Benchmark scenarios for low $\tan\beta$ in the MSSM

Pietro Slavich

(LPTHE Paris)

Higgs Days 2015

Santander, Spain, 13 –18 September 2015

LHCHXSWG-2015-002

August 1, 2015

LHC Higgs Cross Section Working Group

Public Note

Benchmark scenarios for low $\tan\beta$ in the MSSM

Emanuele Bagnaschi[1,a], Felix Frensch[2,b], Sven Heinemeyer[3,c],
Gabriel Lee[4,d], Stefan Liebler[1,e], Margarete Mühlleitner[2,f] Allison Mc Carn[5,g],
Jérémie Quevillon[6,h], Nikolaos Rompotis[7,i], Pietro Slavich[8,j], Michael Spira[9,k],
Carlos E.M. Wagner[10,11,l], and Roger Wolf[2,m]

Reopening the low (M_A, $\tan\beta$) window

[see e.g.: Arbey *et al.*, 1303.7450; Djouadi+Quevillon, 1304.1787]

Appeal of the low (M_A, $\tan\beta$) region:

- For low M_A, extended Higgs sector potentially accessible at the LHC
- For low $\tan\beta$, not yet ruled out by the *H, A* —> tau tau searches
- Away from the decoupling limit, sizable couplings of *H, A* to gauge bosons and *h*

Interesting Higgs phenomenology: H —> hh, H —> WW, H —> ZZ, A —> Zh

However...

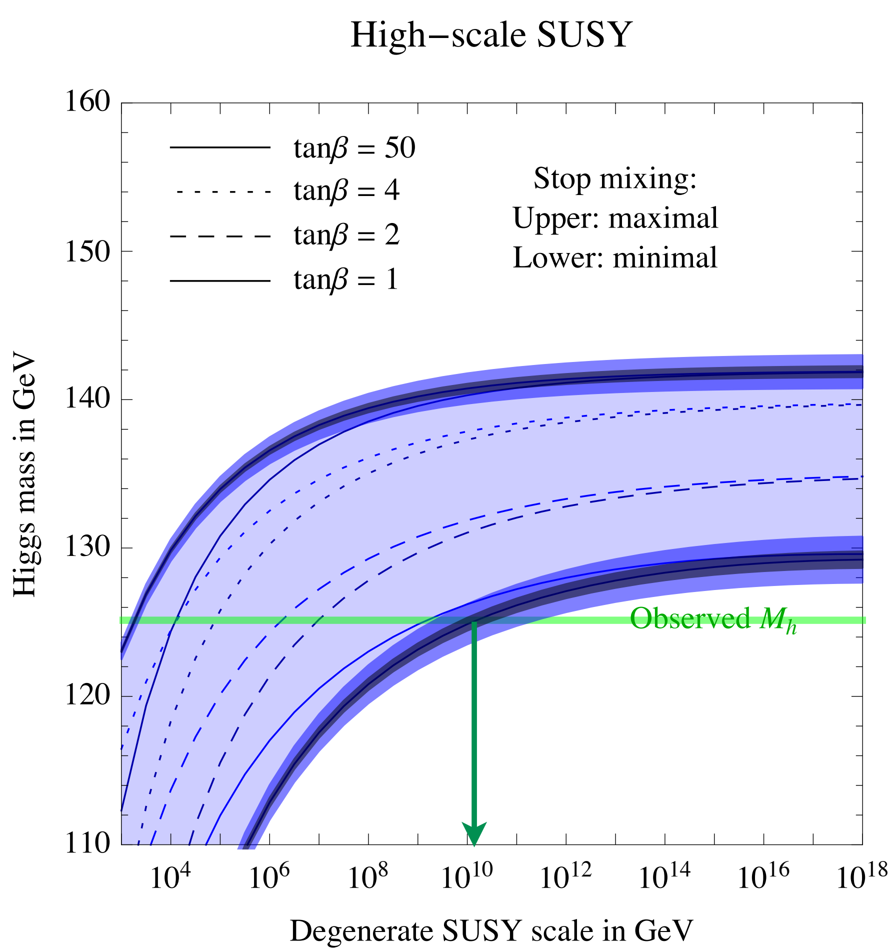
- At low $\tan\beta$, $M_h \approx 125$ GeV requires large stop masses M_S:
  - For $M_A \approx M_S$, $\tan\beta = 1$ implies $M_S \approx 10^8 - 10^{10}$ GeV

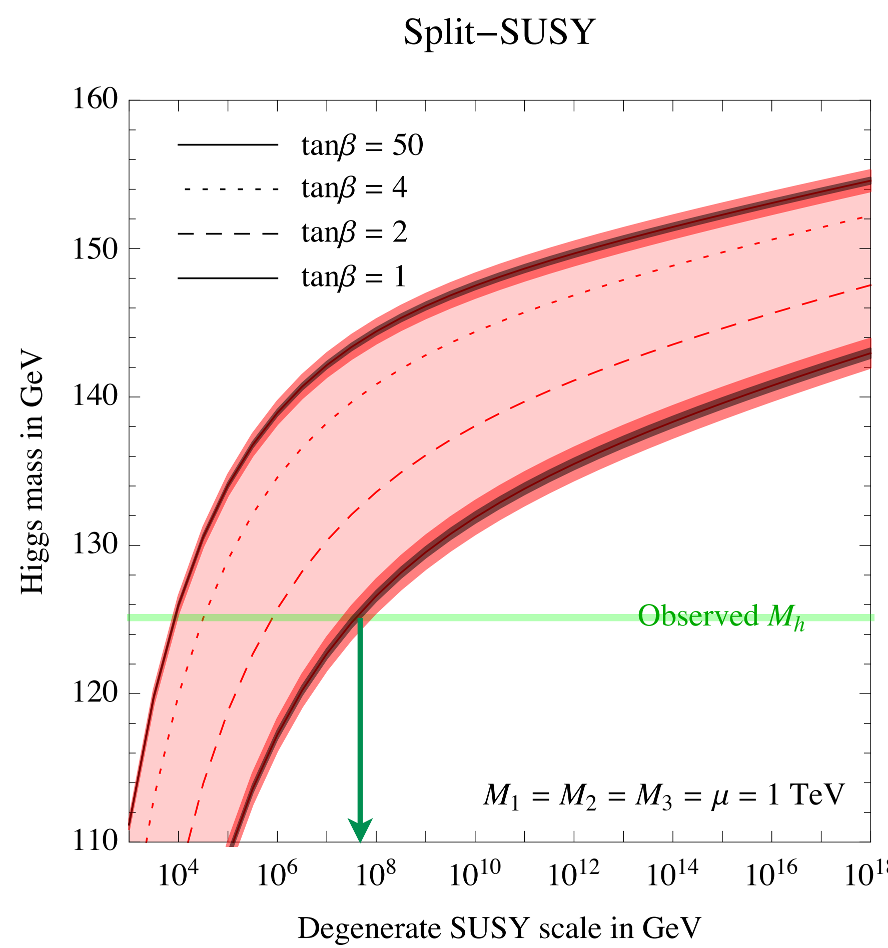
    For low M_A, we might need an even larger M_S

This calls for the resummation of large logarithms in the EFT approach

Reopening the low (M_A, $\tan\beta$) window

[see e.g.: Arbey *et al.*, 1303.7450; Djouadi+Quevillon, 1304.1787]





Bagnaschi *et al.*, 1407.4081

This calls for the resummation of large logarithms in the EFT approach

Reopening the low (M_A, tanβ) window

[see e.g.: Arbey *et al.*, 1303.7450; Djouadi+Quevillon, 1304.1787]

Appeal of the low (M_A, tanβ) region:

- For low M_A, extended Higgs sector potentially accessible at the LHC
- For low tanβ, not yet ruled out by the *H, A* —> tau tau searches
- Away from the decoupling limit, sizable couplings of *H, A* to gauge bosons and *h*

Interesting Higgs phenomenology: H —> hh, H —> WW, H —> ZZ, A —> Zh

However...

- At low tanβ, $M_h \approx 125$ GeV requires large stop masses M_S :
  - For $M_A \approx M_S$, tan$\beta = 1$ implies $M_S \approx 10^8 - 10^{10}$ GeV

    For low M_A, we might need an even larger M_S

This calls for the resummation of large logarithms in the EFT approach

Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

$$
\begin{aligned}
V \;=\;& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 \;+\; \text{h.c.} \right] \\
& + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] (\Phi_1^\dagger \Phi_2) \;+\; \text{h.c.} \right\}
\end{aligned}
$$

1) SUSY boundary conditions at the scale M_S :

$$
\lambda_1 = \lambda_2 = -(\lambda_3 + \lambda_4) = \frac{1}{4}(g^2 + g'^2) \,,
$$

$$
\lambda_4 = -\frac{g^2}{2} \,, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0
$$

(NOTE: loop corrections)

2) RG evolution of all seven lambdas from M_S to the weak scale;

3) scalar mass matrix in terms of the weak-scale lambdas:

$$
M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta\, c_\beta \\ -s_\beta\, c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

$$
\begin{aligned}
L_{11} &= \lambda_1\, c_\beta^2 + 2\,\lambda_6\, s_\beta\, c_\beta + \lambda_5\, s_\beta^2 \\
L_{12} &= (\lambda_3 + \lambda_4)\, s_\beta\, c_\beta + \lambda_6\, c_\beta^2 + \lambda_7\, s_\beta^2 \\
L_{22} &= \lambda_2\, s_\beta^2 + 2\,\lambda_7\, s_\beta\, c_\beta + \lambda_5\, c_\beta^2
\end{aligned}
$$

Recently studied by Lee & Wagner, no public code available yet

Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

$$\lambda_1 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\Big(y_b^4\frac{A_b^2}{M_S^2}(1-\frac{A_b^2}{12M_S^2}) - y_t^4\frac{\mu^4}{12M_S^4}\Big)$$

$$\lambda_2 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\Big(y_t^4\frac{A_t^2}{M_S^2}(1-\frac{A_t^2}{12M_S^2}) - y_b^4\frac{\mu^4}{12M_S^4}\Big)$$

$$\lambda_3 = \frac{1}{4}(g^2-g'^2) + \frac{2\,N_c}{(4\pi)^2}\Big(y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\Big)$$

$$\lambda_4 = -\frac{1}{2}g^2 + \frac{2\,N_c}{(4\pi)^2}\Big(-y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\Big)$$

$$\lambda_5 = -\frac{2\,N_c}{(4\pi)^2}\Big(y_t^4\frac{\mu^2A_t^2}{12M_S^4} + y_b^4\frac{\mu^2A_b^2}{12M_S^4}\Big),$$

$$\lambda_6 = \frac{2\,N_c}{(4\pi)^2}\Big(y_b^4\frac{\mu A_b}{M_S^2}(-\frac{1}{2}+\frac{A_b^2}{12M_S^2}) + y_t^4\frac{\mu^3A_t}{12M_S^4}\Big),$$

$$\lambda_7 = \frac{2\,N_c}{(4\pi)^2}\Big(y_t^4\frac{\mu A_t}{M_S^2}(-\frac{1}{2}+\frac{A_t^2}{12M_S^2}) + y_b^4\frac{\mu^3A_b}{12M_S^4}\Big),$$

$$M_A^2\begin{pmatrix} s_\beta^2 & -s_\beta\,c_\beta \\ -s_\beta\,c_\beta & c_\beta^2\end{pmatrix} + v^2\begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22}\end{pmatrix}$$

$$\begin{aligned} L_{11} &= \lambda_1\,c_\beta^2 + 2\,\lambda_6\,s_\beta\,c_\beta + \lambda_5\,s_\beta^2 \\ L_{12} &= (\lambda_3+\lambda_4)\,s_\beta\,c_\beta + \lambda_6\,c_\beta^2 + \lambda_7\,s_\beta^2 \\ L_{22} &= \lambda_2\,s_\beta^2 + 2\,\lambda_7\,s_\beta\,c_\beta + \lambda_5\,c_\beta^2 \end{aligned}$$

Recently studied by Lee & Wagner, no public code available yet

Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

$$
\begin{aligned}
V \;=\;& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 \;+\; \text{h.c.} \right] \\
&+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] (\Phi_1^\dagger \Phi_2) \;+\; \text{h.c.} \right\}
\end{aligned}
$$

1) SUSY boundary conditions at the scale M_S :

$$
\lambda_1 \;=\; \lambda_2 \;=\; -(\lambda_3 + \lambda_4) \;=\; \frac{1}{4} (g^2 + g'^2) \;,
$$

$$
\lambda_4 \;=\; -\frac{g^2}{2} \;, \qquad \lambda_5 \;=\; \lambda_6 \;=\; \lambda_7 \;=\; 0
$$

(NOTE: loop corrections)

2) RG evolution of all seven lambdas from M_S to the weak scale;

3) scalar mass matrix in terms of the weak-scale lambdas:

$$
M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta\, c_\beta \\ -s_\beta\, c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

$$
\begin{aligned}
L_{11} &= \lambda_1\, c_\beta^2 \;+\; 2\,\lambda_6\, s_\beta\, c_\beta \;+\; \lambda_5\, s_\beta^2 \\
L_{12} &= (\lambda_3 + \lambda_4)\, s_\beta\, c_\beta \;+\; \lambda_6\, c_\beta^2 \;+\; \lambda_7\, s_\beta^2 \\
L_{22} &= \lambda_2\, s_\beta^2 \;+\; 2\,\lambda_7\, s_\beta\, c_\beta \;+\; \lambda_5\, c_\beta^2
\end{aligned}
$$

Recently studied by Lee & Wagner, no public code available yet

Two workarounds for the analysis of low-*tanβ* scenarios

- The "low-tb-high" scenario: Combine the fixed-order calculation of `FeynHiggs` with a partial resummation of large logs, then find a set of SUSY parameters that lead to $M_h \approx 125$ GeV

- The hMSSM approach: Trade the knowledge of M_h for the element of the Higgs mass matrix where the large logs arise, set the other elements to their tree-level values, then obtain simple formulae for M_H and alpha

We also compared the predictions of the two approaches for the Higgs masses and mixing with the preliminary results of the EFT calculation by Lee and Wagner

(see Gabriel's talk later in the afternoon)

The "low-tb-high" scenario

[Sven Heinemeyer for the LHC-HXSWG]

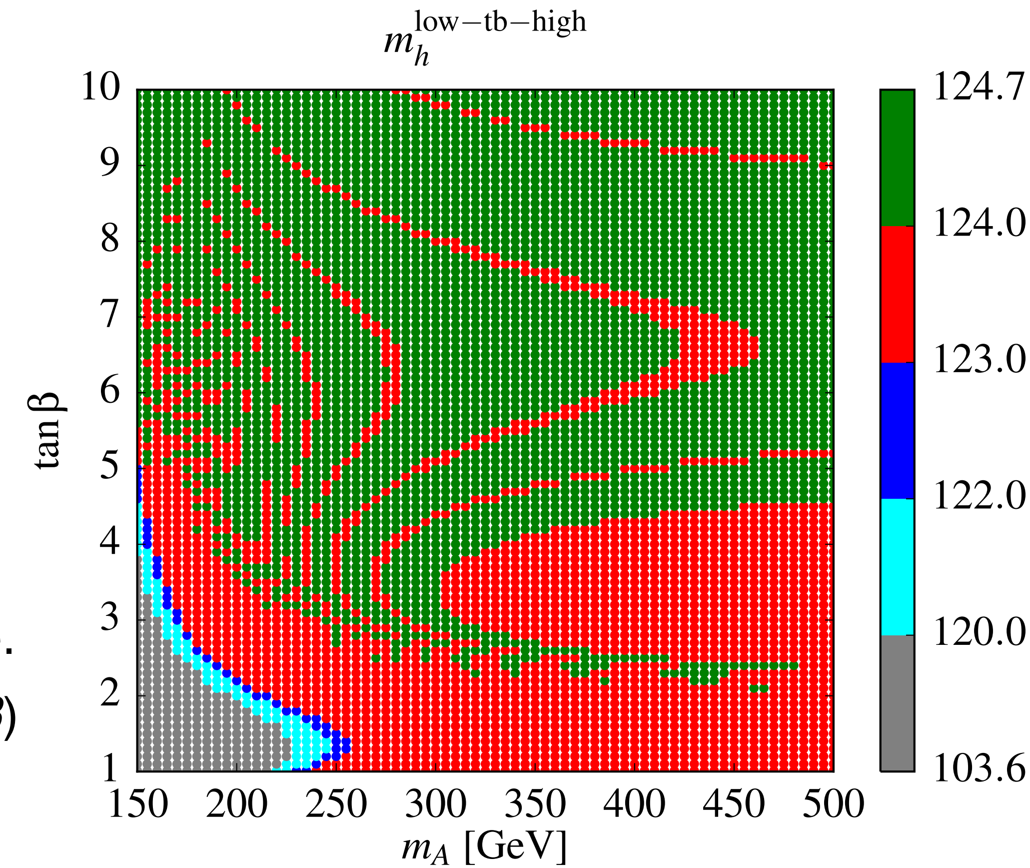
FeynHiggs > 2.10.0 includes a (simplified) NLL resummation of large logs [see Wolfgang's talk]

Low (M_A, tanβ) scenario with heavy sfermions & gluino, TeV-scale EW-inos:

$$m_{\tilde{f}} = M_3 = M_S, \quad 0 \leq X_t/M_S \leq 2,$$

$$M_2 = 2\ \text{TeV}, \quad \mu = 1.5\ \text{TeV}$$

M_S and X_t adjusted to get $M_h > 122$ GeV [taking $(\Delta M_h)^{theo} = 3$ GeV] in most of the plane. In particular, $M_S = 100$ TeV for lowest (M_A, tanβ)



NOTE: the resummation procedure in FeynHiggs does not account for low μ, $M_{1,2}$ and M_A

EFT comparison:
[Lee+Wagner, 1508.00576]

The EFT calculation finds in general smaller M_h than FeynHiggs. Discrepancies about 2 GeV for tan$\beta > 5.5$, much worse at lower tanβ (e.g., more than 10 GeV for tan$\beta < 2$)

The hMSSM approach [demystified]

[Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]

When diagonalizing a 2x2 matrix, we can trade one eigenvalue for one matrix element.

Namely, use the knowledge of M_h to get rid of either the (2,2) or the (1,1) element:

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2} = \mathcal{M}_{22}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{22}^2 - M_h^2}$$

$$\tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2} = \frac{\mathcal{M}_{22}^2 - M_h^2}{\mathcal{M}_{12}^2}$$

[Carena *et al.*, 1310.2248]

The hMSSM approach [demystified]

[Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]

When diagonalizing a 2x2 matrix, we can trade one eigenvalue for one matrix element.

Namely, use the knowledge of M_h to get rid of either the (2,2) or the (1,1) element:

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2} = \mathcal{M}_{22}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{22}^2 - M_h^2}$$

$$\tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2} = \frac{\mathcal{M}_{22}^2 - M_h^2}{\mathcal{M}_{12}^2}$$

[Carena *et al.*, 1310.2248]

The smart move is to remove the (2,2) element, subject to large top/stop corrections

The hMSSM approach [demystified]

[Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]

When diagonalizing a 2x2 matrix, we can trade one eigenvalue for one matrix element. Namely, use the knowledge of M_h to get rid of either the (2,2) or the (1,1) element:

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2} = \mathcal{M}_{22}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{22}^2 - M_h^2}$$

$$\tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2} = \frac{\mathcal{M}_{22}^2 - M_h^2}{\mathcal{M}_{12}^2}$$

[Carena *et al.*, 1310.2248]

The smart move is to remove the (2,2) element, subject to large top/stop corrections

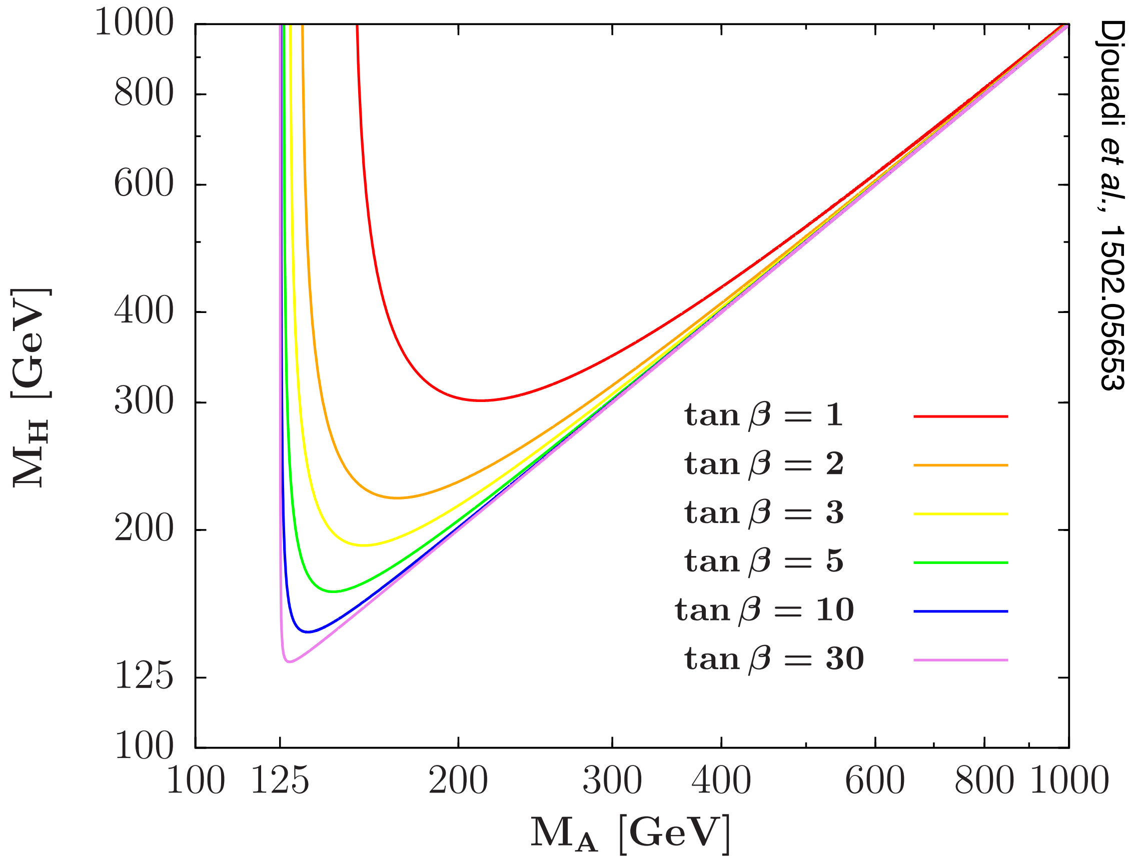
Note the infamous denominator:

If $M_{12}^2 \neq 0$, when $M_h^2 \to M_{11}^2$

we need $M_{22}^2 \approx M_H^2 \to \infty$

The hMSSM approach [demystified]

[Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]



Note the infamous denominator:

If $M_{12}^2 \neq 0$, when $M_h^2 \rightarrow M_{11}^2$

we need $M_{22}^2 \approx M_H^2 \rightarrow \infty$

The hMSSM approach [demystified]

[Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]

When diagonalizing a 2x2 matrix, we can trade one eigenvalue for one matrix element.
Namely, use the knowledge of M_h to get rid of either the (2,2) or the (1,1) element:

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2} = \mathcal{M}_{22}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{22}^2 - M_h^2}$$

$$\tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2} = \frac{\mathcal{M}_{22}^2 - M_h^2}{\mathcal{M}_{12}^2}$$

[Carena *et al.*, 1310.2248]

The smart move is to remove the (2,2) element, subject to large top/stop corrections

Note the infamous denominator:

If $M_{12}^2 \neq 0$, when $M_h^2 \to M_{11}^2$

we need $M_{22}^2 \approx M_H^2 \to \infty$

“Exact” relations for M_H and alpha *(modulo external momentum effects!)*

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2}\,, \qquad \tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2}$$

The hMSSM approximation: *neglect radiative corrections to the (1,1) and (1,2) elements*

$$M_H^2 \overset{\text{hMSSM}}{=} (\mathcal{M}_{11}^2)_{\texttt{tree}} + \frac{(\mathcal{M}_{12}^2)^2_{\texttt{tree}}}{(\mathcal{M}_{11}^2)_{\texttt{tree}} - M_h^2}\,, \qquad \tan\alpha \overset{\text{hMSSM}}{=} \frac{(\mathcal{M}_{12}^2)_{\texttt{tree}}}{(\mathcal{M}_{11}^2)_{\texttt{tree}} - M_h^2}$$

When is this a good approximation?

Easier to see for tan(alpha):

$$\Delta\mathcal{M}_{12}^2 \ll (\mathcal{M}_{12}^2)_{\texttt{tree}}$$

$$\Delta\mathcal{M}_{11}^2 \ll (\mathcal{M}_{11}^2)_{\texttt{tree}} - M_h^2$$

The dominant one-loop corrections from top-stop loops depend on μ/M_S and X_t/M_S

$$\Delta\mathcal{M}_{11}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu^2 X_t^2}{M_S^4}\,, \qquad \Delta\mathcal{M}_{12}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu X_t}{M_S^2}\left(6 - \frac{X_t A_t}{M_S^2}\right)\,,$$

E.g., better approximation for $\mu \ll M_S$ (which also suppresses Δ_b effects in Higgs couplings)

When $\mu,\, X_t \approx M_S$, expect a worse approximation for tan(alpha) at increasing $\tan\beta$

Wait for Gabriel’s talk for a comparison with the proper EFT calculation

“Exact” relations for M_H and alpha *(modulo external momentum effects!)*

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2}\,, \qquad \tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2}$$

The hMSSM approximation: *neglect radiative corrections to the (1,1) and (1,2) elements*

$$M_H^2 = \frac{(M_Z^2 + M_A^2 - M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

$$\tan\alpha = -\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

The dominant one-loop corrections from top-stop loops depend on μ/M_S and X_t/M_S

$$\Delta\mathcal{M}_{11}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu^2 X_t^2}{M_S^4}\,, \qquad \Delta\mathcal{M}_{12}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu X_t}{M_S^2}\left(6 - \frac{X_t A_t}{M_S^2}\right)\,,$$

E.g., better approximation for $\mu \ll M_S$ (which also suppresses Δ_b effects in Higgs couplings)

When $\mu,\, X_t \approx M_S$, expect a worse approximation for tan(alpha) at increasing $\tan\beta$

Wait for Gabriel’s talk for a comparison with the proper EFT calculation

“Exact” relations for M_H and alpha *(modulo external momentum effects!)*

$$M_H^2 = \mathcal{M}_{11}^2 + \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2}\,, \qquad \tan\alpha = \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2}$$

The hMSSM approximation: *neglect radiative corrections to the (1,1) and (1,2) elements*

$$M_H^2 \overset{\text{hMSSM}}{=} (\mathcal{M}_{11}^2)_{\rm tree} + \frac{(\mathcal{M}_{12}^2)^2_{\rm tree}}{(\mathcal{M}_{11}^2)_{\rm tree} - M_h^2}\,, \qquad \tan\alpha \overset{\text{hMSSM}}{=} \frac{(\mathcal{M}_{12}^2)_{\rm tree}}{(\mathcal{M}_{11}^2)_{\rm tree} - M_h^2}$$

When is this a good approximation?

Easier to see for tan(alpha):

$$\Delta\mathcal{M}_{12}^2 \ll (\mathcal{M}_{12}^2)_{\rm tree}$$

$$\Delta\mathcal{M}_{11}^2 \ll (\mathcal{M}_{11}^2)_{\rm tree} - M_h^2$$

The dominant one-loop corrections from top-stop loops depend on μ/M_S and X_t/M_S

$$\Delta\mathcal{M}_{11}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu^2 X_t^2}{M_S^4}\,, \qquad \Delta\mathcal{M}_{12}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu X_t}{M_S^2}\left(6 - \frac{X_t A_t}{M_S^2}\right),$$

E.g., better approximation for $\mu \ll M_S$ (which also suppresses Δ_b effects in Higgs couplings)

When $\mu,\, X_t \approx M_S$, expect a worse approximation for tan(alpha) at increasing $\tan\beta$

Wait for Gabriel’s talk for a comparison with the proper EFT calculation

“Exact” relations for M_H and alpha *(modulo external momentum effects!)*

$$M_H^2 \;=\; \mathcal{M}_{11}^2 \;+\; \frac{(\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2}\;, \qquad \tan\alpha \;=\; \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2}$$

The hMSSM approximation: *neglect radiative corrections to the (1,1) and (1,2) elements*

$$M_H^2 \;\stackrel{\rm hMSSM}{=}\; (\mathcal{M}_{11}^2)_{\tt tree} \;+\; \frac{(\mathcal{M}_{12}^2)^2_{\tt tree}}{(\mathcal{M}_{11}^2)_{\tt tree} - M_h^2}\;, \qquad \tan\alpha \;\stackrel{\rm hMSSM}{=}\; \frac{(\mathcal{M}_{12}^2)_{\tt tree}}{(\mathcal{M}_{11}^2)_{\tt tree} - M_h^2}$$

When is this a good approximation?

$$\Delta\mathcal{M}_{12}^2 \;\ll\; (\mathcal{M}_{12}^2)_{\tt tree} \;= -s_\beta\, c_\beta\,(M_A^2 + M_Z^2)$$

Easier to see for tan(alpha):

$$\Delta\mathcal{M}_{11}^2 \;\ll\; (\mathcal{M}_{11}^2)_{\tt tree} - M_h^2$$

The dominant one-loop corrections from top-stop loops depend on μ/M_S and X_t/M_S

$$\Delta\mathcal{M}_{11}^2 \;\approx\; -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu^2 X_t^2}{M_S^4}\;, \qquad \Delta\mathcal{M}_{12}^2 \;\approx\; -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu X_t}{M_S^2}\left(6 - \frac{X_t A_t}{M_S^2}\right)\;,$$

E.g., better approximation for $\mu << M_S$ (which also suppresses Δ_b effects in Higgs couplings)

When μ, $X_t \approx M_S$, expect a worse approximation for tan(alpha) at increasing $\tan\beta$

Wait for Gabriel’s talk for a comparison with the proper EFT calculation

particle. In the Minimal Supersymmetric Standard Model [75–81], the matrix describing the mixing of the neutral CP-even Higgs bosons is:

ATLAS, 1509.00672, p15

$$\mathcal{M}_S^2 = (m_Z^2 + \delta_1) \begin{bmatrix} \cos^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \sin^2\beta \end{bmatrix} + m_A^2 \begin{bmatrix} \sin^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \cos^2\beta \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \delta/\sin^2\beta \end{bmatrix} , \tag{18}$$

where δ_1 and δ are radiative corrections involving primarily top quarks and top squarks (stops), and other radiative corrections not related to the top quark mass have been neglected. The couplings in the hMSSM ?

The dominant one-loop corrections from top-stop loops depend on μ/M_S and X_t/M_S

$$\Delta\mathcal{M}_{11}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu^2 X_t^2}{M_S^4}\,, \qquad \Delta\mathcal{M}_{12}^2 \approx -\frac{m_t^4}{8\,\pi^2\,v^2\,s_\beta^2}\,\frac{\mu X_t}{M_S^2}\left(6 - \frac{X_t A_t}{M_S^2}\right)\,,$$

E.g., better approximation for $\mu << M_S$ (which also suppresses Δ_b effects in Higgs couplings)

When μ, $X_t \approx M_S$, expect a worse approximation for tan(alpha) at increasing $\tan\beta$

Wait for Gabriel's talk for a comparison with the proper EFT calculation

ROOT files for “low-tb-high” and hMSSM

[Available on the twiki pages of the MSSM subgroup of the LHC-HXSWG]

Cross sections and branching ratios for h, H and A for a grid of values of M_A and $\tan\beta$

- The “low-tb-high” files:

  M_h, M_H and α with `FeynHiggs`

  ggF and $b\bar{b}\phi$ Xsecs with `SusHi` (THDM + Δ_b)

  Widths with `FeynHiggs + PROPHECY4f + HDECAY`

  (LHC-HXSWG recommendation for MSSM BRs)

- The hMSSM files:

  M_h = 125 GeV, M_H and α from hMSSM formulae

  ggF and $b\bar{b}\phi$ Xsecs with `SusHi` (THDM)

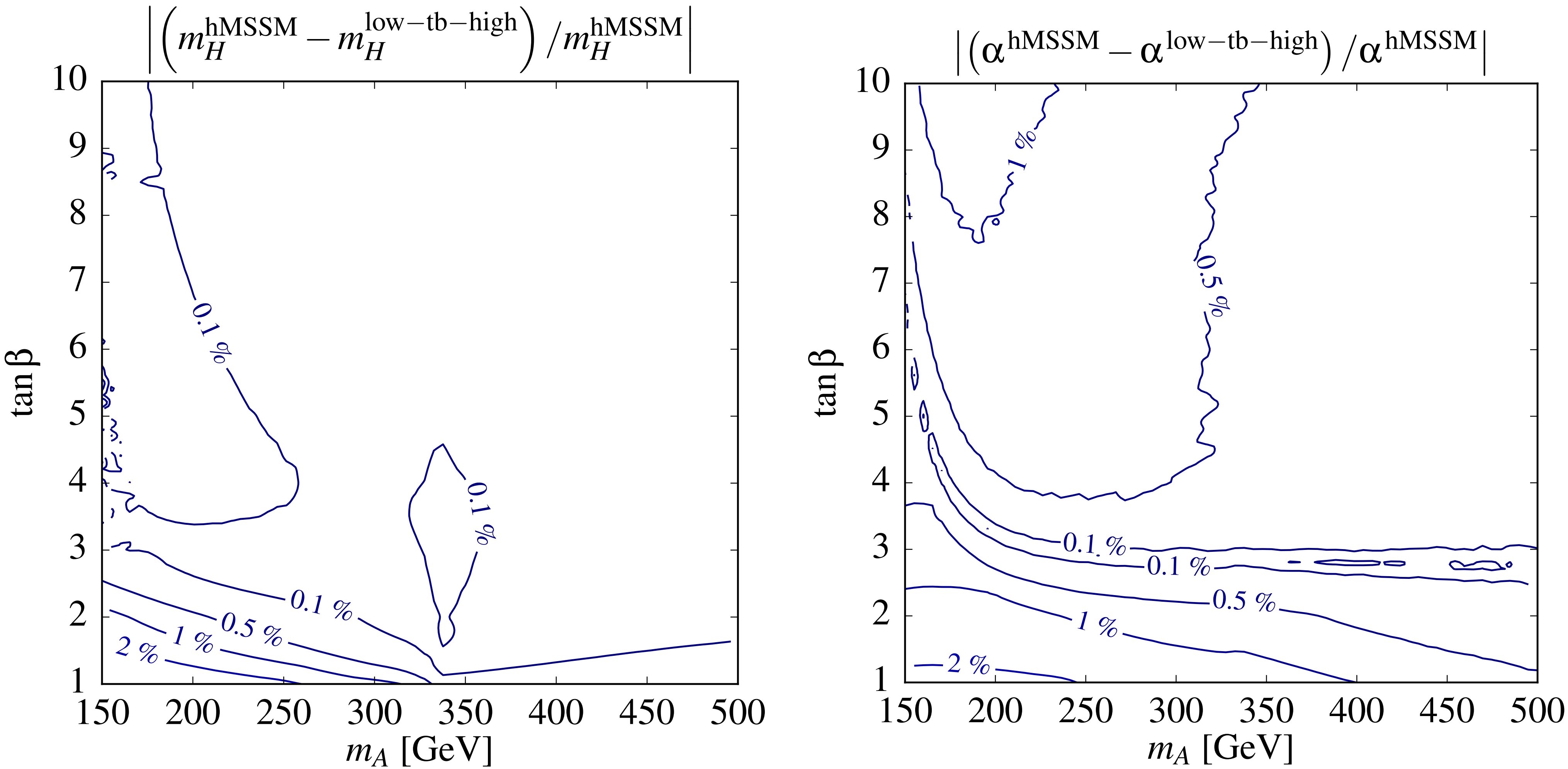
  All widths with `HDECAY`

A direct comparison of Xsecs and BRs in the two sets of files is biased by the different M_h

We produced “validation” files with M_h from “low-tb-high”, M_H and α from hMSSM formulae

We then compared the “validation” files with the “low-tb-high” files

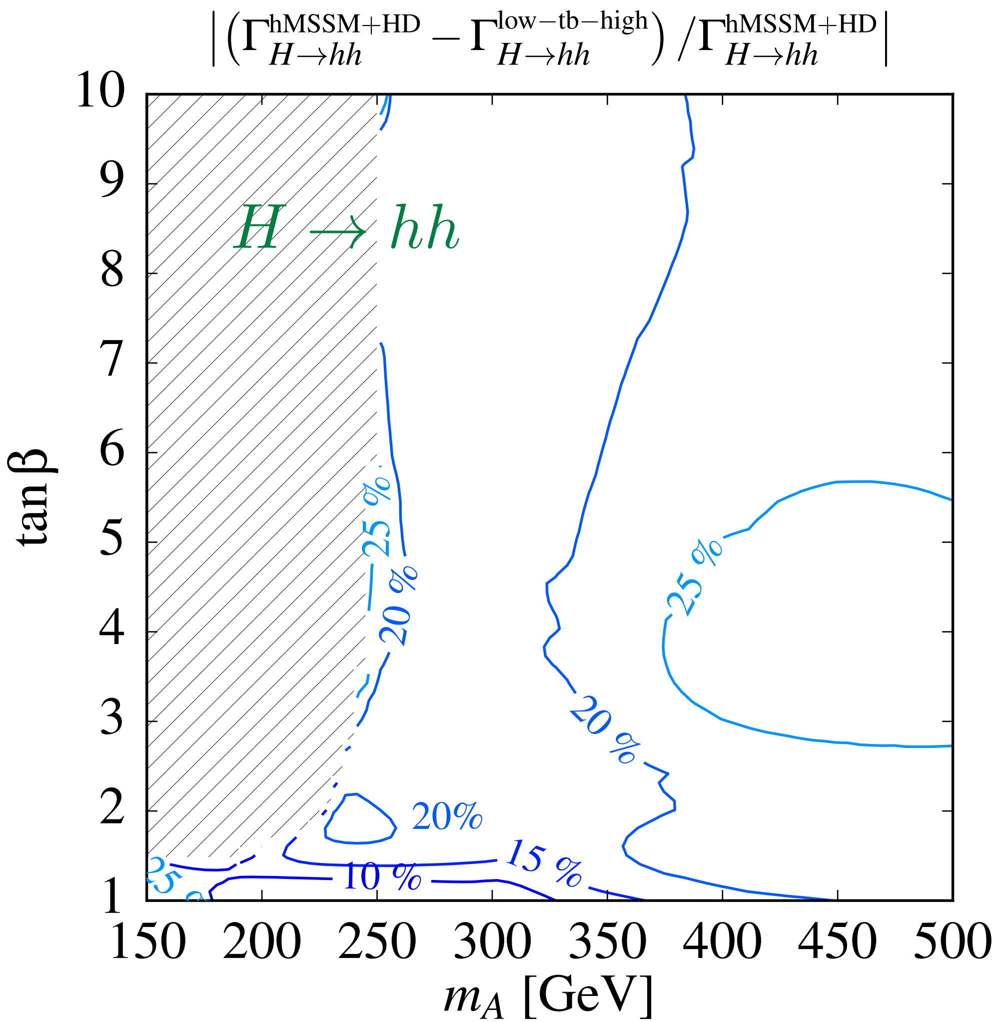
Comparing FeynHiggs with hMSSM in the “low-tb-high” scenario

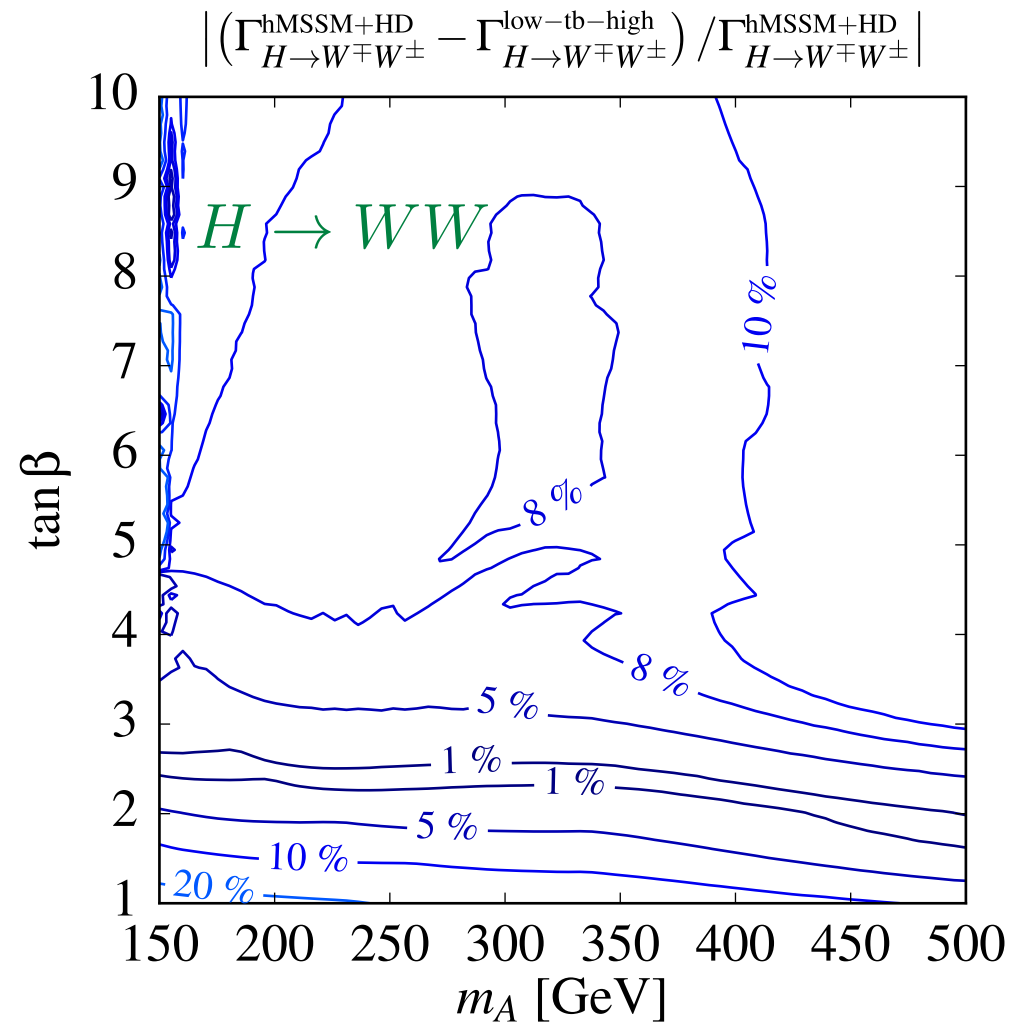


Agreement at the level of 0.1% – 1% except at very low $\tan\beta$

[in this scenario $\mu/M_S \ll 1$, so corrections to (1,1) & (1,2) are suppressed and hMSSM approx. works well]

Discrepancies about (10–20)% in some widths from the different accuracy of the calculations





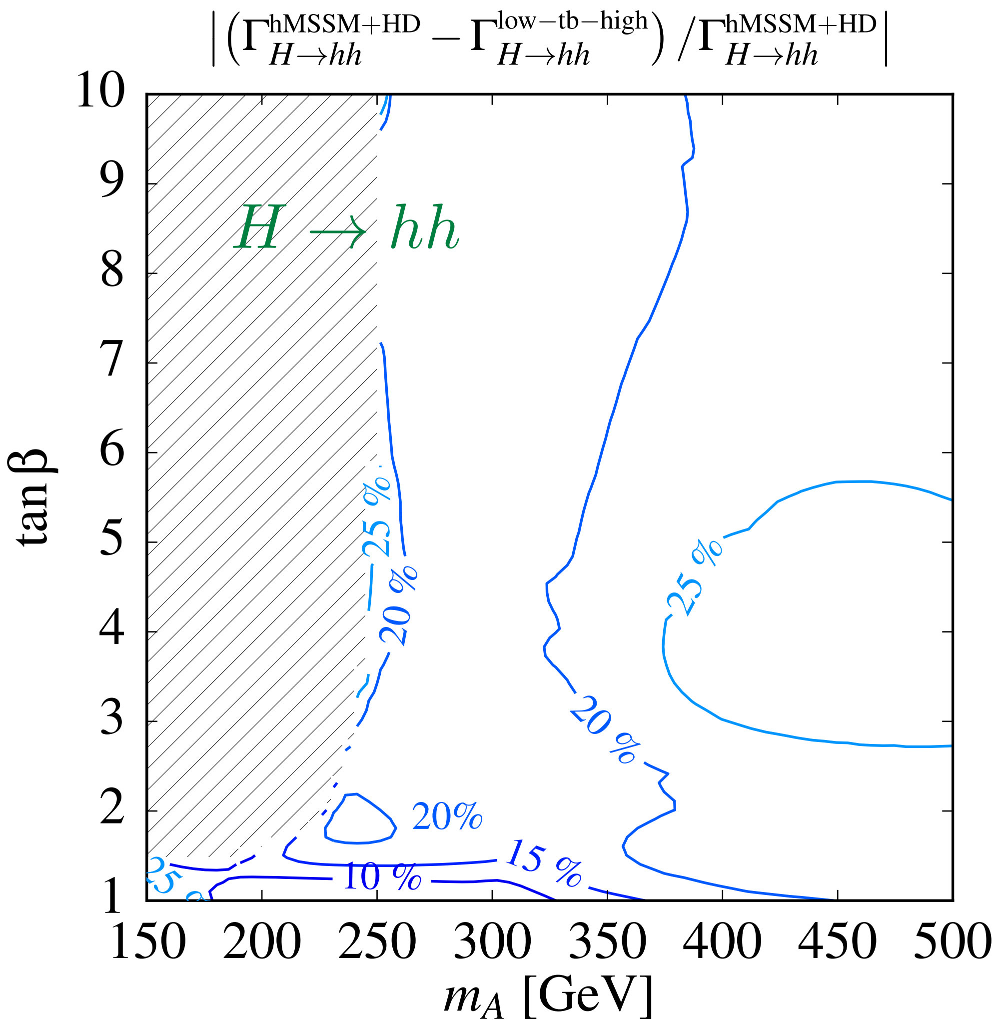
"low-tb-high" files: FeynHiggs (1-loop with log resummation)

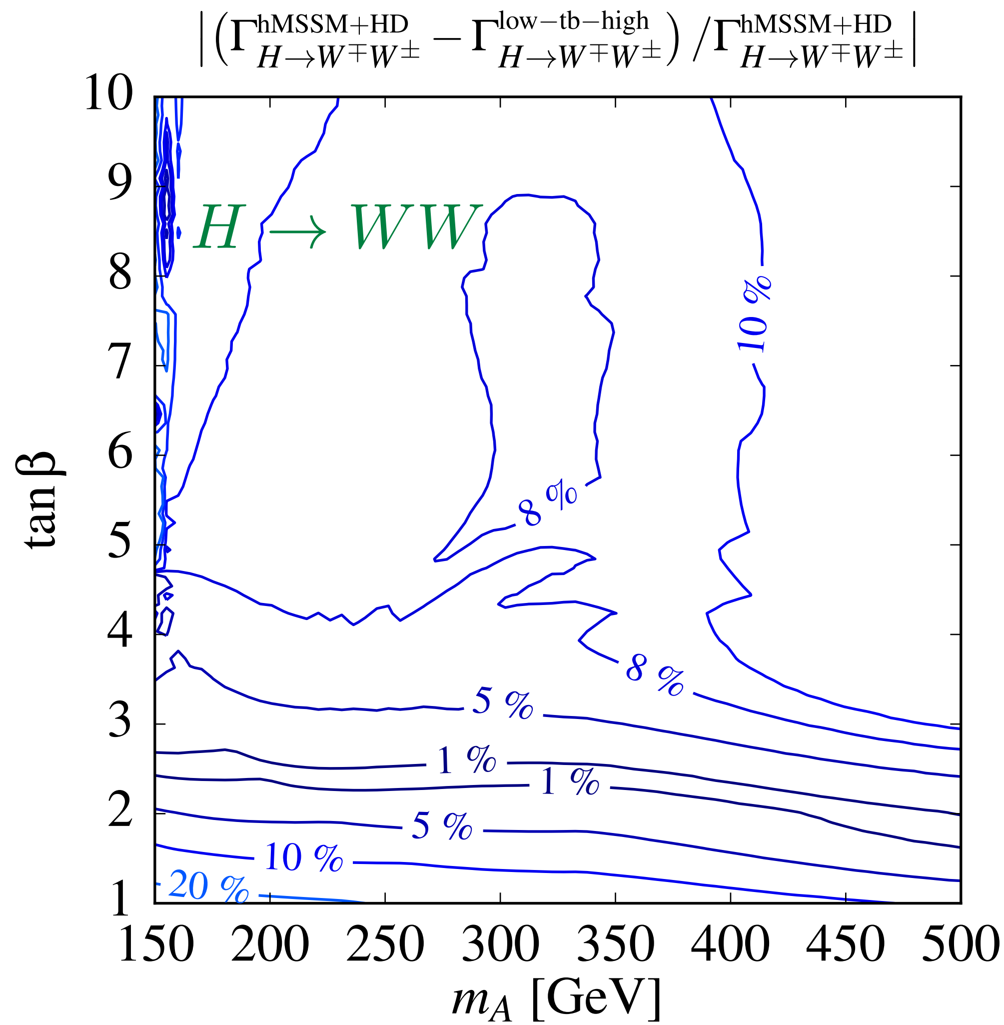
hMSSM files: HDECAY (LO with effective *Hhh* coupling)

"low-tb-high" files: PROPHECY4f (scaled with MSSM couplings)

hMSSM files: HDECAY (LO)

Discrepancies about (10–20)% in some widths from the different accuracy of the calculations





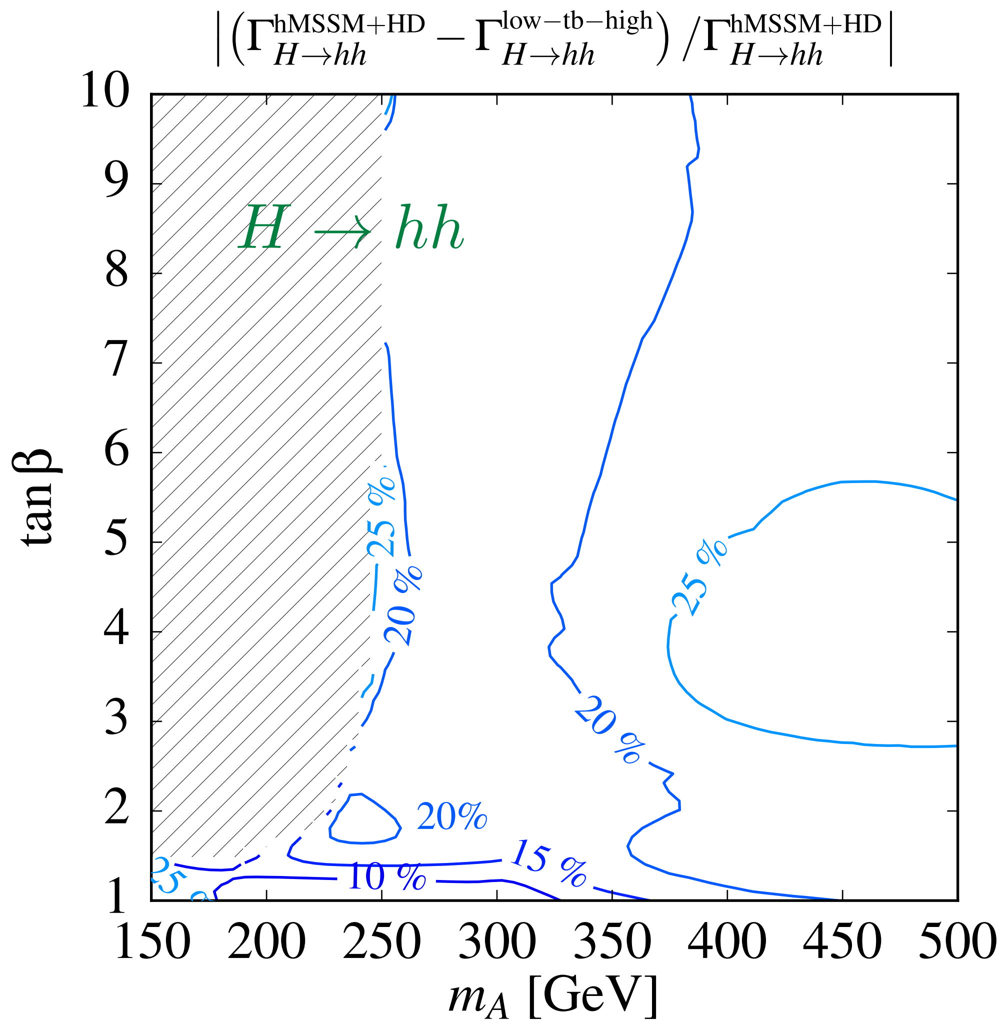
"low-tb-high" files: FeynHiggs (1-loop with log resummation)

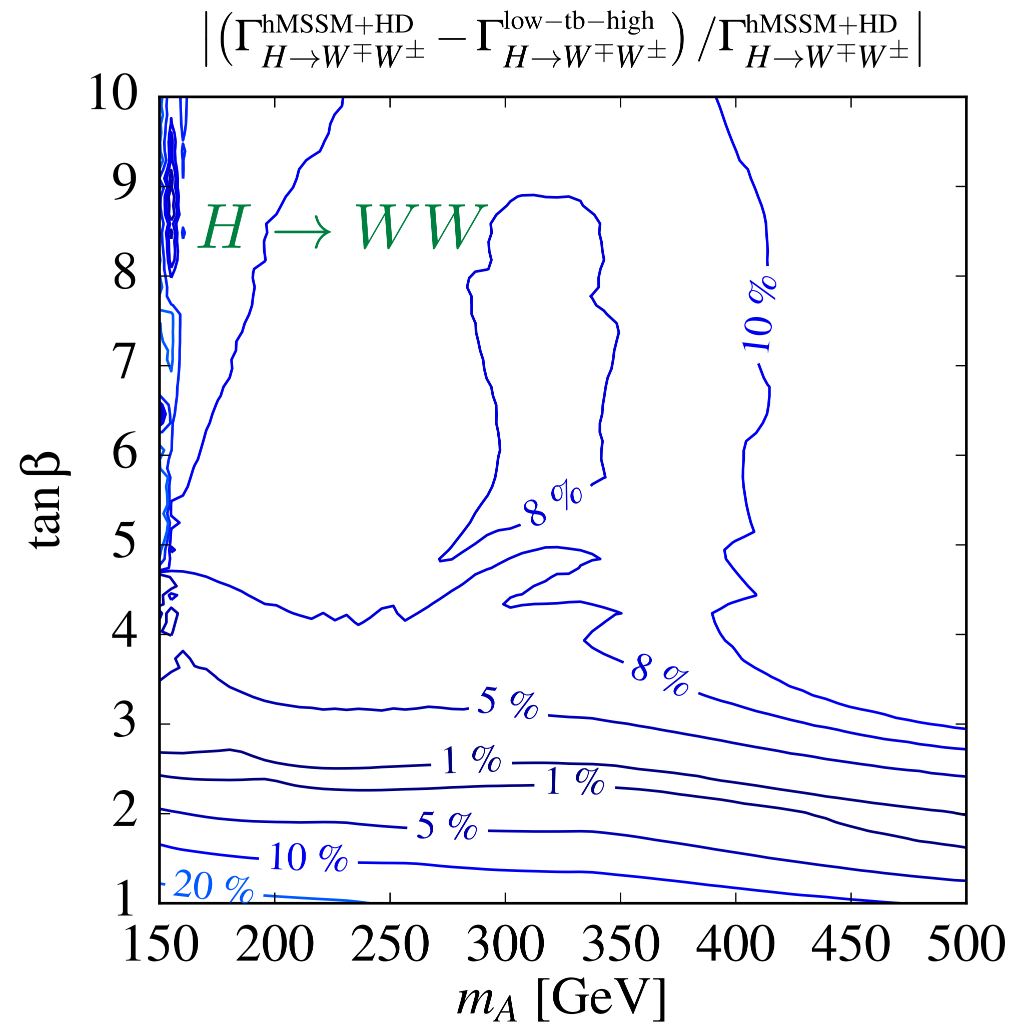
$$\lambda_{Hhh} = \lambda_{Hhh,\,{\rm tree}} + 3\,\frac{\Delta\mathcal{M}^2_{22}}{m_Z^2}\,\frac{\sin\alpha}{\sin\beta}\,\cos^2\alpha$$

"low-tb-high" files: PROPHECY4f (scaled with MSSM couplings)

hMSSM files: HDECAY (LO)

Discrepancies about (10–20)% in some widths from the different accuracy of the calculations





"low-tb-high" files:	FeynHiggs (1-loop with log resummation)	"low-tb-high" files:	PROPHECY4f (scaled with MSSM couplings)
hMSSM files:	HDECAY (LO with effective *Hhh* coupling)	hMSSM files:	HDECAY (LO)

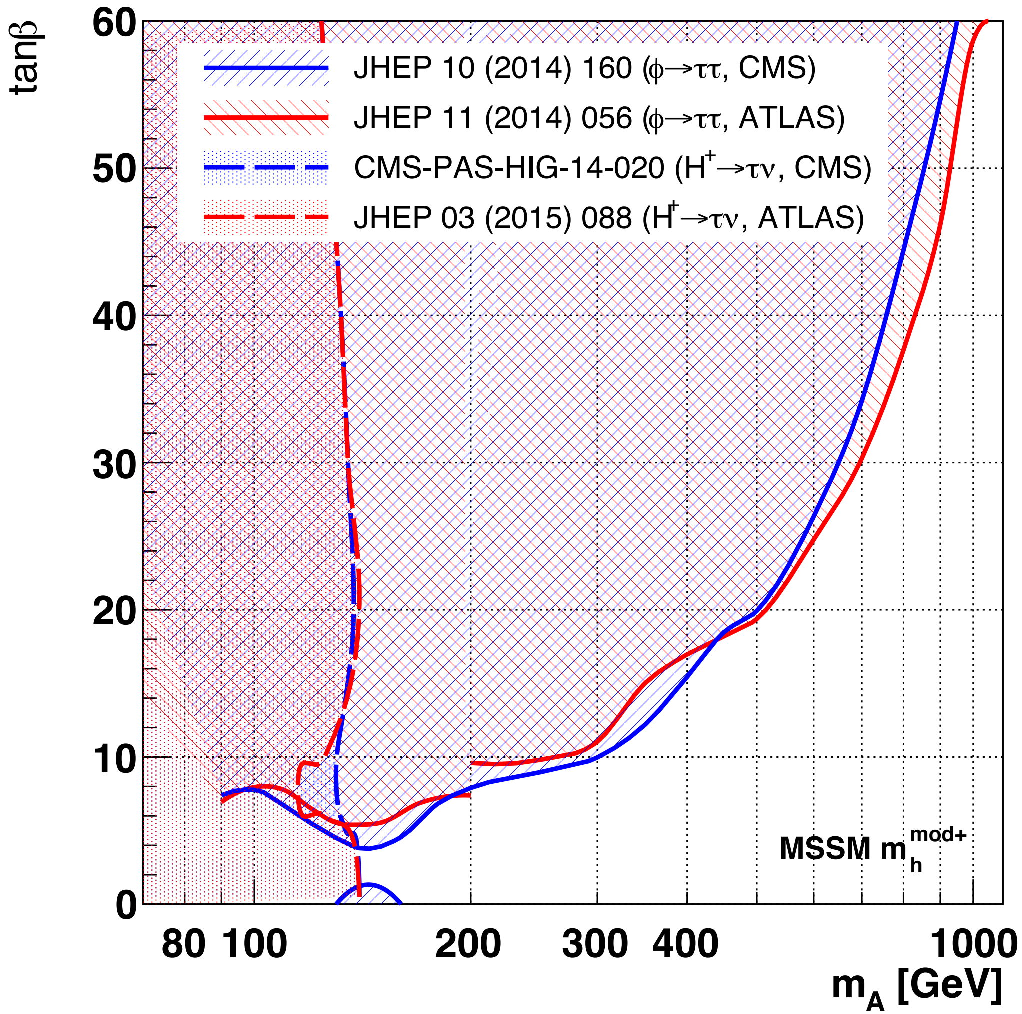
Constraints on low (M_A, $\tan\beta$) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios

- Couplings of the 125-GeV scalar (must be SM-like within 10-20%)
- Direct searches for $\phi^0 \longrightarrow \tau\,\tau$ (constrain low M_A for large $\tan\beta$)
- Direct searches for $H^\pm \longrightarrow \tau\,\nu$ (constrain low M_A for all $\tan\beta$)
- *B*-physics observables, especially $B \longrightarrow X_s\,\gamma$ (constrain low M_A for all $\tan\beta$)
- Any others?

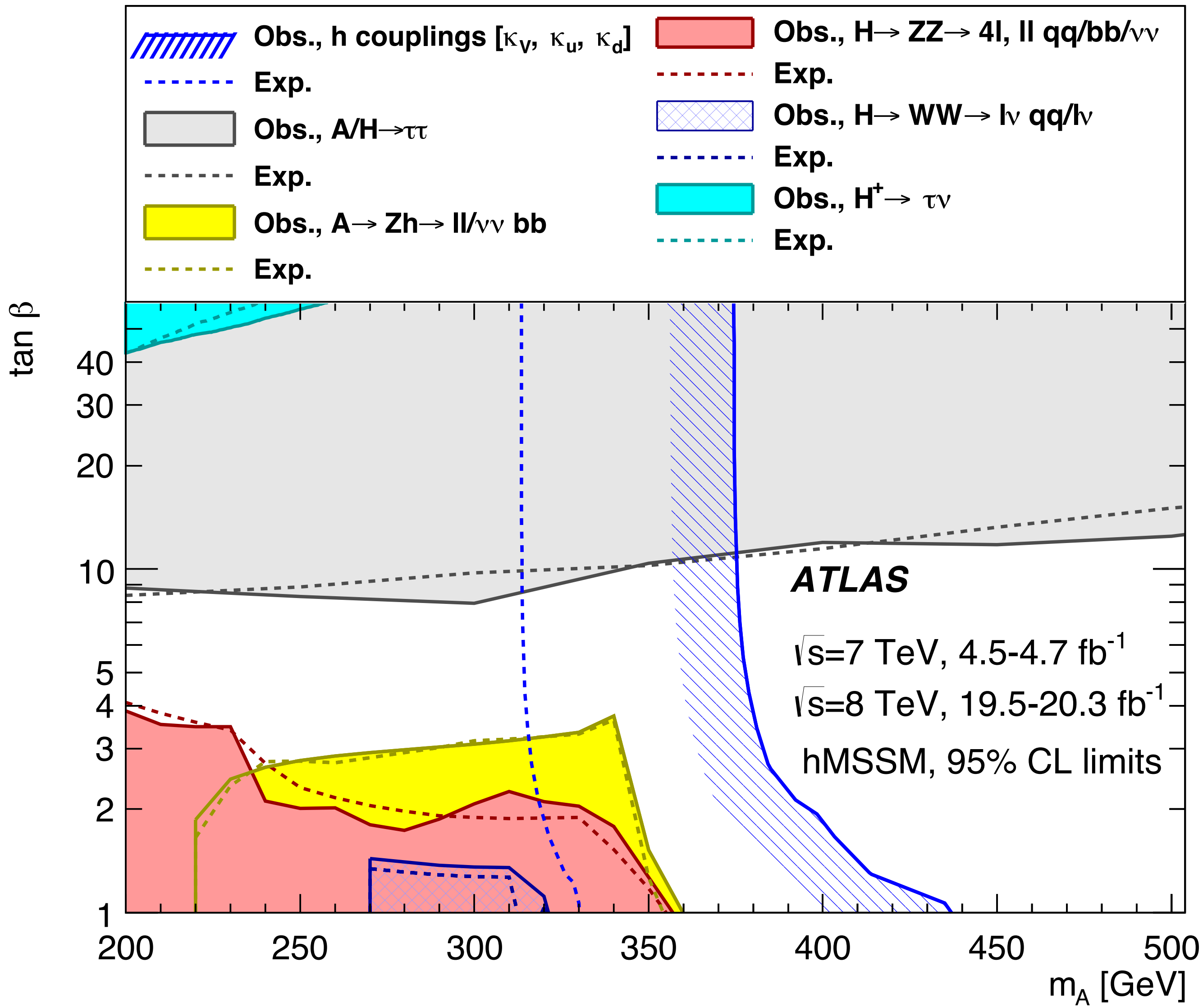
Constraints on low (M_A, tanβ) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios



Constraints on low (M_A, tanβ) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios



ATLAS, 1509.00672

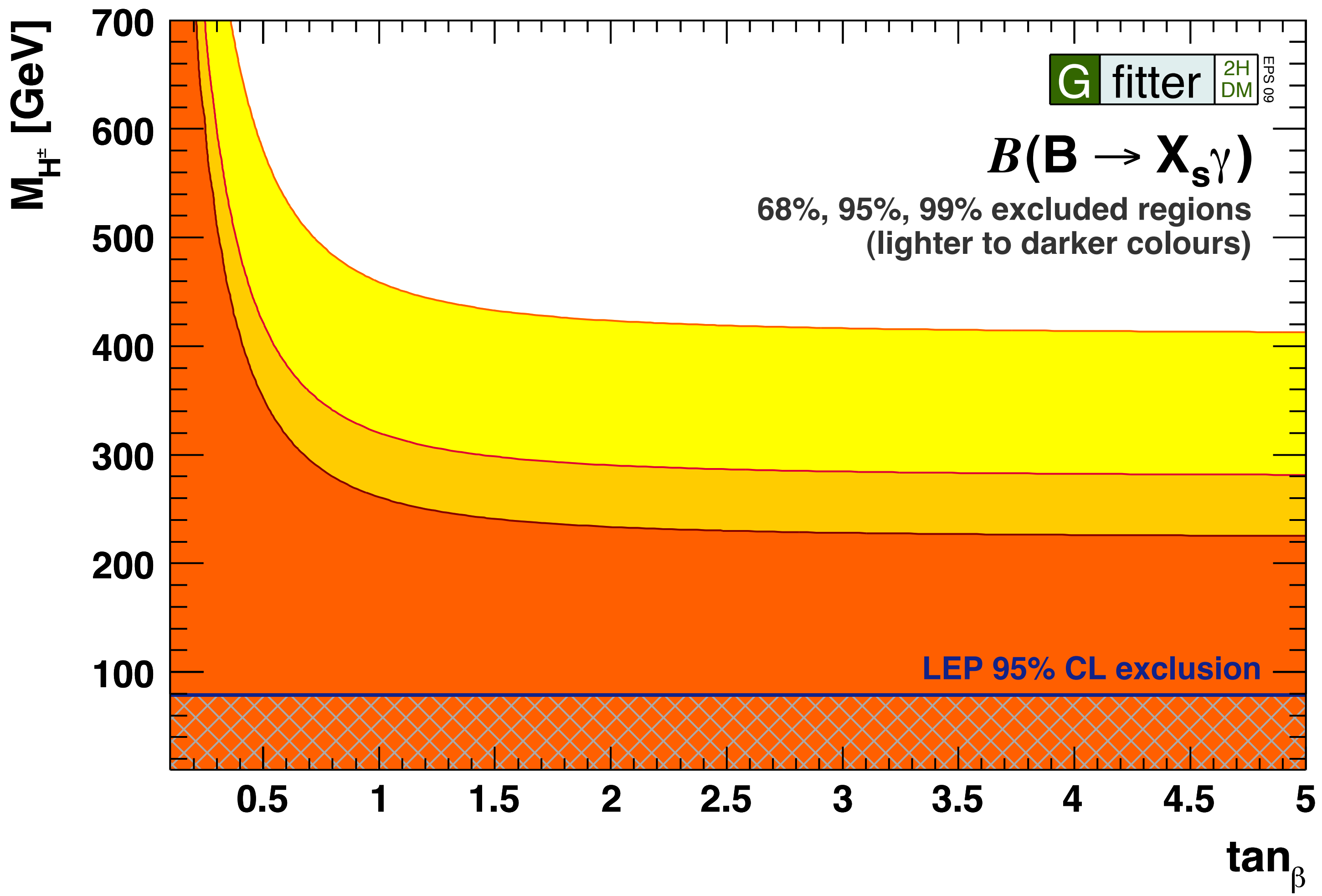
Constraints on low (M_A, tanβ) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios

- Couplings of the 125-GeV scalar (must be SM-like within 10-20%)
- Direct searches for $\phi^0 \longrightarrow \tau\,\tau$ (constrain low M_A for large tanβ)
- Direct searches for $H^\pm \longrightarrow \tau\,\nu$ (constrain low M_A for all tanβ)
- *B*-physics observables, especially $B \longrightarrow X_s\,\gamma$ (constrain low M_A for all tanβ)
- Any others?

Constraints on low (M_A, tanβ) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios



Constraints on low (M_A, tanβ) / heavy-SUSY scenarios

Our note did not discuss existing constraints on the parameter space of these scenarios

- Couplings of the 125-GeV scalar (must be SM-like within 10-20%)
- Direct searches for $\phi^0 \longrightarrow \tau\,\tau$ (constrain low M_A for large tanβ)
- Direct searches for $H^\pm \longrightarrow \tau\,\nu$ (constrain low M_A for all tanβ)
- *B*-physics observables, especially $B \longrightarrow X_s\,\gamma$ (constrain low M_A for all tanβ)
- Any others?

Final Recommendations:

1) Read the note

2) Use the files!!!

Thank you!!!