Precise Higgs mass predictions in the (N)MSSM

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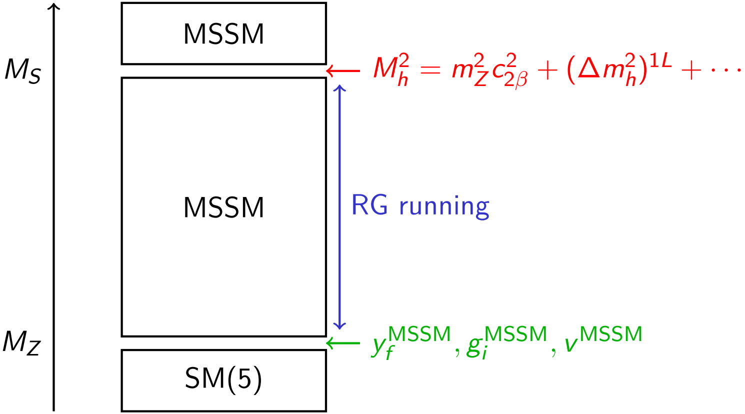
Higgs mass calculation at fixed loop order in $\overline{\text{DR}}'$



Known/unknown fixed order $\overline{\text{DR}}'$ loop corrections

Loop corrections in the determination of the running MSSM parameters y_f^{MSSM}, g_i^{MSSM}:

$$y_t^{\text{MSSM}} = \frac{\sqrt{2}\,M_t}{v_u}\Big[1 + \hbar(\text{full}) + \hbar^2(\alpha_s^2 + \alpha_t\alpha_s + \alpha_t^2) + \cdots\Big]$$

$$\alpha_s^{\text{MSSM}} = \alpha_s^{\text{SM(5)}}\Big[1 + \hbar(\text{full}) + \hbar^2(\alpha_s^2 + \alpha_t\alpha_s + \alpha_b\alpha_s) + \cdots\Big]$$

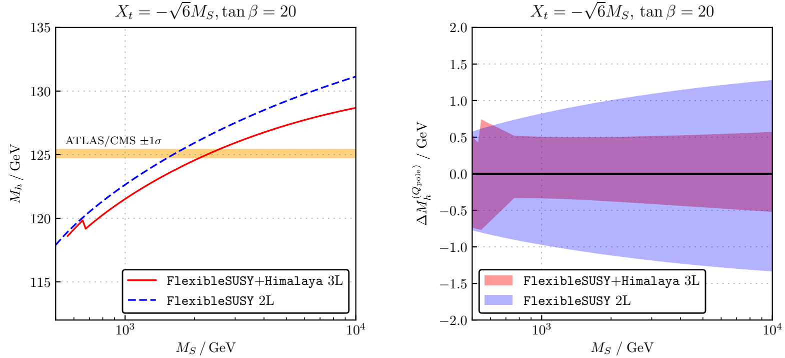
[0210258, 0507139, 0707.0650, 0509048, 0810.5101, 1009.5455]

Loop corrections to M_h^2 in the MSSM:

$$M_h^2 = m_h^2 + \hbar(\text{full}) + \hbar^2\Big[m_t^2(\alpha_t\alpha_s + \alpha_t^2 + \cdots) + m_Z^2\alpha_{\text{em}}^2 + \cdots\Big]$$
$$+ \hbar^3\Big[m_t^2(\underline{\alpha_t\alpha_s^2} + \alpha_t^2\alpha_s + \alpha_t^3) + \cdots\Big]$$

[0105096, 0112177, 0212132, 0206101, 0305127, 1005.5709, 1708.05720, 1807.03509]

Effect of the 3-loop $O(\alpha_t \alpha_s^2)$ corrections to M_h



[1708.05720]

Uncertainty estimate of the fixed-order $\overline{\text{DR}}'$ calculation

In [1804.09410] 5 sources of uncertainty were combined:

$$\Delta M_h^{(Q_{\text{pole}})} = \max_{Q_{\text{pole}} \in [M_S/2, 2M_S]} |M_h(Q_{\text{pole}}) - M_h(M_S)| \qquad \text{[1609.00371]}$$

$$\Delta M_h^{(Q_{\text{match}})} = \max_{Q_{\text{match}} \in [M_Z/2, 2M_Z]} |M_h(Q_{\text{match}}) - M_h(M_Z)| \qquad \text{[1804.09410]}$$

$$\Delta M_h^{(m_t)} = \left| M_h(m_t^{[1]}) - M_h(m_t^{[2]}) \right| \qquad \text{[1609.00371]}$$

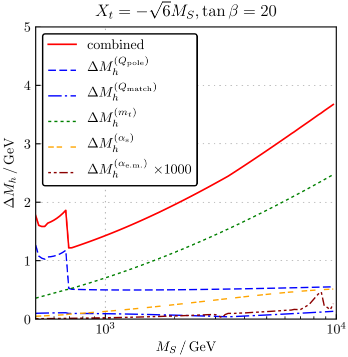
$$\Delta M_h^{(\alpha_s)} = \left| M_h(\alpha_s^{[1]}) - M_h(\alpha_s^{[2]}) \right| \qquad \text{[1804.09410]}$$

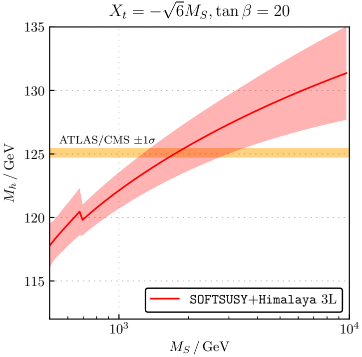
$$\Delta M_h^{(\alpha_{\text{em}})} = \left| M_h(\alpha_{\text{em}}^{[1]}) - M_h(\alpha_{\text{em}}^{[2]}) \right| \qquad \text{[1804.09410]}$$

Combination:

$$\Delta M_h^{(\text{FO})} = \Delta M_h^{(Q_{\text{pole}})} + \Delta M_h^{(Q_{\text{match}})} + \Delta M_h^{(m_t)} + \Delta M_h^{(\alpha_s)} + \Delta M_h^{(\alpha_{\text{em}})}$$

Uncertainty estimate of the fixed-order $\overline{\text{DR}}'$ calculation





[1804.09410]

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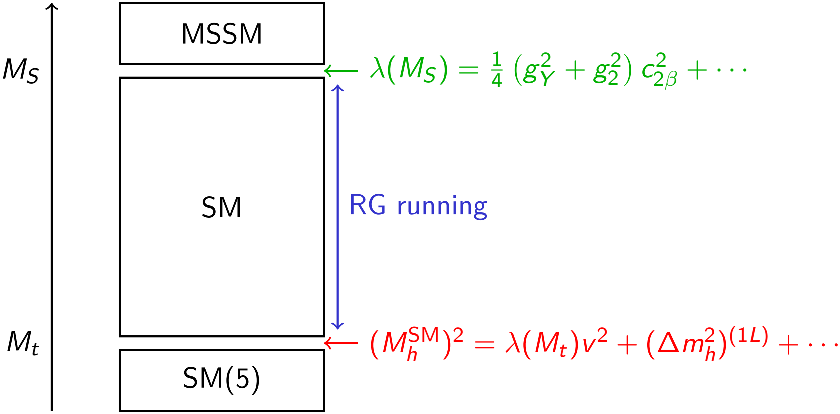
Higgs mass calculation in an EFT

Idea: Integrate out SUSY particles at M_S (expand in v^2/M_S^2)
$\Rightarrow \lambda(M_S)$ is fixed by the MSSM
$\Rightarrow$ effectively: separation of scales M_S and M_t.



Known/unknown loop corrections in the EFT calculation

SM contributions:

- Loop corrections in the determination of the running SM parameters y_f^{SM}, g_i^{SM}:

$$y_t^{\text{SM}} = \frac{\sqrt{2}\,M_t}{v}\Big[1 + \hbar(\text{full}) + \hbar^2(\alpha_s^2 + \alpha_t\alpha_s + \alpha_t^2) + \hbar^3(\alpha_s^3 + \cdots)\Big]$$

$$\alpha_s^{\text{SM}} = \alpha_s^{\text{SM}(5)}\Big[1 + \hbar(\text{full}) + \hbar^2(\alpha_s^2 + \cdots) + \hbar^3(\alpha_s^3 + \cdots) + \cdots\Big]$$

[9912391, 1205.2892, 9305305, 9707474, 9708255, 0004189]

- Loop corrections to M_h^2 in the SM:

$$\begin{aligned} M_h^2 = m_h^2 + \hbar(\text{full}) + \hbar^2\Big[m_t^2(\alpha_t\alpha_s + \alpha_t^2 + \cdots) + m_Z^2\alpha_{\text{em}}^2 + \cdots\Big] \\ + \hbar^3\Big[m_t^2(\alpha_t\alpha_s^2 + \alpha_t^2\alpha_s + \alpha_t^3) + m_Z^2\alpha_{\text{em}}^3 + \cdots\Big] \\ + \hbar^4\Big[m_t^2(\alpha_t\alpha_s^4 + \cdots) + \cdots\Big] \end{aligned}$$

[1205.6497, 1407.4336, 1508.00912]

Known/unknown loop corrections in the EFT calculation

SUSY contributions: Loop corrections to $\lambda(M_S)$:

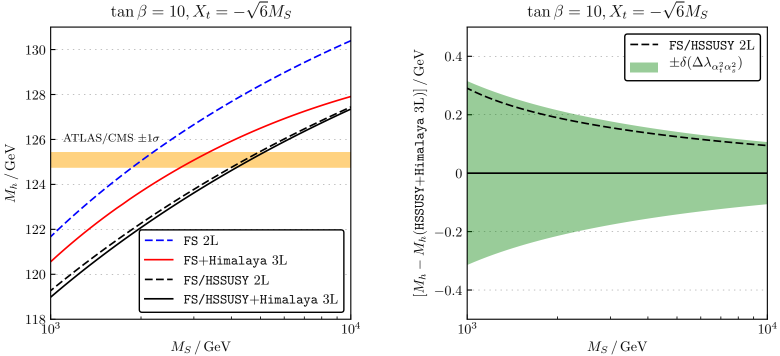
$$\lambda(M_S) = \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 + \hbar(\text{full}) + \hbar^2\Big[(\alpha_t^2\alpha_s + \alpha_b^2\alpha_s + \alpha_t^2\alpha_b + \alpha_t\alpha_b^2 + \alpha_t^3 + \cdots) + \alpha_{\text{em}}^3 + \cdots\Big] + \hbar^3\Big[(\underline{\alpha_t^2\alpha_s^2} + \alpha_t^3\alpha_s + \alpha_t^4) + \alpha_{\text{em}}^4 + \cdots\Big]$$

[1407.4081, 1504.05200, 1703.08166, 1807.03509]

Neglected contributions: Terms of $O(v^2/M_S^2)$

Effect of the 3-loop corrections to $\lambda(M_S)$

3-loop corrections to $\lambda(M_S)$ allow for an N^{3}LL resummation of strong corrections $O(\alpha_t^2\alpha_s^2)$:



[1807.03509]

Uncertainty estimate of the EFT calculation

In [1804.09410] 5 sources of uncertainty were combined:

$$\Delta M_h^{(Q_{\text{pole}})} = \max_{Q_{\text{pole}} \in [M_t/2, 2M_t]} |M_h(Q_{\text{pole}}) - M_h(M_t)|$$ [1609.00371]

$$\Delta M_h^{(Q_{\text{match}})} = \max_{Q_{\text{match}} \in [M_S/2, 2M_S]} |M_h(Q_{\text{match}}) - M_h(M_S)|$$ [1407.4081]

$$\Delta M_h^{(y_t^{\text{SM}})} = \left| M_h(y_t^{\text{SM},(2L)}(M_Z)) - M_h(y_t^{\text{SM},(3L)}(M_Z)) \right|$$ [1504.05200]

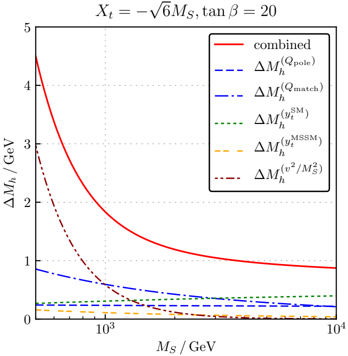
$$\Delta M_h^{(v^2/M_S^2)} = \left| M_h - M_h(v^2/M_S^2) \right|$$ [1504.05200]

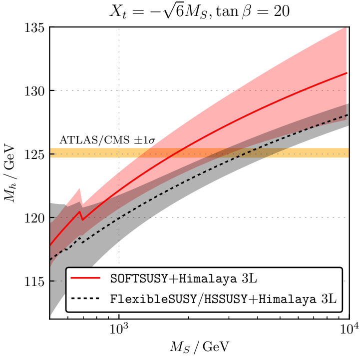
$$\Delta M_h^{(y_t^{\text{MSSM}})} = \left| M_h - M_h(y_t^{\text{MSSM}}(M_S)) \right|$$ [Bagnaschi,AV,Weiglein]

Combination:

$$\Delta M_h^{(\text{EFT})} = \Delta M_h^{(Q_{\text{pole}})} + \Delta M_h^{(Q_{\text{match}})} + \Delta M_h^{(y_t^{\text{SM}})} + \Delta M_h^{(y_t^{\text{MSSM}})} + \Delta M_h^{(v^2/M_S^2)}$$

Comparison of fixed-order and EFT approaches





$$\Delta M_h^{(\text{FO})} \stackrel{!}{=} \Delta M_h^{(\text{EFT})}$$

$$\Rightarrow M_S^{\text{equal}} = 1.0\text{–}1.3\,\text{TeV for small/large } \tan\beta \text{ and/or } X_t$$

[1804.09410]

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Hybrid fixed-order/EFT calculation

Goal: resume large logarithms **and** include suppressed $O(v^2/M_S^2)$ terms

Two known approaches:

- FeynHiggs [1312.4937, 1706.00346, 1805.00867]: Replace logs from fixed-order calculation by resummed logs

$$M_h^2 = (M_h^2)_{\text{fixed-order}} - (M_h^2)_{\text{logs}} + (M_h^2)_{\text{resummed logs}}$$

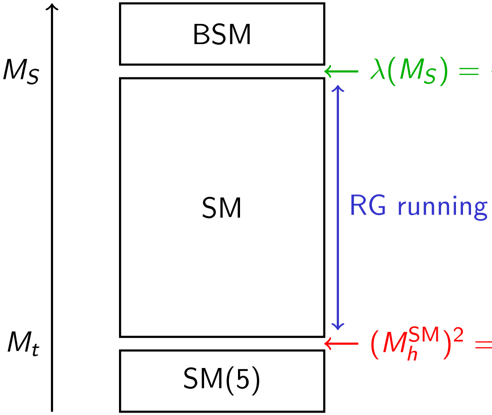
- FlexibleEFTHiggs [1609.00371, 1710.03760]: Incorporate $O(v^2/M_S^2)$ terms into λ by using the matching condition

$$(M_h^2)_{\text{SM}} \stackrel{!}{=} (M_h^2)_{\text{BSM}} \qquad \text{at } Q = M_S$$

FlexibleEFTHiggs approach [1609.00371, 1710.03760]

Idea: Determine $\lambda(M_S)$ from the condition

$$(M_h^2)_{\text{SM}} \equiv \lambda(M_S)v^2 + (\Delta m_h^2)_{\text{SM}} \stackrel{!}{=} (M_h^2)_{\text{BSM}}, \qquad Q = M_S$$

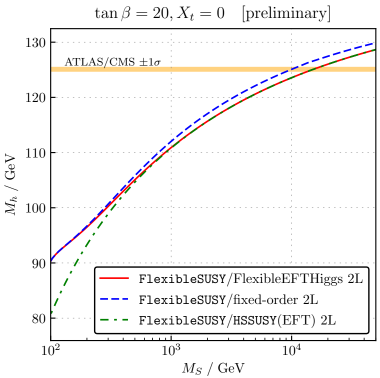


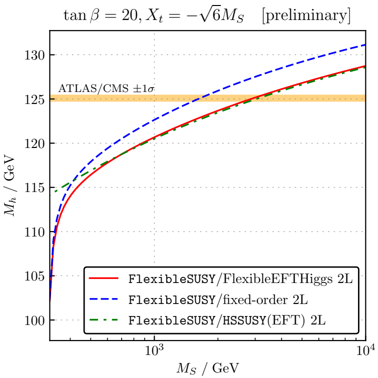
$$\leftarrow \lambda(M_S) = \frac{1}{v^2}\left[(M_h^2)_{\text{BSM}} - (\Delta m_h^2)_{\text{SM}}\right]$$

$$\leftarrow (M_h^{\text{SM}})^2 = \lambda(M_t)v^2 + (\Delta m_h^2)_{\text{SM}} + \cdots$$

Comparison of the three approaches in the MSSM

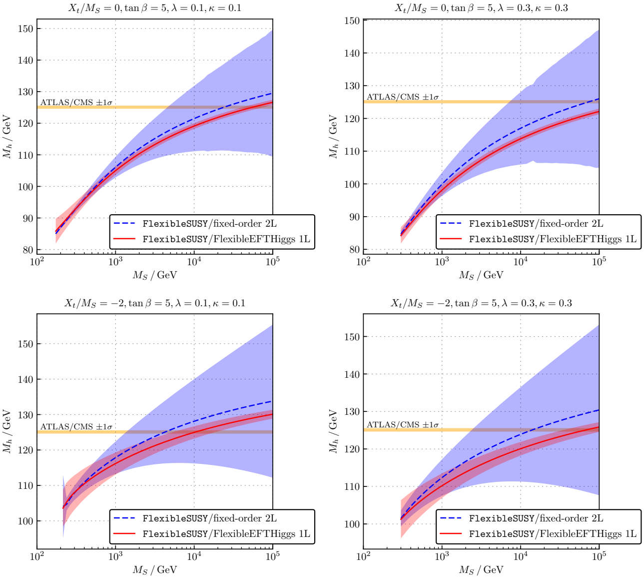
Currently NLO + NLL is available [1609.00371, 1710.03760].
Extension to NNLO + NNLL is work in progress:





Preliminary work by Thomas Kwasnitza, Dominik Stöckinger, AV

Comparison in the NMSSM



Summary

Supersymmetry is still viable, but

- $M_S \gtrsim 1\,\text{TeV}$ required in the MSSM to predict $M_h = 125.09\,\text{GeV}$

Recent advances in the calculation of M_h in the MSSM:

- fixed-order ($\overline{\text{DR}}'$): 3-loop $O(\alpha_t \alpha_s^2)$ correction to M_h
- EFT (single-scale): 3-loop $O(\alpha_t \alpha_s^2)$ correction to λ
  $\rightarrow$ N^3LL resummation of strong corrections
- hybrid (FlexibleEFTHiggs): NLO + NLL available,
  NNLO + NNLL comming soon

When to use the MSSM $\overline{\text{DR}}'$ fixed-order/EFT calculation?

- $M_S \lesssim 1\,\text{TeV} \Rightarrow$ use fixed-order
- $M_S \gtrsim 1\,\text{TeV} \Rightarrow$ use EFT

Current status of (N)MSSM spectrum generators

MSSM

Spectrum generator	fixed order	EFT	hybrid
FeynHiggs	2L	2L	NNLO + NNLL
FlexibleSUSY	3L	3L	NNLO + NNLL†
SOFTSUSY	3L	–	–
SARAH/SPheno	2L	–	NNLO + LL

NMSSM

Spectrum generator	fixed order	EFT	hybrid
FeynHiggs	–	–	–
FlexibleSUSY	2L*	–	NNLO + NNLL†
SOFTSUSY	2L*	–	–
SARAH/SPheno	2L	–	NNLO + LL

†: not released yet

*: $O(\alpha_t^2)$ corrections in the MSSM limit, no $O(\alpha_t \lambda^2)$ corrections

Backup

Uncertainty estimate of the fixed-order $\overline{\text{DR}}'$ calculation

Calculation of m_t in two different ways as proposed in [1609.00371]:

$$
\begin{aligned}
m_t^{[1]} &= M_t + \widetilde{\Sigma}_t^{(1L),S} + M_t \left[\widetilde{\Sigma}_t^{(1L),L} + \widetilde{\Sigma}_t^{(1L),R} \right] \\
&\quad + M_t \left[\widetilde{\Sigma}_t^{(1L),\text{SQCD}} + \widetilde{\Sigma}_t^{(2L),\text{SQCD}} + \left(\widetilde{\Sigma}_t^{(1L),\text{SQCD}} \right)^2 \right] \\
m_t^{[2]} &= M_t + \widetilde{\Sigma}_t^{(1L),S} + m_t \left[\widetilde{\Sigma}_t^{(1L),L} + \widetilde{\Sigma}_t^{(1L),R} \right] \\
&\quad + m_t \left[\widetilde{\Sigma}_t^{(1L),\text{SQCD}} + \widetilde{\Sigma}_t^{(2L),\text{SQCD}} \right]
\end{aligned}
$$

Calculation of α_s and α_{em} in two different ways:

$$
\begin{aligned}
\alpha_s^{[1]} &= \frac{\alpha_s^{\text{SM}(5)}}{1 - \Delta^{(1L)}\alpha_s - \Delta^{(2L)}\alpha_s} \\
\alpha_s^{[2]} &= \alpha_s^{\text{SM}(5)} \left[1 + \Delta^{(1L)}\alpha_s + (\Delta^{(1L)}\alpha_s)^2 + \Delta^{(2L)}\alpha_s \right]
\end{aligned}
$$

Uncertainty estimate of FlexibleEFTHiggs-1L

$$\Delta M_h^{(Q_{\text{pole}})} = \max_{Q_{\text{pole}} \in [M_t/2, 2M_t]} |M_h(Q_{\text{pole}}) - M_h(M_t)|$$ [1609.00371]

$$\Delta M_h^{(Q_{\text{match}})} = \max_{Q_{\text{match}} \in [M_S/2, 2M_S]} |M_h(Q_{\text{match}}) - M_h(M_S)|$$ [1407.4081]

$$\Delta M_h^{(y_t^{\text{SM}})} = \left| M_h(y_t^{\text{SM},(2L)}(M_Z)) - M_h(y_t^{\text{SM},(3L)}(M_Z)) \right|$$ [1504.05200]

$$\Delta M_h^{(v^2/M_S^2)} = 0 \quad \text{(has no EFT uncertainty!)}$$ [1609.00371]