Higgs Bosons in Heavy SUSY with Intermediate m_A

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arXiv:1508.00576 with Carlos E. M. Wagner

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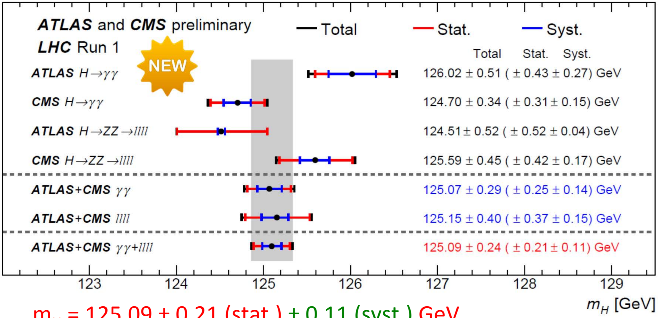
Outline

1. THDM as Effective Theory
2. Results for M_h for low $\tan\beta, m_A$
3. Comparison with hMSSM at low $\tan\beta$
4. The Low-$\tan\beta$-High Scenario

New M_h Combination



m_H = 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV

dominated by energy/momentum scale calibration
(which is also dominated by available statistics)

Overall 0.19% precision already achieved!

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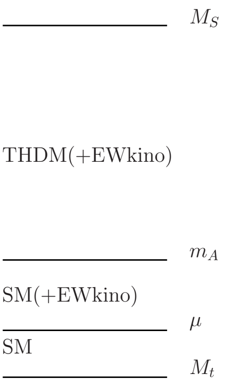
From Moriond 2015.

Method Outline



- Begin with SM couplings at M_t. Buttazzo et al. 1307.3536
- Use SM RGE's (possibly with EWkino contributions beginning at μ) to evolve $\{g_i, y_j, \lambda\}$ from M_t to m_A.
- Use THDM RGE's (in the $\lambda_i = 0$ approximation) to evolve $\{g_i, h_j, \tan\beta\}$ from m_A to M_S.
- Compute 1-loop threshold corrections to h_j.
- Compute THDM quartic couplings $\lambda_i(M_S)$ in the MSSM (with 1-loop, select 2-loop corrections).
- Use THDM RGE's to evolve $\{g_i, h_j, \lambda_k\}$ from M_S to m_A.
- Compute λ_k combinations appearing in Higgs mass matrix $\mathcal{M}^2_{H^0}$ at m_A. Gunion & Haber 0207010
- Evolve $\{g_i, y_j, \lambda\}$ using SM RGE's in "Higgs basis", where λ corresponds to the Higgs doublet that receives a vev.
- Diagonalize $\mathcal{M}^2_{H^0}$ at M_t.
- Compute masses, couplings, angles, etc.

Matching the THDM to the MSSM at M_S

The general CP-conserving THDM potential is Haber & Hempfling 1993

$$V = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \left\{ \frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}.$$

Matching to the MSSM at tree level yields

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_Y^2)\,,$$
$$\lambda_3 = \frac{1}{4}(g_2^2 - g_Y^2)\,,$$
$$\lambda_4 = -\frac{1}{2} g_2^2\,,$$
$$\lambda_5 = \lambda_6 = \lambda_7 = 0\,.$$

Higgs Masses and the Higgs Basis

In the original basis used in the THDM potential, the CP-even neutral Higgs mass matrix is

$$\mathcal{M}^2_{H^0} = m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} f_{11} & f_{12} \\ f_{12} & f_{22} \end{pmatrix}$$

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

In the Higgs basis, $\{\phi_a^0, \phi_b^0\}$, for which $\langle \phi_b \rangle = 0$, Gunion & Haber 0207010, Carena et al. 1410.4969

$$\mathcal{M}^2_{H^0} = \begin{pmatrix} g_{11} v^2 & g_{12} v^2 \\ g_{12} v^2 & m_A^2 + g_{22} v^2 \end{pmatrix}$$

$$\begin{aligned} g_{11} &\equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) s_{2\beta}^2 + 2 s_{2\beta}\left[c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7\right] \,, \\ g_{12} &\equiv -\frac{1}{2} s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta}\right] + c_\beta c_{3\beta} \lambda_6 + s_\beta s_{3\beta} \lambda_7 \,, \\ g_{22} &\equiv \frac{1}{4} s_{2\beta}^2 \left[\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\right] + \lambda_5 - s_{2\beta} c_{2\beta} (\lambda_6 - \lambda_7) \,. \end{aligned}$$

Below m_A, $g_{11} \equiv \lambda$, and is evolved using the SM RGE's.
Also evolve g_{12} with the dominant 1-loop $\beta \sim 12\kappa y_t^4 / t_\beta$ from λ_2.

Thresholds at M_S

The 1-loop $\tilde{t}, \tilde{b}, \tilde{\tau}$ thresholds from triangle and box diagrams are well known, e.g. Carena et al. 9504316

$$\Delta_{\text{th}}^{(1)}\lambda_2 = 6\kappa h_t^4 \widehat{A}_t^2\left(1 - \frac{\widehat{A}_t^2}{12}\right) - \frac{\kappa}{2}h_b^4\hat{\mu}^4 - \frac{\kappa}{6}h_\tau^4\hat{\mu}^4$$
$$- \kappa\frac{g_2^2 + g_Y^2}{4}\left[3h_t^2\widehat{A}_t^2 - 3h_b^2\hat{\mu}^2 - h_\tau^2\hat{\mu}^2\right].$$

We also include the 1-loop terms from self-energy corrections to the Higgs fields (e.g. $\mathcal{O}(h_t^2 g^2)$).

Add leading 2-loop $h_t^4 g_3^2$ and h_t^6 contributions taken from effective potential in the $m_A = M_S$ case by assigning the corrections to the λ_k based on powers of c_β, s_β in the expression for g_{11}, e.g. Espinosa & Zhang 0003246

$$\Delta_{\text{th}}^{(h_t^4 g_3^2)}\lambda_2 = 16\kappa^2 h_t^4 g_3^2\left(-2\widehat{A}_t + \frac{1}{3}\widehat{A}_t^3 - \frac{1}{12}\widehat{A}_t^4\right).$$

NB:

- The Yukawas above h_t, h_b, h_τ include the one-loop MSSM threshold corrections, e.g. from squarks/gluinos, electroweakinos, that are necessary for consistency with our included thresholds to the quartic couplings. Carena et al. 0003180, Draper et al. 1312.5743, Bagnaschi et al. 1407.4081
- All parameters above are in the $\overline{\text{MS}}$ scheme.

RG Evolution

g_i	$g_i(M_t)$	y_j	$y_j(M_t)$
g_3	1.1666	y_t	0.94018
g_2	0.64779	y_b	0.0156
$g_Y = \sqrt{3/5} g_1$	0.35830	y_τ	0.0100

Boundary conditions at low scale M_t are SM NNLO values of g_i, y_j, λ. Buttazzo et al. 1307.3536

Between M_t and m_A, 3-loop SM RGE's (g_i, y_j, λ, anom. dim.). see paper for refs.

Between m_A and M_S: 2-loop type-II THDM RGE's (g_i, h_j, λ_k, anom. dims.). SARAH, Dev & Pilaftsis 1408.3405, 1508.00576

Caveats:

- Threshold corrections to Yukawas spoil assumption of type-II THDM below M_S.

  $$\mathcal{L} = (h_b + \delta h_b)\, \bar{b}_R \Phi_1^{i,*} Q_L^i + \epsilon_{ij} (h_t + \delta h_t)\, \bar{t}_R Q_L^i \Phi_2^j + \Delta h_b \bar{b}_R Q_L^i \Phi_2^{i*} + \epsilon_{ij} \Delta h_t \bar{t}_R Q_L^i \Phi_1^j + h.c.$$

  However, since the “wrong” couplings are loop- and t_β suppressed, we expect them to have a small effect on the Higgs mass, so we assume they are frozen at the high scale.
- We assume tree-level gauge couplings of electroweakinos to Higgs bosons, and use these in the 1-loop RGE's above the scales $\mu = M_1 = M_2$.

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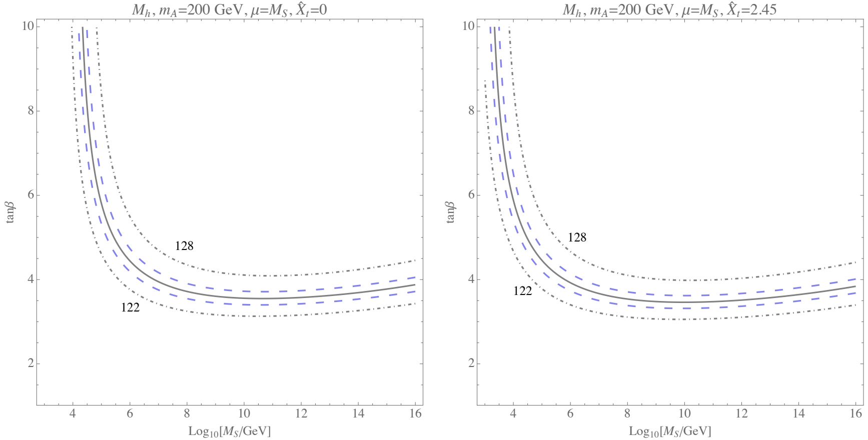
$m_A = 200$ GeV, $\mu = M_S$

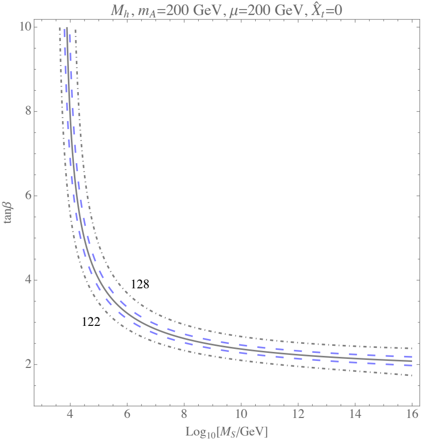


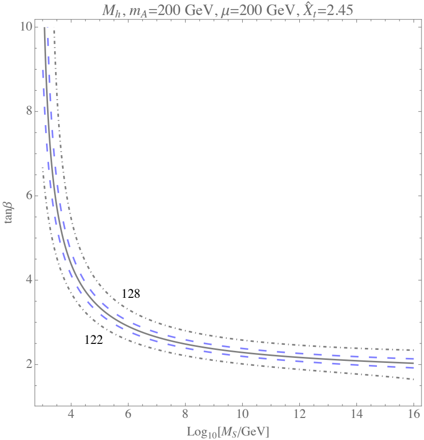
$(A_b = A_\tau = M_S, M_2 = M_1 = \mu, y_{t,\text{NNLO}} = 0.94018)$

Effect of mixing is more important at lower M_S; regardless of $\widehat{X}_t$, $t_\beta \gtrsim 3.5$ for $M_h \sim 125$ GeV.

The curves in the maximal mixing case exhibit some turnaround: may be due to mixing effects and how large h_t values at low t_β affect running.

$m_A = 200$ GeV, $\mu = 200$ GeV

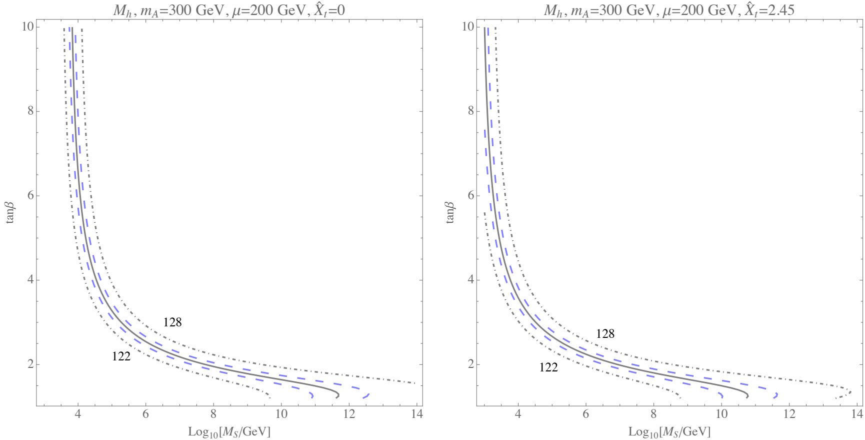




$(A_b = A_\tau = M_S,\, M_2 = M_1 = \mu,\, y_{t,\text{NNLO}} = 0.94018)$

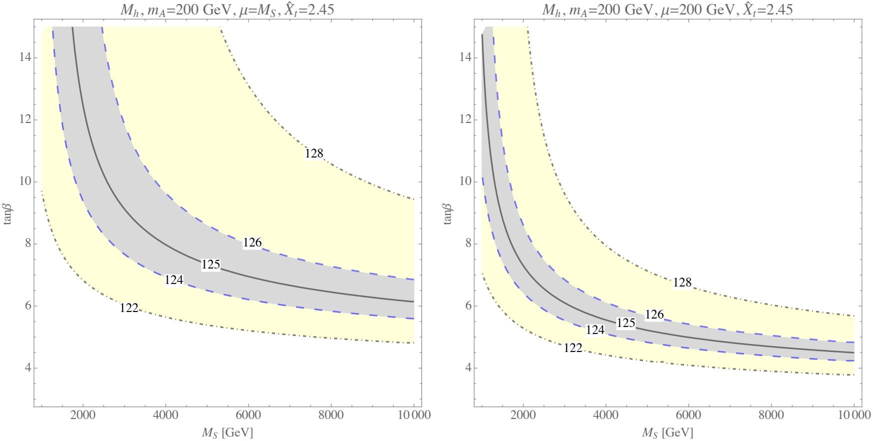
With light electroweakinos, can push t_β to 2 at $M_S = M_{\text{GUT}}$.

$m_A = 300$ GeV, $\mu = 200$ GeV



($A_b = A_\tau = M_S$, $M_2 = M_1 = \mu$, $y_{t,\text{NNLO}} = 0.94018$)
Requiring $M_h \sim 125$ GeV and $t_\beta > 1$, we obtain upper limits on $M_S < 10^{11}$–10^{12} GeV.

TeV scale: $m_A = 200$ GeV, $\widehat{X}_t = \sqrt{6}$



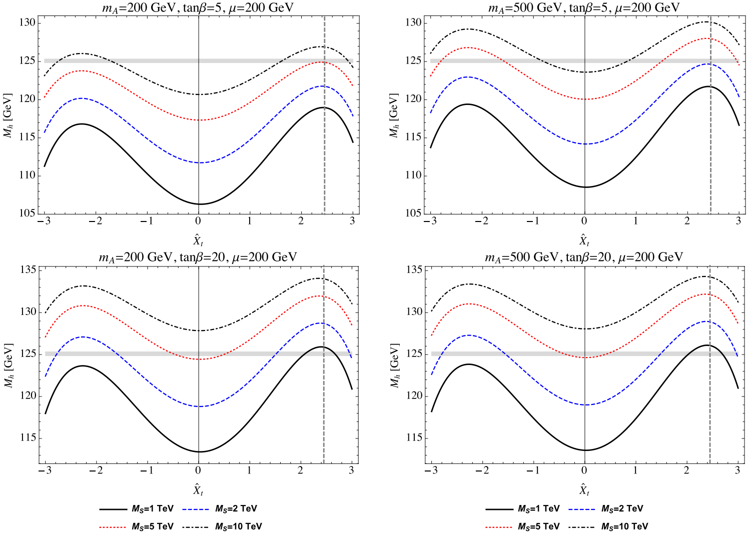
$(A_b = A_\tau = M_S, M_2 = M_1 = \mu, y_{t,\text{NNLO}} = 0.94018)$

In 1312.5743, found that to get $M_h = 125$ GeV for $m_A = M_S, \widehat{X}_t = \sqrt{6}, t_\beta = 4,$

$\mu = M_S$: $M_S = 8.5$ TeV

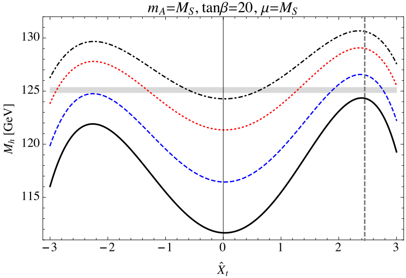
$\mu = 200$ GeV: $M_S = 3$ TeV

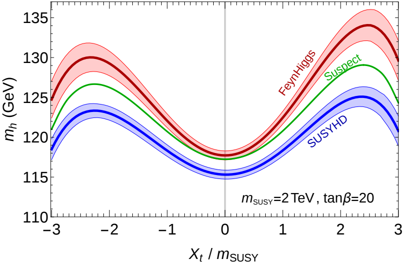
M_h vs. X_t for Different t_β



Significant effect of Higgs mixing at low t_β. For $t_\beta = 5$, the difference in M_h between curves for the same M_S is 2–3 GeV lower for $m_A = 200$ GeV compared to for $m_A = 500$ GeV (which is essentially the decoupling limit).

Comparison with SUSYHD





Pardo Vega and Villadoro, 1504.05200

At maximal mixing for $M_S = 2$ TeV (blue curves), we obtain $M_h = 126.1$ GeV vs. ~ 125 GeV, but within uncertainties of the SUSYHD calculation.

Two possible explanations:

- Use of lower $y_{t,\mathrm{N^3LO\ QCD}}(M_t) = 0.93690$ value in SUSYHD, about 0.5 GeV effect.
- More complete calculation of thresholds in the $m_A \sim M_S$ case. see also Draper et al. 1312.5743

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The hMSSM

The hMSSM approximation assumes that the

Djouadi et al. 1307.5205, 1502.05653

- observed Higgs boson is the light CP-even scalar h,
- only the radiative correction to the diagonal element in $\mathcal{M}^2_{H^0}$ corresponding to h is relevant.

In the original basis of the THDM, this implies

$$\lambda_1 = -(\lambda_3 + \lambda_4 + \lambda_5) = M_Z^2/v^2\,, \qquad \lambda_6 = \lambda_7 = 0\,,$$
$$\lambda_2 = M_Z^2/v^2 + \Delta\mathcal{M}^2_{22}/(v^2 s_\beta^2)\,.$$

For the mass matrix in the original basis, this implies that $\Delta\mathcal{M}^2_{12}, \Delta\mathcal{M}^2_{11} \ll \Delta\mathcal{M}^2_{22}$. For fixed m_A, t_β, trade $\Delta\mathcal{M}^2_{22}$ for known M_h,

$$\Delta\mathcal{M}^2_{22} = \frac{M_h^2(m_A^2 + M_Z^2 - M_h^2) - m_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - M_h^2}\,.$$

This yields the expressions:

$$m_H^2 = \frac{(m_A^2 + M_Z^2 - M_h^2)(M_Z^2 c_\beta^2 + m_A^2 s_\beta^2) - m_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + m_A^2 s_\beta^2 - M_h^2}\,,$$

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

$$g_{Hhh} = -\frac{M_Z^2}{v}\left\{2 s_{2\alpha} s_{\beta+\alpha} - c_{2\alpha} c_{\beta+\alpha} + 3\frac{\Delta\mathcal{M}^2_{22}}{M_Z^2}\frac{s_\alpha}{s_\beta} c_\alpha^2\right\} \qquad \text{(later)}\,.$$

When does the hMSSM approximation fail?

In the Higgs basis, recall the off-diagonal element in $\mathcal{M}^2_{H^0}$:

$$\Delta g_{12} \equiv -\frac{1}{2} s_{2\beta} \left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta} \right] + c_\beta c_{3\beta} \lambda_6 + s_\beta s_{3\beta} \lambda_7 \,.$$

For moderate values of $\tan\beta$, the only non-c_β suppressed term involves λ_7,

$$\lambda_7 \sim \frac{N_c}{(4\pi)^2} y_t^4 \frac{\mu A_t}{M_S^2} \left[-\frac{1}{2} + \frac{1}{12} \frac{A_t^2}{M_S^2} \right] .$$

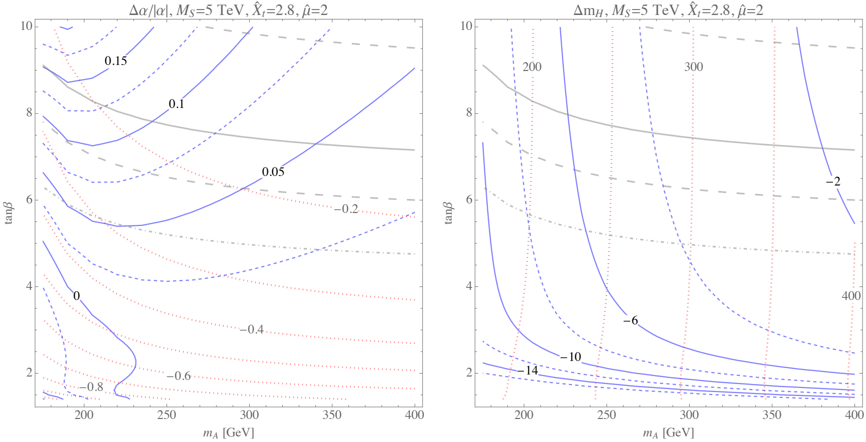
For large $A_t, \mu \sim M_S$, this can be non-trivial.

Another approach is to examine the expressions for the dominant corrections to g_{11}, g_{12} for values of m_H larger than the weak scale and moderate values of t_β, from which one can show alignment limit in e.g. Carena et al., 1310.2248, 1410.4969

$$t_\beta \; c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2} \left[m_h^2 + m_Z^2 + \frac{3 m_t^4}{4\pi^2 v^2 M_S^2} \left\{ A_t \mu t_\beta \left(1 - \frac{A_t^2}{6 M_S^2} \right) - \mu^2 \left(1 - \frac{A_t^2}{2 M_S^2} \right) \right\} \right] .$$

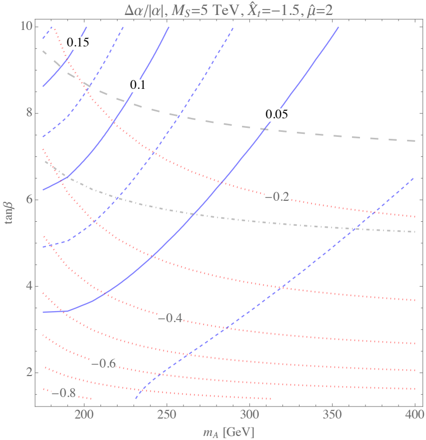
The RG corrections to m_h can be absorbed into the first term, but if the third term is large, then the hMSSM approximation for the mixing angle α fails.

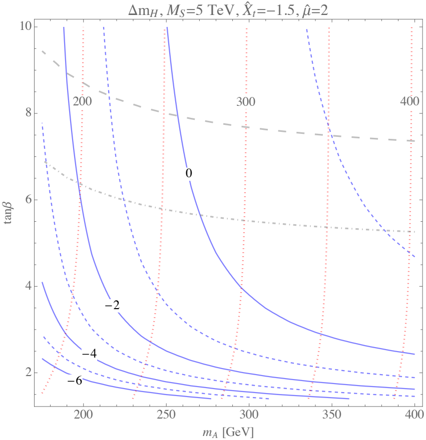
Comparison with hMSSM: $M_S = 5$ TeV, $\widehat{X}_t = 2.8$, $\mu/M_S = 2$



Blue solid lines: $(\alpha_{\text{THDM}} - \alpha_{\text{hMSSM}})/|\alpha_{\text{THDM}}|$ or $m_{H,\text{THDM}} - m_{H,\text{hMSSM}}$
Red dashed lines: values for α_{THDM} or $m_{H,\text{THDM}}$
Grey lines, bottom–top: (dot-dash, dash, solid, dash, dot-dash) are $M_h = (122, 124, 125, 126, 128)$ GeV

Comparison with hMSSM: $M_S = 5$ TeV, $\widehat{X}_t = -1.5$, $\mu/M_S = 2$





For $\hat{\mu} > 0$, we can achieve a similar discrepancy of 15% with negative mixing values that are smaller in magnitude.

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Description of the Low-$\tan\beta$-High Scenario

Scenario proposed by the LHCHXSWG BR group to investigate parameter choices necessary in the MSSM to obtain $M_h = 125$ GeV for low t_β, m_A. LHCHXSWG-2015-002

At low t_β, even with maximal stop mixing, large values of the SUSY scale M_S are required to obtain $M_h = 125$ GeV. For such large values of M_S, fixed-order calculations are less reliable, so resummation was introduced in FeynHiggs 2.10.

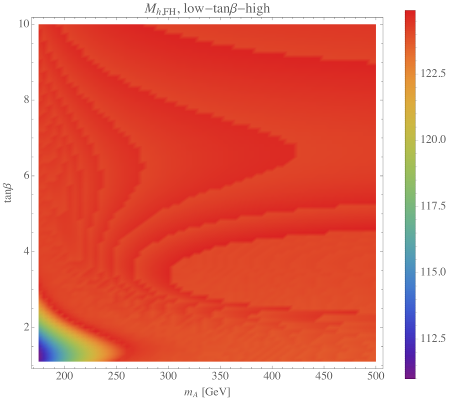
Assumptions:

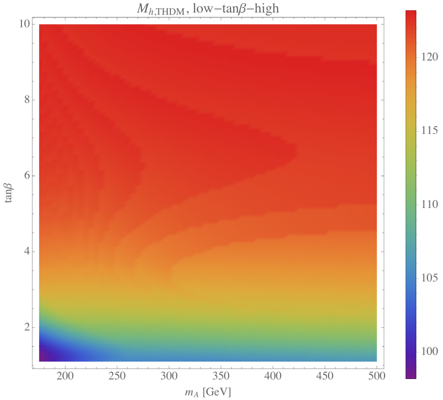
- All sfermions and the gluino have masses at M_S.
- The stop mixing parameter in the OS-scheme is set according to
  - $t_\beta \leq 2$: $\widehat{X}_t^{\mathrm{OS}} = 2$,
  - $2 \leq t_\beta \leq 8.6$: $\widehat{X}_t^{\mathrm{OS}} = 0.0375 t_\beta^2 - 0.7 t_\beta + 3.25$,
  - $8.6 \leq t_\beta \leq 10$: $\widehat{X}_t^{\mathrm{OS}} = 0$.
- Other Higgs-sfermion trilinears are fixed at 2 TeV.
- $\mu = 1.5$ TeV, $M_2 = 2$ TeV, and $M_1 = M_2 \cdot 5/3 \tan^2\theta_W$ (GUT relation).

We examine the parameter space for $175 \leq m_A \leq 500$ GeV, $1.1 \leq t_\beta \leq 10$.
We compare Higgs masses computed by FeynHiggs 2.10.2 with our calculation.

NB: we convert the OS parameters M_S, X_t to their $\overline{\mathrm{MS}}$ values at 1-loop.

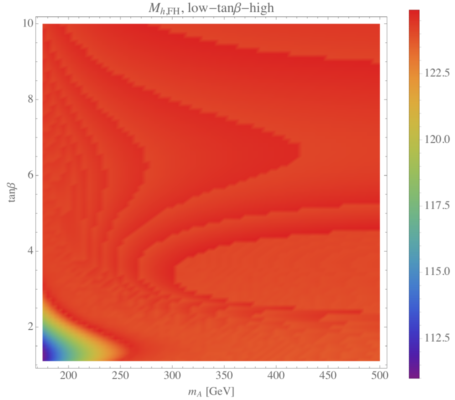
M_h

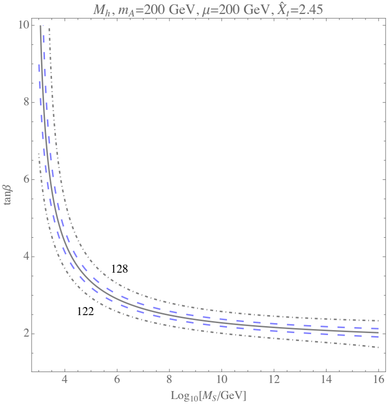




Our effective THDM calculation clearly yields much lower values of M_h at low t_β across the range of m_A.

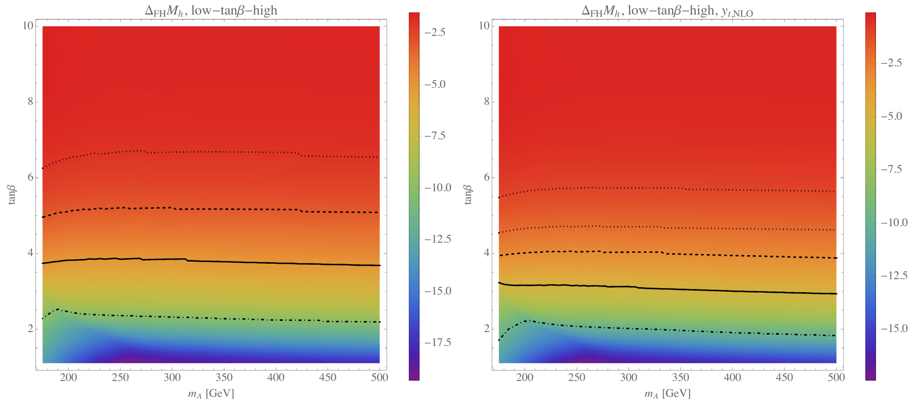
M_h





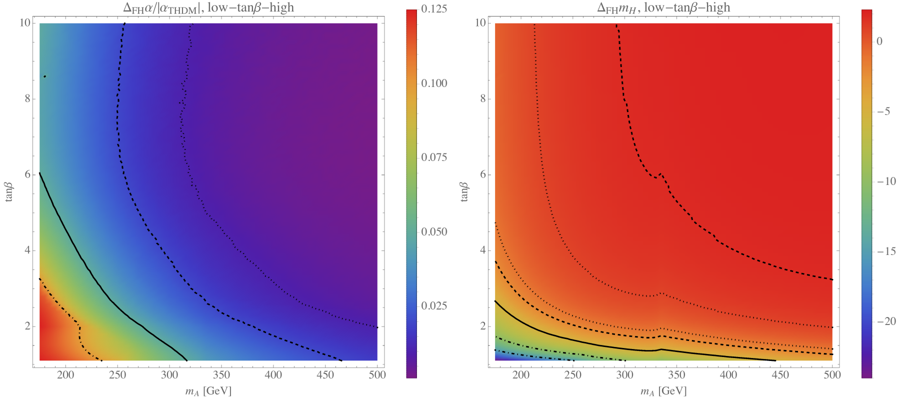
Earlier result: for even lighter electroweakinos, $M_h = 122$ GeV not achieved for $M_S = 100$ TeV until $t_\beta \sim 3$.

ΔM_h



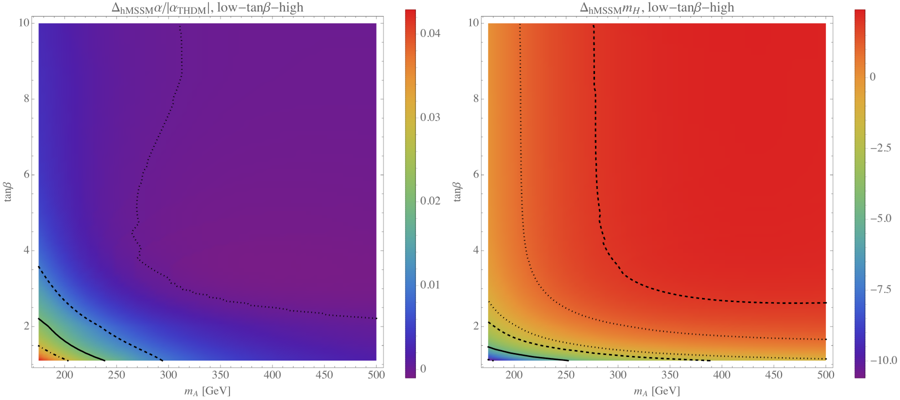
$\Delta M_h = M_{h,\mathrm{THDM}} - M_{h,\mathrm{FH}}$ using $y_{t,\mathrm{NNLO}} = 0.94018$ (left) and $y_{t,\mathrm{NLO}} = 0.95113$ (right).
Top–bot: ([dot,] dot, dash, solid, dot-dash) are $\Delta M_h = -([1,]2,3,5,10)$ GeV, with [] for the right plot.
L: $\Delta M_h \sim -2$ to -3 (-3 to -5) GeV for $5 \lesssim t_\beta \lesssim 6.5$ ($4 \lesssim t_\beta \lesssim 5$).
R: $\Delta M_h \sim -2$ to -3 (-3 to -5) GeV for $4 \lesssim t_\beta \lesssim 4.5$ ($3 \lesssim t_\beta \lesssim 4$).
Note that with $y_{t,\mathrm{NLO}}$, agreement with FeynHiggs is within 1 GeV for $t_\beta \gtrsim 5.5$.

Comp. with FEYNHIGGS: α, m_H



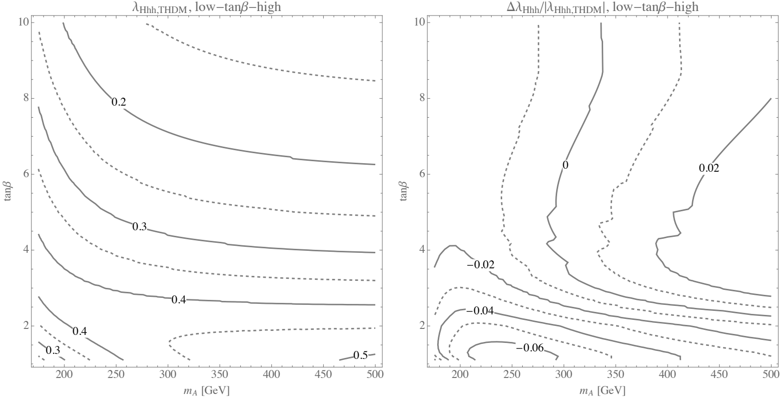
$y_{t,\text{NNLO}} = 0.94018.$
L: Top–bot: (dot, dash, solid, dot-dash) are $|\alpha_{\text{THDM}} - \alpha_{\text{FH}}|/|\alpha_{\text{THDM}}| = -(1, 2, 5, 10)\%$
R: Top–bot: (dash, dot, dot, dash, solid, dot-dash) are
$m_{H,\text{THDM}} - m_{H,\text{FH}} = (2, 1, -1, -2, -5, -10, -15)$ GeV.

Comp. with hMSSM: α, m_H



Using M_h from THDM.
L: Top–bot: (dot, dash, solid, dot-dash) are $|\alpha_{\mathrm{THDM}} - \alpha_{\mathrm{hMSSM}}|/|\alpha_{\mathrm{THDM}}| = -(0, 1, 2, 3)\%$.
R: Top–bot: (dash, dot, dot, dash, solid, dot-dash) are $m_{H,\mathrm{THDM}} - m_{H,\mathrm{hMSSM}} = (2, 1, -1, -2, -5, -10)$ GeV.

Comp. with hMSSM: g_{Hhh}



THDM on left, difference with hMSSM using M_h from THDM on right.
THDM expression:

Gunion & Haber 0207010

$$g_{Hhh} = -3vs_\beta c_\beta^3\Big\{-\lambda_6 s_{\alpha\beta}^3 t_\beta^{-1} + s_{\alpha\beta}c_{\alpha\beta}\Big[(\lambda_1-\lambda_{345})s_{\alpha\beta} + t_\beta\Big(\lambda_6(2c_{\alpha\beta}+s_{\alpha\beta}) - \lambda_7(2s_{\alpha\beta}+c_{\alpha\beta})\Big) + c_{\alpha\beta}t_\beta^2(-\lambda_2+\lambda_{345})\Big] + \lambda_7 c_{\alpha\beta}^3 t_\beta^3\Big\} - \lambda_{345} v c_{\alpha-\beta}\,.$$

Summary of the Low-$\tan\beta$-High Scenario

- We obtain values of M_h that are at least 2 GeV lower than that of FeynHiggs. Between $t_\beta \sim 4$–5 ($t_\beta \sim 2$–4), this disagreement worsens to 3–5 (5–10) GeV.
- Using the $\sim 1\%$ higher NLO value for the top Yukawa softens the discrepancy, especially at larger t_β, but large discrepancies at low $t_\beta < 2$ still exist. The remaining difference may be due to the implementation of resummation in FeynHiggs.
- Fractional discrepancies in α, m_H reach 10–12% at very low values of $t_\beta < 1.5$ and $m_A < 200$ GeV.
- Using our value of M_h, discrepancies in m_H, α, g_{Hhh} with the hMSSM are at most about 5–7%.
- Choice of M_h value (which controls the radiative correction) used in hMSSM equations has large effect on agreement with THDM, especially for values of α, g_{Hhh}.

Overall, we conclude that the hMSSM is a reasonable approximation in this scenario due to mixing values generally away from maximal mixing, except low t_β when M_S is large; however μ, M_1, M_2 are fixed to be small.

According to our results, larger M_S input values are at low t_β in order to achieve $M_h = 125$ GeV.

Conclusion

- The effective THDM method provides a simple approach for precision calculations of M_h in simplified heavy SUSY, intermediate m_A models.
- Depending on whether there are light or heavy electroweakinos, requiring $M_h \sim 125$ GeV and $t_\beta > 1$ for fixed values of m_A can yield lower bounds on t_β or upper bounds on M_S.
- There are well-motivated parts of parameter space (large A_t, μ, moderate t_β, *alignment limit*) in which off-diagonal radiative corrections to the Higgs mass matrix cannot be ignored, as in the hMSSM.
- In the low-$\tan\beta$-high scenario, we find values of M_h that are between 2 GeV lower (for $t_\beta \gtrsim 6.5$) and 15 GeV lower (for $t_\beta < 1.5$) compared to FeynHiggs.
- Disagreements for α, m_H with the results of FeynHiggs and the hMSSM approximation in the above scenario can reach 10–12% and 5–7%, respectively.
- A careful study of the difference between our effective theory calculation and those of FeynHiggs is needed, especially of the resummation.

1-loop Corrections to λ_i

Thresholds from decoupling $\tilde{t}, \tilde{b}, \tilde{\tau}$:

$$\begin{aligned}
\Delta_{\text{th}}^{(1)}\lambda_1 &= -\frac{\kappa}{2}h_t^4\hat{\mu}^4 + 6\kappa h_b^4\widehat{A}_b^2\left(1 - \frac{\widehat{A}_b^2}{12}\right) + 2\kappa h_\tau^4\widehat{A}_\tau^2\left(1 - \frac{\widehat{A}_\tau^2}{12}\right) \\
&\quad + \kappa\frac{g_2^2 + g_Y^2}{4}\left[3h_t^2\hat{\mu}^2 - 3h_b^2\widehat{A}_b^2 - h_\tau^2\widehat{A}_\tau^2\right], \\
\Delta_{\text{th}}^{(1)}\lambda_2 &= 6\kappa h_t^4\widehat{A}_t^2\left(1 - \frac{\widehat{A}_t^2}{12}\right) - \frac{\kappa}{2}h_b^4\hat{\mu}^4 - \frac{\kappa}{6}h_\tau^4\hat{\mu}^4 \\
&\quad - \kappa\frac{g_2^2 + g_Y^2}{4}\left[3h_t^2\widehat{A}_t^2 - 3h_b^2\hat{\mu}^2 - h_\tau^2\hat{\mu}^2\right], \\
\Delta_{\text{th}}^{(1)}\lambda_3 &= \frac{\kappa}{6}\hat{\mu}^2\left[3h_t^4(3 - \widehat{A}_t^2) + 3h_b^4(3 - \widehat{A}_b^2) + h_\tau^4(3 - \widehat{A}_\tau^2)\right] \\
&\quad + \frac{\kappa}{2}h_t^2h_b^2\left[3(\widehat{A}_t + \widehat{A}_b)^2 - (\hat{\mu}^2 - \widehat{A}_t\widehat{A}_b)^2 - 6\hat{\mu}^2\right] \\
&\quad - \frac{\kappa}{2}\frac{g_2^2 - g_Y^2}{4}\left[3h_t^2(\widehat{A}_t^2 - \hat{\mu}^2) + 3h_b^2(\widehat{A}_b^2 - \hat{\mu}^2) + h_\tau^2(\widehat{A}_\tau^2 - \hat{\mu}^2)\right], \\
\Delta_{\text{th}}^{(1)}\lambda_4 &= \frac{\kappa}{6}\hat{\mu}^2\left[3h_t^4(3 - \widehat{A}_t^2) + 3h_b^4(3 - \widehat{A}_b^2) + h_\tau^4(3 - \widehat{A}_\tau^2)\right] \\
&\quad - \frac{\kappa}{2}h_t^2h_b^2\left[3(\widehat{A}_t + \widehat{A}_b)^2 - (\hat{\mu}^2 - \widehat{A}_t\widehat{A}_b)^2 - 6\hat{\mu}^2\right] \\
&\quad + \frac{\kappa}{2}\frac{g_2^2}{2}\left[3h_t^2(\widehat{A}_t^2 - \hat{\mu}^2) + 3h_b^2(\widehat{A}_b^2 - \hat{\mu}^2) + h_\tau^2(\widehat{A}_\tau^2 - \hat{\mu}^2)\right], \\
\Delta_{\text{th}}^{(1)}\lambda_5 &= -\frac{\kappa}{6}\hat{\mu}^2\left[3h_t^4\widehat{A}_t^2 + 3h_b^4\widehat{A}_b^2 + h_\tau^4\widehat{A}_\tau^2\right],
\end{aligned}$$

1-loop Corrections to λ_i (cont.)

$$\Delta_{\text{th}}^{(1)}\lambda_6 = \frac{\kappa}{6}\hat{\mu}\left[3h_t^4\hat{\mu}^2\widehat{A}_t + 3h_b^4\widehat{A}_b(\widehat{A}_b^2 - 6) + h_\tau^4\widehat{A}_\tau(\widehat{A}_\tau^2 - 6)\right],$$

$$\Delta_{\text{th}}^{(1)}\lambda_7 = \frac{\kappa}{6}\hat{\mu}\left[3h_t^4\widehat{A}_t(\widehat{A}_t^2 - 6) + 3h_b^4\hat{\mu}^2\widehat{A}_b + h_\tau^4\hat{\mu}^2\widehat{A}_\tau\right].$$

From redefinition of the Higgs fields (self-energies):

$$\Delta_{\Phi}^{(1)}\lambda_1 = -\frac{\kappa}{6}\frac{g_2^2 + g_Y^2}{2}\left[3h_t^2\hat{\mu}^2 + 3h_b^2\widehat{A}_b^2 + h_\tau^2\widehat{A}_\tau^2\right],$$

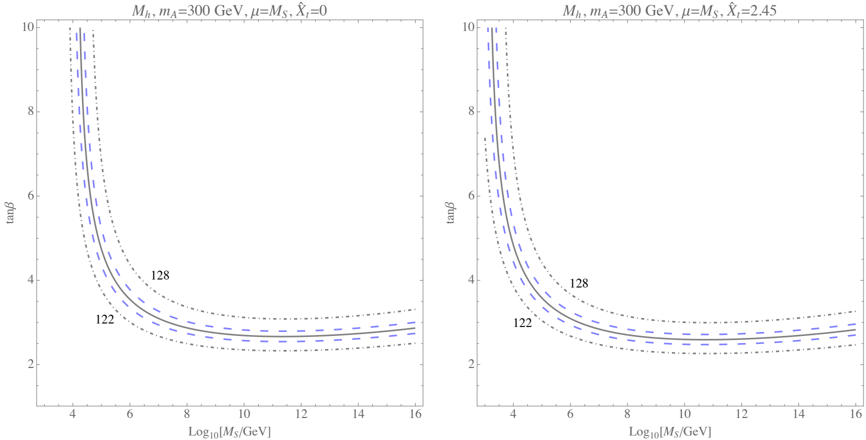
$$\Delta_{\Phi}^{(1)}\lambda_2 = -\frac{\kappa}{6}\frac{g_2^2 + g_Y^2}{2}\left[3h_t^2\widehat{A}_t^2 + 3h_b^2\hat{\mu}^2 + h_\tau^2\hat{\mu}^2\right],$$

$$\Delta_{\Phi}^{(1)}\lambda_3 = -\frac{\kappa}{6}\frac{g_2^2 - g_Y^2}{4}\left[3h_t^2(\widehat{A}_t^2 + \hat{\mu}^2) + 3h_b^2(\widehat{A}_b^2 + \hat{\mu}^2) + h_\tau^2(\widehat{A}_\tau^2 + \hat{\mu}^2)\right],$$

$$\Delta_{\Phi}^{(1)}\lambda_4 = \frac{\kappa}{6}\frac{g_2^2}{2}\left[3h_t^2(\widehat{A}_t^2 + \hat{\mu}^2) + 3h_b^2(\widehat{A}_b^2 + \hat{\mu}^2) + h_\tau^2(\widehat{A}_\tau^2 + \hat{\mu}^2)\right],$$

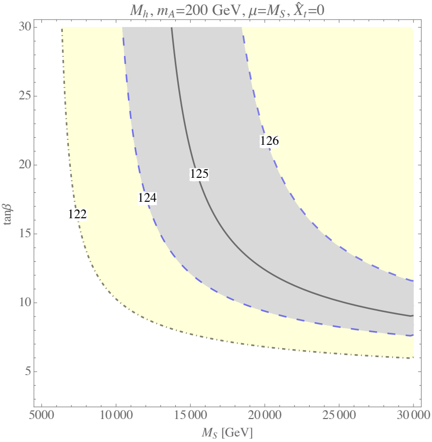
$$\Delta_{\Phi}^{(1)}\lambda_5 = \Delta_{\Phi}^{(1)}\lambda_6 = \Delta_{\Phi}^{(1)}\lambda_7 = 0.$$

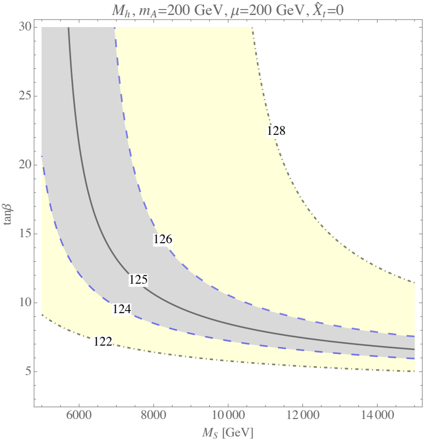
$m_A = 300$ GeV, $\mu = M_S$



($A_b = A_\tau = M_S$, $M_2 = M_1 = \mu$, $y_{t,\text{NNLO}} = 0.94018$)
$t_\beta \gtrsim$ 2.5–3 is needed to achieve $M_h \sim 125$ GeV.

TeV scale: $m_A = 200$ GeV, $\widehat{X}_t = 0$





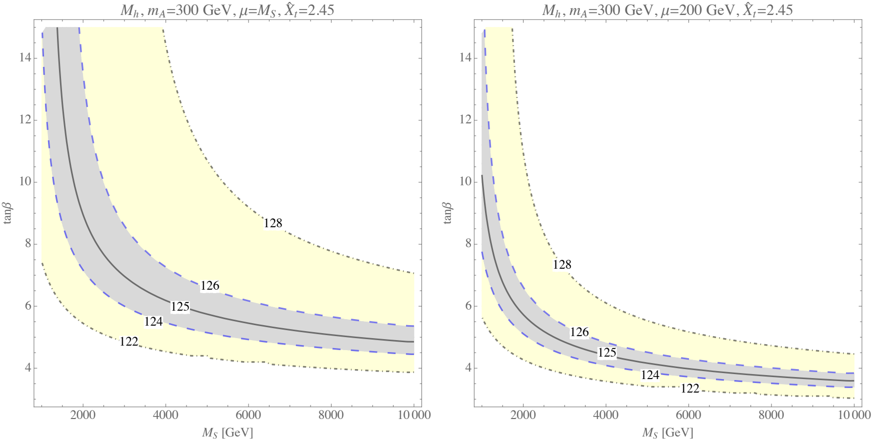
$(A_b = A_\tau = M_S, M_2 = M_1 = \mu, y_{t,\text{NNLO}} = 0.94018)$

In 1312.5743, found that to get $M_h = 125$ GeV for $m_A = M_S, \widehat{X}_t = 0, t_\beta = 20$,

$\mu = M_S$: $M_S = 15$ TeV

$\mu = 200$ GeV: $M_S = 6$ TeV

TeV scale: $m_A = 300$ GeV, $\widehat{X}_t = \sqrt{6}$



$(A_b = A_\tau = M_S, M_2 = M_1 = \mu, y_{t,\text{NNLO}} = 0.94018)$

In 1312.5743, found that to get $M_h = 125$ GeV for $m_A = M_S, \widehat{X}_t = \sqrt{6}, t_\beta = 4$,

$\mu = M_S$: $M_S = 8.5$ TeV

$\mu = 200$ GeV: $M_S = 3$ TeV

Deriving Differences with the hMSSM

The dominant 1-loop radiative corrections to the 11 and 12 elements of $\mathcal{M}^2_{H^0}$ in the Higgs basis are

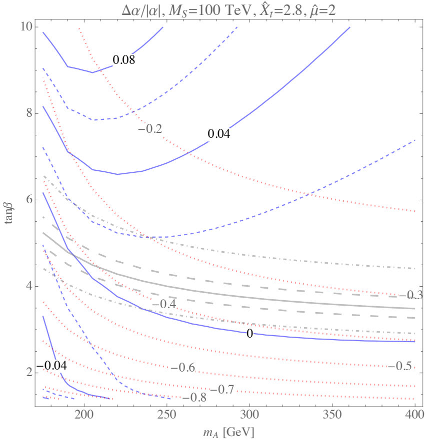
$$
\begin{aligned}
g_{11}v^2 &= m_Z^2 c_{2\beta}^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \widehat{X}_t^2\left(1 - \frac{\widehat{X}_t^2}{12}\right)\right], \\
g_{12}v^2 &= -s_{2\beta}\left\{m_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{\widehat{X}_t(\widehat{X}_t + \widehat{Y}_t)}{2} - \frac{\widehat{X}_t^3 \widehat{Y}_t}{12}\right]\right\},
\end{aligned}
$$

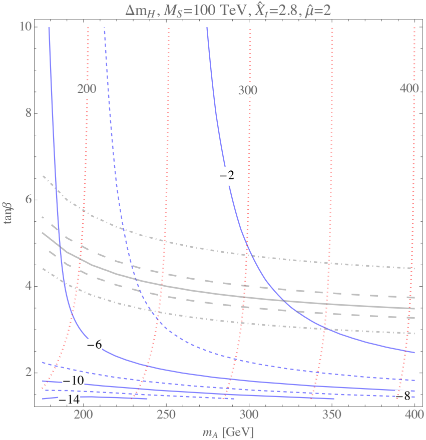
where $\widehat{X}_t = X_t/M_S$, $X_t = A_t - \mu/t_\beta$ is the stop mixing parameter associated with the coupling of the SM-like Higgs to the stops, $\widehat{Y}_t = Y_t/M_S$ and $Y_t = A_t + \mu t_\beta$.
The mixing angle is

$$
c_{\beta-\alpha} = \frac{-g_{12}v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - g_{11}v^2)}}
$$

and for moderate-large values of t_β, doing a Taylor expansion yields the result.

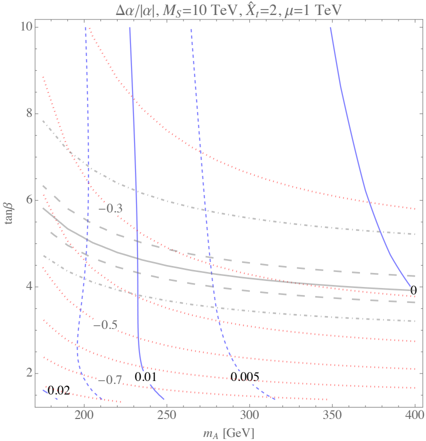
Comparison with hMSSM: $M_S = 100$ TeV, $\widehat{X}_t = 2.8$, $\mu/M_S = 2$

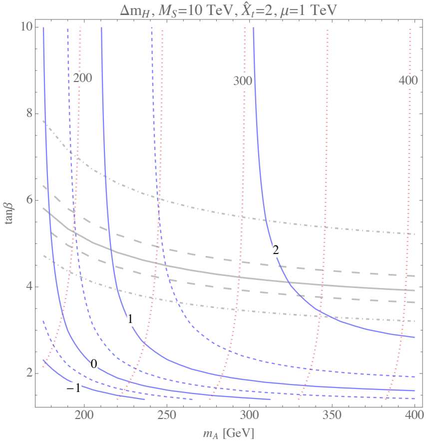




Larger M_S implies smaller t_β needed for $M_h = 125$ GeV, so effect is reduced.
Here, $\sim 2\%$ differences compared to up to 20% in previous slide.

Comparison with hMSSM: $M_S = 10$ TeV, $\widehat{X}_t = 2.8$, $\mu/M_S = 0.1$

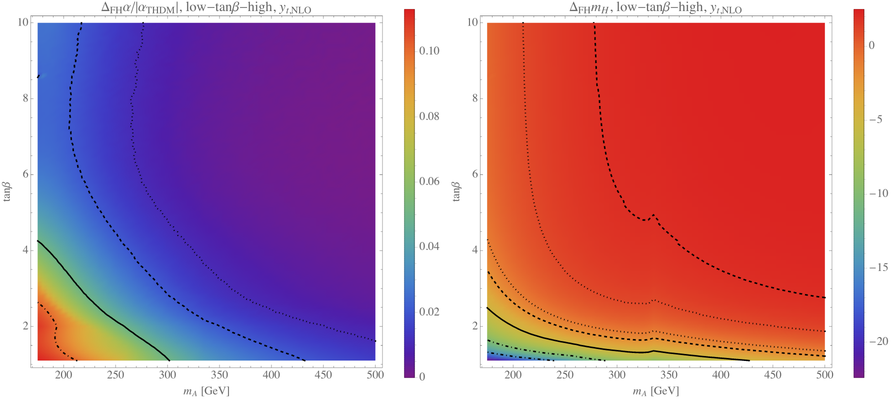




Small values of μ have two effects:

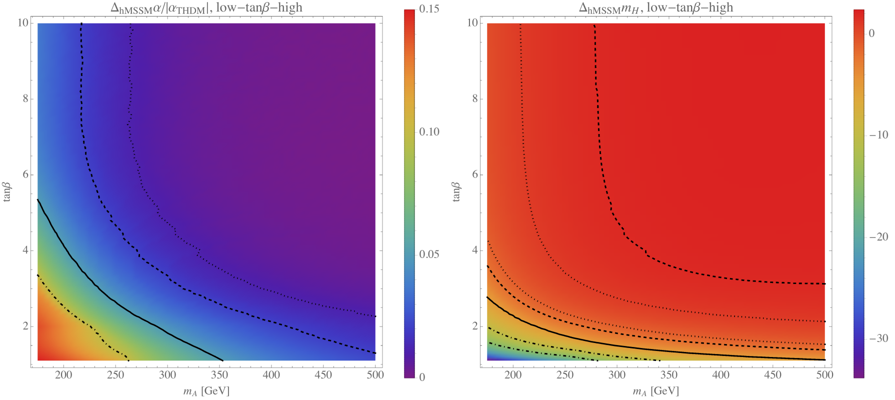
1. Off-diagonal element is suppressed with $\mu \ll M_S$,
2. Light EWkinos push M_h up, so smaller t_β is needed for M_h.

Comp. with FEYNHIGGS Using $y_{t,\text{NLO}}$: α, m_H



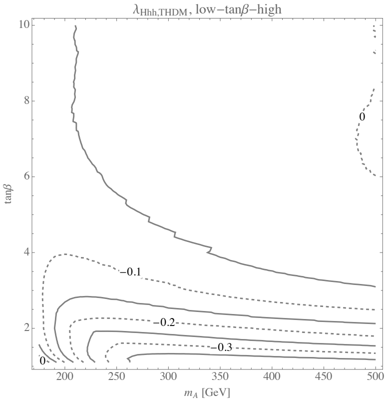
$y_{t,\text{NLO}} = 0.95113.$
L: Top–bot: (dot, dash, solid, dot-dash) are $|\alpha_{\text{THDM}} - \alpha_{\text{FH}}|/|\alpha_{\text{THDM}}| = -(1, 2, 5, 10)\%$ R: Top–bot: (dash, dot, dot, dash, solid, dot-dash) are $m_{H,\text{THDM}} - m_{H,\text{FH}} = (2, 1, -1, -2, -5, -10, -15)$ GeV.

Comp. with hMSSM with M_h from FEYNHIGGS: α, m_H



Using M_h from FEYNHIGGS].
L: Top–bot: (dot, dash, solid, dot-dash) are $|\alpha_{\rm THDM} - \alpha_{\rm hMSSM}|/|\alpha_{\rm THDM}| = -(1, 2, 5, 10)\%$.
R: Top–bot: (dash, dot, dot, dash, solid, dot-dash, dot-dash) are $m_{H,\rm THDM} - m_{H,\rm hMSSM} = (2, 1, -1, -2, -5, -10, -15)$ GeV.

Comp. with hMSSM with M_h from FEYNHIGGS: g_{Hhh}



THDM result:

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$$g_{Hhh} = -3 v s_\beta c_\beta^3 \Big\{ - \lambda_6 s_{\alpha\beta}^3 t_\beta^{-1} + s_{\alpha\beta} c_{\alpha\beta} \Big[(\lambda_1 - \lambda_{345}) s_{\alpha\beta} + t_\beta \Big(\lambda_6 (2 c_{\alpha\beta} + s_{\alpha\beta}) - \lambda_7 (2 s_{\alpha\beta} + c_{\alpha\beta}) \Big) + c_{\alpha\beta} t_\beta^2 (-\lambda_2 + \lambda_{345}) \Big] + \lambda_7 c_{\alpha\beta}^3 t_\beta^3 \Big\} - \lambda_{345} v c_{\alpha-\beta} \,,$$