Higgs mass calculations in supersymmetry at the 2-loop level for high and low SUSY scales

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RWTH AACHEN UNIVERSITY

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FlexibleSUSY = spectrum generator generator

FlexibleSUSY

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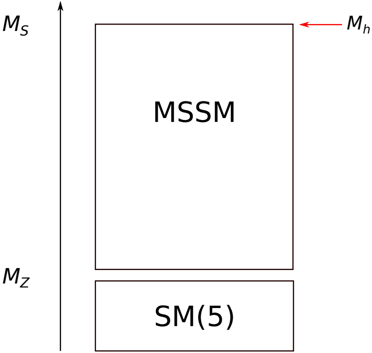
Full model approach



Idea: Calculate M_h in the MSSM at the scale $Q = M_S$ as a function of the $\overline{\text{DR}}$ parameters:

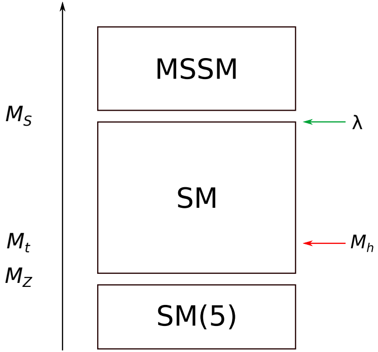
$$g_i,\ y^f_{ij},\ v_i,\ \mu,\ B\mu,\ m^2_{H_i},\ m^2_{\tilde{f},ij},\ M_i,\ T^f_{ij}$$

Full model approach

$$(M_h^{\text{MSSM}})^2 = \text{eigenvalue of} \left[(M_\phi^{\text{MSSM}})^2 - \Sigma_\phi^{\text{MSSM}}(p^2, M_S) + t_\phi^{\text{MSSM}}\right]$$

Advantage: includes all 1L terms $O(v^2/M_S^2)$
Disadvantage: suffers from large logarithms $\propto \log(M_t/M_S)$ if $M_S \gg M_t$

EFT approach



Idea: Calculate M_h in the SM at the scale $Q = M_t$ as a function of the $\overline{\text{MS}}$ parameters:

$$g_i,\ y_{ij}^f,\ v,\ \mu^2,\ \lambda$$

EFT approach with Γ matching

Determine $\lambda(M_S)$ from mathching all $\Gamma^{(k)}_{\phi_1,\ldots,\phi_n}(p^2 = 0, Q = M_S)$:
$\Rightarrow$

$$\lambda(M_S) = \frac{1}{4}\left[g_Y^2 + g_2^2\right]\cos^2 2\beta + \Delta\lambda$$

RG running to $Q = M_t \Rightarrow$

$$(M_h^{\text{SM}})^2 = \lambda v^2 - \Sigma_h^{\text{SM}}((M_h^{\text{SM}})^2) + \frac{t_h^{\text{SM}}}{v}$$

Advantage: resums large logarithms $\propto \log(M_t/M_S)$
Disadvantage: difficult to automatize; neglects terms $O(v^2/M_S^2)$ from SUSY particles

EFT approach with M_h matching (FlexibleEFTHiggs-1L)

$$M_h^{\text{SM}} \stackrel{!}{=} M_h^{\text{MSSM}} \quad \text{at} \quad Q = M_S, 1L$$

$\Rightarrow$

$$\lambda \leftarrow \frac{1}{v^2}\left[(m_h^{\text{SM}})^2 + (M_h^{\text{MSSM}})^2 - (M_h^{\text{SM}})^2\right]$$

3-loop RG running to $Q = M_t$:

$$M_h^2 = \lambda v^2 - \Sigma_h^{\text{SM}}(M_h^2) + \frac{t_h^{\text{SM}}}{v} \qquad \text{(1L)}$$

EFT approach with M_h matching (FlexibleEFTHiggs-1L)

Matching condition for y_t:

$$M_t^{\text{SM}} \overset{!}{=} M_t^{\text{MSSM}} \quad \text{at} \quad Q = M_S, 2L$$

$\Rightarrow$

$$y_t^{\text{MSSM}} \leftarrow \frac{\sqrt{2}}{v_u} \left[m_t^{\text{MSSM}} - M_t^{\text{MSSM}} + M_t^{\text{SM}} \right]$$

Matching conditions for g_i:

$$M_V^{\text{SM}} \overset{!}{=} M_V^{\text{MSSM}} \quad \text{at} \quad Q = M_S, 1L \quad (V = W, Z)$$
$$\alpha_{\text{em}}^{\text{MSSM}}(M_S) = \alpha_{\text{em}}^{\text{SM}}(M_S) \left(1 + \Delta\alpha_{\text{em}}\right)$$
$$\alpha_s^{\text{MSSM}}(M_S) = \alpha_s^{\text{SM}}(M_S) \left(1 + \Delta\alpha_s\right)$$

Incorrect 2L logs in FlexibleEFTHiggs-1L

Matching condition:

$$\lambda \leftarrow \frac{1}{v^2}\left[(m_h^{\text{SM}})^2 + (M_h^{\text{MSSM}})^2 - (M_h^{\text{SM}})^2\right]$$

Expansion of momentum iteration up to 1L level:

$$\lambda = \frac{1}{v^2}\Big[(m_h^{\text{MSSM}})^2 + \Delta m^2_{h,\text{MSSM}} - \Delta m^2_{h,\text{SM}} + O(\hbar^2)\Big]$$

with

$$\begin{aligned}\Delta m^2_{h,\text{MSSM}} &= -\Sigma^{1L}_{\text{MSSM}} + t^{1L}_{\text{MSSM}}/v_{\text{MSSM}} \\ \Delta m^2_{h,\text{SM}} &= -\Sigma^{1L}_{\text{SM}} + t^{1L}_{\text{SM}}/v_{\text{SM}}\end{aligned}$$

Incorrect 2L logs in FlexibleEFTHiggs-1L

Problem: $y_t^{\text{MSSM}} = y_t^{\text{SM}}/s_\beta[1 + O(\hbar)]$
$\Rightarrow$

$$\begin{aligned}\Delta m^2_{h,\text{MSSM}} - \Delta m^2_{h,\text{SM}} &\propto \hbar\left[(y_t^{\text{MSSM}} s_\beta)^4 \log\frac{m_t}{M_S} - (y_t^{\text{SM}})^4 \log\frac{m_t}{M_S}\right] \\ &= \hbar\left[0 + \propto \hbar y_t^4 \log\frac{m_t}{M_S} + O(\hbar^2)\right] \\ &= O(\hbar^2 y_t^4 \log\frac{m_t}{M_S})\end{aligned}$$

$\Rightarrow$
incorrect 2L logs remain in FlexibleEFTHiggs-1L

FlexibleEFTHiggs-1L

Advantages:

- ✓ easily automatizable
- ✓ correctly resums LL
- ✓ all non-log terms correct at 1L, including all terms $O(v^n/M_S^n)$

Disadvantage:

- ✗ incorrect 2L logs $O(\hbar^2 \log(m_t/M_S))$

Improvement 1: FlexibleEFTHiggs-2L

Improvement 1: M_h matching at 2L
(FlexibleEFTHiggs-2L)

Improvement 1: FlexibleEFTHiggs-2L

$$M_h^{\text{SM}} \stackrel{!}{=} M_h^{\text{MSSM}} \qquad \text{at} \qquad Q = M_S, 2L$$

$$M_t^{\text{SM}} \stackrel{!}{=} M_t^{\text{MSSM}} \qquad \text{at} \qquad Q = M_S, 1L$$

$$\alpha_s^{\text{SM}}(M_S) = \alpha_s^{\text{MSSM}}(M_S) \qquad \text{at} \qquad Q = M_S, 0L$$

$\Rightarrow$

$$\lambda \leftarrow \frac{1}{v^2}\left[(m_h^{\text{SM}})^2 + (M_h^{\text{MSSM}})^2 - (M_h^{\text{SM}})^2\right]$$

3-loop RG running to $Q = M_t$:

$$M_h^2 = \lambda v^2 - \Sigma_h^{\text{SM}}(M_h^2) + \frac{t_h^{\text{SM}}}{v} \qquad \text{(2L)}$$

Improvement 1: FlexibleEFTHiggs-2L

Advantages:

- ✓ easily automatizable
- ✓ correctly resums LL
- ✓ all non-log terms correct at 1L,
  including all terms $O(v^n/M_S^n)$
- ✓ all non-log terms correct at 2L $O(\alpha_t(\alpha_t + \alpha_s))$,
  including all terms $O(v^n/M_S^n)$

Disadvantage:

- ✗ incorrect 3L logs $O(\hbar^3 \log^2(m_t/M_S))$

Improvement 2: FlexibleEFTHiggs-1L*

Improvement 2: M_h matching at 1L,
but avoid appearance of incorrect higher-order logs
(FlexibleEFTHiggs-1L*)

Improvement 2: FlexibleEFTHiggs-1L*

Idea: stricter handling of loop orders in matching condition

$$(M_h^{\text{SM}})^2 = \lambda v^2 - \Sigma_h^{\text{SM}}((m_h^{\text{MSSM}})^2) + \frac{t_h^{\text{SM}}}{v}$$

$$(M_h^{\text{MSSM}})^2 = \text{EV of } \left[M_\phi^{(1)} - \Sigma_\phi^{\text{MSSM}}((m_h^{\text{MSSM}})^2) + \tilde{t}_\phi^{\text{MSSM}}\right]$$

with

$$M_\phi^{(1)} = \text{tree-level mass matrix w/ 1L parameters}$$

$$\Sigma_\phi^{\text{MSSM}} = \text{1L self-energy w/ 0L parameters}$$

$$t_{\phi_i}^{\text{MSSM}} = \text{1L tadpole w/ 0L parameters}$$

$$m_h^{\text{MSSM}} = \text{tree-level mass w/ 0L parameters}$$

$$(\tilde{t}_\phi^{\text{MSSM}})_i = t_{\phi_i}^{\text{MSSM}}/v_i$$

Improvement 2: FlexibleEFTHiggs-1L*

Advantages:

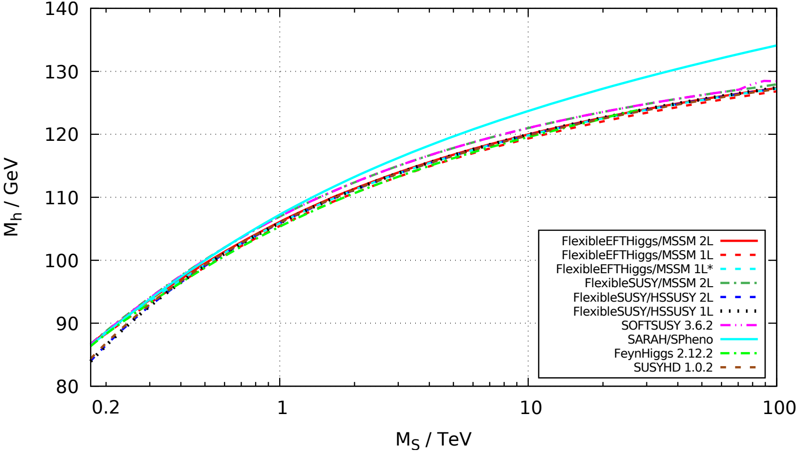
- ✓ easily automatizable
- ✓ correctly resums LL + NLL
- ✓ all non-log terms correct at 1L, including all terms $O(v^n/M_S^n)$

Disadvantage:

- – non-logarithmic 2L terms arise at M_S
- ✗ difficult to add 2L corrections

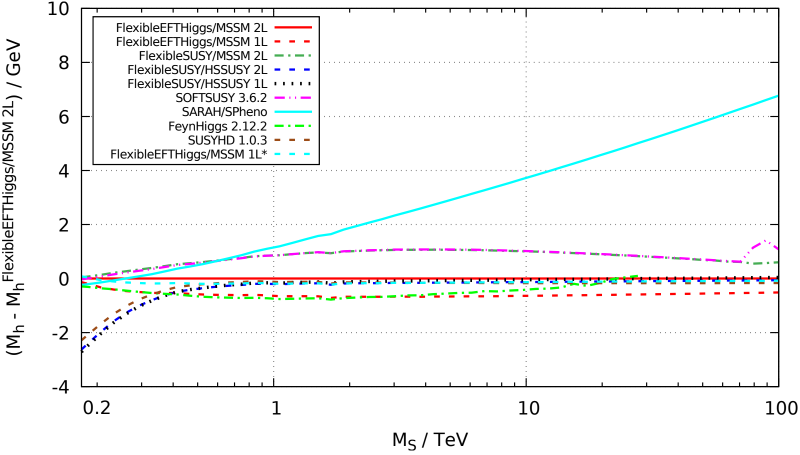
Contents

Numerical comparison



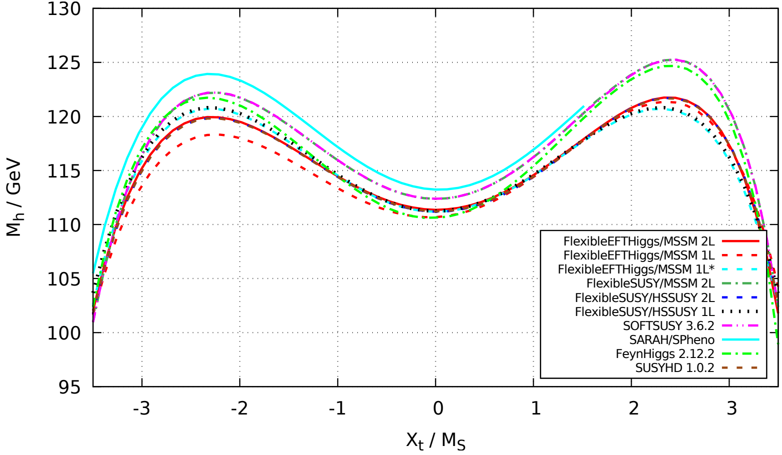
$\tan\beta = 5,\ X_{t,b,\tau} = 0$

Numerical comparison



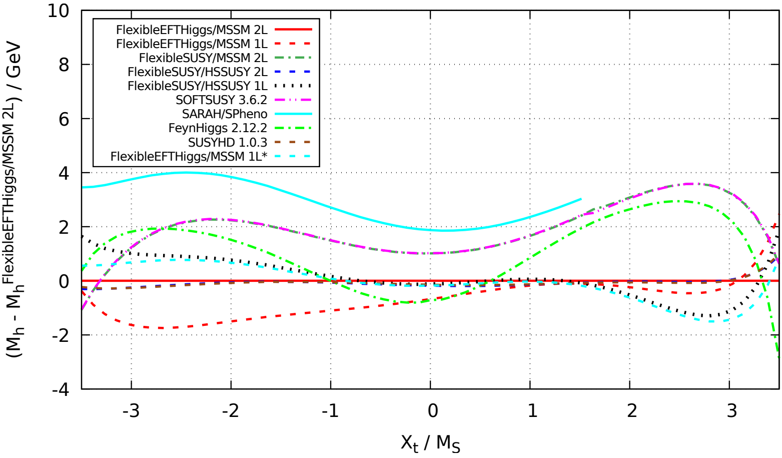
$\tan\beta = 5,\ X_{t,b,\tau} = 0$

Numerical comparison



$\tan\beta = 5,\ M_S = 2\,\text{TeV},\ X_{b,\tau} = 0$

Numerical comparison



$\tan\beta = 5$, $M_S = 2\,\text{TeV}$, $X_{b,\tau} = 0$

For large X_t deviation from HSSUSY-1L due to $p \neq 0 \neq v$.

Uncertainty estimation of FlexibleEFTHiggs-1L/2L

Three sources:

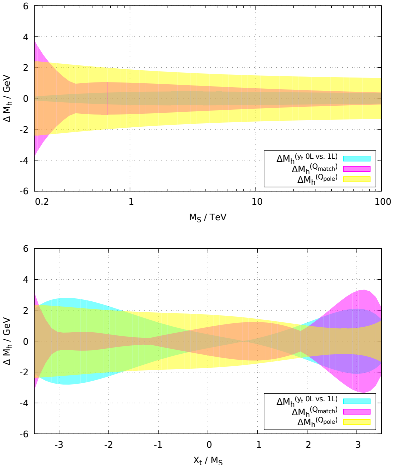
- relation between y_t^{SM} and y_t^{MSSM} one loop order higher
  FlexibleEFTHiggs-1L: $\to \Delta M_h^{(y_t\ \text{0L vs. 1L})}$
  FlexibleEFTHiggs-2L: $\to \Delta M_h^{(y_t\ \text{1L vs. 2L})}$
- variation of Q_{match} within $[M_S/2, 2M_S] \to \Delta M_h^{(Q_{\text{match}})}$
- variation of Q_{pole} within $[M_t/2, 2M_t] \to \Delta M_h^{(Q_{\text{pole}})}$

Combination:

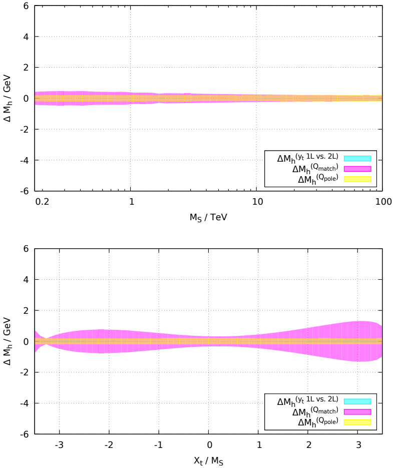
$$\left(\Delta M_h^{\text{FlexibleEFTHiggs-}n\text{L}}\right)^2 = \left(\max\left\{\Delta M_h^{(y_t\ (n-1)\text{L vs. } n\text{L})}, \Delta M_h^{(Q_{\text{match}})}\right\}\right)^2 + \left(\Delta M_h^{(Q_{\text{pole}})}\right)^2$$

Uncertainty estimation of FlexibleEFTHiggs-1L/2L

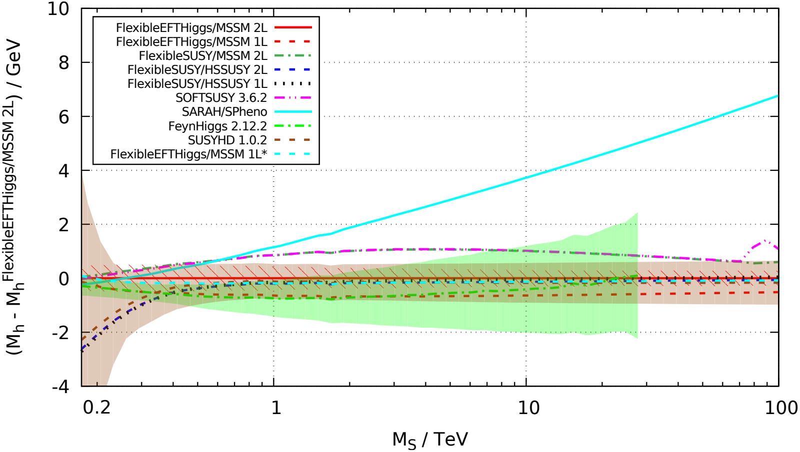
FlexibleEFTHiggs-1L



FlexibleEFTHiggs-2L

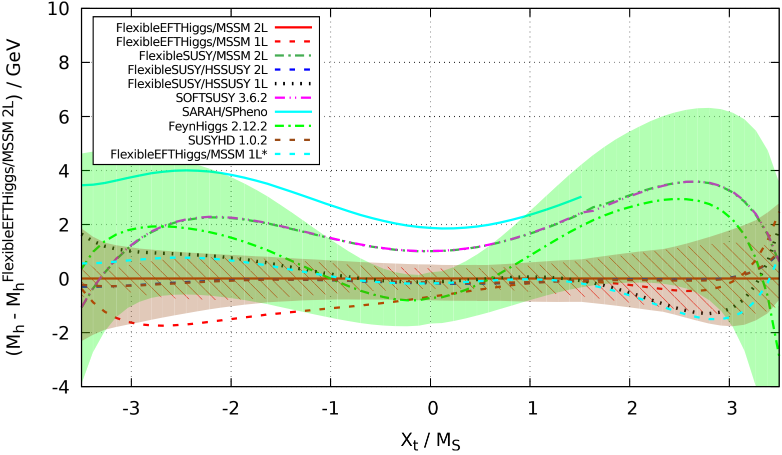


FlexibleEFTHiggs-2L combined uncertainty



$\tan\beta = 5,\ X_{t,b,\tau} = 0$

FlexibleEFTHiggs-2L combined uncertainty



$\tan\beta = 5,\ X_{t,b,\tau} = 0$

Summary

FlexibleEFTHiggs-1L:

- ✓ easily automatizable
- ✓ correctly resums LL
- ✓ all non-log terms correct at 1L, including all terms $O(v^n/M_S^n)$
- ✗ incorrect 2L logs $O(\hbar^2 \log(M_t/M_S))$

FlexibleEFTHiggs-2L:

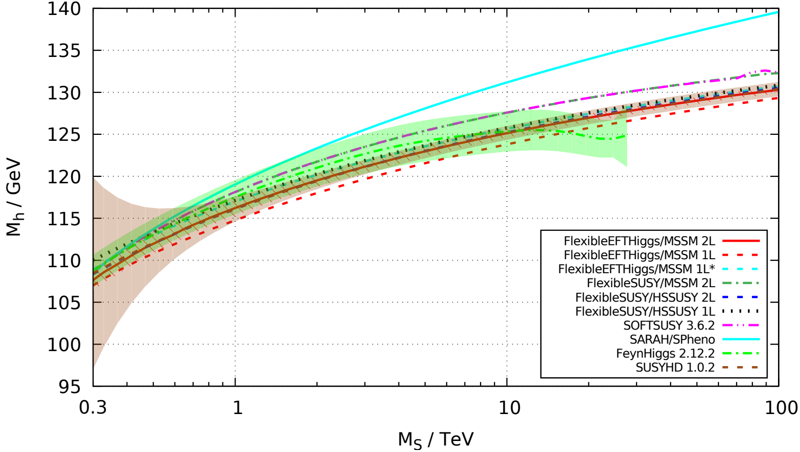
- ✓ same advantages as FlexibleEFTHiggs-1L
- ✓ all non-log terms correct at 2L $O(\alpha_t(\alpha_t + \alpha_s))$, including all terms $O(v^n/M_S^n)$
- ✗ incorrect 3L logs $O(\hbar^3 \log^2(m_t/M_S))$

FlexibleEFTHiggs-1L*:

- ✓ correctly resums LL + NLL
- ✓ all non-log terms correct at 1L, including all terms $O(v^n/M_S^n)$
- – non-logarithmic 2L terms arise at M_S
- ✗ difficult to add 2L corrections

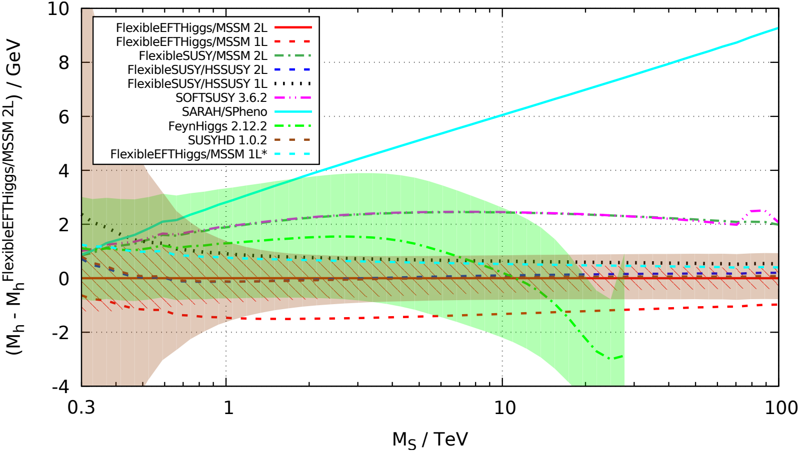
Backup

Numerical comparison



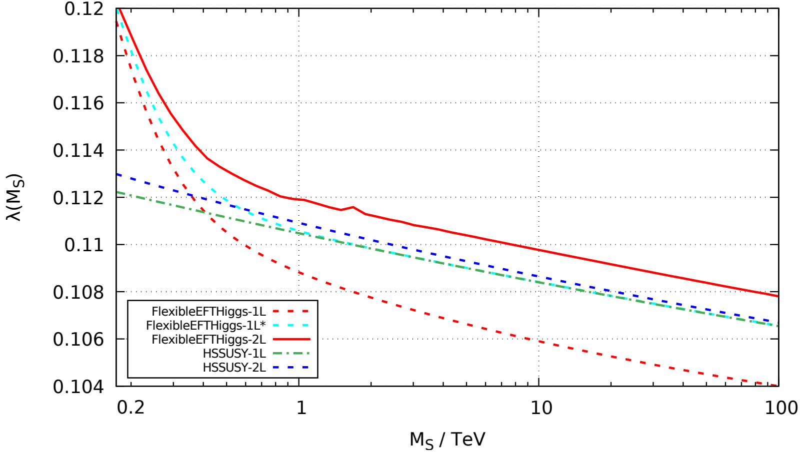
$\tan\beta = 5,\ X_t = -2M_S,\ X_{b,\tau} = 0$

Numerical comparison



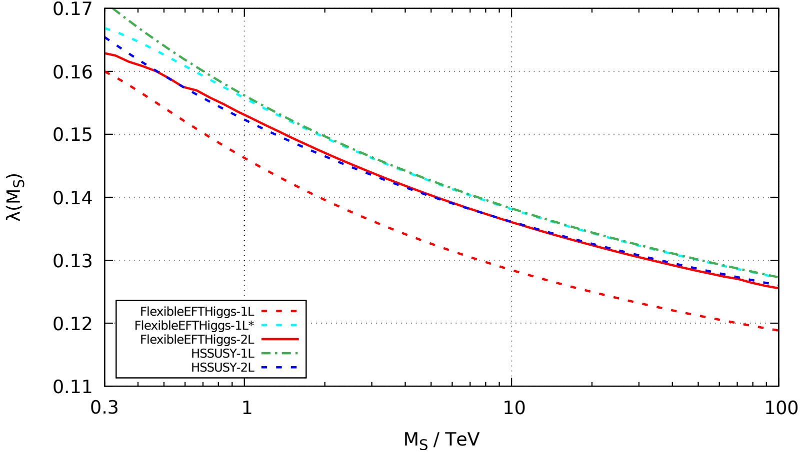
$\tan\beta = 5,\ X_t = -2M_S,\ X_{b,\tau} = 0$

Numerical comparison



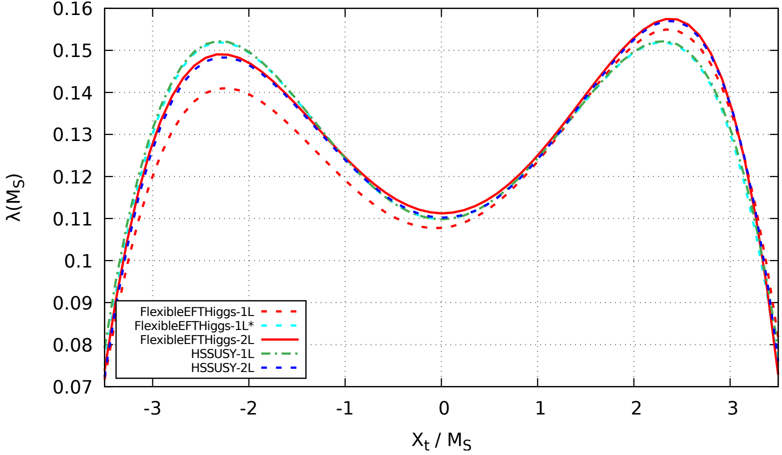
$\tan\beta = 5,\ X_{t,b,\tau} = 0$

Numerical comparison



$\tan\beta = 5,\ X_t = -2M_S,\ X_{b,\tau} = 0$

Numerical comparison



$\tan\beta = 5,\ M_S = 2\,\text{TeV},\ X_{b,\tau} = 0$

Equivalence of pure EFT and FlexibleEFTHiggs

Equivalence pure EFT and FlexibleEFTHiggs $O(\hbar y_t^4)$

$$M_h^{\text{SM}} \stackrel{!}{=} M_h^{\text{MSSM}} \quad \text{at} \quad Q = M_S, 1L$$

where

$$(M_h^{\text{SM}})^2 = \lambda v^2 - \Sigma_h^{\text{SM}} + t_h^{\text{SM}}/v$$
$$t_h^{\text{SM}}/v = -6(y_t^{\text{SM}})^2 A_0(m_t)/(4\pi)^2$$

and [neglecting stop mass mixing $O(m_t X_t/M_S^2)$]

$$(M_h^{\text{MSSM}})^2 = \frac{1}{4}(g_Y^2 + g_2^2)(v_u^2 + v_d^2)c_{2\beta}^2 - \Sigma_h^{\text{MSSM}} + t_h^{\text{MSSM}}/v$$
$$\Sigma_h^{\text{MSSM}} = \Sigma_h^{\text{SM}} \frac{c_\alpha^2}{s_\beta^2} + 3\frac{(y_t^{\text{SM}})^2}{(4\pi)^2}\frac{c_\alpha^2}{s_\beta^2}\Big\{A_0(m_{Q_3}) + A_0(m_{U_3})$$
$$+ 2m_t\big[B_0(m_{Q_3}, m_{Q_3}) + B_0(m_{U_3}, m_{U_3})\big]\Big\}$$
$$t_h^{\text{MSSM}}/v = -3\frac{(y_t^{\text{SM}})^2}{(4\pi)^2}\frac{c_\alpha^2}{s_\beta^2}\Big[2A_0(m_t) - A_0(m_{Q_3}) - A_0(m_{U_3})\Big]$$

Equivalence pure EFT and FlexibleEFTHiggs $O(\hbar y_t^4)$

in SM limit $\frac{c_\alpha^2}{s_\beta^2} \to 1$
$\Rightarrow$

$$
\begin{aligned}
\lambda &= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 \\
&\quad - 3\frac{(y_t^{\text{SM}})^4}{(4\pi)^2}\Big[B_0(p^2, m_{Q_3}, m_{Q_3}) + B_0(p^2, m_{U_3}, m_{U_3})\Big] \\
&= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 \\
&\quad - 3\frac{(y_t^{\text{SM}})^4}{(4\pi)^2}\Big[- \log\frac{m_{Q_3}^2}{Q^2} + \frac{p^2}{6m_{Q_3}^2} + O\Big(\frac{p^4}{m_{Q_3}^4}\Big) \\
&\qquad\qquad - \log\frac{m_{U_3}^2}{Q^2} + \frac{p^2}{6m_{U_3}^2} + O\Big(\frac{p^4}{m_{U_3}^4}\Big)\Big] \\
&= [\text{Bagnaschi et. al. 2014}] + O\Big(\frac{p^2}{m_{Q_3}^2}\Big) + O\Big(\frac{p^2}{m_{U_3}^2}\Big)
\end{aligned}
$$

Determination of MSSM parameters

Determination of MSSM parameters

Fixed by observables:

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

Fixed by 2 EWSB conditions: $m_{H_u}^2$, $m_{H_d}^2$

Free parameters: $\tan\beta$, μ, $B\mu$, $m_{\tilde{f},ij}^2$, M_i, T_{ij}^f

Determination of SM parameters

Fixed by observables:

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

Fixed by 1 EWSB condition: μ^2

Free parameter: λ

Determination of $g_3^{\mathsf{MSSM}}(M_S)$

$$\alpha_{\mathsf{s}}^{\mathsf{MSSM}}(M_S) = \frac{\alpha_{\mathsf{s}}^{\mathsf{SM}}(M_S)}{1 - \Delta\alpha_{\mathsf{s}}(M_S)}$$

with

$$\Delta\alpha_{\mathsf{s}}(Q) = \frac{\alpha_{\mathsf{s}}}{2\pi}\left[\frac{1}{2} - \sum_{\text{SUSY particle } f} T_f \log\frac{m_f}{Q}\right]$$

$\Rightarrow$

$$g_3^{\mathsf{MSSM}}(M_S) = \sqrt{4\pi\alpha_{\mathsf{s}}^{\mathsf{MSSM}}(M_S)}$$

Determination of $v_i^{\text{MSSM}}(M_S)$

$$M_Z^{\text{SM}} = M_Z^{\text{MSSM}}$$

$\Rightarrow$

$$\begin{aligned}(m_Z^{\text{MSSM}}(M_S))^2 &= (M_Z^{\text{SM}})^2 + \Pi_Z^{\text{MSSM},1L}(Q = M_S) \\ (M_Z^{\text{SM}})^2 &= \frac{1}{4}\left[(g_Y^{\text{SM}})^2 + (g_2^{\text{SM}})^2\right](v^{\text{SM}})^2 - \Pi_Z^{\text{SM},1L}(Q = M_S)\end{aligned}$$

$\Rightarrow$

$$v^{\text{MSSM}}(M_S) = \frac{2 m_Z^{\text{MSSM}}(M_S)}{\sqrt{(g_Y^{\text{MSSM}})^2 + (g_2^{\text{MSSM}})^2}}$$

$\Rightarrow$

$$\begin{aligned}v_u^{\text{MSSM}}(M_S) &= v^{\text{MSSM}}(M_S)\sin\beta(M_S) \\ v_d^{\text{MSSM}}(M_S) &= v^{\text{MSSM}}(M_S)\cos\beta(M_S)\end{aligned}$$

Determination of $y_i^{\mathrm{MSSM}}(M_S)$

$$M_f^{\mathrm{SM}} = M_f^{\mathrm{MSSM}}$$

$\Rightarrow$

$$m_f^{\mathrm{MSSM}}(M_S) = M_f^{\mathrm{SM}} + \Sigma_f^{\mathrm{MSSM},1L}(Q = M_S)$$
$$M_f^{\mathrm{SM}} = \frac{\sqrt{2} m_f^{\mathrm{SM}}}{v_i^{\mathrm{SM}}} - \Sigma_f^{\mathrm{SM},1L}(Q = M_S)$$

$\Rightarrow$

$$y_f^{\mathrm{MSSM}}(M_S) = \frac{\sqrt{2} m_f^{\mathrm{MSSM}}(M_S)}{v_i^{\mathrm{MSSM}}(M_S)}$$

Determination of SM parameters

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

Input: $\alpha_s^{\mathrm{SM}(5)}(M_Z) = 0.1185$

$\rightarrow$

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

with

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

$\Rightarrow$

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

Determination of $y_t^{\mathrm{SM}}(M_Z)$

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

where

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

Determination of v^{SM}

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

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

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

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

Comparison full model vs. EFT approach

Q: Why is FlexibleSUSY/MSSM so close to the EFT approaches and SPheno so far off?

Calculation of $y_t^{\text{MSSM}}(M_Z)$

A: Different treatment of 2-loop corrections to $y_t^{\text{MSSM}}(M_Z)$:

FlexibleSUSY:

$$m_t = M_t + \text{Re}\left[\widetilde{\Sigma}_t^{(1),S}(M_t)\right] + M_t\,\text{Re}\left[\widetilde{\Sigma}_t^{(1),L}(M_t) + \widetilde{\Sigma}_t^{(1),R}(M_t)\right] + M_t\left[\widetilde{\Sigma}_t^{(1),\text{qcd}}(m_t) + \left(\widetilde{\Sigma}_t^{(1),\text{qcd}}(m_t)\right)^2 + \widetilde{\Sigma}_t^{(2),\text{qcd}}(m_t)\right]$$

SPheno:

$$m_t = M_t + \text{Re}\left[\widetilde{\Sigma}_t^{(1),S}(m_t)\right] + m_t\,\text{Re}\left[\widetilde{\Sigma}_t^{(1),L}(m_t) + \widetilde{\Sigma}_t^{(1),R}(m_t)\right] + m_t\left[\widetilde{\Sigma}_t^{(1),\text{qcd}}(m_t) + \widetilde{\Sigma}_t^{(2),\text{qcd}}(m_t)\right]$$

Calculation of $y_t^{\text{MSSM}}(M_Z)$

$\Rightarrow$

$$\tilde{y}_t^{\text{FlexibleSUSY}} = y_t + t^2\kappa^2\left(\frac{184}{9}g_3^4 y_t - 24 g_3^2 y_t^3 + \frac{9}{8}y_t^5\right) + \dots$$

$$\tilde{y}_t^{\text{SPheno}} = y_t + t^2\kappa^2\left(\frac{248}{9}g_3^4 y_t - 16 g_3^2 y_t^3 + \frac{27}{8}y_t^5\right) + \dots$$

with

$$y_t \equiv y_t^{\text{SM}}(M_S), \qquad g_3 \equiv g_3^{\text{SM}}(M_S),$$

$$\tilde{y}_t \equiv y_t^{\text{MSSM}}(M_S), \qquad \tilde{g}_3 \equiv g_3^{\text{MSSM}}(M_S),$$

$$t \equiv \log\frac{M_S}{M_t}, \qquad \kappa \equiv \frac{1}{(4\pi)^2}$$

Calculation of $y_t^{\text{MSSM}}(M_Z)$

$$
\begin{aligned}
(M_h^2)^{\text{EFT}} &= m_h^2 + v^2 y_t^4 \Big[12 t\kappa + 12 t^2\kappa^2 \left(16 g_3^2 - 9 y_t^2\right) \\
&\quad + 4 t^3 \kappa^3 \left(736 g_3^4 - 672 g_3^2 y_t^2 + 90 y_t^4\right) + \ldots \Big], \\
(M_h^2)^{\text{FlexibleSUSY}} &= m_h^2 + v^2 y_t^4 \Big[12 t\kappa + 12 t^2\kappa^2 \left(16 g_3^2 - 9 y_t^2\right) \\
&\quad + 4 t^3 \kappa^3 \left(\frac{736 g_3^4}{3} - 288 g_3^2 y_t^2 + \frac{27 y_t^4}{2}\right) + \ldots \Big], \\
(M_h^2)^{\text{SPheno}} &= m_h^2 + v^2 y_t^4 \Big[12 t\kappa + 12 t^2\kappa^2 \left(16 g_3^2 - 9 y_t^2\right) \\
&\quad + 4 t^3 \kappa^3 \left(\frac{992 g_3^4}{3} - 192 g_3^2 y_t^2 + \frac{81 y_t^4}{2}\right) + \ldots \Big].
\end{aligned}
$$