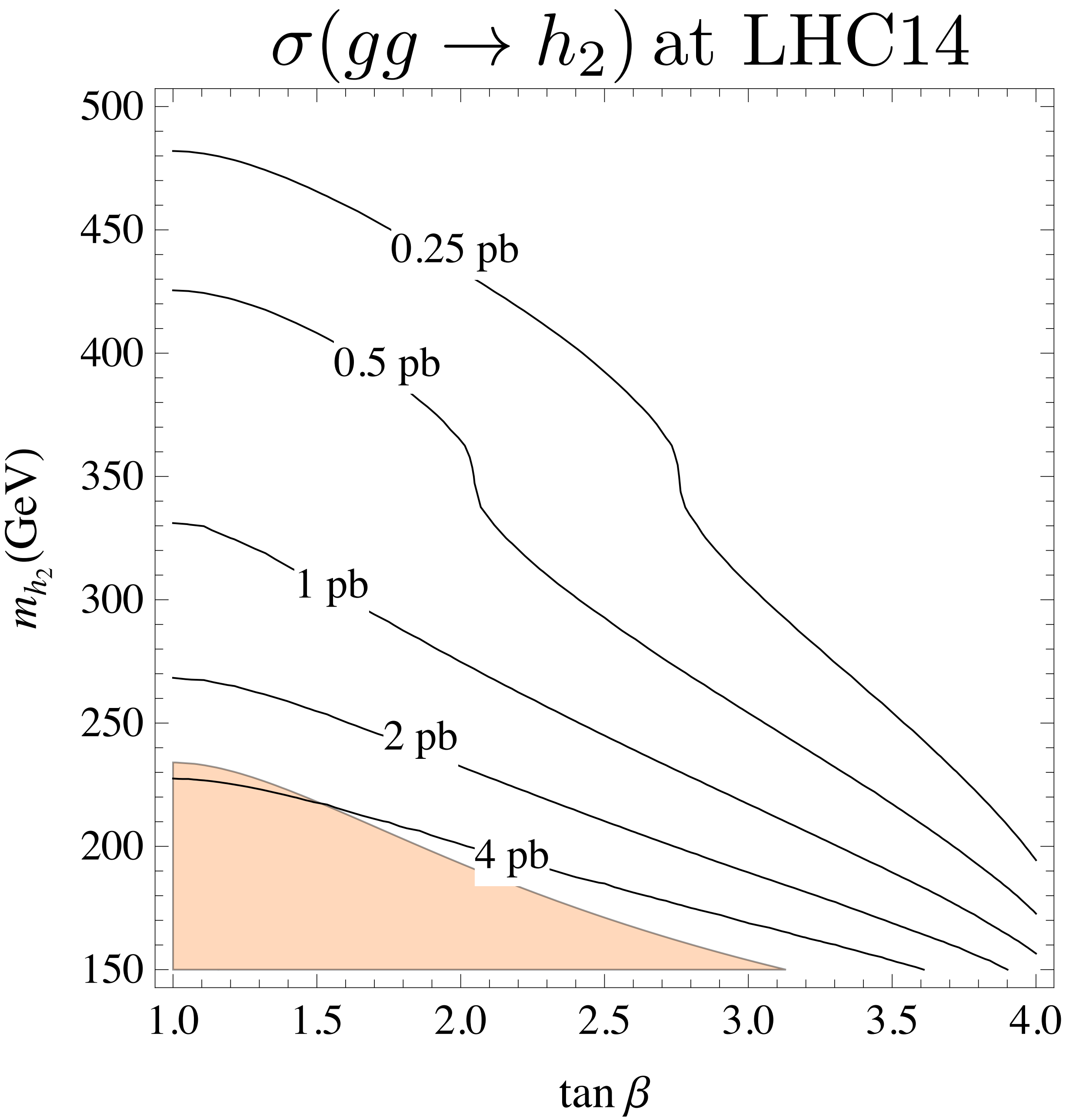


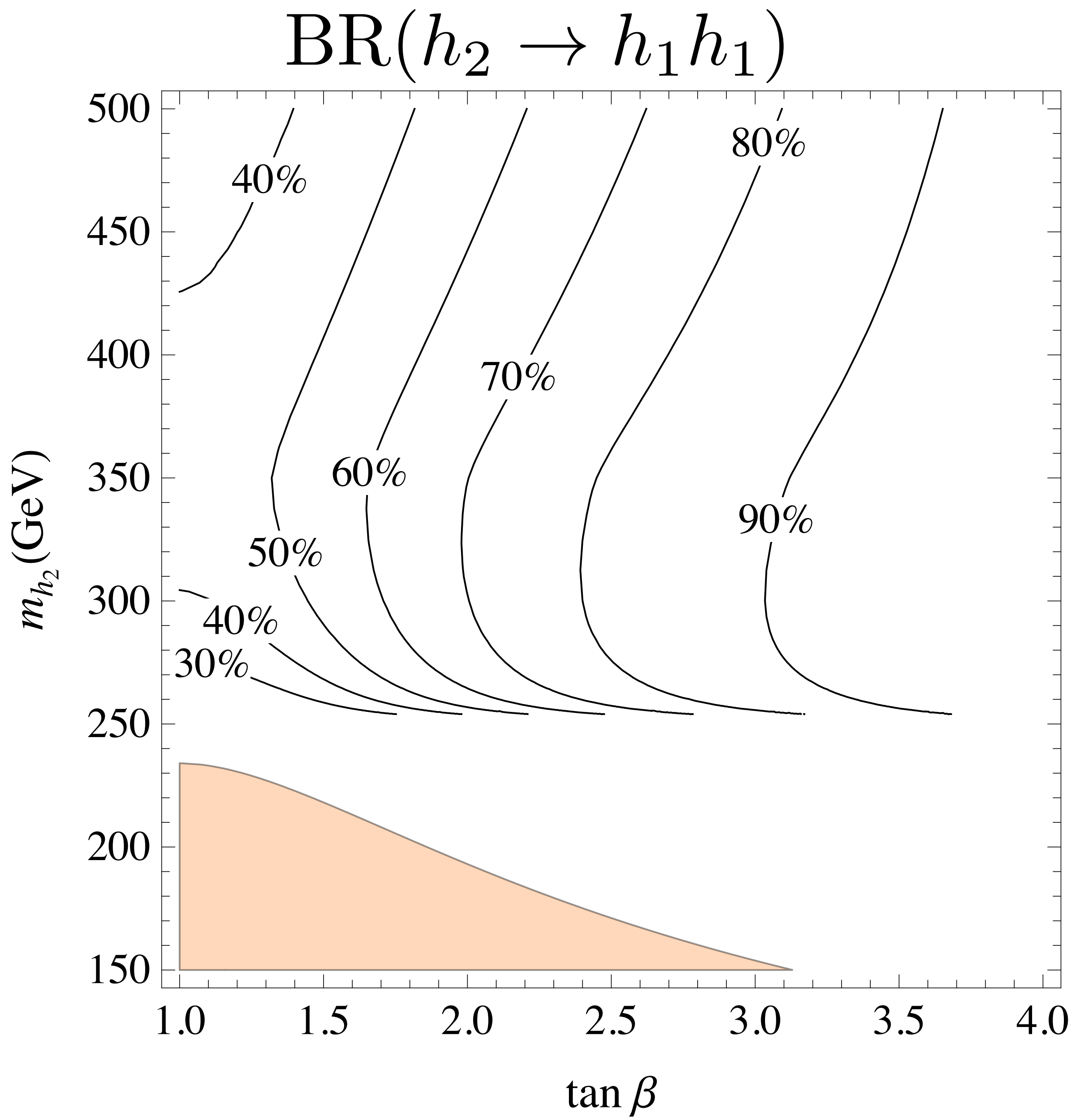
H decoupled: direct searches

$m_{h_1} < m_{h_2}$

Small cross-section, but... $h_2 \to h_1 h_1 \to b\bar{b}b\bar{b}$ may be observable
(no big improvement on $\sin^2\gamma$ at 14 TeV)

$\lambda = 0.8$





Other relevant decay mode into a vector boson pair

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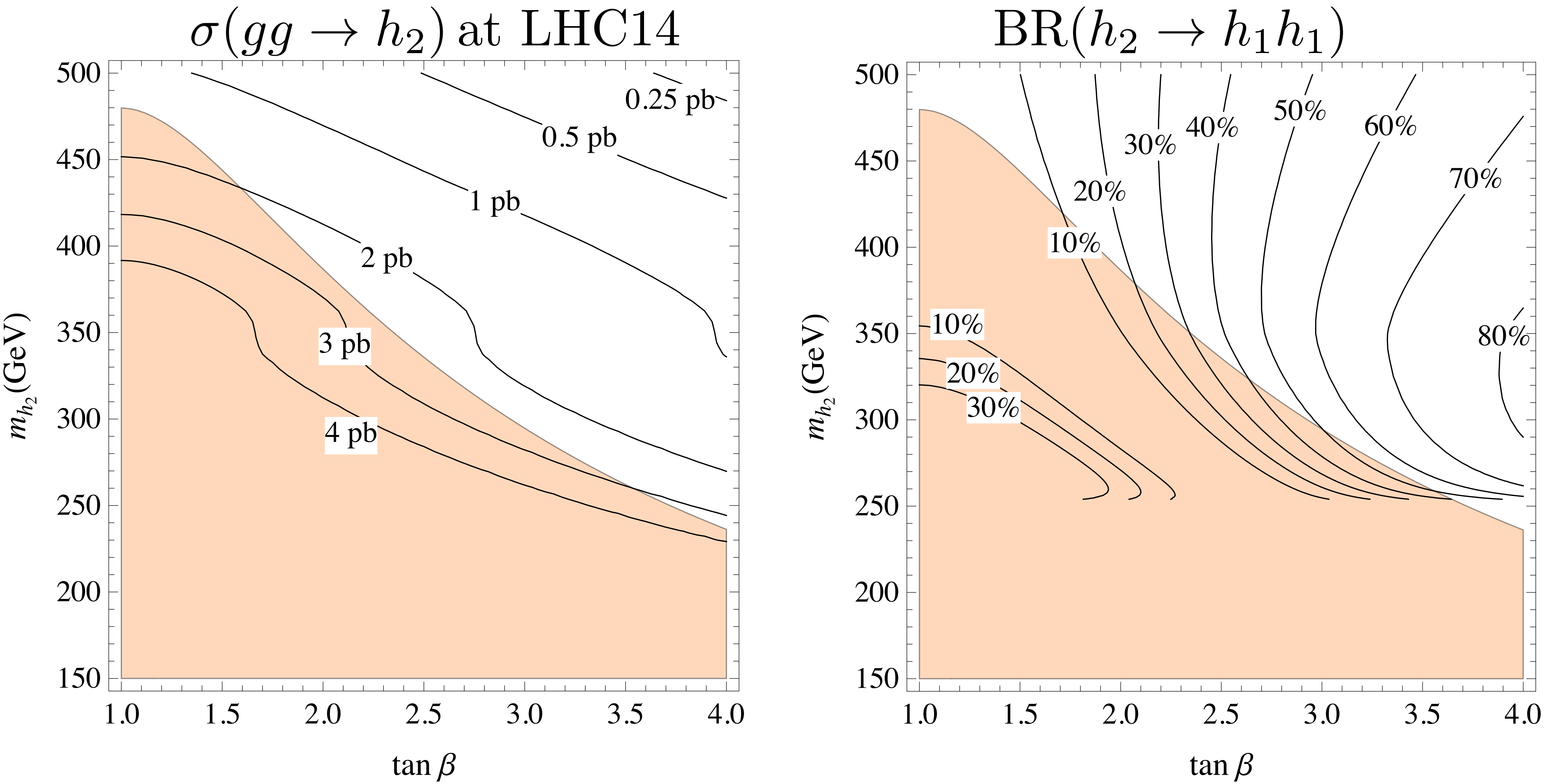
$\lambda = 1.4$

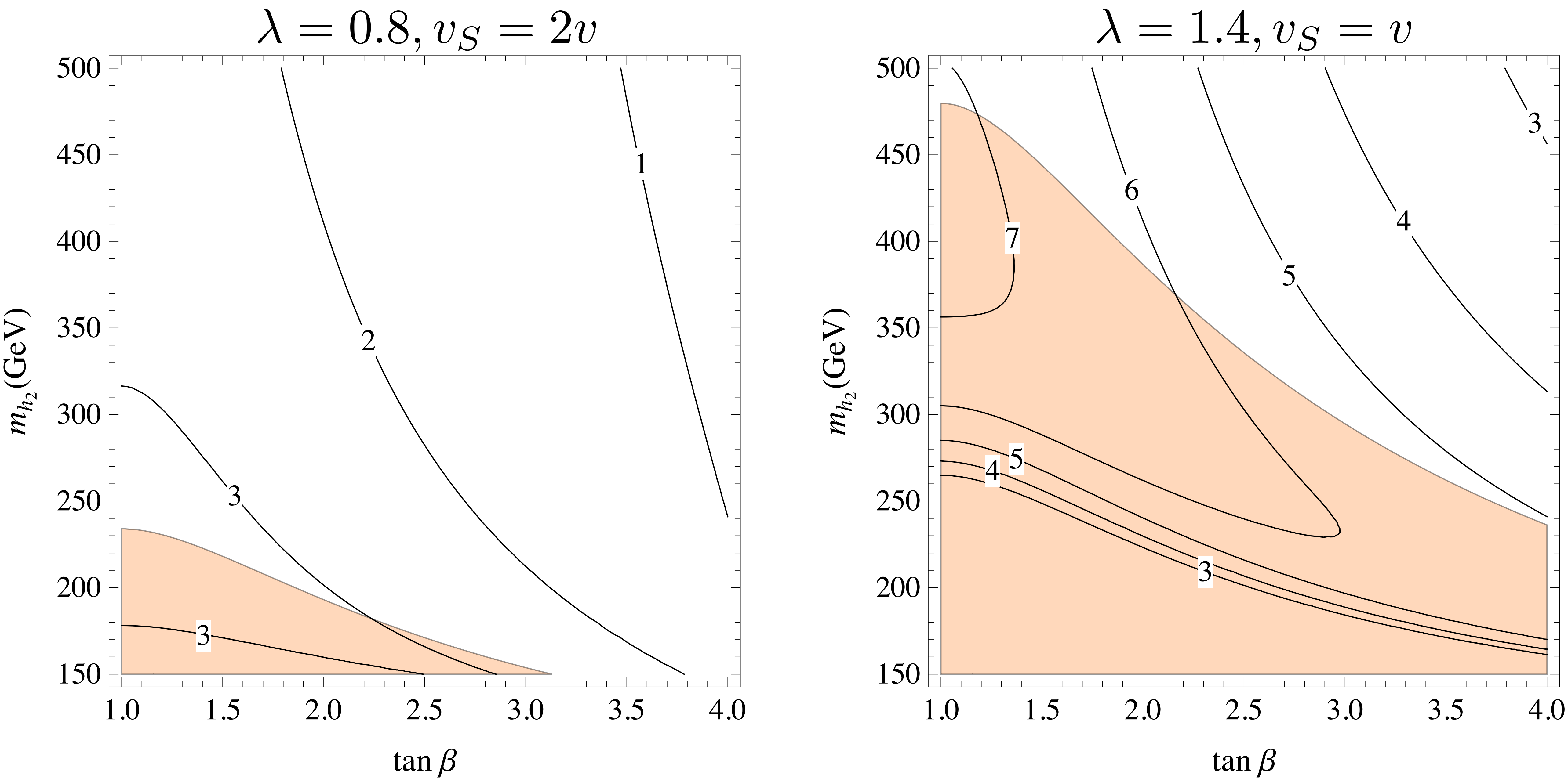


Other relevant decay mode into a vector boson pair

H decoupled: modified $h_1{}^3$ coupling

Significant deviations from 1 of $\frac{g_{h_1 h_1 h_1}}{g_{hhh}^{\text{SM}}}$ are possible. $m_{h_1} < m_{h_2}$

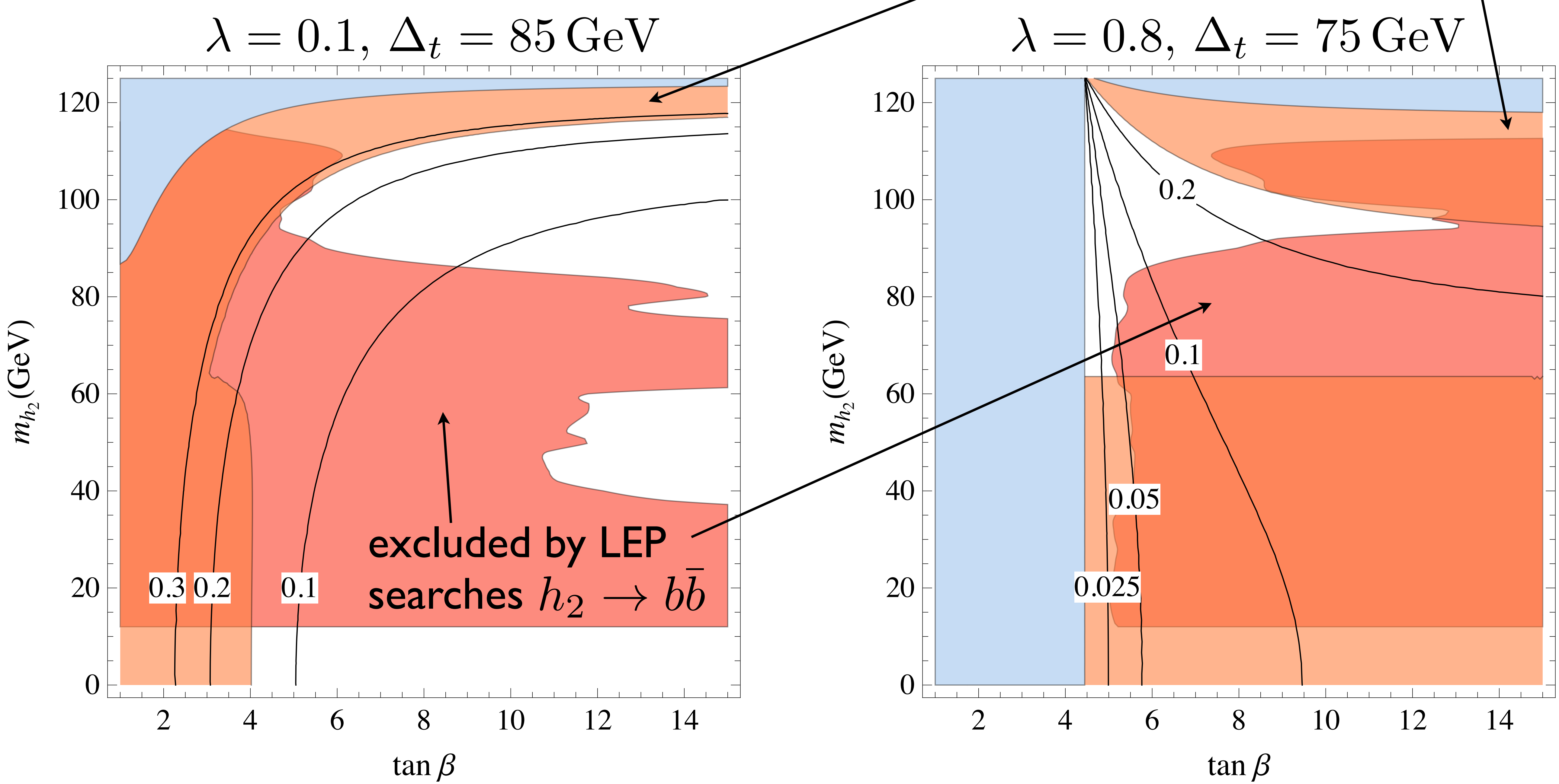
(There is a dependence on the parameters of the S potential...)



What if h_{LHC} is not the lightest one?

$m_{h_1} > m_{h_2}$

- In MSSM and S-decoupled very disfavored by light $H^{\pm}$
- H decoupled (small and large λ)

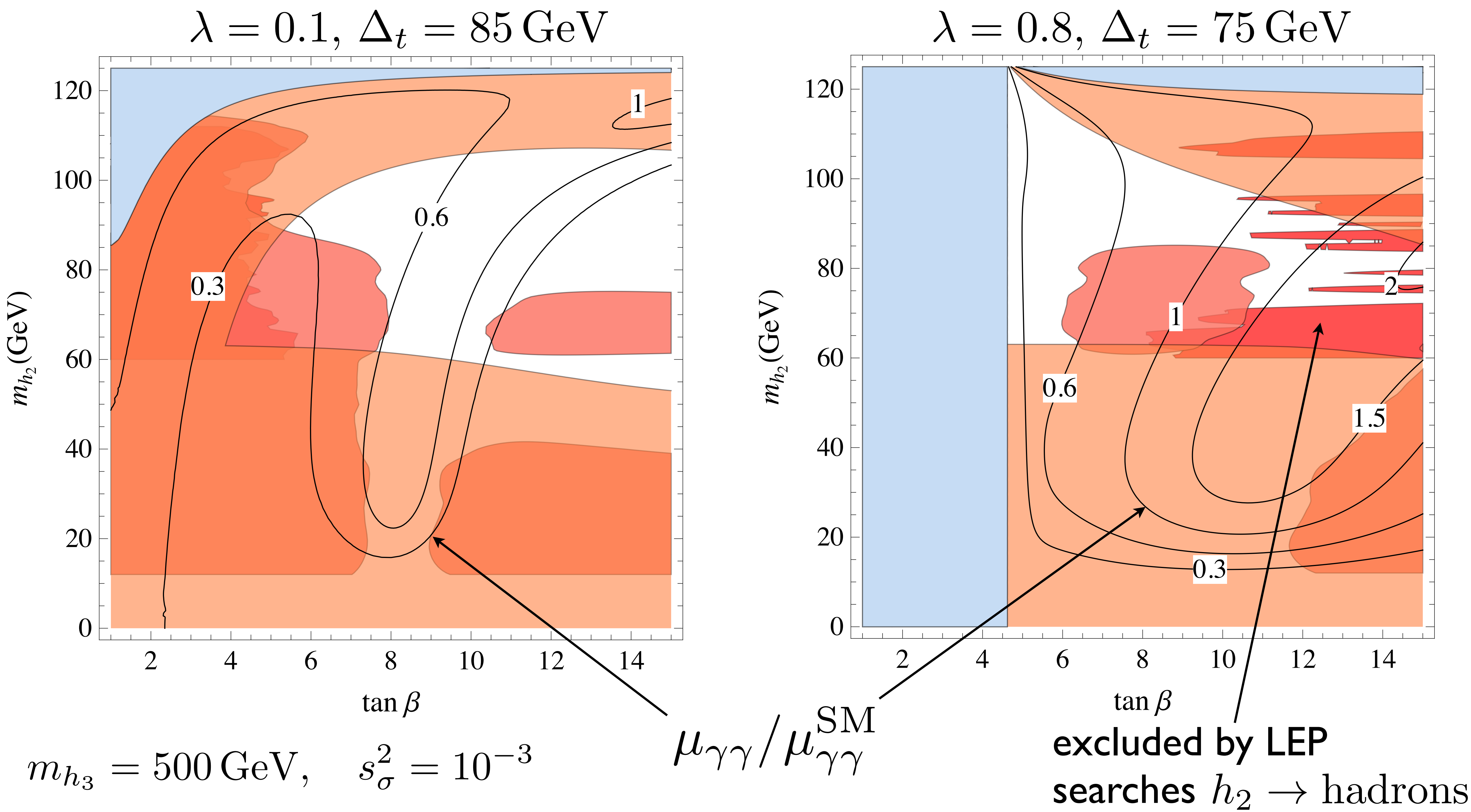


All the signals scale like $\mu_i(h_2) = \sin^2\gamma\, \mu_i(h_{\text{SM}})$, difficult search at the LHC

What if h_{LHC} is not the lightest one?

- 3-state mixing: μ's are different than in the SM, search for $h_2 \to \gamma\gamma$ may be possible.

see also Badziak et al.'13
→ Badziak's talk



$m_{h_3} = 500\,\text{GeV}, \quad s_\sigma^2 = 10^{-3}$

Conclusions and outlook

Are there extra scalar bosons? How to answer this question in natural SUSY?

- NMSSM insisting on physical parameters, 2 limiting cases.
- Fit of Higgs couplings still allows for light h_2, h_3 (not in MSSM)
  - almost entire parameter space covered by LHC14 in S decoupled and MSSM (not in H decoupled),
  - no substantial changes to the fit in full 3-state mixing case.
- Discovery looks challenging: need improved collider studies
  - $h_2 \to h_1 h_1$ if H decoupled,
  - $h_3 \to f\bar{f}$ if S decoupled (~ MSSM).
- Still possible that $m_{h2} < m_{h1}$ (or $m_{h3} < m_{h1}$).

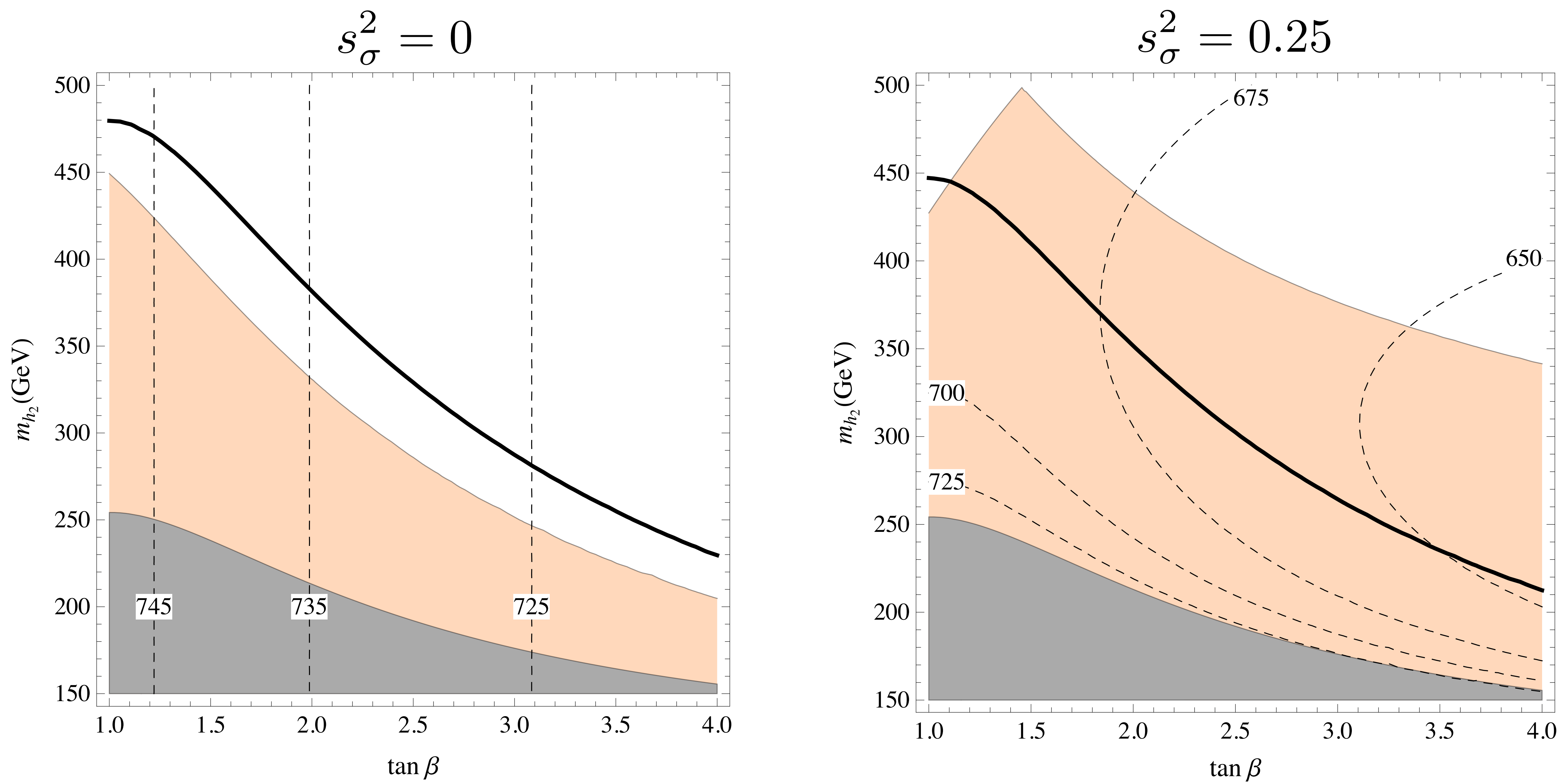
Backup

General case: 3-state mixing

$m_{h_1} < m_{h_2}$

- Milder bounds when both δ and γ are different from zero
- If also $\sigma \neq 0$, h_2 and h_3 are not decoupled, their masses are correlated

$m_{h_3} = 750\,\text{GeV}, \lambda = 1.4$



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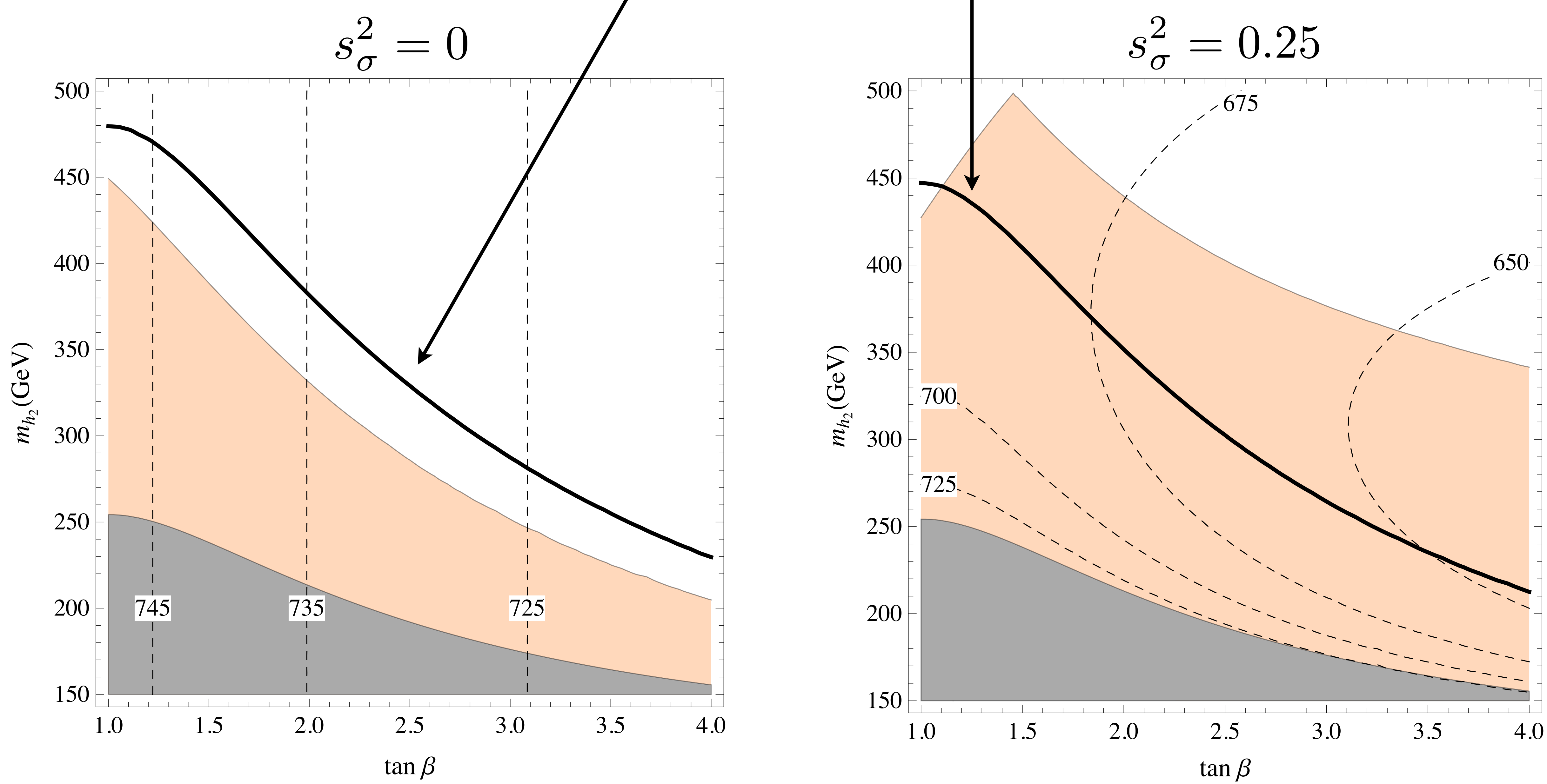
Naïve exclusion from γ only



ElectroWeak Precision Tests

Relevant contribution from loops of the new Higgses?

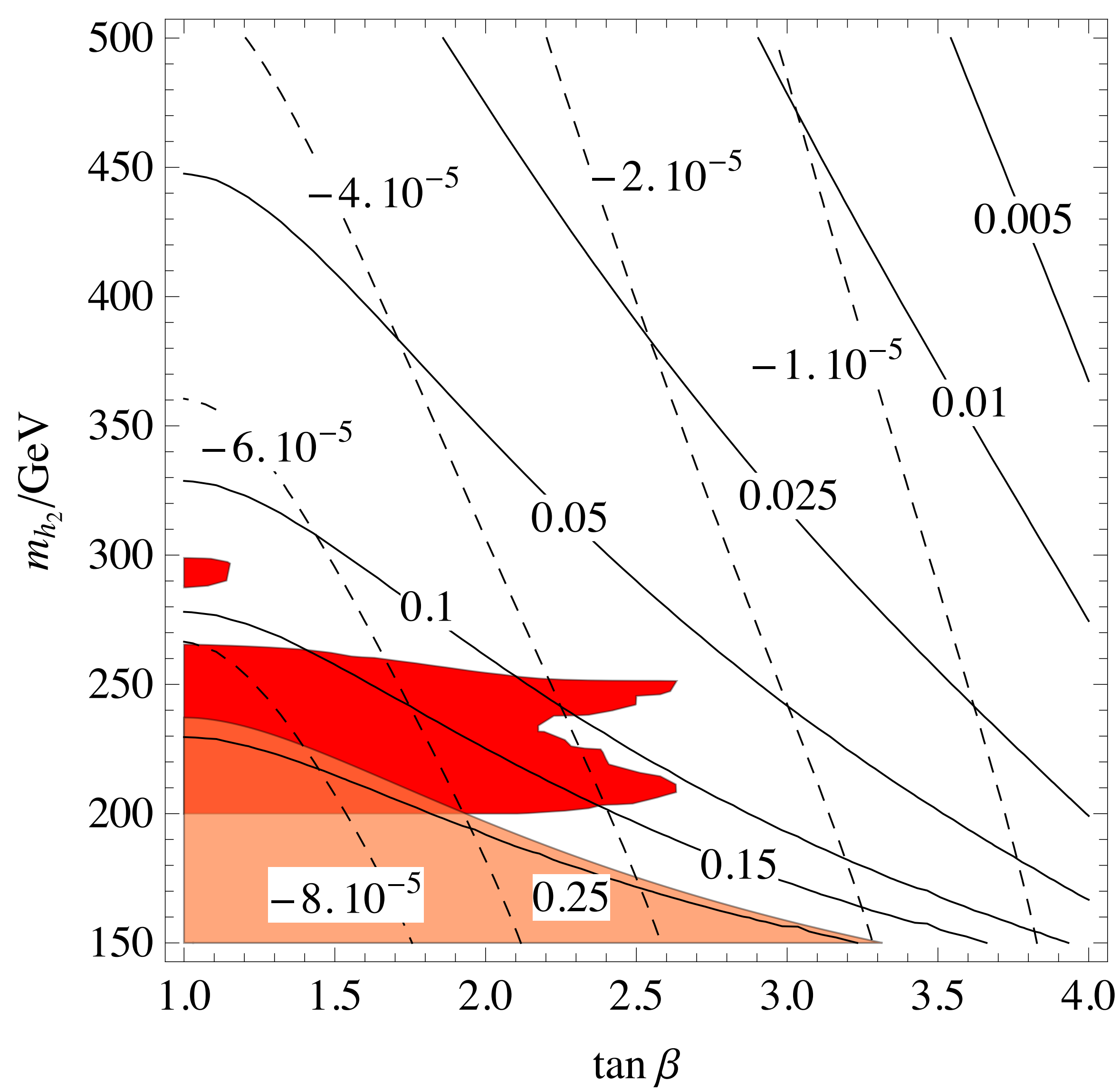
- H decoupled: couplings scale as $\sin^2\gamma\ (\cos^2\gamma)$

$$\Delta\hat{S} = \frac{\alpha}{48\pi s_w^2}\sin^2\gamma\log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2},$$

$$\Delta\hat{T} = -\frac{3\alpha}{16\pi c_w^2}\sin^2\gamma\log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2}$$

- S decoupled: larger effects possible in general,
  but limits on the mixing angle
  $\delta\simeq 0 \ \Rightarrow$ no new constraint

Barbieri, Tesi '13



ElectroWeak Precision Tests

Relevant contribution from loops of the new Higgses? NO ✓

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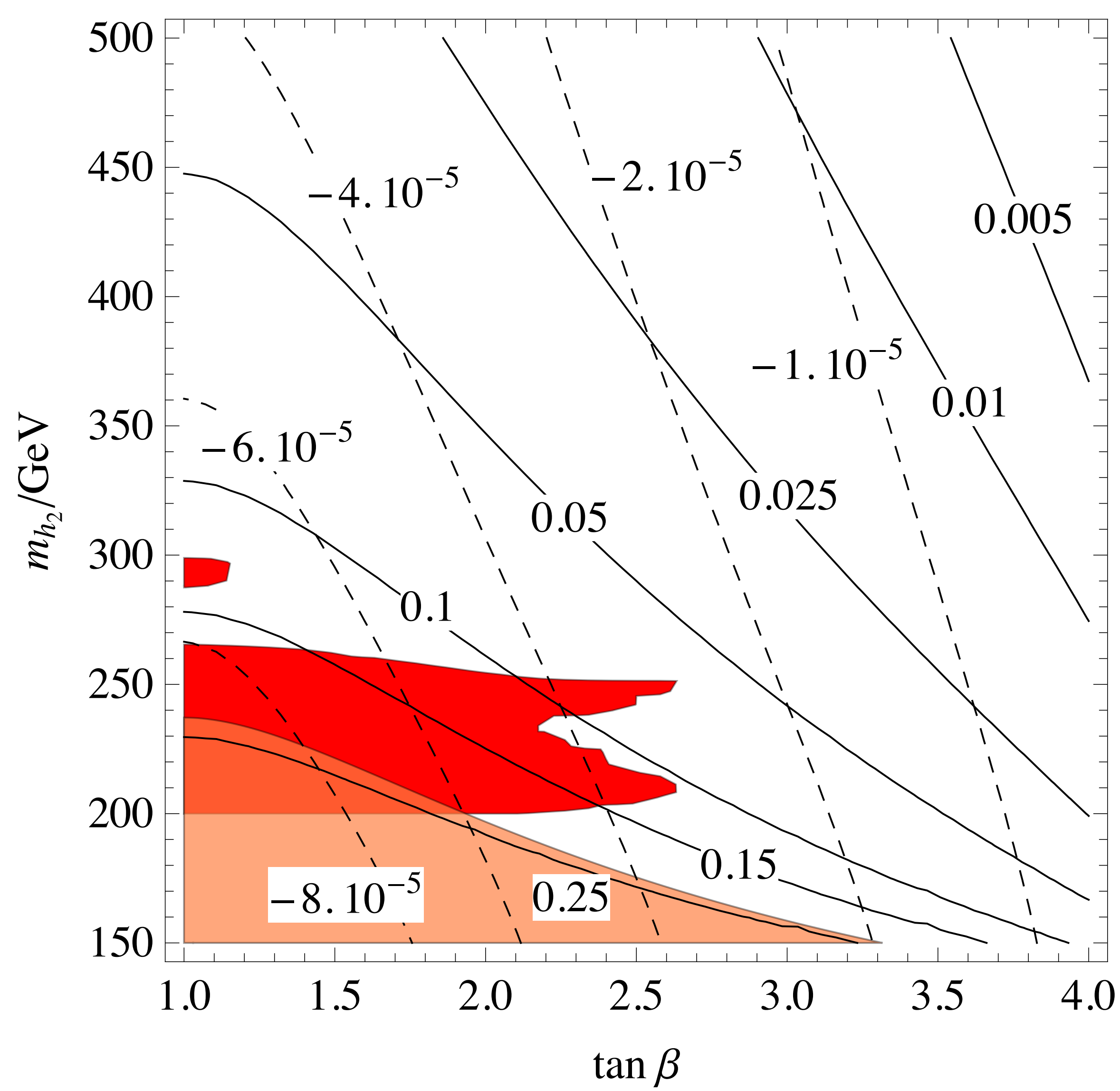
Barbieri, Tesi ‘13



- S decoupled: larger effects possible in general, but limits on the mixing angle $\delta \simeq 0 \ \Rightarrow$ no new constraint

General solutions for the mixing angles

$$s_\gamma^2 = \frac{\det M^2 + m_{h_1}^2(m_{h_1}^2 - \mathrm{tr} M^2)}{(m_{h_1}^2 - m_{h_2}^2)(m_{h_1}^2 - m_{h_3}^2)},$$

$$s_\sigma^2 = \frac{m_{h_2}^2 - m_{h_1}^2}{m_{h_2}^2 - m_{h_3}^2} \frac{\det M^2 + m_{h_3}^2(m_{h_3}^2 - \mathrm{tr} M^2)}{\det M^2 - m_{h_2}^2 m_{h_3}^2 + m_{h_1}^2(m_{h_2}^2 + m_{h_3}^2 - \mathrm{tr} M^2)},$$

$$\begin{aligned}\sin 2\alpha = &\Big(\pm 2|s_\gamma s_\sigma| \sqrt{1 - s_\sigma^2}\sqrt{1 - \sin^2 2\xi}(m_{h_3}^2 - m_{h_2}^2) \\ &+ \left[m_{h_3}^2 - m_{h_2}^2 s_\gamma^2 + s_\sigma^2(1 + s_\gamma^2)(m_{h_2}^2 - m_{h_3}^2) - (1 - s_\gamma^2)m_{h_1}^2\right] \sin 2\xi\Big) \\ &\times \Big(\left[m_{h_3}^2 - m_{h_1}^2 + s_\gamma^2(m_{h_1}^2 - m_{h_2}^2)\right]^2 + (m_{h_3}^2 - m_{h_2}^2)(1 - s_\gamma^2)s_\sigma^2 \\ &\times \left[2m_{h_1}^2(1 + s_\gamma^2) - 2(m_{h_3}^2 + s_\gamma^2 m_{h_2}^2) + s_\sigma^2(m_{h_3}^2 - m_{h_2}^2)(1 - s_\gamma^2)\right]\Big)^{-1/2}\end{aligned}$$

where M is the 2x2 submatrix of $\mathcal{M}$ in the 1-2 sector
(contains the dependence on λ and Δ_t)

Sketch of a model for λ ~ 1

- Field content: NMSSM + vector-like F_u ~ **5**, F_d ~ **5** of SU(5)

$$F_u \supset h_u, \quad F_d \supset h_d$$ with same quantum numbers as H_u, H_d

- PQ-symmetric superpotential W, SU(5) broken only by mixings m_u, m_d

$$W = \lambda_S S F_u F_d + M_u F_u \bar{F}_u + M_d F_d \bar{F}_d + m_u H_u \bar{h}_u + m_d H_d \bar{h}_d + \lambda_t H_u \bar{Q} t$$

  - $S, \hat{H}_u = c_u H_u + s_u h_u, \hat{H}_d = c_d H_d + s_d h_d$ are massless
  - $\hat{W} = \lambda S \hat{H}_u \hat{H}_d + y_t \hat{H}_u \bar{Q} t, \qquad \lambda = \lambda_S s_u s_d, \quad y_t = \lambda_t c_u$

- Add PQ-breaking soft terms at the Fermi scale

Growth of λ cured above $M_{u,d}$, $m_{u,d}$ < 1000 TeV (λ < 1.5)