Higgs masses and mixing at low (m_A, $\tan\beta$): FeynHiggs, hMSSM and effective THDM

Pietro Slavich

(LPTHE Paris)

“Reopening the low-tanß regime”

[e.g.: Djouadi & Quevillon, 1304.1787]

Appeal of the low (*m_A, tanß*) region:

- For low m_A, extended Higgs sector potentially accessible at the LHC
- For low *tanß,* 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*

However...

- At low *tanß*, $m_h \approx 125$ GeV requires a large SUSY scale M_S:
  - For $m_A \approx M_S$, $\tan\beta = 1$ implies $M_S \approx 10^9 - 10^{10}$ GeV
    [see e.g. 1407.4081, as well as “SM vacuum stability” papers]
  - At low m_A we might need an even larger M_S
    [see later, Lee & Wagner]

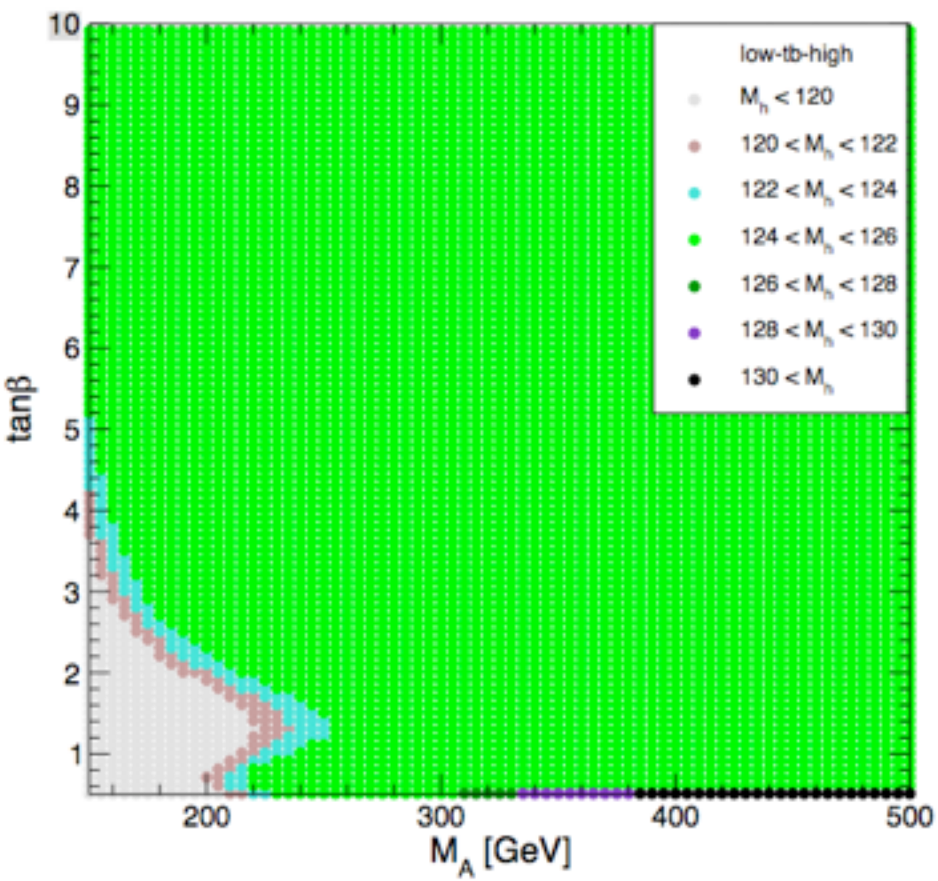
This calls for the resummation of large logarithms in an effective-theory approach

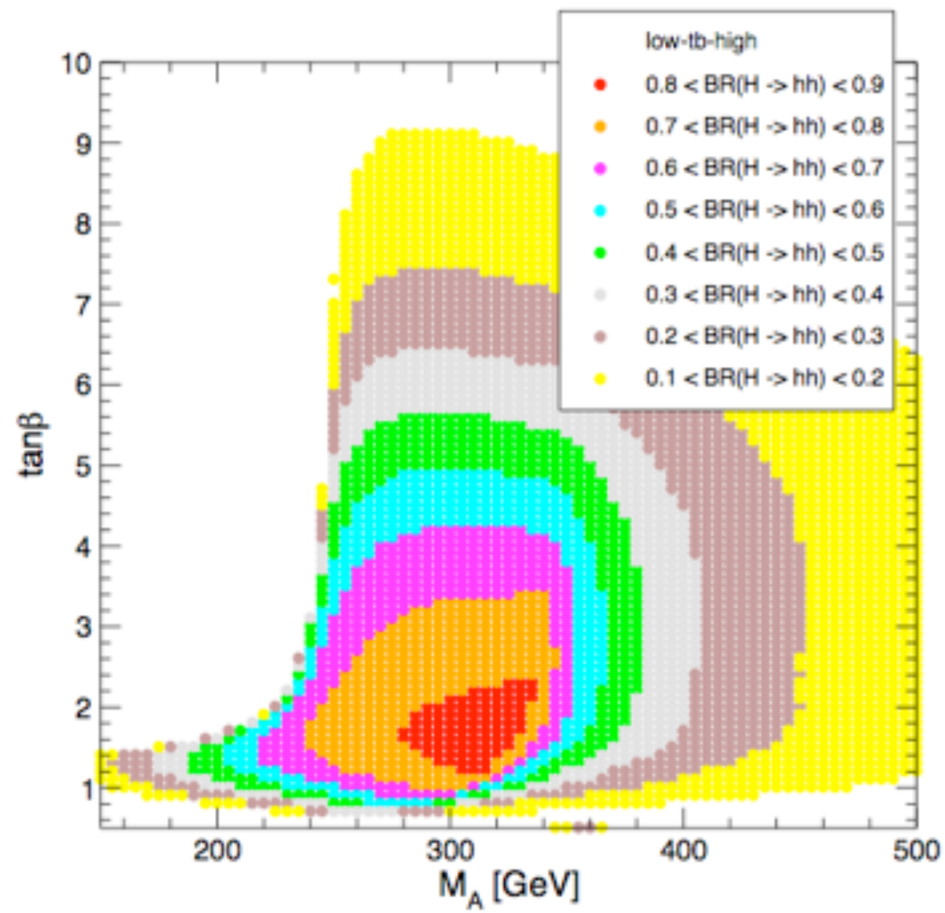
Sven's "low-tb-high" scenario for the HXSWG

FeynHiggs > 2.10.0 includes a (simplified) NLL resummation

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

$$m_{\tilde{f}} = M_3 = M_S, \quad 0 \leq X_t/M_S \leq 2, \quad M_2 = 2\ \mathrm{TeV}, \quad \mu = 1.5\ \mathrm{TeV}$$





However...

- For $\tan\beta = 1$, Sven obtains $m_h \approx 125$ GeV with $M_S = 2\text{x}10^5$ GeV (suspiciously low)
- The resummation procedure in FH does not account for low μ, $M_{1,2}$ and m_A

The resummed logs (computed in the decoupling limit and divided by $\sin\beta^2$)
are crammed in the (2,2) element of the mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -s_\beta c_\beta (m_Z^2 + m_A^2) \\ -s_\beta c_\beta (m_Z^2 + m_A^2) & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta_{11}^{2\ell} & \Delta_{12}^{2\ell} \\ \Delta_{21}^{2\ell} & \Delta_{22}^{2\ell} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & -\Delta^{\rm NLL} + \Delta^{\rm res} \end{pmatrix}$$

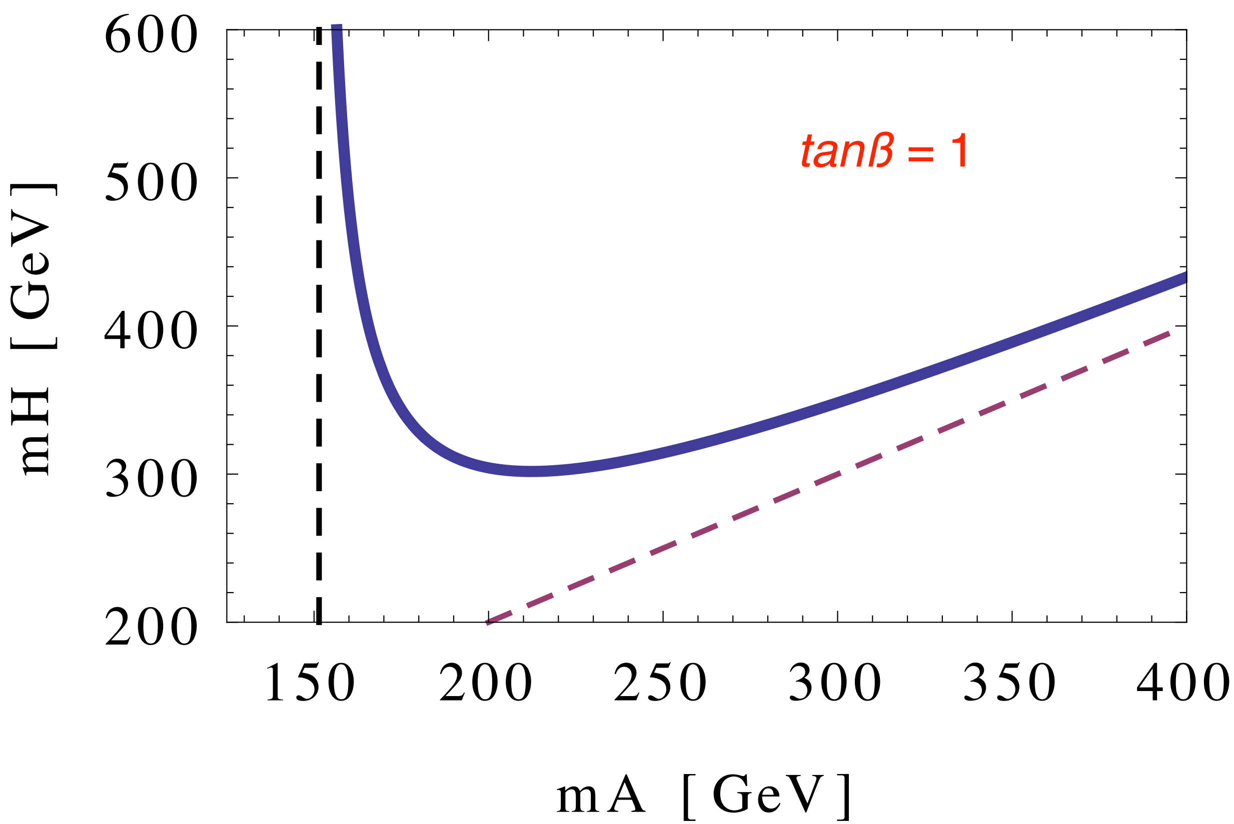
Is this a valid approximation at low (m_A, $\tan\beta$) ?

NOTE: the hMSSM relies on a more extreme version of this approximation

$$\mathcal{M}^2_{\rm hMSSM} = \begin{pmatrix} m_Z^2 c_\beta^2 + m_A^2 s_\beta^2 & -s_\beta c_\beta (m_Z^2 + m_A^2) \\ -s_\beta c_\beta (m_Z^2 + m_A^2) & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \Delta \end{pmatrix}$$

(then one trades Δ for m_h and obtains m_H and α)

Not all values of *(m_A, tanβ)* lead to meaningful hMSSM predictions for $m_h \approx 125$ GeV



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

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

Djouadi *et al.*, (1307.5205)

The safe approach: effective THDM with heavy SUSY

[Lee & Wagner, 1412.xxxx ???]

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} ,$$

Carena *et al.*, (1410.4969)

1) SUSY boundary conditions at the scale M_S :

$$\lambda_1 = \lambda_2 = -(\lambda_3 + \lambda_4) = \tfrac{1}{4}(g^2 + g'^2) = m_Z^2/v^2 ,$$
$$\lambda_4 = -\tfrac{1}{2}g^2 = -2m_W^2/v^2 ,$$
$$\lambda_5 = \lambda_6 = \lambda_7 = 0 .$$

(NOTE: tree level)

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:

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

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

Does the full calculation show significant deviations from (2,2) dominance?

In other words: are there significant corrections to any lambdas other than λ_2?

Threshold corrections from squark loops mess things up:

$$
\begin{aligned}
\lambda_1 &= \frac{1}{8}(g^2+g'^2) + \frac{N_c}{(4\pi)^2}\Big(y_b^4\frac{A_b^2}{M_S^2}(1-\frac{A_b^2}{12M_S^2}) - y_t^4\frac{\mu^4}{12M_S^4}\Big)\\
\lambda_2 &= \frac{1}{8}(g^2+g'^2) + \frac{N_c}{(4\pi)^2}\Big(y_t^4\frac{A_t^2}{M_S^2}(1-\frac{A_t^2}{12M_S^2}) - y_b^4\frac{\mu^4}{12M_S^4}\Big)\\
\lambda_3 &= \frac{1}{8}(g^2-g'^2) + \frac{N_c}{(4\pi)^2}\Big(y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\Big)\\
\lambda_4 &= -\frac{1}{4}g^2 + \frac{N_c}{(4\pi)^2}\Big(-y_b^2y_t^2\frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2}-\frac{\mu^2A_b^2}{12M_S^4})\Big)\\
\lambda_5 &= -\frac{N_c}{(4\pi)^2}\Big(y_t^4\frac{\mu^2A_t^2}{12M_S^4} + y_b^4\frac{\mu^2A_b^2}{12M_S^4}\Big),\\
\lambda_6 &= \frac{N_c}{(4\pi)^2}\Big(y_b^4\frac{\mu A_b}{M_S^2}(-\frac{1}{2}+\frac{A_b^2}{12M_S^2}) + y_t^4\frac{\mu^3A_t}{12M_S^4}\Big),\\
\lambda_7 &= \frac{N_c}{(4\pi)^2}\Big(y_t^4\frac{\mu A_t}{M_S^2}(-\frac{1}{2}+\frac{A_t^2}{12M_S^2}) + y_b^4\frac{\mu^3A_b}{12M_S^4}\Big),
\end{aligned}
$$

Cheng *et al.*, (1411.7329)

also Haber-Hempfling early ‘90s

NOTE: stop corrections relevant only when μ, $A_t \approx M_S$

Then the RG evolution mixes the lambdas

How bad is this? Comparing FeynHiggs and effective THDM

A problem: different renormalization schemes for SUSY parameters

—> we start from the case $X_t \approx 0$ where this is less important

First benchmark: $m_{\tilde{f}} = \mu = M_{1,2,3} = 200\ \mathrm{TeV}, \quad X_t = 0, \quad m_A = 250\ \mathrm{GeV}, \quad \tan\beta = 3$

FeynHiggs:	m_h = 121.01,	m_H = 259.74,	*alpha* = -0.4635
Lee-Wagner: (y_t NNLO)	m_h = 119.13,	m_H = 259.68,	*alpha* = -0.4565
Lee-Wagner: (y_t NLO)	m_h = 121.17,	m_H = 259.87,	*alpha* = -0.4608

Discrepancy in m_h mostly due to top Yukawa (!!!), m_H and *alpha* seem OK

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hMSSM: (m_h from FH)	m_h = 121.01,	m_H = 260.22,	*alpha* = -0.4641

hMSSM works fine here

More comparisons: zero-mixing points from Sven's "low-tb-high"

$$m_{\tilde{f}} = M_3 = 17\ \mathrm{TeV}, \quad X_t = 0, \quad M_2 = 2M_1 = 2\ \mathrm{TeV}, \quad \mu = 1.5\ \mathrm{TeV}, \quad \tan\beta = 9$$

		m_h	m_H	*alpha*
m_A = 175 GeV	FeynHiggs:	m_h = 127.03,	m_H = 177.95,	*alpha* = -0.2938
	Lee-Wagner: (y_t NLO)	m_h = 127.18,	m_H = 177.84,	*alpha* = -0.2902
	hMSSM: (m_h from FH)	m_h = 127.03,	m_H = 177.87,	*alpha* = -0.2920
m_A = 150 GeV	FeynHiggs:	m_h = 124.88,	m_H = 155.31,	*alpha* = -0.4673
	Lee-Wagner: (y_t NLO)	m_h = 124.71,	m_H = 153.96,	*alpha* = -0.4776
	hMSSM: (m_h from FH)	m_h = 124.88,	m_H = 155.00,	*alpha* = -0.4656

Summary

- For low (m_A, $\tan\beta$), the assumptions underlying both the hMSSM approximation and the "log resummation" implemented in FeynHiggs should be questioned

- We compared FeynHiggs with the effective-theory calculation in "easy" points with $X_t = 0$: (m_A = 250 GeV, $\tan\beta = 3$) and (m_A = 150,175 GeV, $\tan\beta = 9$)

- The discrepancy in m_h depends on the top Yukawa; m_H and *alpha* are OK (a case for upgrading the top-Yukawa calculation in FeynHiggs?)

- In these "easy" points, the hMSSM approximation works well (it tracks FH)

- Things might get more complicated at large X_t or lower (m_A, $\tan\beta$)