Uncertainties of M_h in the MSSM: fixed-order vs. EFT predictions

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[1804.09410]

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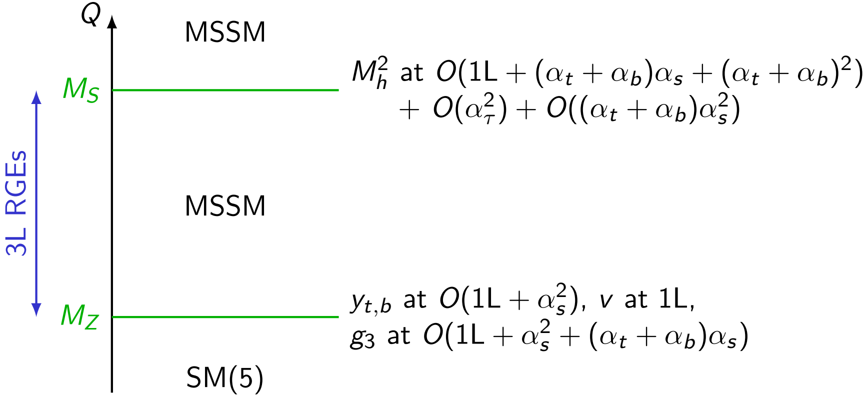
Fixed-order calculation (SOFTSUSY)



M_h^2: [0105096, 0112177, 0212132, 0206101, 0305127, 1708.05720]

$y_{t,b}$: [0210258, 0507139, 0707.0650, 0912.4652], g_3: [0509048, 0810.5101, 1009.5455]

α_{em}: [1411.7040], β_i: [0308231, 0408128]

Uncertainty estimate of the fixed-order calculation

Inspired by [1609.00371], we consider 5 sources of uncertainty:

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

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

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

$$\Delta M_h^{(\alpha_s)} = \left|M_h(\alpha_s^{(1)}) - M_h(\alpha_s^{(2)})\right|$$ New!

$$\Delta M_h^{(\alpha_{\text{em}})} = \left|M_h(\alpha_{\text{em}}^{(1)}) - M_h(\alpha_{\text{em}}^{(2)})\right|$$ New!

Combination:

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

Uncertainty estimate of the fixed-order calculation

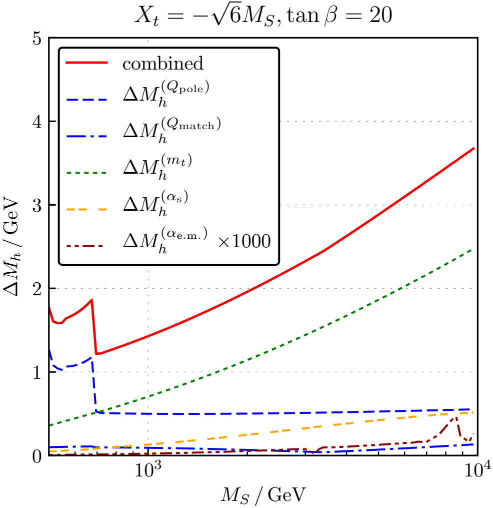
Calculation of m_t in two different ways as proposed in [1609.00371]:

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

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

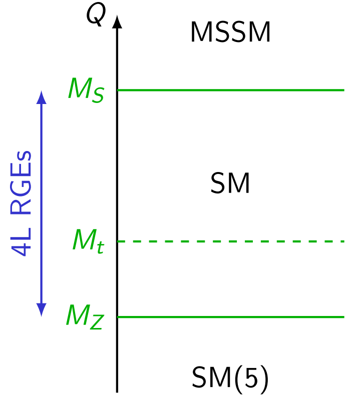
$$\begin{aligned}
\alpha_s^{(1)} &= \frac{\alpha_s^{\mathrm{SM}(5)}}{1 - \Delta^{(1)}\alpha_s - \Delta^{(2)}\alpha_s} \\
\alpha_s^{(2)} &= \alpha_s^{\mathrm{SM}(5)} \left[1 + \Delta^{(1)}\alpha_s + (\Delta^{(1)}\alpha_s)^2 + \Delta^{(2)}\alpha_s\right]
\end{aligned}$$

Uncertainty estimate of the fixed-order calculation



EFT calculation from FlexibleSUSY (HSSUSY)

EFT calculation from `FlexibleSUSY` (`HSSUSY`)



λ at $O(1\text{L} + (\alpha_t + \alpha_b)\alpha_s + (\alpha_t + \alpha_b)^2)$
$+ O(\alpha_b\alpha_\tau + \alpha_\tau^2) +$ ~~$O(\alpha_t\alpha_s^2)$~~

M_h^2 at $O(1\text{L} + (\alpha_t + \alpha_b)\alpha_s + (\alpha_t + \alpha_b)^2)$
$+ O(\alpha_t^3 + \alpha_t^2\alpha_s + \alpha_t\alpha_s^2 + \alpha_t\alpha_s^3)$

y_t at $O(1\text{L} + \alpha_s^2 + \alpha_s^3)$, v at 1L,
g_3 at $O(1\text{L} + \alpha_s^2 + \alpha_s^3)$

λ: [1407.4081, 1504.05200, 1703.08166] M_h^2: [1205.6497, 1504.05200, 1407.4336, 1508.00912]

y_t: [9912391, 1205.2892], g_3: [9305305, 9707474, 9708255, 0004189]

β_i: [1201.5868, 1210.6873, 1212.6829, 1205.2892, 1303.4364, 1508.00912, 1508.02680, 1604.00853]

Uncertainty estimate of the EFT calculation

Inspired by [1407.4081, 1504.05200, 1609.00371], we consider 5 sources of uncertainty:

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

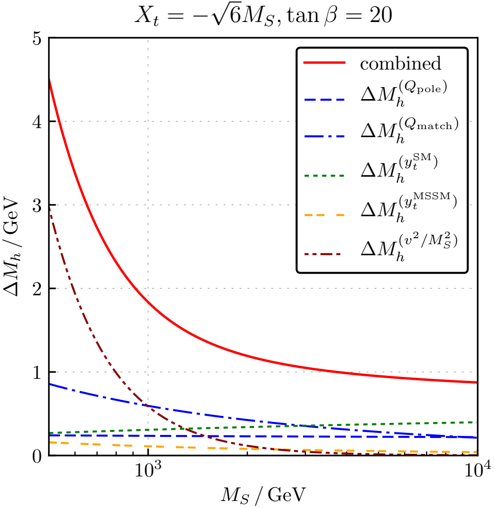
$$\Delta M_h^{(v^2/M_S^2)} = \left|M_h - M_h(v^2/M_S^2)\right|$$ [1504.05200]

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

Combination:

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

Uncertainty estimate of the EFT calculation



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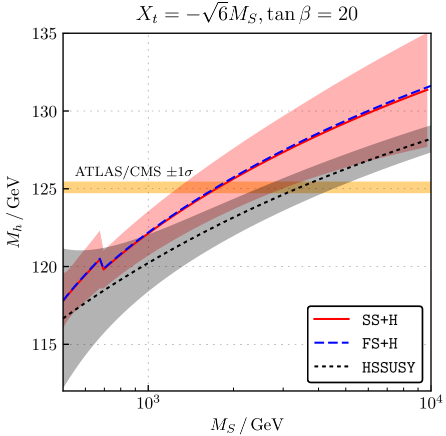
When should the EFT be used?



$$\Delta M_h^{(\texttt{SS+H})} \overset{!}{=} \Delta M_h^{(\texttt{HSSUSY})}$$

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

Contents

How heavy can the lightest stop be?

Derive an upper bound on $m_{\tilde{t}_1}$ from the MSSM parameter region where

1. the Higgs boson mass is in agreement with experiment (including the theoretical uncertainty from the EFT calculation):

$$M_h = 125.09\,\text{GeV} \pm \Delta M_h^{(\texttt{HSSUSY})}$$

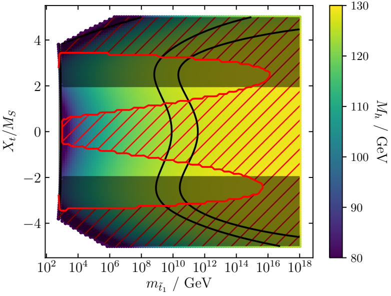
2. there is no CCB minimum that is deeper than the EW vacuum [1407.4081]:

$$\frac{X_t^2}{m_{\tilde{Q}_3} m_{\tilde{u}_3}} < \left(4 - \frac{1}{\sin^2\beta}\right)\left(\frac{m_{\tilde{Q}_3}}{m_{\tilde{u}_3}} + \frac{m_{\tilde{u}_3}}{m_{\tilde{Q}_3}}\right)$$

How heavy can the lightest stop be?

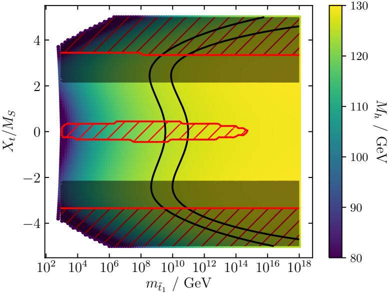
Chose $\tan\beta = 1$ so that $(m_h^2)_{\text{tree}} = 0 \Rightarrow$ largest corrections from stops are required

$\tan\beta = 1$



$m_{\tilde{t}_1} \leq 3.7 \cdot 10^{11}$ GeV

$\tan\beta = 1.2$



$m_{\tilde{t}_1} \leq 9.6 \cdot 10^{10}$ GeV

Backup

Uncertainty estimate in FlexibleSUSY

Fixed-order calculation (FS+H):

- vary $Q_{\text{pole}} \in [M_S/2, 2M_S]$
- $\alpha_s^{1L}(M_Z)$ vs. $\alpha_s^{2L}(M_Z)$

EFT calculation (HSSUSY):

- vary $Q_{\text{pole}} \in [M_t/2, 2M_t]$ [SM uncertainty]
- $y_t^{2L}(M_Z)$ vs. $y_t^{3L}(M_Z)$ [SM uncertainty]
- $\lambda(M_S)$ vs. $\lambda(M_S) + v^2/M_S^2$ [EFT uncertainty]
- vary $Q_{\text{match}} \in [M_S/2, 2M_S]$ [SUSY uncertainty]
- $y_t^{\text{SM}}(M_S)$ vs. $y_t^{\text{MSSM}}(M_S)$ [SUSY uncertainty]

Hybrid calculation (FlexibleEFTHiggs-2.0):

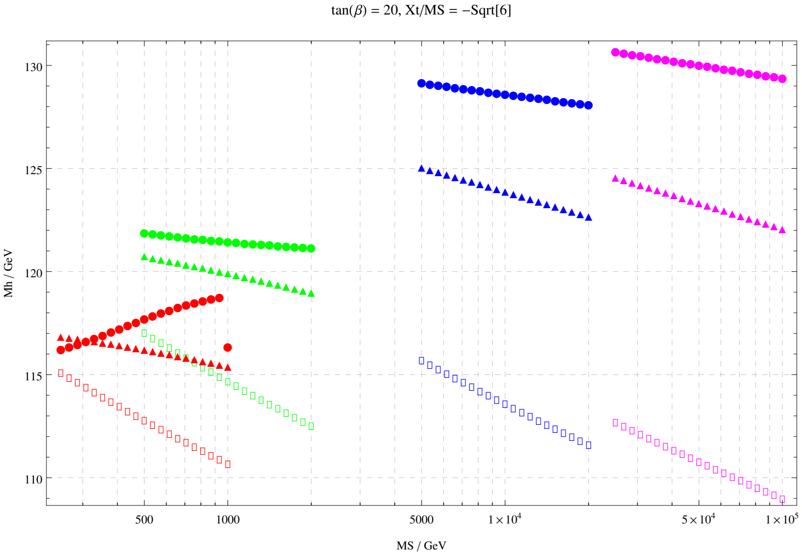
- vary $Q_{\text{pole}} \in [M_t/2, 2M_t]$ [SM uncertainty]
- $y_t^{2L}(M_Z)$ vs. $y_t^{3L}(M_Z)$ [SM uncertainty]
- vary $Q_{\text{match}} \in [M_S/2, 2M_S]$ [SUSY uncertainty]

M_h at 1-loop and scale variation

$$M_h^2 = \frac{1}{4}(g_Y^2 + g_2^2)v^2 \cos^2 2\beta + \frac{6y_t^4 v^2}{(4\pi)^2}\left[\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^4}\right]$$

$$\begin{aligned}(4\pi)^2\beta_{y_t} &= -\frac{13}{15}g_1^2 y_t - 3g_2^2 y_t - \frac{16}{3}g_3^2 y_t + 6y_t^3 \approx -2 \\ &= y_t\left(6y_t^2 - 5.33g_3^2\right) \approx 0 \quad \text{for} \quad g_1 = g_2 = 0\end{aligned}$$

M_h scale variation



square: 1L, triangle: 2L, circle: 3L