One or more Higgs bosons?

Beyond the SM after the first run of the LHC

GGI, July 9-12, 2013

Riccardo Barbieri
SNS and INFN, Pisa

B, Buttazzo, Kannike, Sala, Tesi 2013

Conclusion (no lack of ? marks)

1. The discovery of the Higgs boson:

Is it the coronation of the Standard Model
OR
a first step towards unexplored territory?

2. Natural or unnatural theories?

before accepting a shift of paradigm,
useful to be patient and careful (but courageous as well)

3. One or more Higgs bosons?

could be the lightest new particle(s) around

4. What about the flavour puzzle?

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

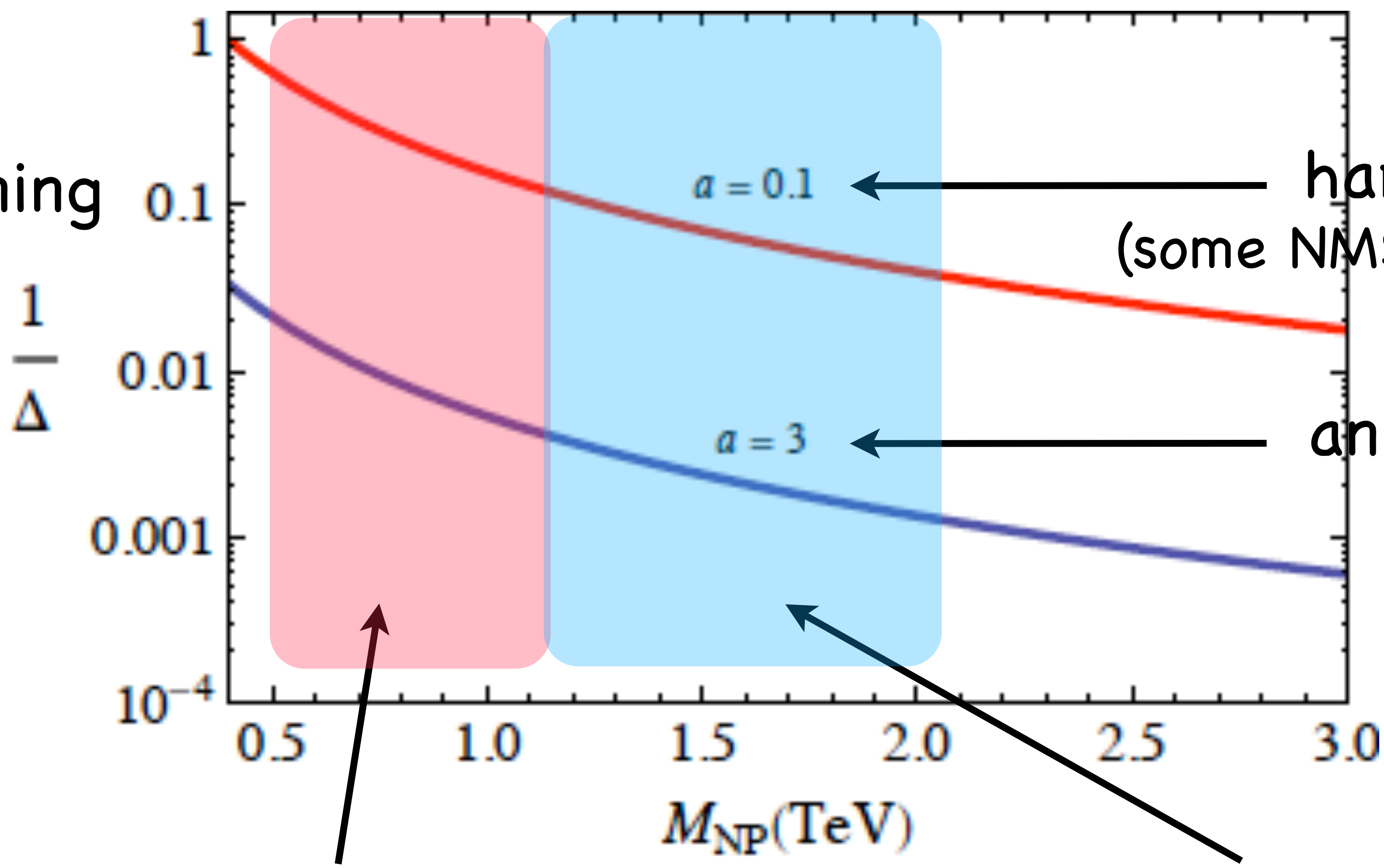
A quantitative measure (!?) of naturalness

$$\delta m_h^2 \approx a M_{NP}^2 < \Delta m_h^2$$

model dependent

a measure of fine tuning
(which exist in nature)

fine tuning



hard to achieve
(some NMSSM gets to 0.2-0.3)

an indicative MSSM

≈ LHC now

≈ LHC14 (?)

NMSSM $\Delta f = \lambda H_u H_d$

Fayet 1975

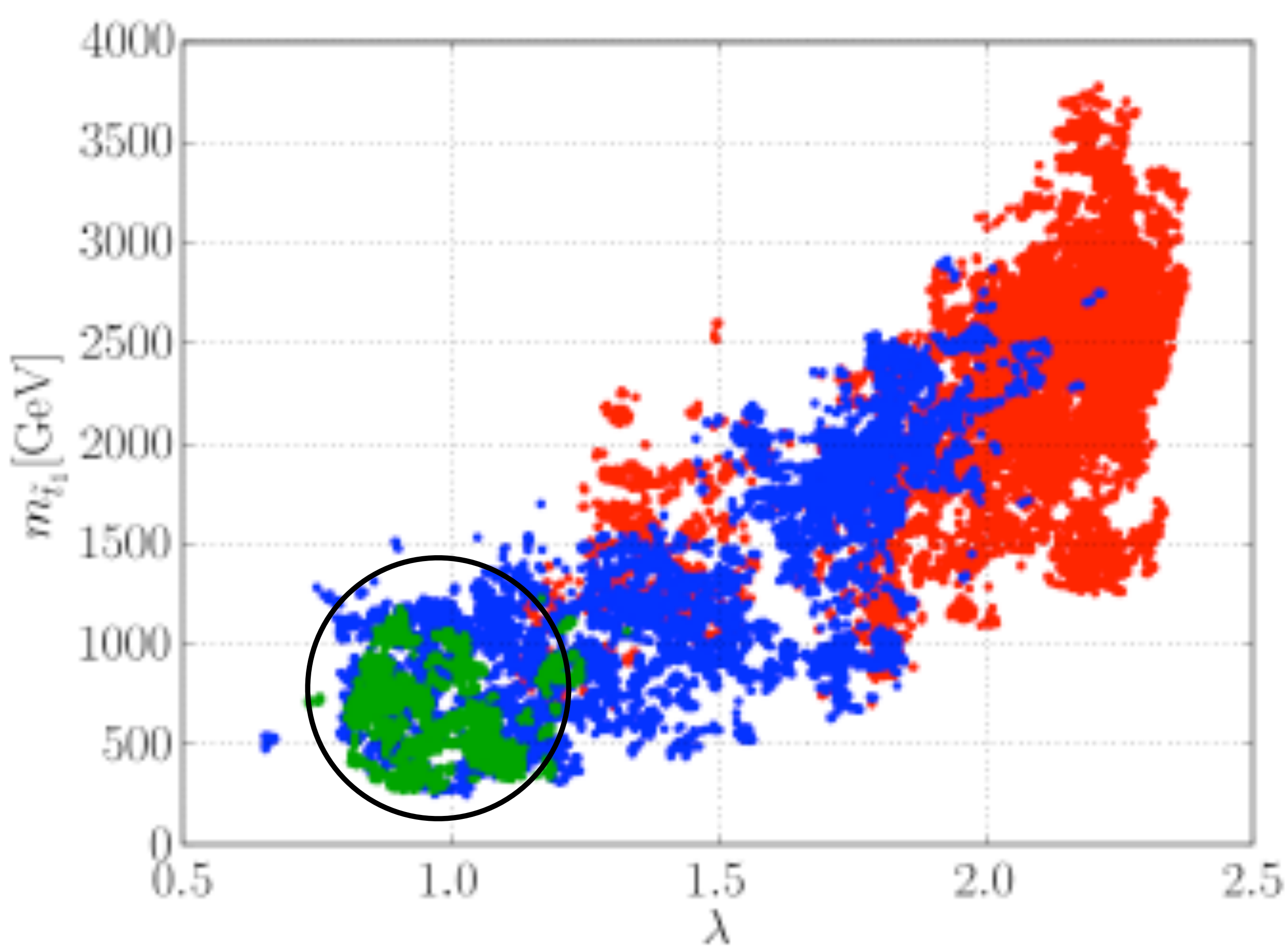
Two independent reasons to consider it:

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 $\lambda \approx 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{1}{\lambda^2} \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$

B, Hall, Nomura, Rychkov 2007



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

The pro's for just one Higgs boson

1. simplicity

How about the 12 (18) matter and the 12 (3) vector states?

2. electromagnetism always preserved

From 2 to 3 phases only

3. flavour

No big reason to be proud of the λ_{ij}

4. a single tuning, in case

None is better, which often demands more Higgs bosons

Can some extra Higgs bosons be the lightest new particles around?

Two ways to attack the problem

⇒ By direct search $pp \to h_{\neq LHC} + X$

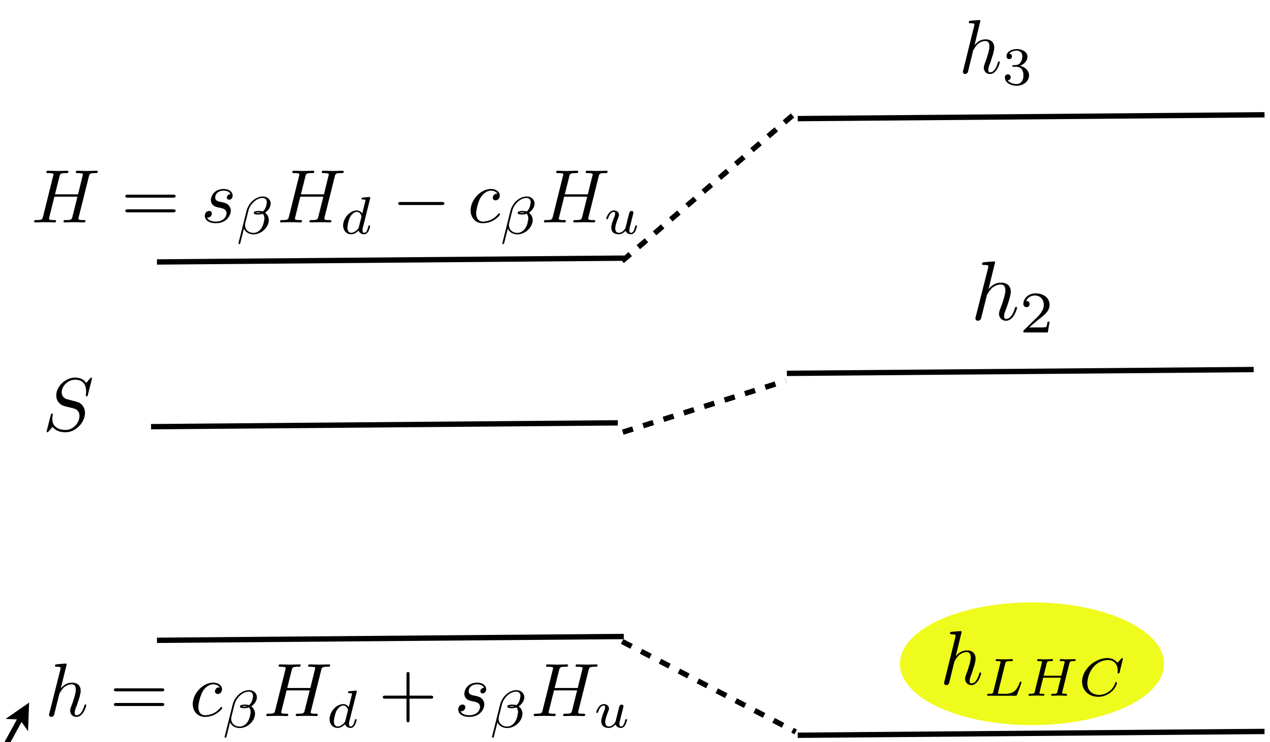
$\hookrightarrow$ decay products

(perhaps itself in the decay products of...)

⇒ By precision measurements of the couplings of the 125 GeV (quasi-standard) Higgs boson

(the NMSSM example)

$\lambda S H_u H_d$



has SM properties

Purpose

Outline an overall strategy

See the impact of the $\mu(h_{LHC})$'s

Look at connection with the EWPT

How to deal with the plethora 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 rad. corr.)

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

general NMSSM (with CP ≃ OK)

$$(H_d^0, H_u^0, S)^T = R_\alpha^{12} R_\gamma^{23} R_\sigma^{13} (h_3, h_1, h_2)^T \qquad h_1 \equiv h_{LHC}$$

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

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

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

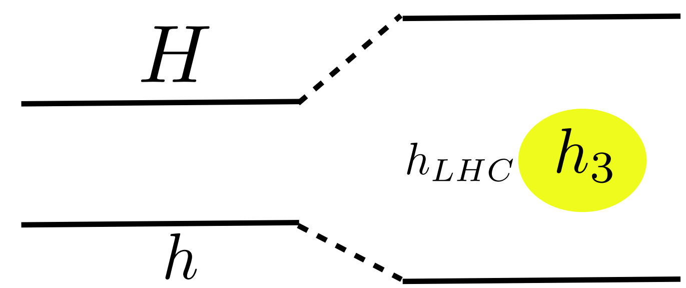
$$\Rightarrow \; \alpha, \gamma, \sigma = \alpha, \gamma, \sigma(m_i^2, m_{H^+}^2; \tan\beta, \lambda, \Delta_t)$$

An orientation table

S-"decoupled" (similarities with the MSSM)

$$h_3 < h_{LHC} < h_2(\approx S)$$

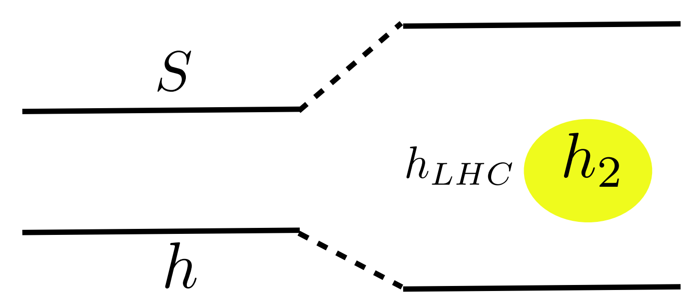
$$h_{LHC} < h_3 < h_2(\approx S)$$



H-"decoupled"

$$h_2 < h_{LHC} < h_3(\approx H)$$

$$h_{LHC} < h_2 < h_3(\approx H)$$



with comments on full triple mixing

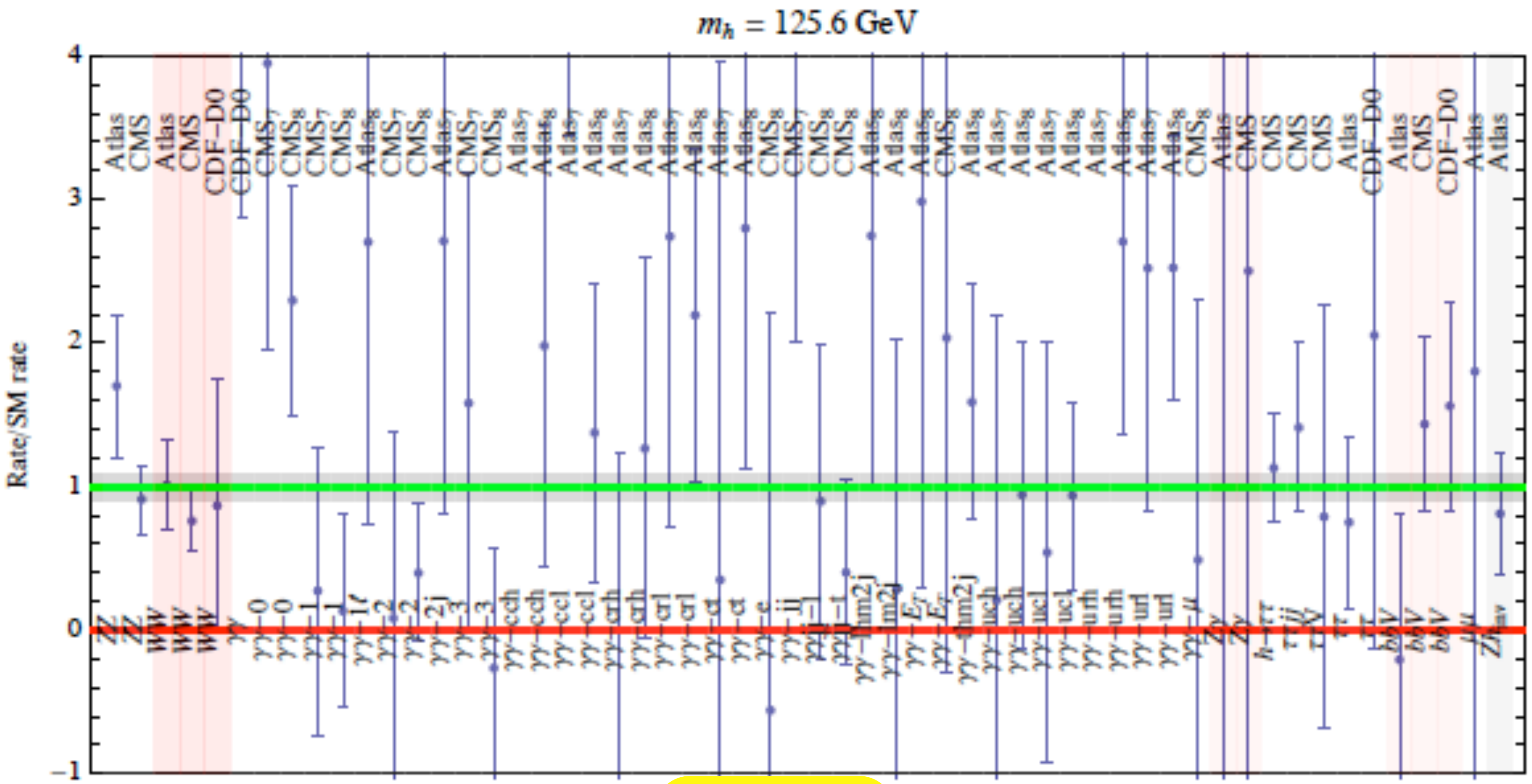
(no "invisible" decays)

(CP-odd not considered)

The signal strengths of h_{LHC}

From a theorist's informal combination of ATLAS&CMS data

Giardino, Kannike, Masina, Raidal, Strumia 2013

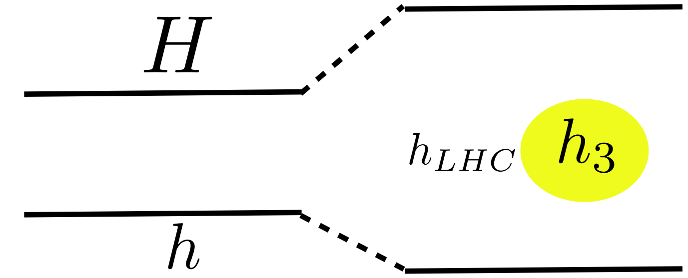


now

	ATLAS	CMS
$h \to \gamma\gamma$	0.16	0.15
$h \to ZZ$	0.15	0.11
$h \to WW$	0.30	0.14
$Vh \to Vb\bar{b}$	–	0.17
$h \to \tau\tau$	0.24	0.11
$h \to \mu\mu$	0.52	–

projected errors after $300\ fb^{-1}$ at LHC14

NMSSM at variable λ S-decoupled

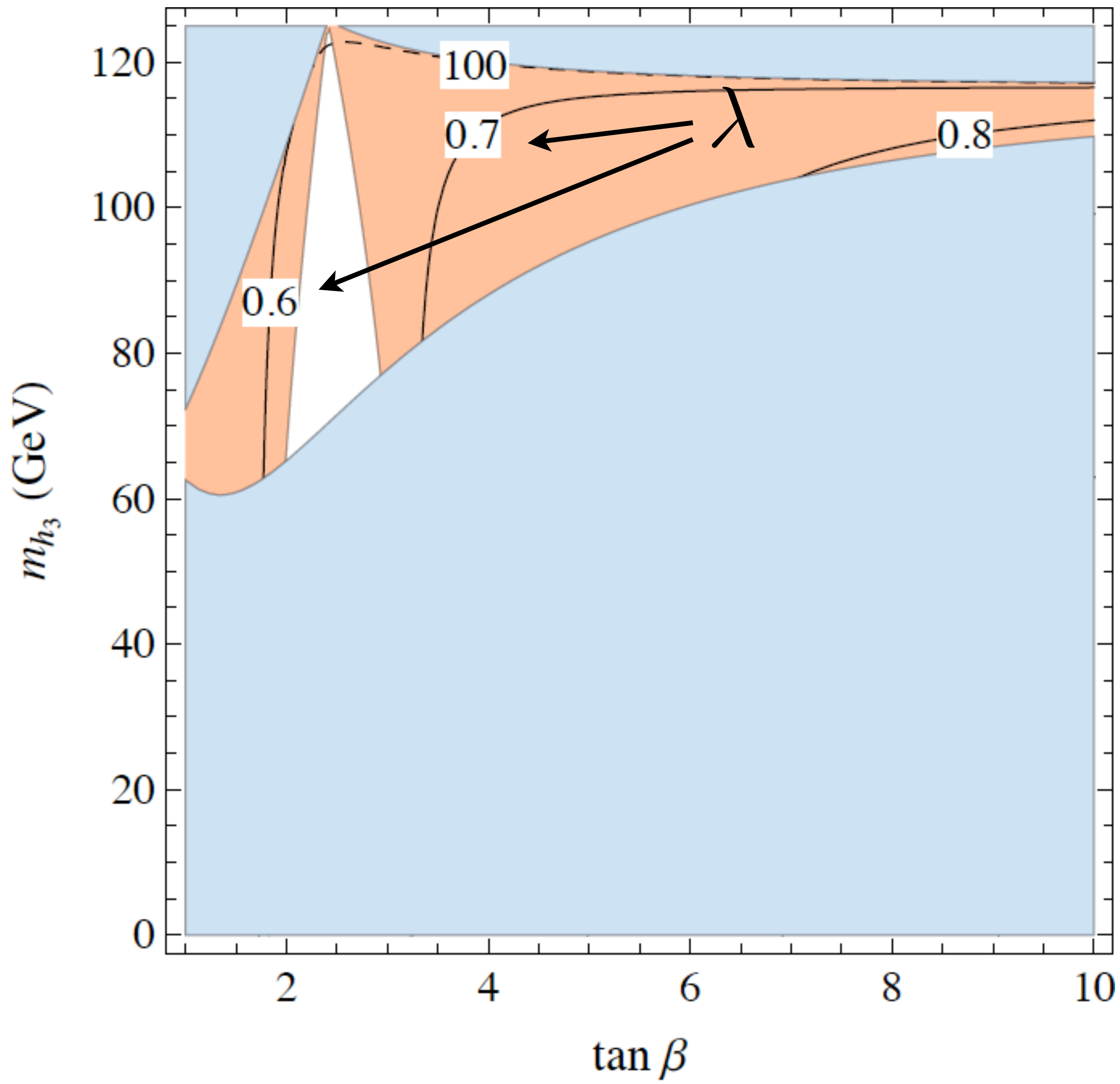


knowing $m_{h_{LHC}} \Rightarrow m_{h_3}, m_{H^+}, \alpha = m_{h_3}, m_{H^+}, \alpha(\tan\beta, \lambda, \Delta_t)$

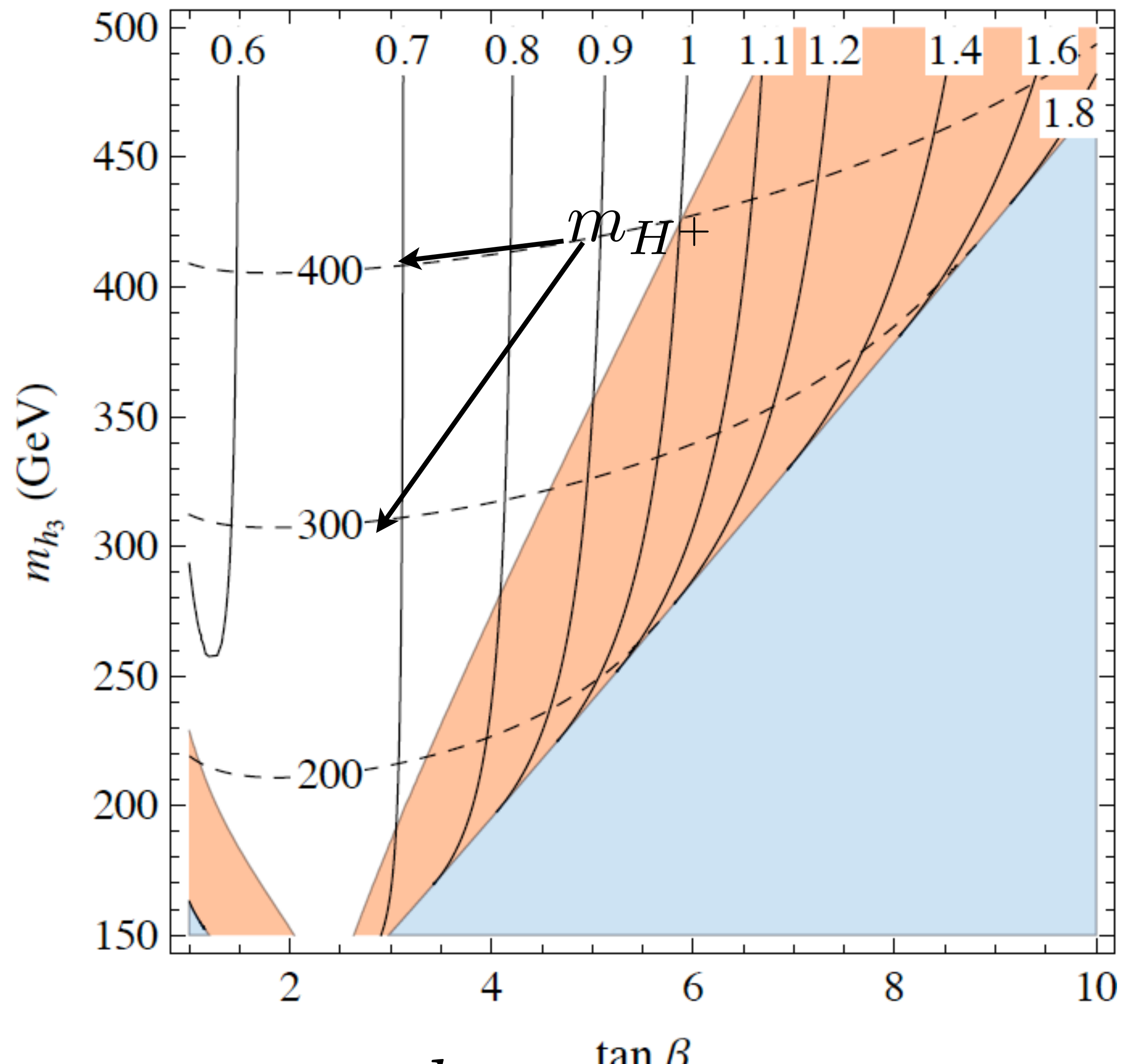
$\left(\frac{\mu A_t}{< m_{\tilde{t}}^2 >} \lesssim 1\right)$

$\Delta_t \leq 75\ GeV$ almost irrelevant

$h_3 < h_{LHC}(< h_2(\approx S))$



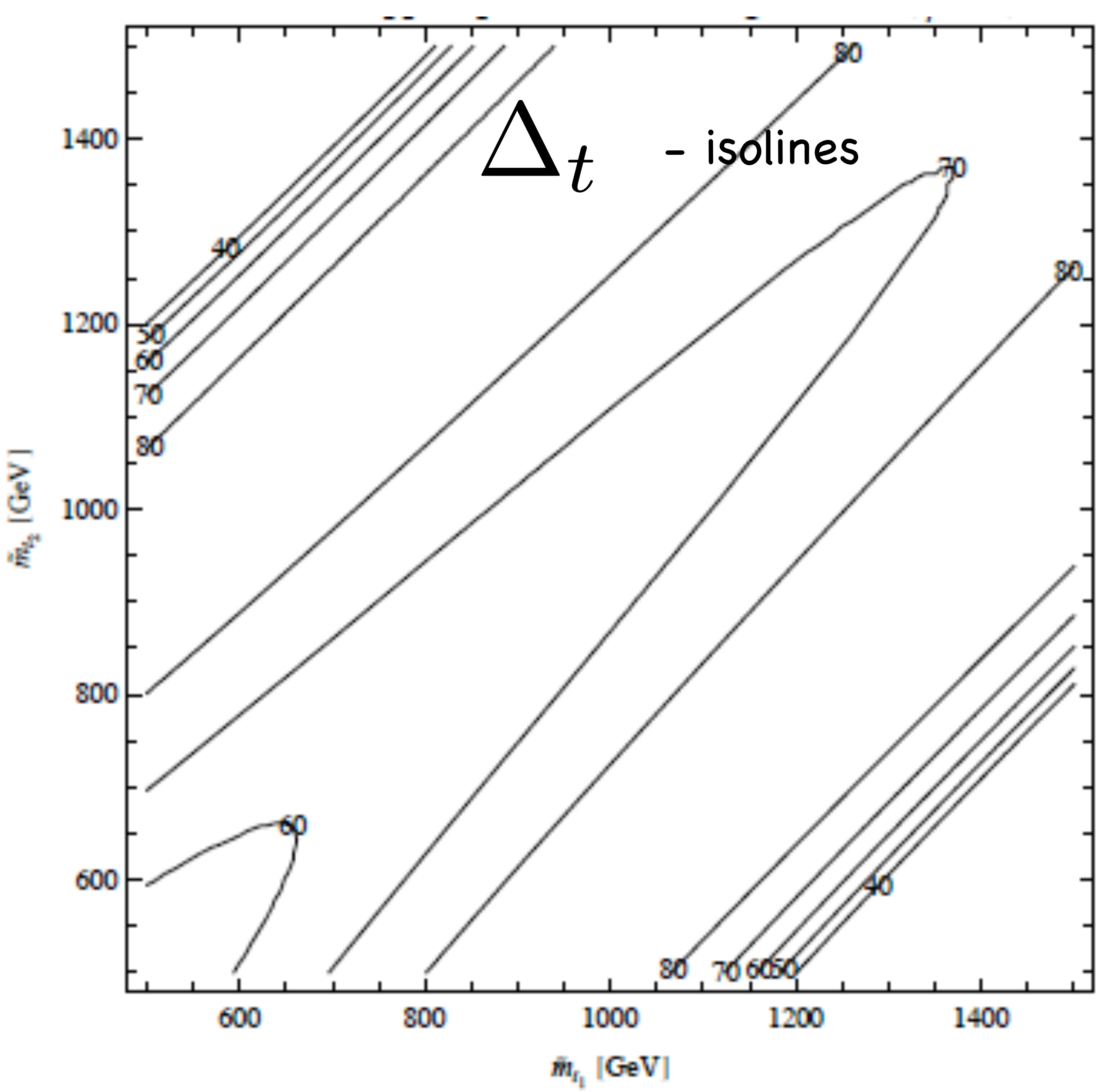
$h_{LHC} < h_3(< h_2(\approx S))$



orange = excluded by h_{LHC} - measurements

blue = unphysical

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



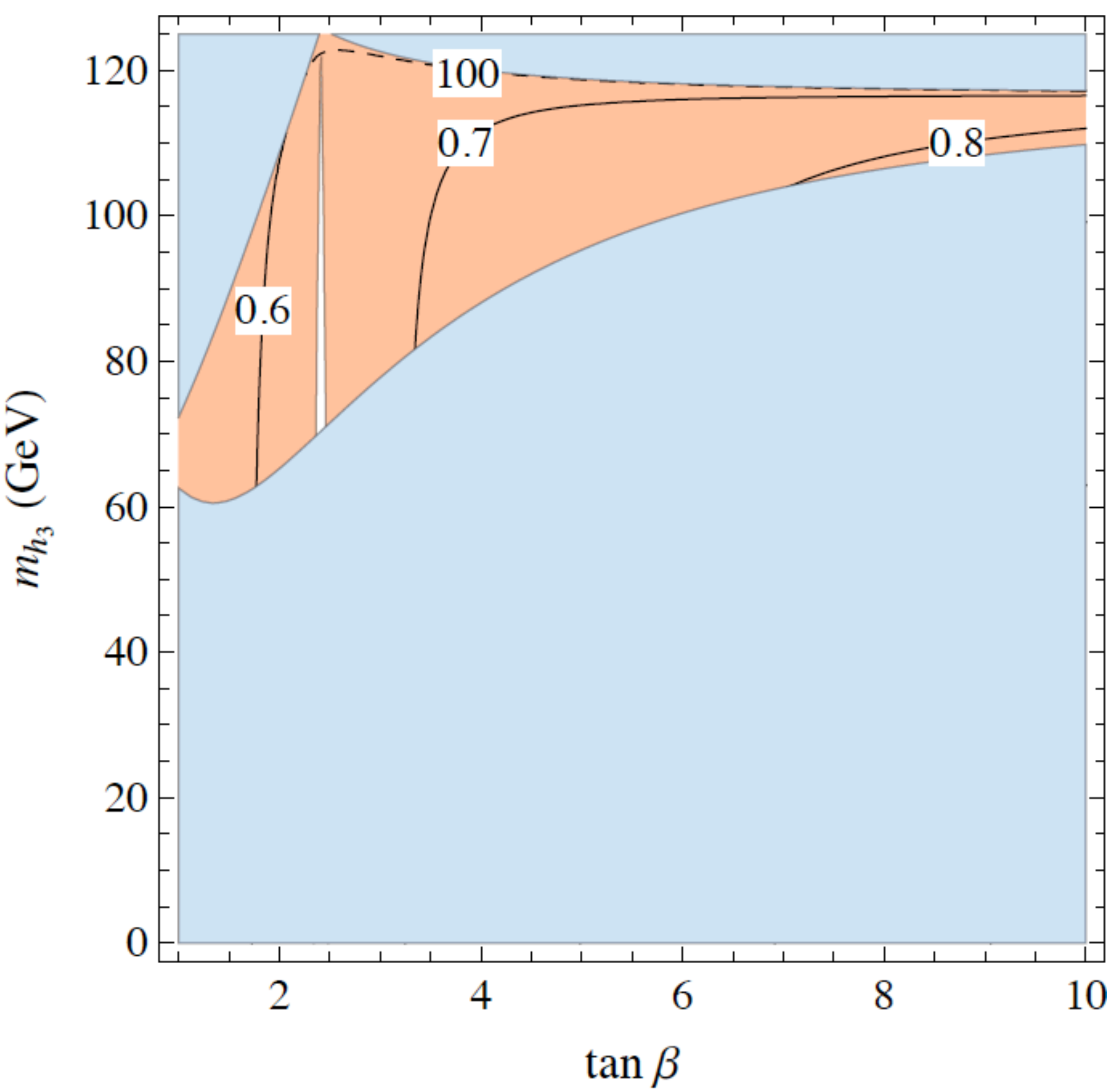
$\theta_t = 45^0$ D-term included

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

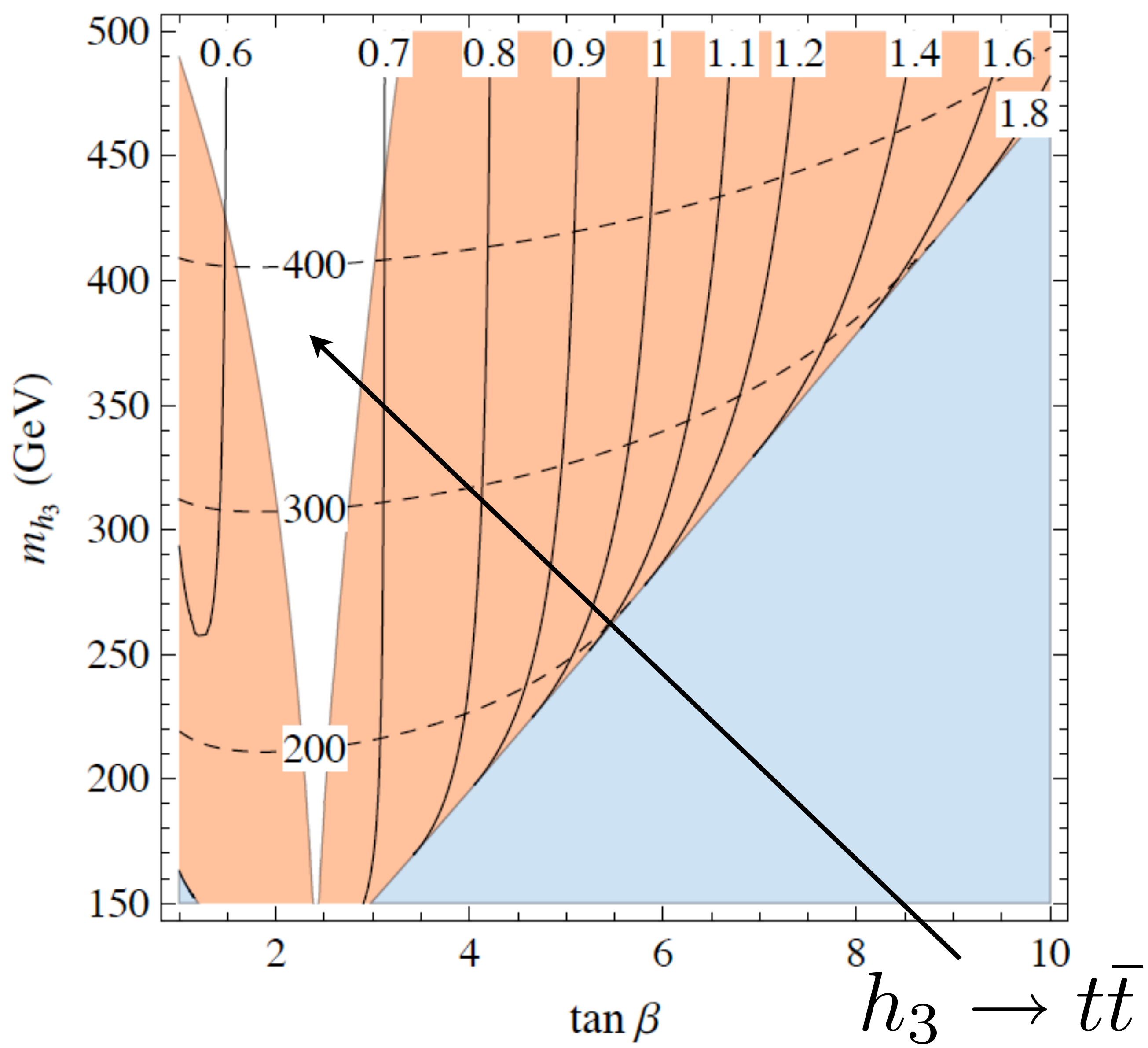
LHC14 at $300 fb^{-1}$ with ATLAS/CMS projected errors

NMSSM at variable λ S-decoupled

$h_3 < h_{LHC}(< h_2(\approx S))$

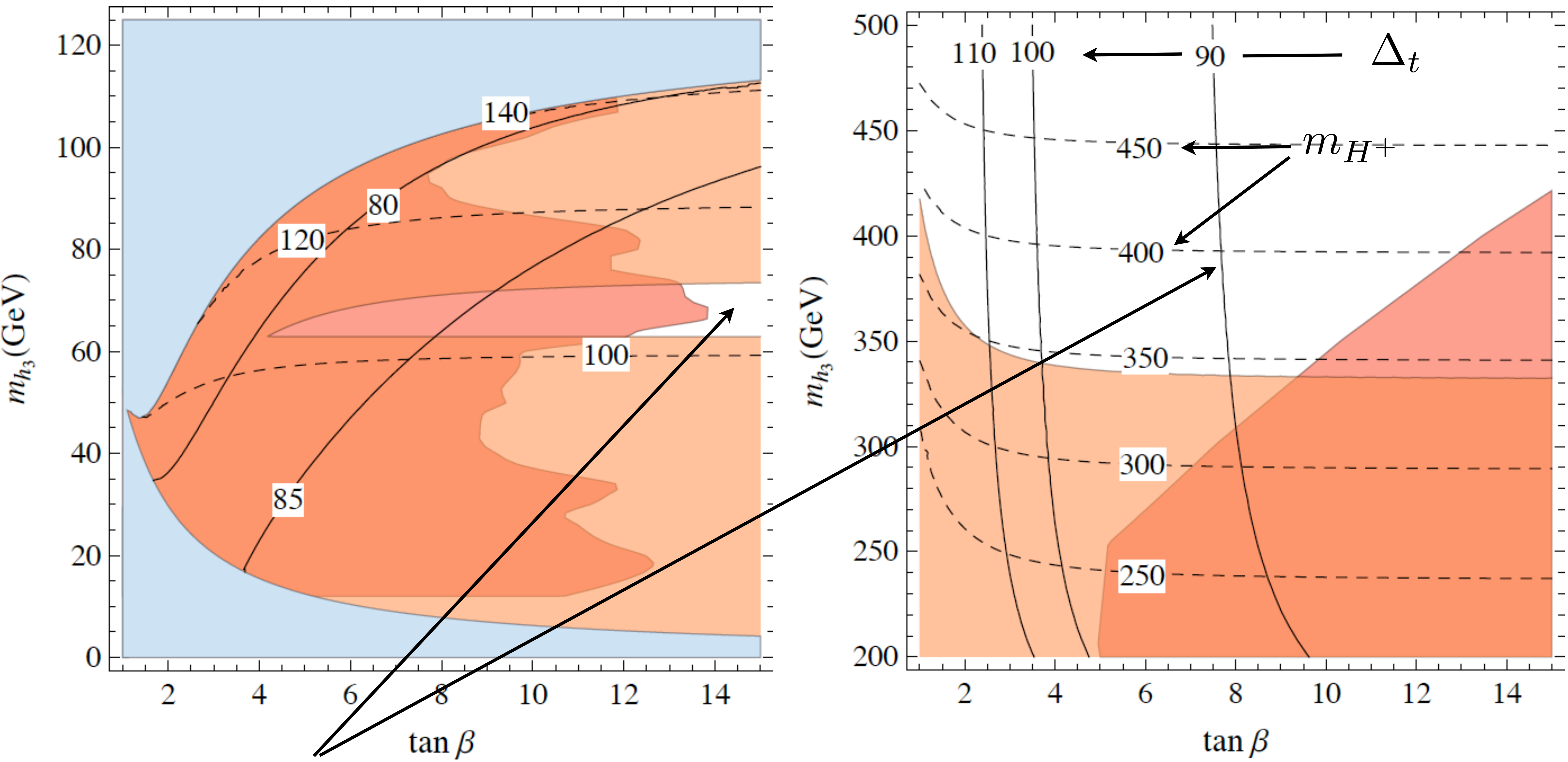


$h_{LHC} < h_3(< h_2(\approx S))$



MSSM at variable Δ_t and $\boxed{\frac{\mu A_t}{< m_{\tilde{t}}^2 >} < 1}$

$h_3 < h_{LHC}$ $\qquad\qquad$ $h_{LHC} < h_3$



region still allowed
only for largish Δ_t

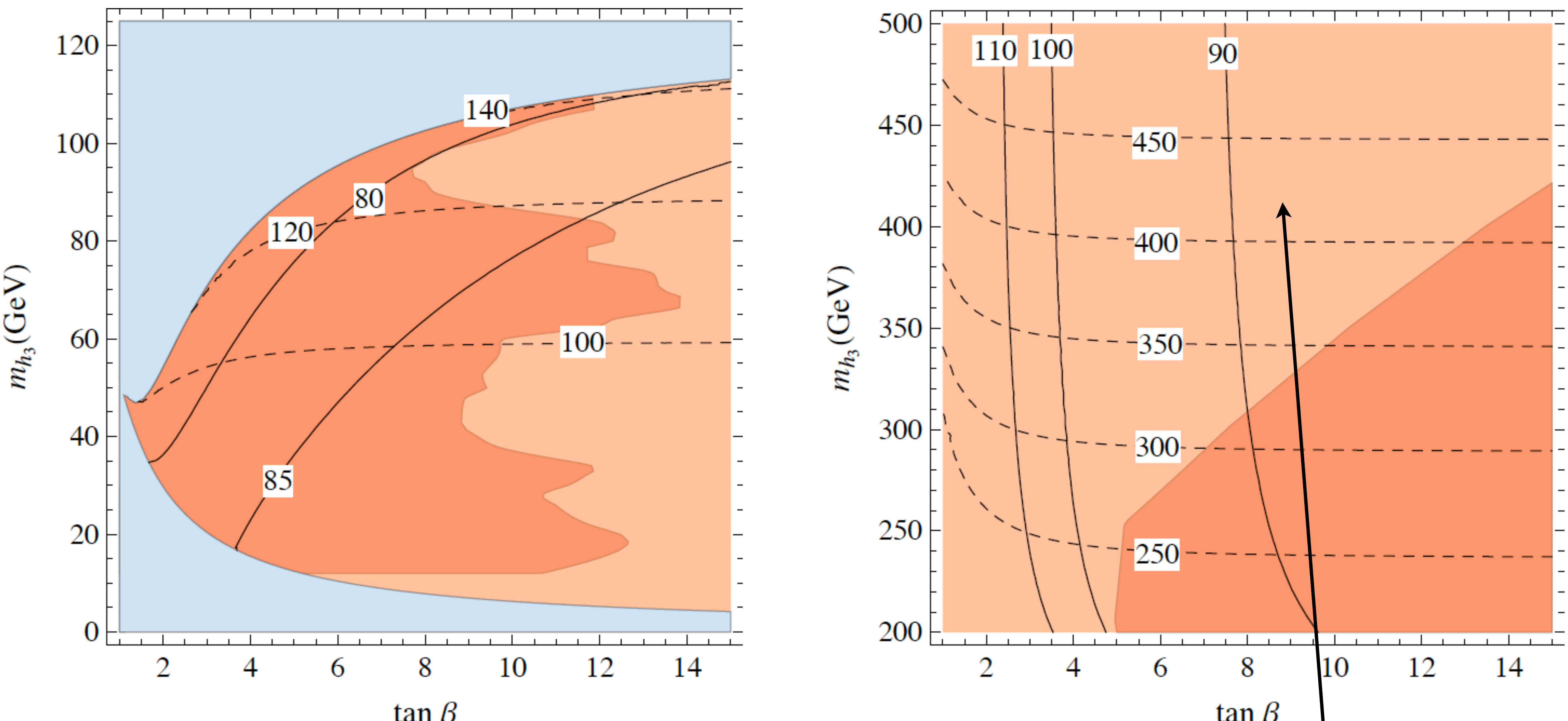
orange = excluded by h_{LHC} - measurements

red = excluded by direct searches

LEP ($h_3 < h_{LHC}$) $\qquad$ LHC ($h_{LHC} < h_3$)

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

$h_3 < h_{LHC}$ **MSSM** $h_{LHC} < h_{2/3}$



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

Summary so far

S-"decoupled" (similarities with the MSSM)

$$h_3 < h_{LHC} < h_2(\approx S)$$

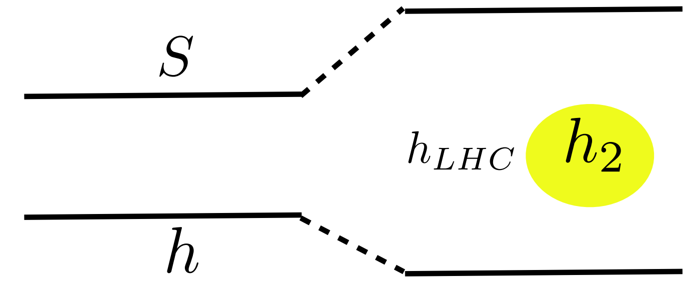
$$h_{LHC} < h_3 < h_2(\approx S)$$

$\mu(h_{LHC})'s$

Any restriction from the EWPT on the figures above?

No, because for $\delta = \alpha - \beta + \pi/2 \to 0$ H does not contribute at one loop to S or T (no breaking of $SU(2) \times U(1)$) and the signal strengths of h_{LHC} strongly constrain δ

NMSSM: H-decoupled

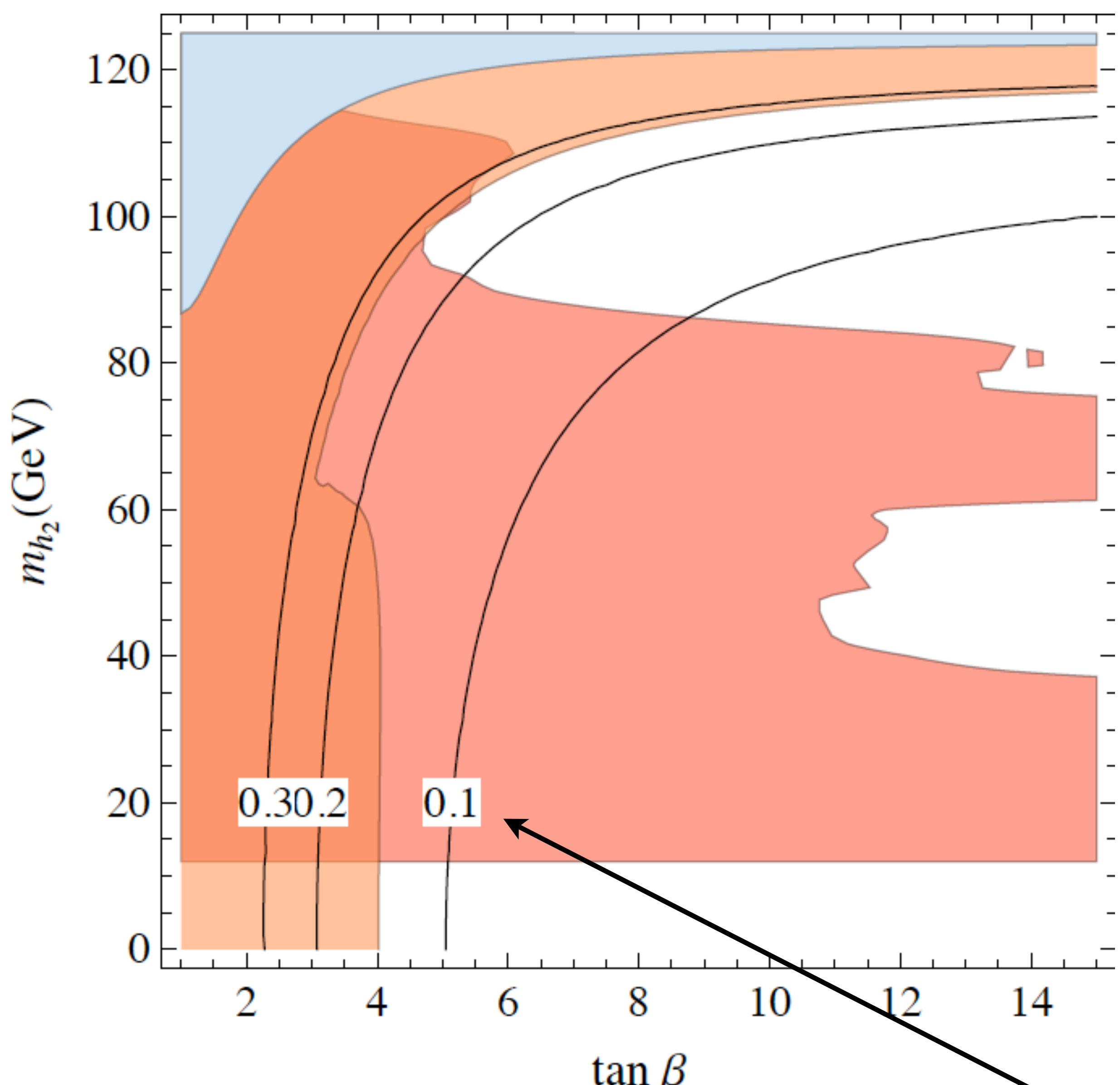


$$\gamma = \gamma(m_{h_2}; \tan\beta, \lambda, \Delta_t)$$

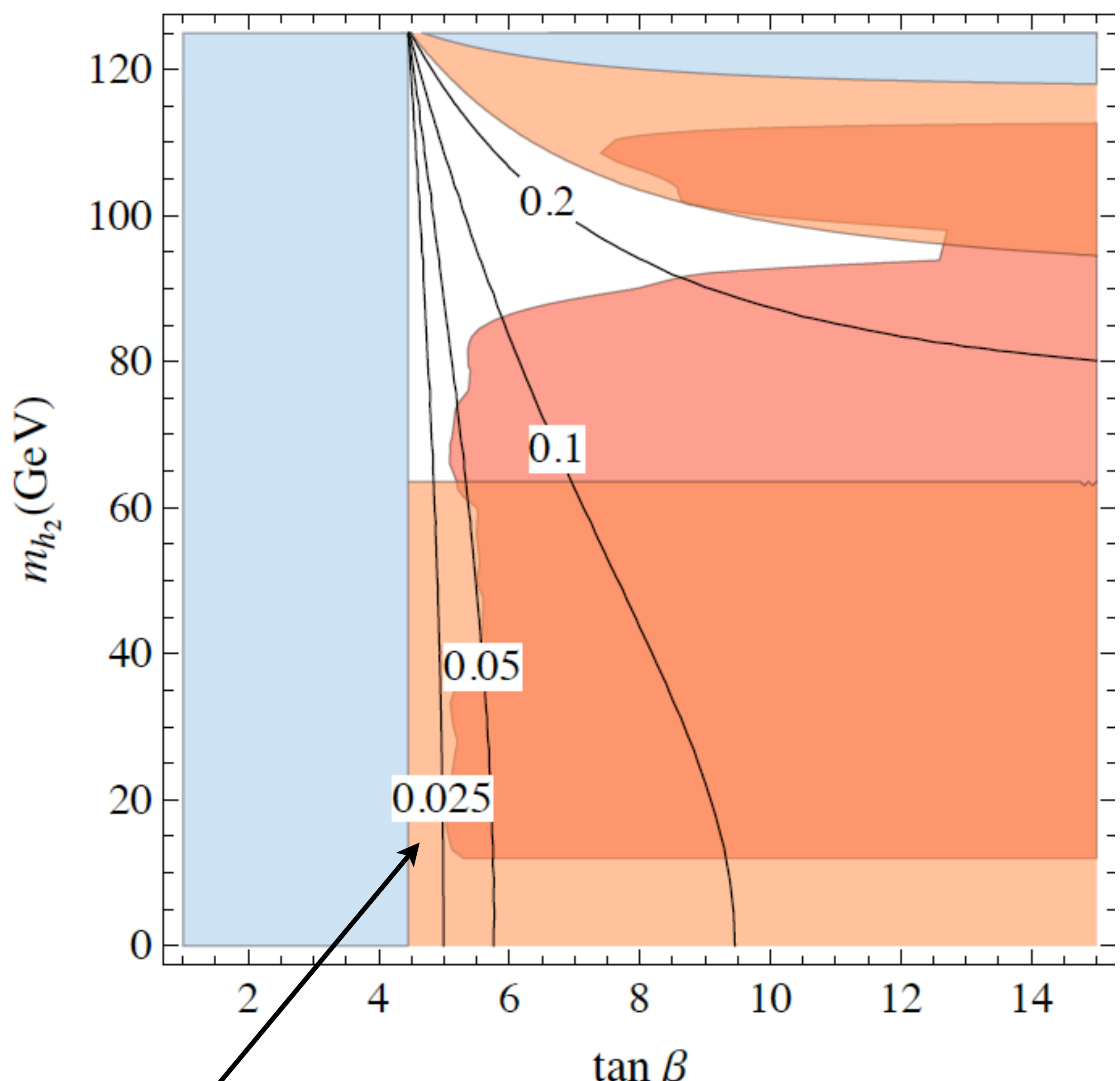
$\sin^2\gamma < 0.22$ at 95% CL now

$\sin^2\gamma < 0.15$ after $300\ fb^{-1}$

$\lambda = 0.1,\ \Delta_t = 85\ GeV$



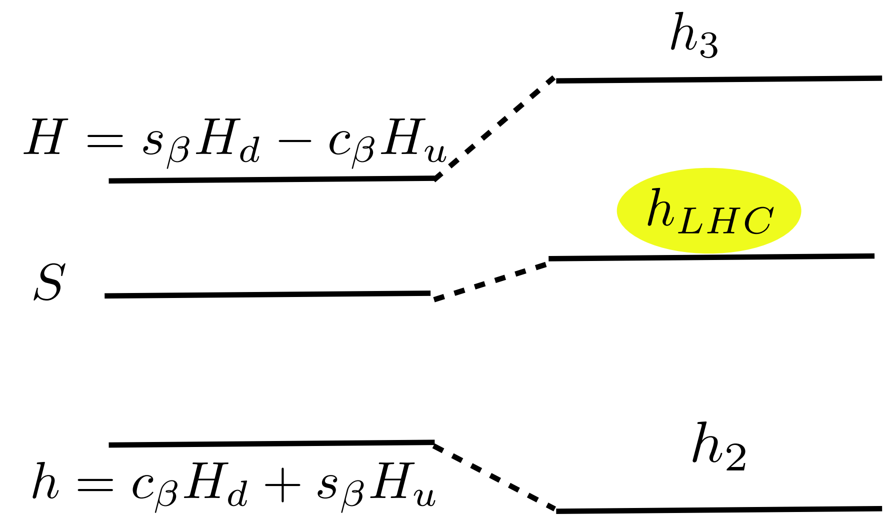
$\lambda = 0.8,\ \Delta_t \lesssim 75\ GeV$



Regions allowed at low λ only for largish Δ_t

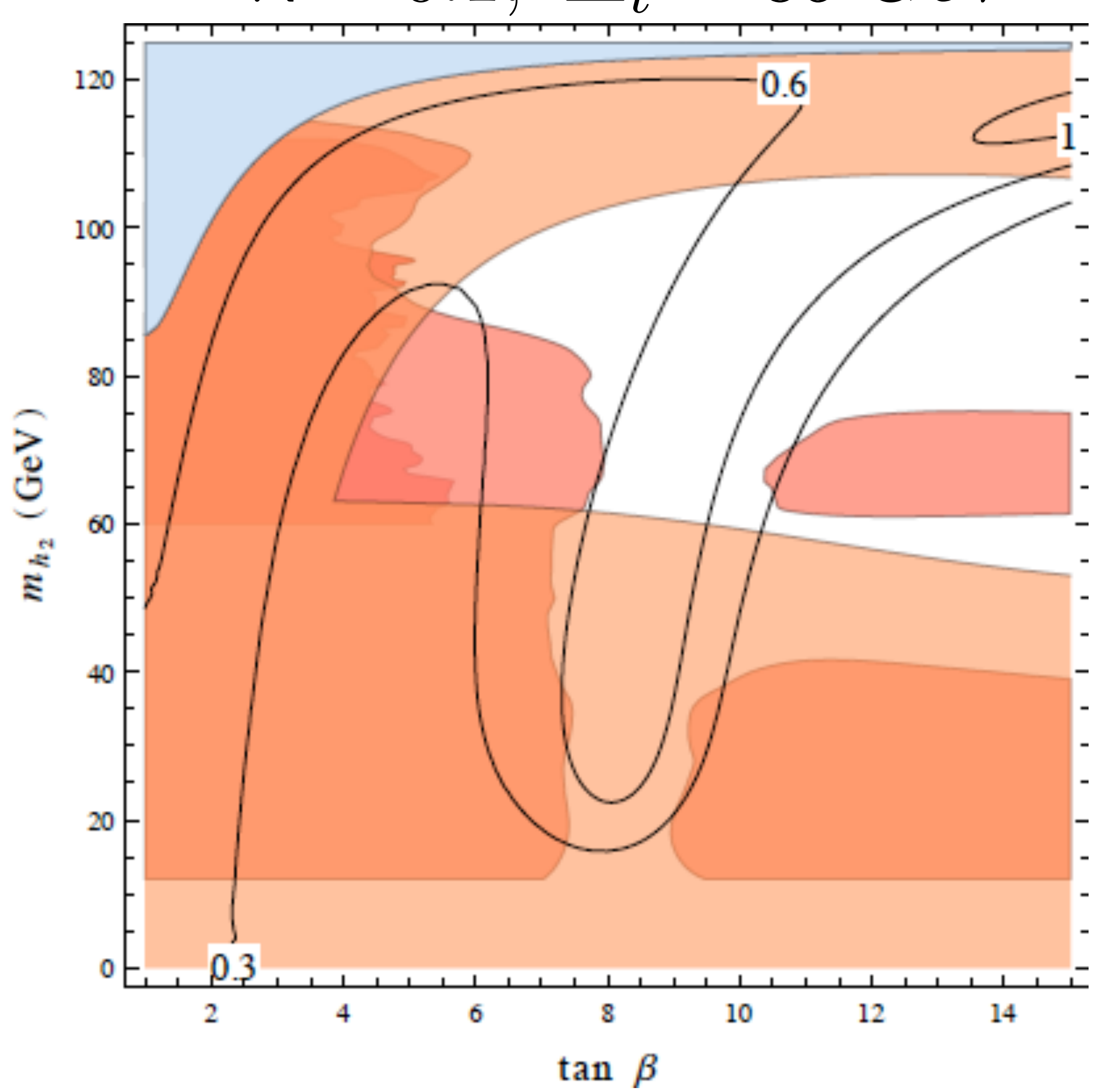
$\sin^2\gamma$

Fully mixed case and the $\gamma\gamma$ signal

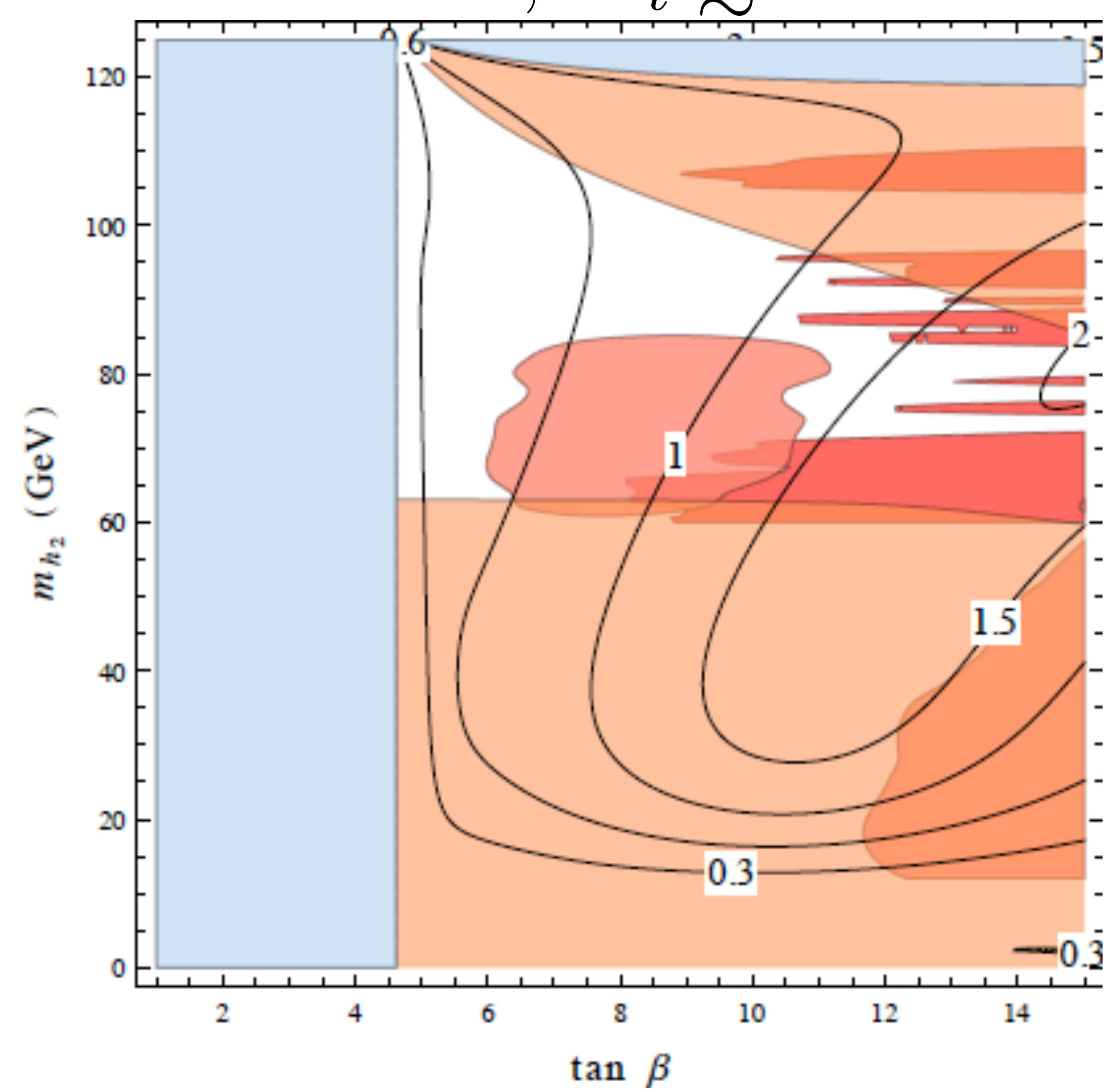


isolines of $\mu(h_2 \to \gamma\gamma)$ normalized to SM

$\lambda = 0.1,\ \Delta_t = 85\ GeV$

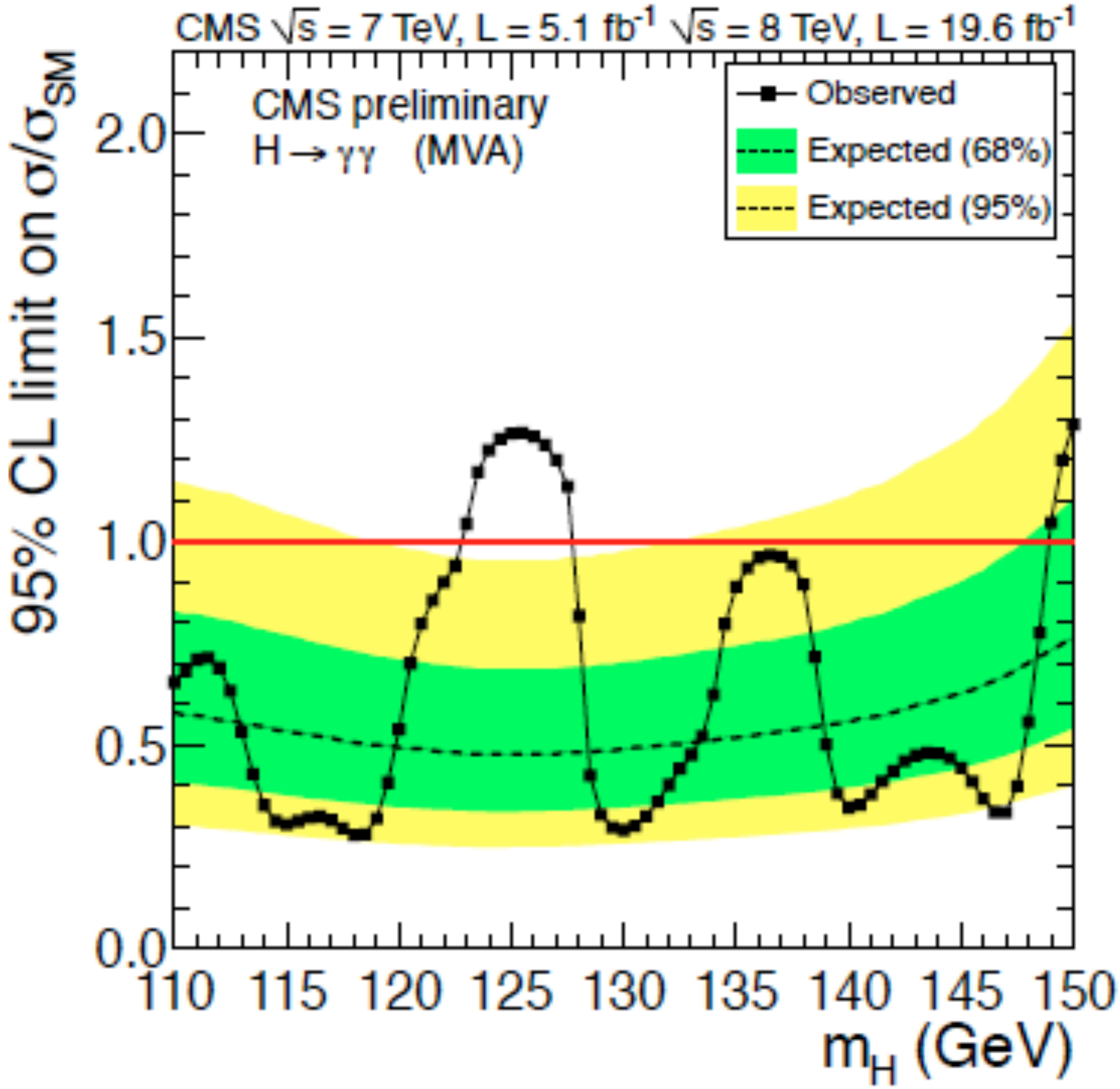


$\lambda = 0.8,\ \Delta_t \lesssim 75\ GeV$



magenta = excluded by LEP in h_2 → hadrons

$\sigma^2 = 0.001,\ m_{h_3} = 500\ GeV$



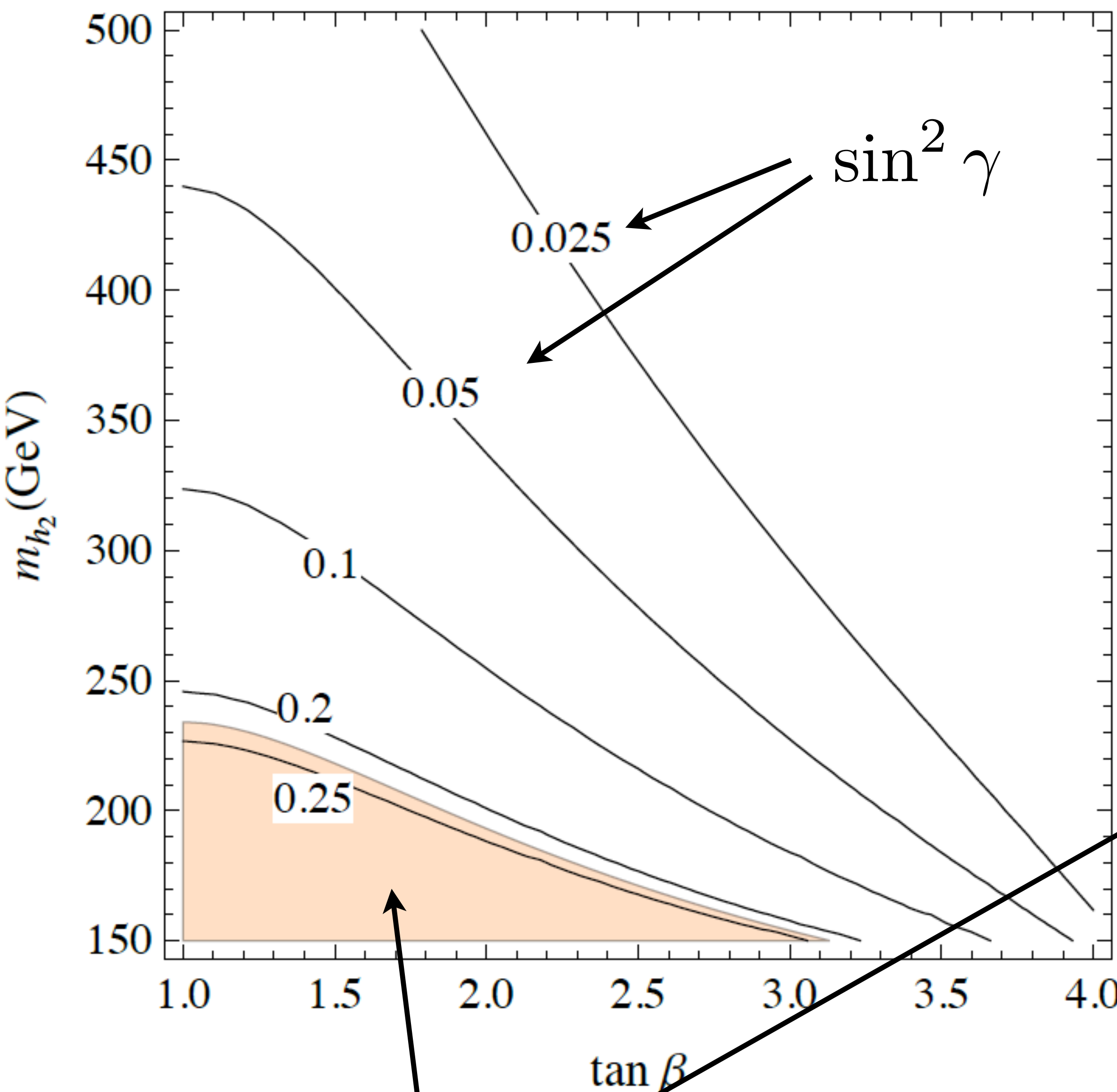
CMS $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}
CMS preliminary
H → γγ (MVA)
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σ$_{SM}$
m$_H$ (GeV)

H-decoupled

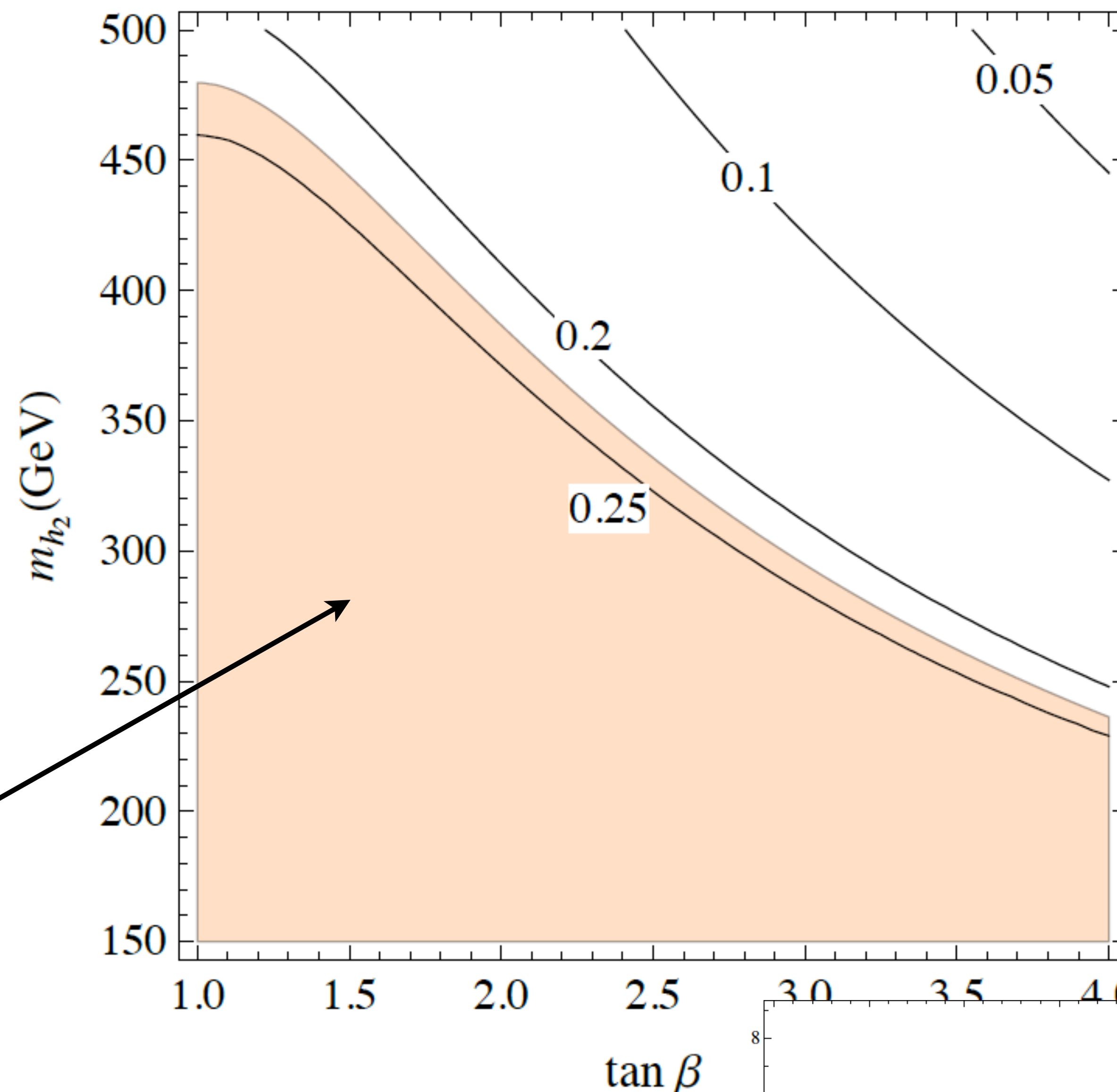
$$h_{LHC} < h_2(< h_3(\approx H))$$

$\Delta_t \leq 75\ GeV$ almost irrelevant

$\lambda = 0.8$



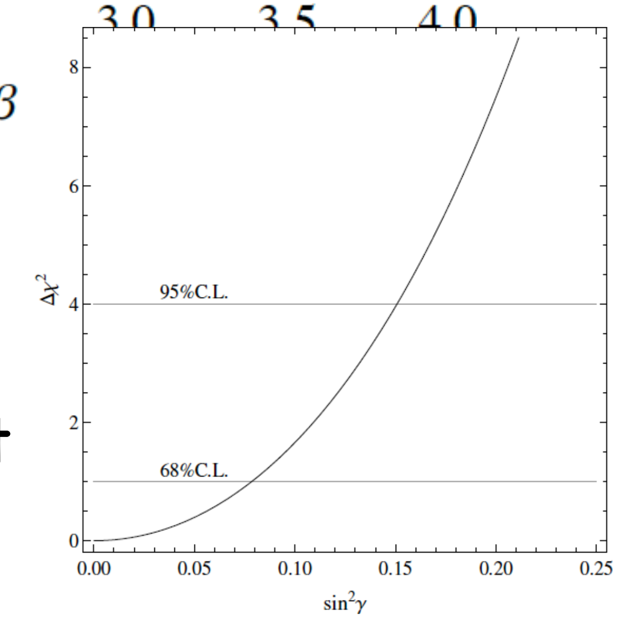
$\lambda = 1.4$



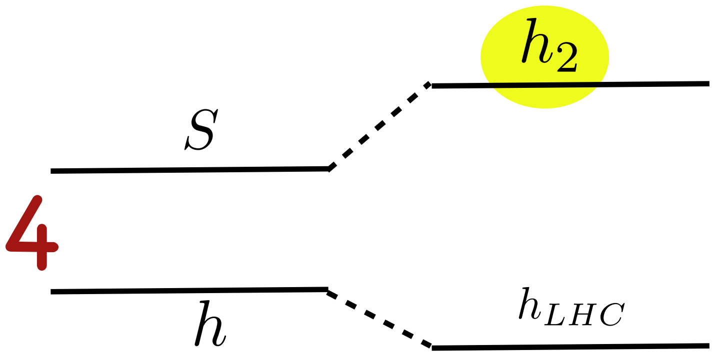
"excluded" by h_{LHC} -signal strenghts

projection on $\sin^2\gamma$

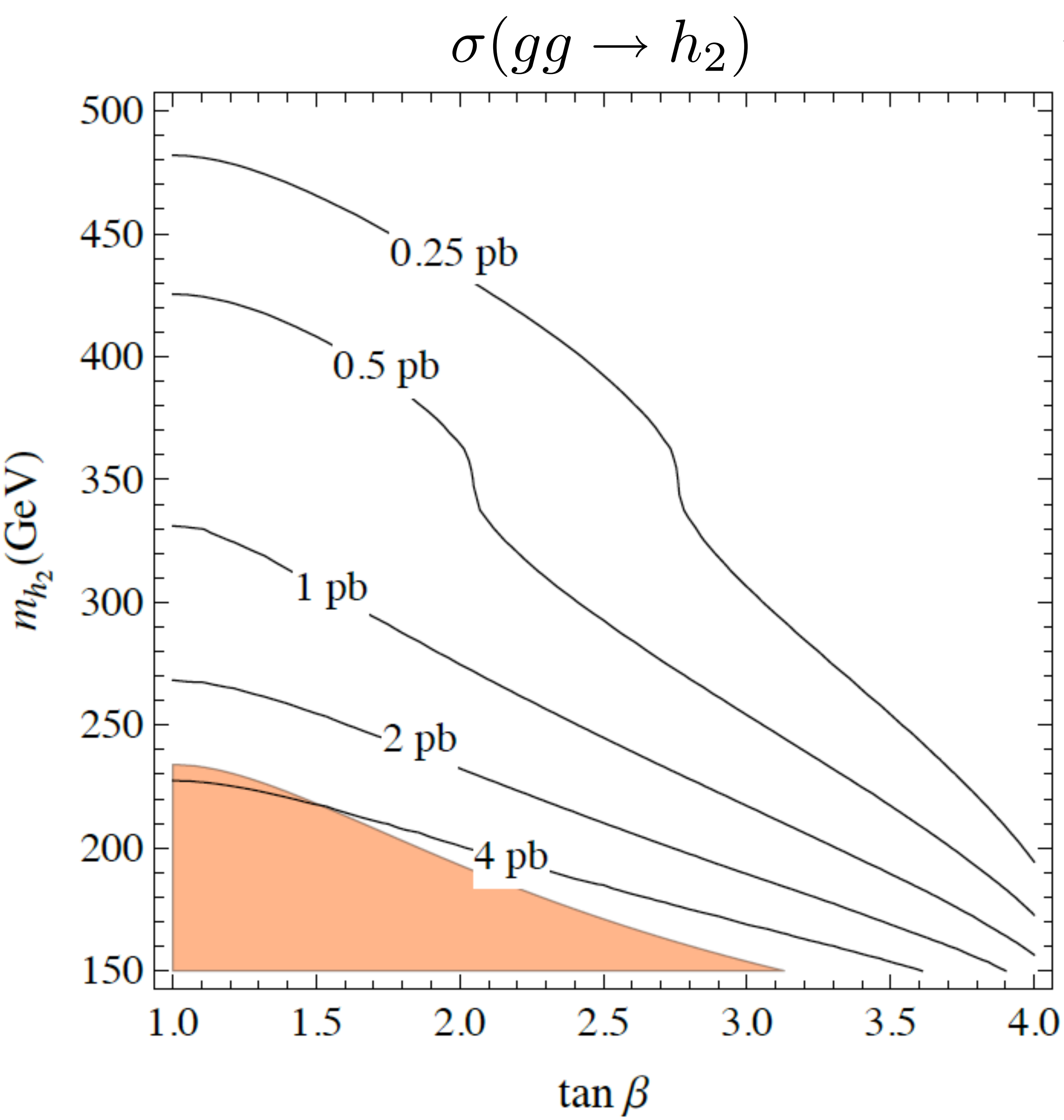
No big improvement

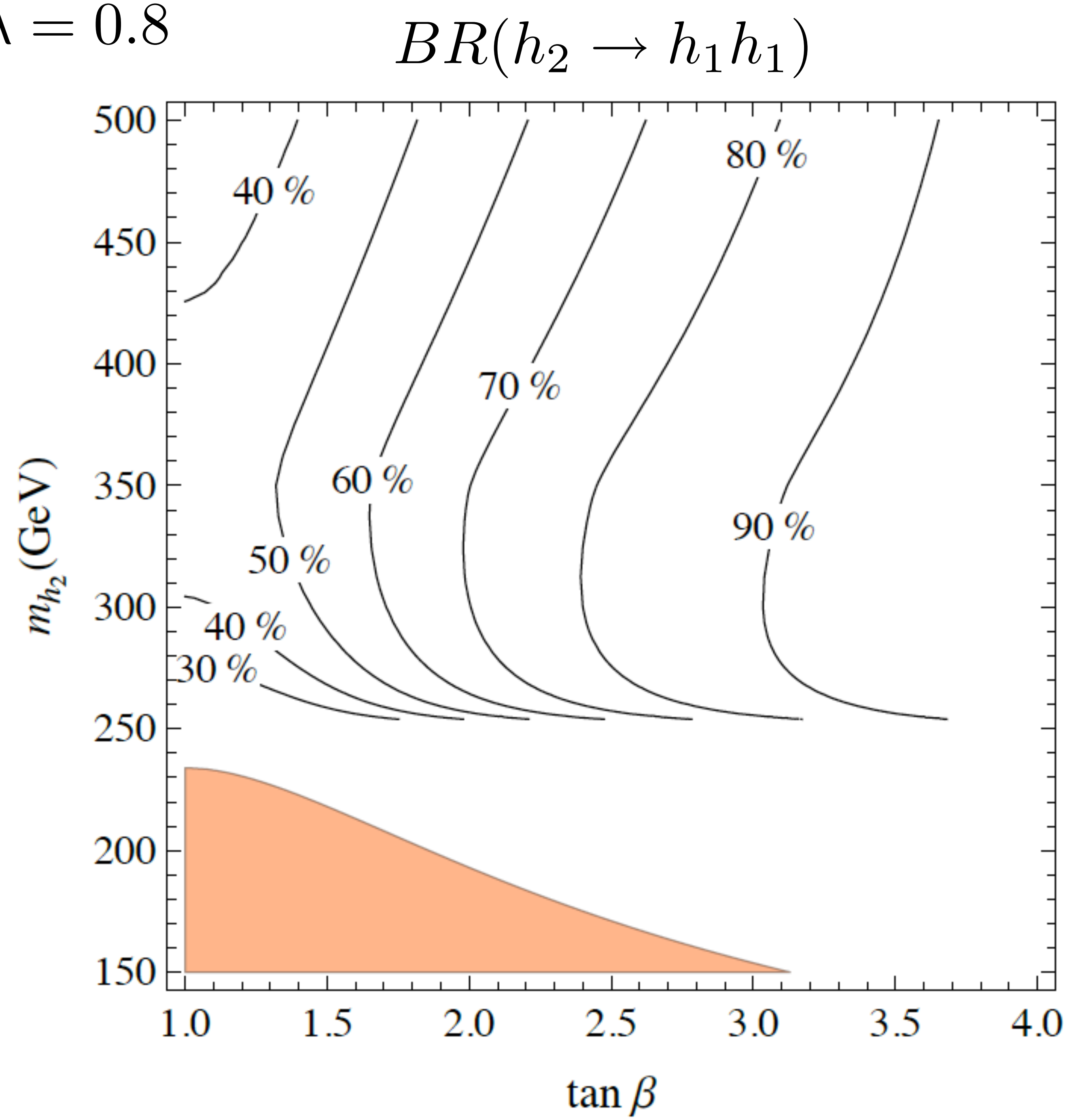


NMSSM: Direct search at LHC14



$\lambda = 0.8$

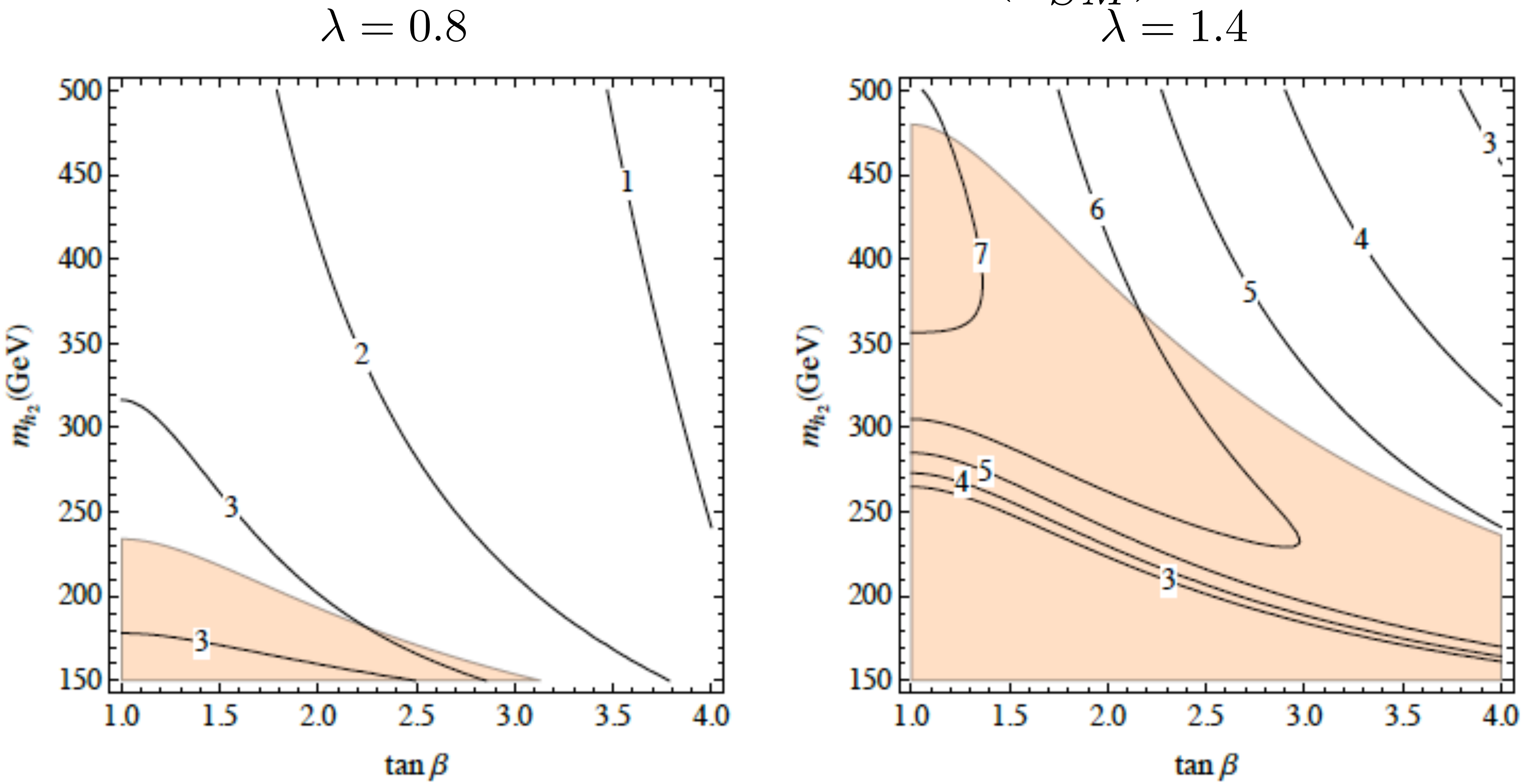




any other BR determined in this plane

NMSSM: H-decoupled $h_{LHC} < h_2(< h_3(\approx H))$

significant deviations from 1 of $\frac{\lambda(h^3_{LHC})}{\lambda(h^3_{SM})}$ possible



but, at the proper time, the game might/should be over

How about the EWPT in the H-decoupled case?

As in the S-decoupled case, not competitive with the measurements of the signal strengths

$\Rightarrow$ Heavy h_2 :

$$\Delta\hat{S} = +\frac{\alpha}{48\pi s_w^2} s_\gamma^2 \log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2}, \quad \Delta\hat{T} = -\frac{3\alpha}{16\pi c_w^2} s_\gamma^2 \log\frac{m_{h_2}^2}{m_{h_{\rm LHC}}^2}$$

$$s_\gamma^2 = \frac{m_{hh}^2 - m_{h_{LHC}}^2}{m_{h_2}^2 - m_{h_{LHC}}^2}$$

B, Bellazzini, Rychkov, Varagnolo 2007

$\Rightarrow$ $m_{h_2} \longrightarrow m_{h_{LHC}}$

No effect on S and T since any mixing can be rotated away

An orientation/summary table

S-"decoupled" (similarities with the MSSM)

$$h_3 < h_{LHC} < h_2 (\approx S)$$

$$h_{LHC} < h_3 < h_2 (\approx S)$$

$\mu(h_{LHC})'s$

H-"decoupled"

$$h_2 < h_{LHC} < h_3 (\approx H)$$

$$h_{LHC} < h_2 < h_3 (\approx H)$$

$h_2 \to \gamma\gamma(?)$

λh_{LHC}^3

$h_2 \to h_{LHC} h_{LHC}$

The triple mixing could help in the H-decoupled case with $\mu(h_2 \to \gamma\gamma)$

The (many) reactions to the FT problem

0. Ignore it and view the SM in isolation (untenable)

1. Cure it by symmetries: SUSY, Higgs as PGB
2. A new strong interaction nearby
3. A new strong interaction not so nearby: quasi-CFT
4. Saturate the UV nearby: extra-dimensions around the corner
5. Warp space-time: RS
6. Accept it: the multiverse, the 10^{120} vacua of string theory

Anything else?

Last but not least

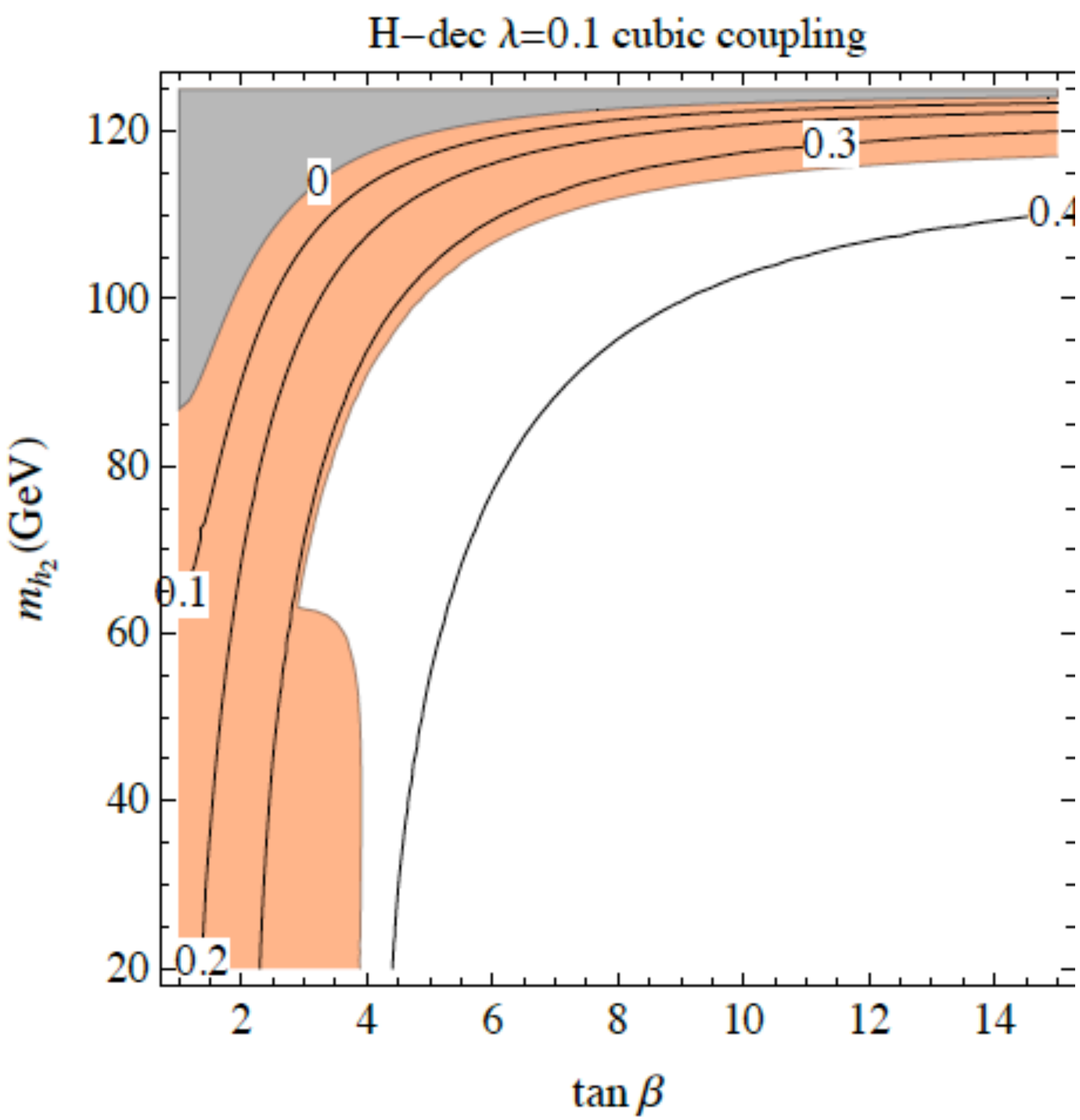
Many thanks for the successful workshop (as usual) to:

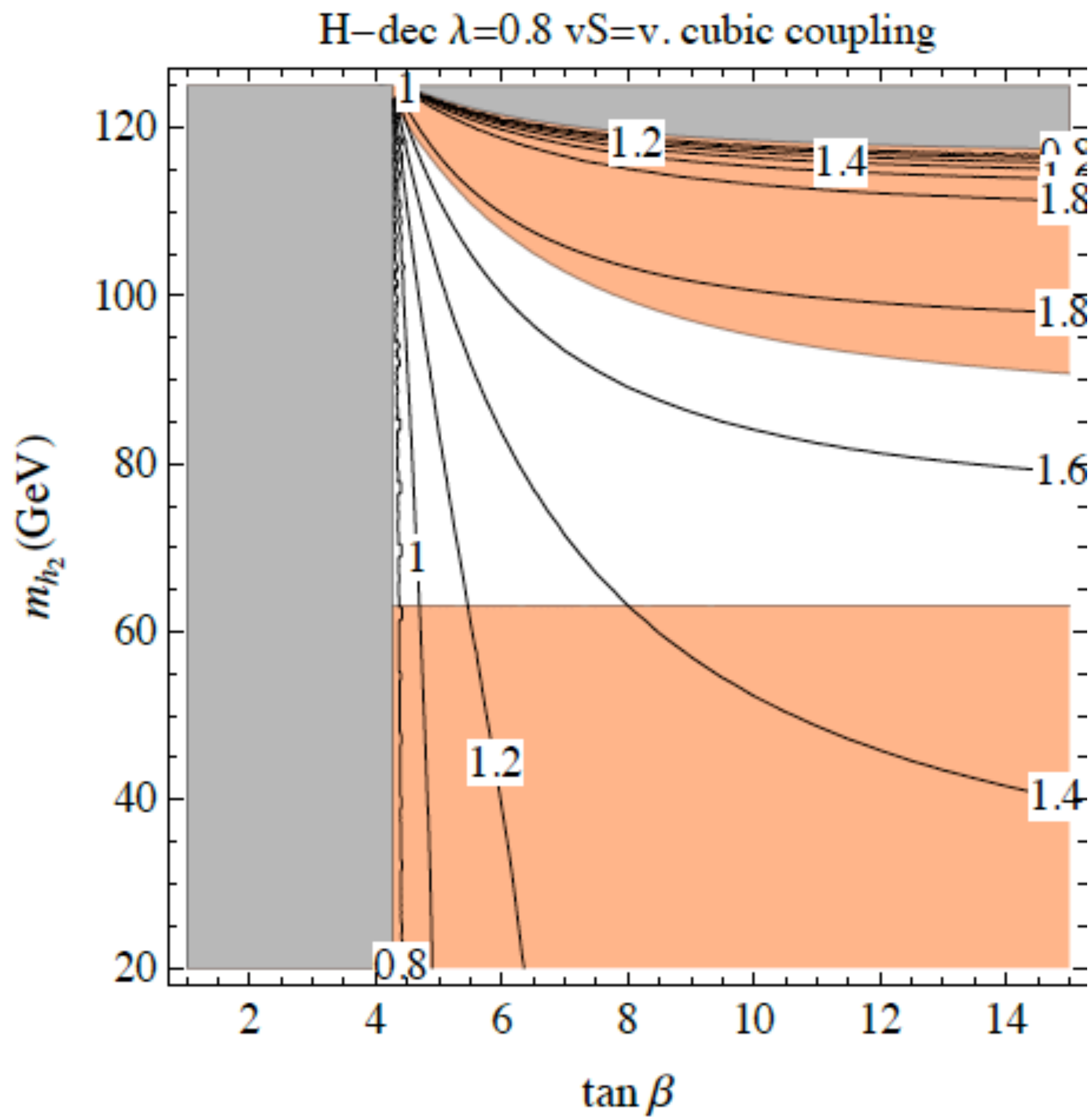
Stefania, Daniele
Emilian
Yasunori
James
Fabio

Annalisa
Mauro

NMSSM: H-decoupled $h_2 < h_{LHC}(< h_3(\approx H))$

significant deviations from 1 of $\frac{\lambda(h^3_{LHC})}{\lambda(h^3_{SM})}$ possible





(and even larger for $h_{LHC} < h_2(< h_3(\approx H))$)

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

$$F_{u,d} + \bar{F}_{u,d} = 5 + \bar{5}$$

$$M_u \approx M_d \approx m_u \approx m_d \approx 1000\ TeV$$

$$S, \quad \hat{H}_u = c_u H_u + s_u h_u, \quad \hat{H}_d = c_d H_d + s_d h_d,$$

$$\hat{f} = \hat{\lambda} S \hat{H}_u \hat{H}_d + \hat{\lambda}_t \hat{H}_u Q t, \quad \hat{\lambda} = \lambda_S s_u s_d, \quad \hat{\lambda}_t = \lambda_t c_u$$