Updates on Higgs mass predictions in FlexibleSUSY in the MSSM with different mass hierarchies

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[17xx.yyyyy]

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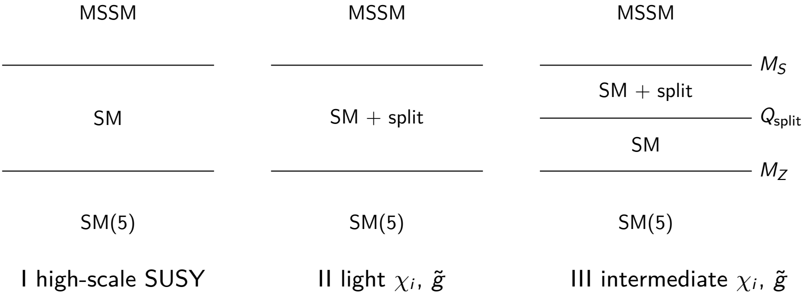
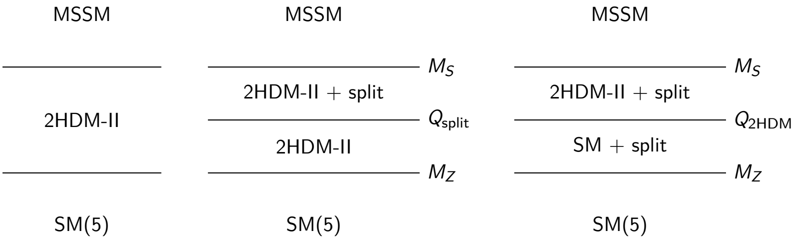
Scenarios with 1 light Higgs doublet



Scenarios with 2 light/intermediate Higgs doublets



IV light h_i, A, $H^{\pm}$

V light h_i, A, $H^{\pm}$, intermediate χ_i, $\tilde{g}$

VI light h, χ_i, $\tilde{g}$, intermediate H, A, $H^{\pm}$

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Considered sources of uncertainty

SM/SM+split/2HDM-II uncertainty:

$$\Delta M_h^{(\mathrm{SM})} = \left| M_h(y_t^{(2L)}) - M_h(y_t^{(3L)}) \right| + \max_{Q \in [M_t/2, 2M_t]} |M_h - M_h(Q)|$$

EFT uncertainty:

$$\Delta M_h^{(\mathrm{EFT})} = \left| M_h - M_h(\Delta\lambda_i \to \Delta\lambda_i [1 + v^2/M_S^2]) \right|$$

SUSY uncertainty:

$$\Delta M_h^{(\mathrm{MSSM})} = \left| M_h - M_h(y_t^{\mathrm{EFT}}(M_S) \to y_t^{\mathrm{EFT}}(M_S)[1 + \Delta y_t]) \right|$$

Parametric uncertainty:

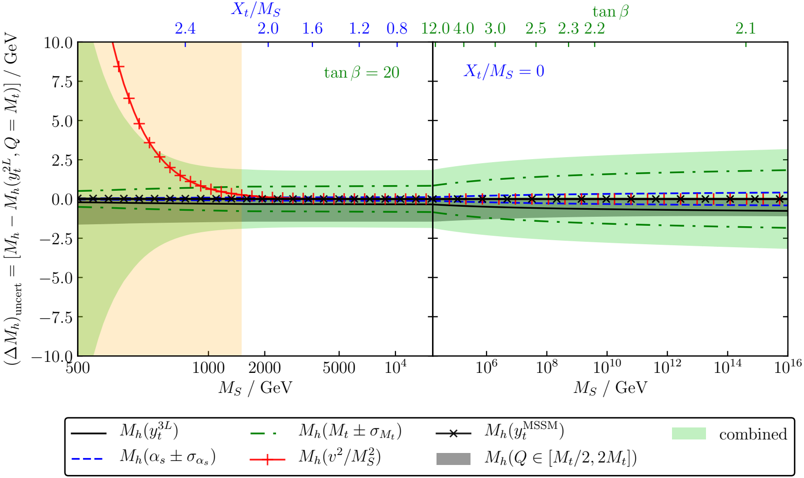
$$\Delta M_h^{(\mathrm{par})} = |M_h - M_h(M_t \pm \sigma_{M_t})| + |M_h - M_h(\alpha_s(M_Z) \pm \sigma_{\alpha_s})|$$
$$\sigma_{M_t} = 0.98\,\mathrm{GeV}, \qquad \sigma_{\alpha_s} = 0.0006$$

Combination of uncertainties

Combination:

$$\Delta M_h = |\Delta M_h^{(\mathrm{SM})}| + |\Delta M_h^{(\mathrm{EFT})}| + |\Delta M_h^{(\mathrm{MSSM})}| + |M_h^{(\mathrm{par})}|.$$

Individual uncertainties in scenario IV (2HDM-II)



Observations

For scenario IV (2HDM-II) in the studied range we find:

- Parametric uncertainty **dominant**:

$$\Delta M_h(M_t \pm \sigma_{M_t}) = (1 \ldots 2)\,\text{GeV}$$
$$\Delta M_h(\alpha_s \pm \sigma_{\alpha_s}) = (0.1 \ldots 0.5)\,\text{GeV}$$

- 2HDM-II uncertainty **important**:

$$\Delta M_h(Q \in [M_t/2, 2M_t]) = (1 \ldots 1.5)\,\text{GeV} \quad \text{(only 1L)}$$
$$\Delta M_h(y_t^{2L} \text{ vs. } y_t^{3L}) = (0.3 \ldots 0.5)\,\text{GeV}$$

- EFT uncertainty $< 100\,\text{MeV}$ for $M_S \gtrsim 2\,\text{TeV}$
- SUSY uncertainty $< 10\,\text{MeV}$ for $M_S \gtrsim 2\,\text{TeV}$

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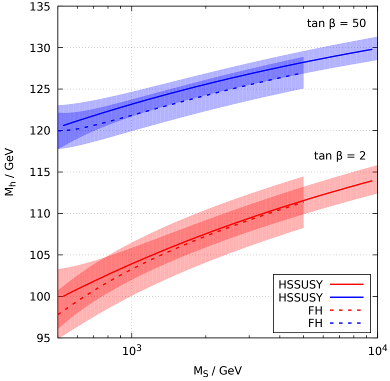
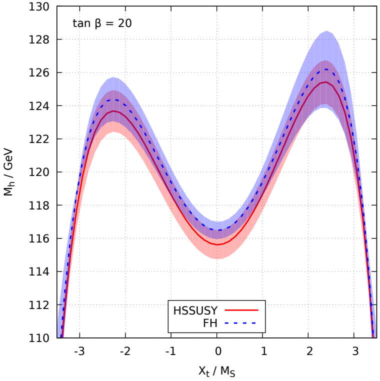
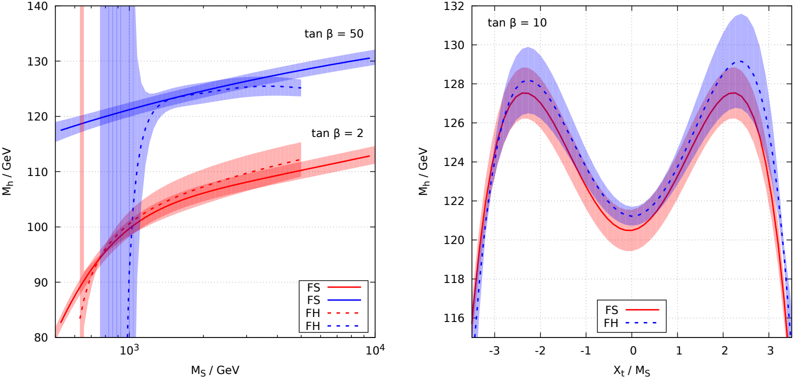
I high-scale SUSY





$$X_t = \sqrt{6} M_S,\ M_S = 2\,\text{TeV}$$

III intermediate χ_i, $\tilde{g}$

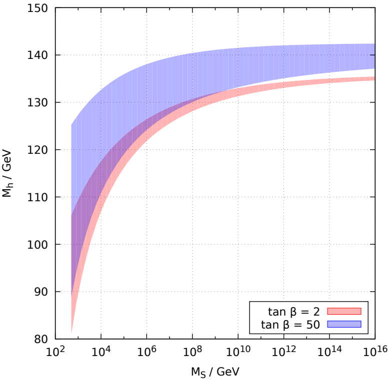


$$X_t = \sqrt{6} M_S,\ M_S = 2\,\text{TeV},\ M_i = \mu = 2\,\text{TeV}$$

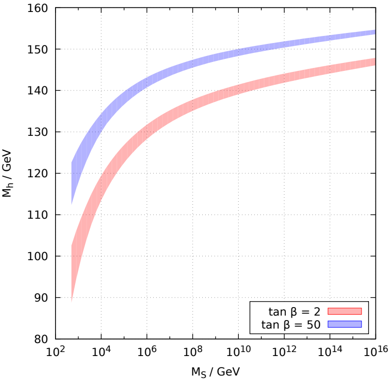
Effect from non-degenerate spectra

Variation of all SUSY mass parameters by factor 2:

I high-scale SUSY

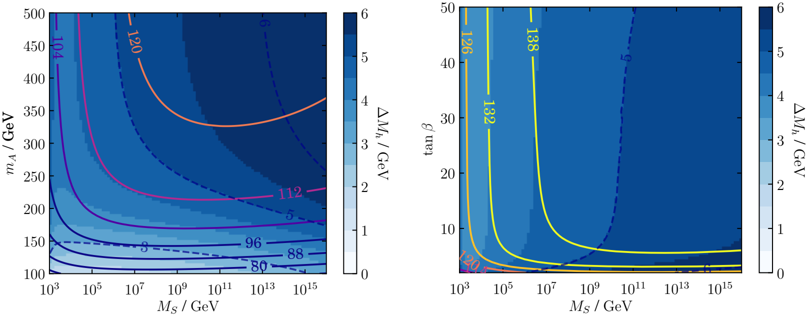


II light χ_i, $\tilde{g}$



$X_t = \sqrt{6} M_S$, $M_i^{\text{central}} = \mu^{\text{central}} = 2\,\text{TeV}$

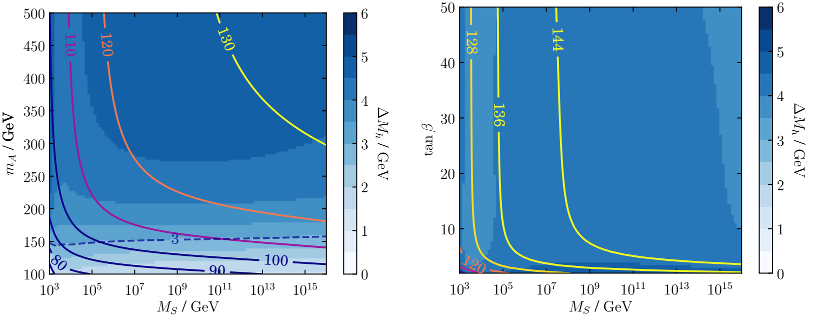
IV light h_i, A, $H^\pm$



$X_t = \sqrt{6} M_S$

left: $\tan\beta = 2$, right: $m_A = 800\,\text{GeV}$

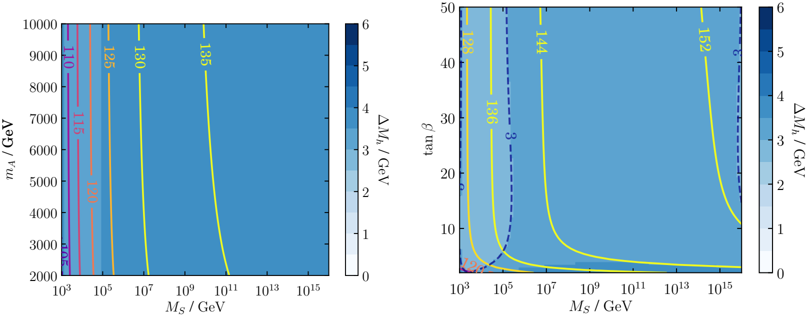
V light h_i, A, $H^\pm$, intermediate χ_i, $\tilde{g}$



$X_t = \sqrt{6} M_S$, $\mu = M_i = 2\,\text{TeV}$

left: $\tan\beta = 2$, right: $m_A = 800\,\text{GeV}$

VI light h, χ_i, $\tilde{g}$, intermediate H, A, $H^{\pm}$



$X_t = \sqrt{6} M_S$, $\mu = M_i = 1\,\text{TeV}$
left: $\tan\beta = 2$, right: $m_A = 2\,\text{TeV}$

Summary

- study 6 different mass hierarchies of the MSSM with FlexibleSUSY
- aim for honest uncertainty estimate
  4 sources:
  - parametric uncertainty (dominant)
  - SM/SM+split/2HDM-II uncertainty (important, can be improved)
  - EFT uncertainty (negligible, $< 100\,\text{MeV}$ for $M_S \gtrsim 2\,\text{TeV}$)
  - SUSY uncertainty (negligible? $< 10\,\text{MeV}$ for $M_S \gtrsim 2\,\text{TeV}$)

Backup

I high-scale SUSY

Input parameters:

$$\tan\beta^{\overline{\text{DR}}}(M_S), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{DR}}}(M_S), \mu^{\overline{\text{DR}}}(M_S), M_i^{\overline{\text{DR}}}(M_S), (m_{\tilde{f}}^2)_{ij}^{\overline{\text{DR}}}(M_S)$$

Threshold correction:

$$\lambda(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right)\cos^2 2\beta + \Delta\lambda^{1L} + \Delta\lambda^{2L}$$

[1407.4081, 1703.08166]

II light χ_i, $\tilde{g}$

$$\mathcal{L}_{\text{SM+split}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{split}},$$

$$\mathcal{L}_{\text{split}} \supset -\frac{M_1}{2}\tilde{B}\tilde{B} - \frac{M_2}{2}\tilde{W}^i\tilde{W}^i - \frac{M_3}{2}\tilde{g}^a\tilde{g}^a - \mu\tilde{H}_u\cdot\tilde{H}_d$$

$$-\frac{H^\dagger}{\sqrt{2}}\left(\tilde{g}_{2u}\sigma^i\tilde{W}^i + \tilde{g}_{1u}\tilde{B}\right)\tilde{H}_u$$

$$-\frac{H}{\sqrt{2}}\cdot\left(-\tilde{g}_{2d}\sigma^i\tilde{W}^i + \tilde{g}_{1d}\tilde{B}\right)\tilde{H}_d + \text{h.c.}$$

II light χ_i, $\tilde{g}$

Input parameters:

$$\tan\beta^{\overline{\text{DR}}}(M_S), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{DR}}}(M_S), \mu^{\overline{\text{MS}}}(M_Z), M_i^{\overline{\text{MS}}}(M_Z), (m^2_{\tilde{f}})_{ij}^{\overline{\text{DR}}}(M_S)$$

Threshold correction:

$$\tilde{\lambda}(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right)\cos^2 2\beta + \Delta\tilde{\lambda}^{1\text{L}} + \Delta\tilde{\lambda}^{2\text{L}},$$

$$\tilde{g}_{1u}(M_S) = \sqrt{\frac{3}{5}}g_1 \sin\beta + \Delta\tilde{g}_{1u}^{1\text{L}},$$

$$\tilde{g}_{1d}(M_S) = \sqrt{\frac{3}{5}}g_1 \cos\beta + \Delta\tilde{g}_{1d}^{1\text{L}},$$

$$\tilde{g}_{2u}(M_S) = g_2 \sin\beta + \Delta\tilde{g}_{2u}^{1\text{L}},$$

$$\tilde{g}_{2d}(M_S) = g_2 \cos\beta + \Delta\tilde{g}_{2d}^{1\text{L}}$$

[1407.4081]

III intermediate χ_i, $\tilde{g}$

Input parameters:

$\tan\beta^{\overline{\text{DR}}}(M_S), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{DR}}}(M_S), \mu^{\overline{\text{MS}}}(Q_{\text{split}}), M_i^{\overline{\text{MS}}}(Q_{\text{split}}), (m^2_{\tilde{f}})_{ij}^{\overline{\text{DR}}}(M_S)$

Threshold correction:

$$\lambda(Q_{\text{split}}) = \tilde{\lambda}(Q_{\text{split}}) + \Delta\lambda^{1\text{L},\chi^1}$$
$$y_t^{\text{SM+split}}(Q_{\text{split}}) = y_t^{\text{SM}}(Q_{\text{split}})(1 + \Delta g_t^{\chi})$$
$$g_i^{\text{SM+split}}(Q_{\text{split}}) = g_i^{\text{SM}}(Q_{\text{split}})(1 + \Delta g_i)$$

[1407.4081]

IV light h_i, A, $H^\pm$

$$
\begin{aligned}
\mathcal{L}_{\text{2HDM}} \supset & - m_1^2|H_1|^2 + m_2^2|H_2|^2 - \lambda_1(H_1^\dagger H_1)^2 - \lambda_2(H_2^\dagger H_2)^2 \\
& - \lambda_3|H_1|^2|H_2|^2 - \lambda_4|H_2^\dagger H_1|^2 \\
& + \left[m_{12}^2 H_1^\dagger H_2 - \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 - \lambda_6(H_1^\dagger H_1)(H_1^\dagger H_2) \right. \\
& \qquad \left. - \lambda_7(H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.} \right].
\end{aligned}
$$

IV light h_i, A, $H^\pm$

Input parameters:

$\tan\beta^{\overline{\text{MS}}}(M_t), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{MS}}}(M_t), \mu^{\overline{\text{DR}}}(M_S), M_i^{\overline{\text{DR}}}(M_S), (m_{\tilde{f}}^2)_{ij}^{\overline{\text{DR}}}(M_S)$

Threshold correction:

$$\lambda_1(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\lambda_1^{1\text{L}} + \Delta\lambda_1^{2\text{L}}$$

$$\lambda_2(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\lambda_2^{1\text{L}} + \Delta\lambda_2^{2\text{L}}$$

$$\lambda_3(M_S) = -\frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \frac{g_2^2}{2} + \Delta\lambda_3^{1\text{L}} + \Delta\lambda_3^{2\text{L}}$$

$$\lambda_4(M_S) = -\frac{g_2^2}{2} + \Delta\lambda_4^{1\text{L}} + \Delta\lambda_4^{2\text{L}}$$

$$\lambda_5(M_S) = 0 + \Delta\lambda_5^{1\text{L}} + \Delta\lambda_5^{2\text{L}}$$

$$\lambda_6(M_S) = 0 + \Delta\lambda_6^{1\text{L}} + \Delta\lambda_6^{2\text{L}}$$

$$\lambda_7(M_S) = 0 + \Delta\lambda_7^{1\text{L}} + \Delta\lambda_7^{2\text{L}}$$

[0901.2065, 1508.00576]

V light h_i, A, $H^{\pm}$, intermediate χ_i, $\tilde{g}$

$$
\begin{aligned}
\mathcal{L}_{\text{2HDM+split}} &= \mathcal{L}_{\text{2HDM}} + \mathcal{L}_{\text{split}}, \\
\mathcal{L}_{\text{split}} \supset &- \frac{M_1}{2}\tilde{B}\tilde{B} - \frac{M_2}{2}\tilde{W}^i\tilde{W}^i - \frac{M_3}{2}\tilde{g}^a\tilde{g}^a - \mu\tilde{H}_u\cdot\tilde{H}_d \\
&- \frac{H_2^\dagger}{\sqrt{2}}\left(\tilde{h}_{2u}\sigma^i\tilde{W}^i + \tilde{h}'_{2u}\tilde{B}\right)\tilde{H}_u \\
&- \frac{H_1}{\sqrt{2}}\cdot\left(-\tilde{h}_{1d}\sigma^i\tilde{W}^i + \tilde{h}'_{1d}\tilde{B}\right)\tilde{H}_d + \text{h.c.}
\end{aligned}
$$

V light h_i, A, $H^\pm$, intermediate χ_i, $\tilde{g}$

Input parameters:

$\tan\beta^{\overline{\text{MS}}}(M_t), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{MS}}}(M_t), \mu^{\overline{\text{MS}}}(Q_{\text{split}}), M_i^{\overline{\text{MS}}}(Q_{\text{split}}), (m_{\tilde{f}}^2)_{ij}^{\overline{\text{DR}}}(M_S)$

Threshold correction:

$$\tilde{\lambda}_1 = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\tilde{\lambda}_1^{\text{1L}} + \Delta\tilde{\lambda}_1^{\text{2L}},$$

$$\tilde{\lambda}_2 = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\tilde{\lambda}_2^{\text{1L}} + \Delta\tilde{\lambda}_2^{\text{2L}},$$

$$\tilde{\lambda}_3 = -\frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \frac{g_2^2}{2} + \Delta\tilde{\lambda}_3^{\text{1L}} + \Delta\tilde{\lambda}_3^{\text{2L}},$$

$$\tilde{\lambda}_4 = -\frac{g_2^2}{2} + \Delta\tilde{\lambda}_4^{\text{1L}} + \Delta\tilde{\lambda}_4^{\text{2L}},$$

$$\tilde{\lambda}_i = 0 + \Delta\tilde{\lambda}_i^{\text{1L}} + \Delta\tilde{\lambda}_i^{\text{2L}}, \quad (i = 5, 6, 7)$$

$$\tilde{h}'_{1d} = \sqrt{\frac{3}{5}}g_1, \qquad \tilde{h}_{1d} = g_2, \qquad \tilde{h}'_{2u} = \sqrt{\frac{3}{5}}g_1, \qquad \tilde{h}_{2u} = g_2$$

[0901.2065, 1508.00576]

VI light h, χ_i, $\tilde{g}$, intermediate H, A, $H^\pm$

Input parameters:

$\tan\beta^{\overline{\text{MS}}}(Q_{\text{2HDM}}), A_t^{\overline{\text{DR}}}(M_S), m_A^{\overline{\text{MS}}}(Q_{\text{2HDM}}), \mu^{\overline{\text{MS}}}(M_Z), M_i^{\overline{\text{MS}}}(M_Z), (m^2_{\tilde{f}})_{ij}^{\overline{\text{DR}}}($

Threshold correction:

$$
\begin{aligned}
\tilde{\lambda} &= 2\tilde{\lambda}_1 c_\beta^4 + 2\tilde{\lambda}_2 s_\beta^4 + 2\left(\tilde{\lambda}_3 + \tilde{\lambda}_4 + \tilde{\lambda}_5\right) c_\beta^2 s_\beta^2 + 4\tilde{\lambda}_6 c_\beta^3 s_\beta + 4\tilde{\lambda}_7 c_\beta s \\
&\quad + \Delta\lambda^{\text{2HDM+split}-\text{SM+split}}, \\
\mu^{\text{SM+split}} &= \mu^{\text{2HDM+split}}, \\
M_i^{\text{SM+split}} &= M_i^{\text{2HDM+split}}, \\
\tilde{g}_{1u} &= \tilde{h}'_{2u}\sin\beta + \Delta\tilde{g}_{1u}^{\text{2HDM+split–SM+split,1L}}, \\
\tilde{g}_{1d} &= \tilde{h}'_{1d}\cos\beta + \Delta\tilde{g}_{1d}^{\text{2HDM+split–SM+split,1L}}, \\
\tilde{g}_{2u} &= \tilde{h}_{2u}\sin\beta + \Delta\tilde{g}_{2u}^{\text{2HDM+split–SM+split,1L}}, \\
\tilde{g}_{2d} &= \tilde{h}_{1d}\cos\beta + \Delta\tilde{g}_{2d}^{\text{2HDM+split–SM+split,1L}}.
\end{aligned}
$$

[0901.2065, 1508.00576]

Determination of EFT parameters

Fixed by observables:

Input				Output
$\alpha_{\text{em}}^{\text{SM(5)}}(M_Z)$	$\rightarrow$	$\alpha_{\text{em}}^{\text{EFT}}(M_Z)$	$\rightarrow$	$g_1^{\text{EFT}}(M_Z)$
G_F	$\rightarrow$	$\sin\theta_W^{\text{EFT}}(M_Z)$	$\rightarrow$	$g_2^{\text{EFT}}(M_Z)$
$\alpha_{\text{s}}^{\text{SM(5)}}(M_Z)$			$\rightarrow$	$g_3^{\text{EFT}}(M_Z)$
M_Z	$\rightarrow$	$m_Z^{\text{EFT}}(M_Z)$	$\rightarrow$	$v^{\text{EFT}}(M_Z)$
M_t	$\rightarrow$	$m_t^{\text{EFT}}(M_Z)$	$\rightarrow$	$y_t^{\text{EFT}}(M_Z)$
$m_b^{\text{SM(5)}}(m_b)$	$\rightarrow$	$m_b^{\text{EFT}}(M_Z)$	$\rightarrow$	$y_b^{\text{EFT}}(M_Z)$
M_τ	$\rightarrow$	$m_\tau^{\text{EFT}}(M_Z)$	$\rightarrow$	$y_\tau^{\text{EFT}}(M_Z)$

Determination of $g_3^{\mathrm{EFT}}(M_Z)$

Input: $\alpha_s^{\mathrm{SM}(5)}(M_Z) = 0.1181$

$\rightarrow$

$$\alpha_s^{\mathrm{EFT}}(M_Z) = \frac{\alpha_s^{\mathrm{SM}(5)}(M_Z)}{1 - \Delta\alpha_s(M_Z)}$$

with

$$\Delta\alpha_s(Q) = \frac{\alpha_s}{2\pi}\left[-\frac{2}{3}\log\frac{m_t}{Q} + \text{BSM contrib.}\right]$$

$\Rightarrow$

$$g_3^{\mathrm{EFT}}(M_Z) = \sqrt{4\pi\alpha_s^{\mathrm{EFT}}(M_Z)}$$

Determination of $y_t^{\text{EFT}}(M_Z)$

$$y_t^{\text{EFT}}(M_Z) = \frac{\sqrt{2}\, m_t^{\text{EFT}}(M_Z)}{v(M_Z)}$$

where

$$\begin{aligned}
m_t^{\text{EFT}}(Q) &= M_t + \operatorname{Re}\Sigma_t^S(M_Z) + M_t\Big[\operatorname{Re}\Sigma_t^L(M_Z) \\
&\quad + \operatorname{Re}\Sigma_t^R(M_Z) + \Delta m_t^{1L,\text{gluon}} + \Delta m_t^{2L,\text{gluon}}\Big] \\
\Delta m_t^{1L,\text{gluon}} &= -\frac{g_3^2}{12\pi^2}\left[4 - 3\log\left(\frac{m_t^2}{Q^2}\right)\right] \\
\Delta m_t^{2L,\text{gluon}} &= \left(\Delta m_t^{1L,\text{gluon}}\right)^2 \\
&\quad - \frac{g_3^4}{4608\pi^4}\left[396\log^2\left(\frac{m_t^2}{Q^2}\right) - 1452\log\left(\frac{m_t^2}{Q^2}\right)\right. \\
&\quad \left. - 48\zeta(3) + 2053 + 16\pi^2(1+\log 4)\right]
\end{aligned}$$

Determination of v^{EFT}

The VEV v^{EFT} is calculated from the running Z mass at $Q = M_Z$:

$$v^{\mathrm{EFT}}(M_Z) = \frac{2m_Z^{\mathrm{EFT}}(M_Z)}{\sqrt{g_Y^2 + g_2^2}}$$

$$m_Z^{\mathrm{EFT}}(M_Z) = \sqrt{M_Z^2 + \Pi_Z^{1L}(p^2 = M_Z^2, Q = M_Z)}$$

v^{EFT} evolves under RG running according to
[Sperling, Stöckinger, AV, 2013, 2014]