MSSM Higgs boson mass including three-loop corrections, NNNLL- and X_t-resummation using FlexibleEFTHiggs

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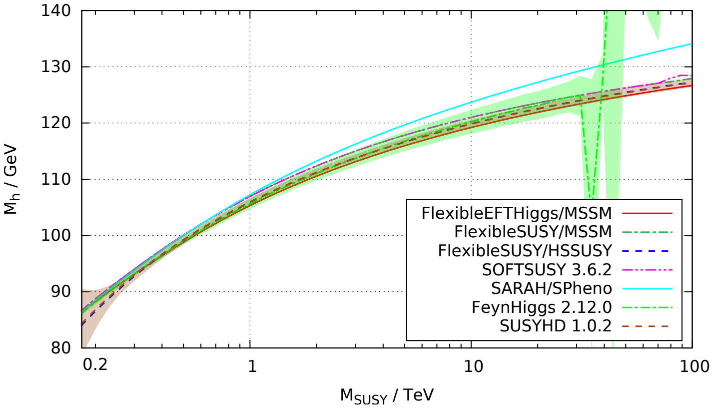
$$M_h^{\text{Exp}} = 125.09 \pm 0.24\text{GeV}$$

vs

MSSM theory 2016:



Hallmark of SUSY: M_h predictable!

Standard Model: $m_h^2 = \lambda v^2$

MSSM: $\lambda \leftrightarrow$ gauge couplings

$HHHH \leftrightarrow HH\tilde{H}\tilde{H}$

$$m_h^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 - \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 c_{2\beta}^2}\right]$$

Huge loop corrections!

Hallmark of SUSY: M_h predictable!

Standard Model: $m_h^2 = \lambda v^2$

MSSM: $\lambda \leftrightarrow$ gauge couplings

$$HHHH \leftrightarrow HH\tilde{H}\tilde{H}$$

$$m^2_{h,\text{tree}} = v^2 \frac{1}{4}\left(g_Y^2 + g_2^2\right)\cos^2 2\beta + \mathcal{O}\left(\frac{1}{m_A^2}\right)$$

Huge loop corrections!

Overview of M_h calculations (and codes)

Two basic approaches

$$\text{standard P.T.} = \text{tree} + \mathcal{O}(\alpha) + \mathcal{O}(\alpha^2) + \mathcal{O}(\alpha^3) + \ldots$$
$$\text{resummed logs} = \text{tree} + \mathcal{O}(\alpha^n L^n) + \mathcal{O}(\alpha^n L^{n-1}) + \ldots$$

Fixed order (explicit self energy/tadpole diagrams/eff.pot.)

(FeynHiggs [Heinemeyer et al], Softsusy [Allanach], SPheno [Porod et al], FlexibleSUSY, 2-loop, FS+Himalaya 3-loop)

Resummation via EFT+RGE $\rightsquigarrow$ neglects terms $\mathcal{O}(1/M_{\text{SUSY}})$

(SUSYHD [Vega,Villadoro], HSSUSY), 2-loop matching/3-loop running

[systematic improvement by orders of $M_{\text{weak}}/M_{\text{SUSY}}$ possible with higher-dimensional operators in EFT]

Hybrid: resummed logs + full M_{SUSY}-dependence at fixed order

(FeynHiggs, FlexibleEFTHiggs)

FlexibleSUSY: Athron, Kotlarski, Kwasnitza, Park, DS, Voigt et al — spectrum generator generator + toolbox

$$M_h^{\mathrm{Exp}} = 125.09 \pm 0.24\mathrm{GeV}$$

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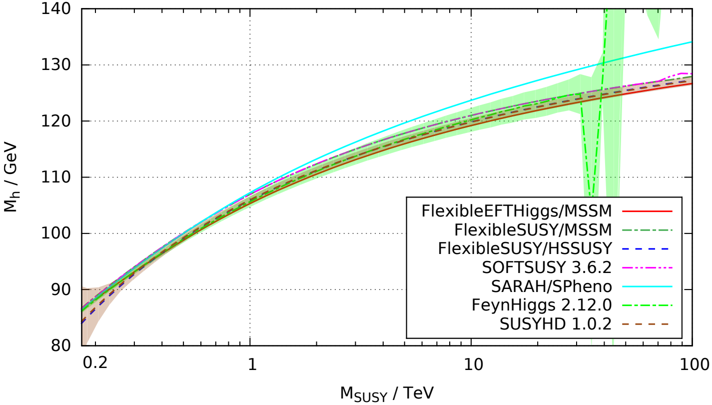
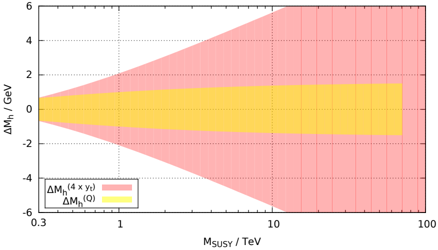


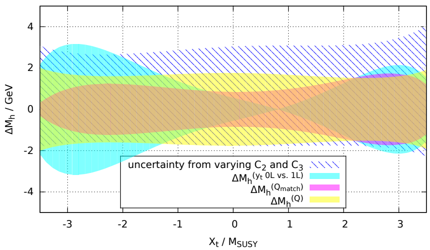
Goal: FlexibleEFTHiggs: hybrid calculation with 3-loop matching, resummation of logs and further improvements

Comments on uncertainty estimates

From [Athron,Park,Steudtner,DS,Voigt'16]:



2-loop FO



1-loop FEFTH

- very difficult in theories with many parameters
- use scale variation, change of scheme ...
- important: clarify which types of missing terms are estimated

Eg: fixed-order scale variation estimates missing subleading logs, but not leading logs; EFT scale variation might miss X_t-terms
Goal: reduce uncertainties

Outline

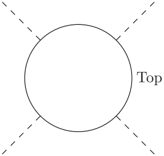
Use

$$m_h^2 = \lambda v^2 + \dots$$

MSSM tree-level relation

$$\lambda^{\text{eff,tree}} = \frac{1}{4}\left(g_Y^2 + g_2^2\right)\cos^2 2\beta$$

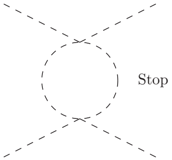
SM top-loop contribution



$$\Delta\lambda^{\text{eff}} = y_{t_{\text{SM}}}^4 \kappa_L \left[12 \log\left(Q/m_t\right) \right]$$

- prefactor corresponds to the SM beta function of λ!

$+$SUSY stop-loop contribution

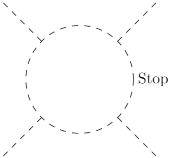


$$\Delta\lambda^{\text{eff}} = y_{t_{\text{SM}}}^4 \kappa_L \left[12 \log\left(m_{\tilde{t}}/m_t\right)\right]$$

- total contribution is finite (λ is given by gauge couplings!)
- Large log! Prefactor $\leftrightarrow$ SM beta function of λ

Note: valid in the limit of all-equal SUSY masses

$+$SUSY stop-loop $\sim \hat{X}_t = (A_t - \mu^* \cot\beta)/M_{\text{SUSY}}$



$$\Delta\lambda^{\text{eff}} = y_{t_{\text{SM}}}^4 \kappa_L \left[12 \log\left(m_{\tilde{t}}/m_t\right) + 6\left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12}\right)\right]$$

- additional X_t-enhancement
- from UV-finite diagrams, not predicted by RGE

M_h calculation:

- Higgs mass expression contains the terms of the form $\Delta\lambda^{\text{eff}} v^2$
- but also additional terms suppressed as v^2/M_{SUSY}^2

Full expression including those terms from self energy and tadpoles:

$$\Delta m_h^2 = X_t\text{-terms} - 3y_{t_{\text{SM}}}^4 \kappa_L v^2 \left[B_0(p^2, m_{\tilde{t}_1}^2, m_{\tilde{t}_1}^2) + B_0(p^2, m_{\tilde{t}_2}^2, m_{\tilde{t}_2}^2) \right].$$

the stop masses are a combination of M_{SUSY} and terms of order v

$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2} \left(m_{Q_3}^2 + m_{U_3}^2 \mp \sqrt{\left(m_{Q_3}^2 - m_{U_3}^2 \right)^2 + 4(m_t X_t)^2} \right),$$

Resulting structure of Higgs mass calculation

- Loops
- large logs $L = \log(M_{\text{SUSY}}/m_t)$
- power-suppressed terms $\propto (v/M_{\text{SUSY}})$

$$m_h^2 = \sum_{nmk} \kappa_L^n L^m \left(\frac{v}{M_{\text{SUSY}}}\right)^k c_{nmk}$$

Coefficients c_{nmk} depend on all SUSY parameters

- can be enhanced by X_t
- contain functions of mass ratios of SUSY masses

$$m_h^2 = m_{h,\text{tree}}^2 +$$

$$\begin{array}{lllll}
\kappa_L L & \kappa_L & & & + \\
\kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\
\kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\
\kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots
\end{array}$$

$$m_h^2 = m_{h,\text{tree}}^2 +$$

$$\begin{array}{ccccc}
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\kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\
\kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots
\end{array}$$

fixed-order 1-loop: need 1-loop self energies/tadpoles (can compute these exactly)

$$
\begin{array}{lllll}
m_h^2 = m^2_{h,\text{tree}} + & & & & \\
\kappa_L L & \kappa_L & & & + \\
\kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\
\kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\
\kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots
\end{array}
$$

fixed-order 2-loop: need 2-loop self energies/tadpoles; computed almost exactly (mostly g-less limit, $p = 0$)

$$m_h^2 = m_{h,\text{tree}}^2 +$$

$$\begin{array}{lllll} \kappa_L L & \kappa_L & & & + \\ \kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\ \kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\ \kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots \end{array}$$

leading log resummation: need 1-loop beta function of SM(!) Haber, Hempfling '93

$$m_h^2 = m_{h,\text{tree}}^2 +$$

$$\begin{array}{lllll}
\kappa_L L & \kappa_L & & & + \\
\kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\
\kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\
\kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots
\end{array}$$

N^{n}LL resummation: need three steps:

- integrate out heavy sparticles at high scale, n-loop matching to SM

  (this calc. does not contain large logs by construction!)

- then RGE running to low scale with $(n+1)$-loop SM beta functions

  (resums large logs)

- then compute Higgs mass at low scale in SM

  (no large logs by construction)

Hence exact wrt leading and n-th subleading logs

[1-loop: Casas, Espinosa,Quiros, Riotto . . . 2-loop: Martin '07]

$$m_h^2 = m_{h,\text{tree}}^2 + $$

$$\begin{array}{lllll} \kappa_L L & \kappa_L & & & + \\ \kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\ \kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\ \kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots \end{array}$$

Status — Huge recent progress: Fixed-order 2-loop Degrassi, Slavich, Baglio, Gröber, Mühlleitner, Nhung, Rzehak, Spira, Drechsel, Galeta, Heinemeyer, Weiglein, Goodsell, Nickel, Staub, Paßehr, Braathen Fixed-order 3-loop Harlander, Kant, Mihaila, Steinhauser, Reyes, Fazio EFT+RGE 2-loop Draper, Lee, Wagner, Bagnaschi, Giudice, Slavich, Strumia, Vega, Villadoro. . . 3-loop HSSUSY Harlander, Klappert, Franco, Voigt, Hybrid: Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, Bahl, Athron, Park, Steudtner, DS, Voigt "DRED is SUSY at 3L" DS, Unger]

$$m_h^2 = m_{h,\text{tree}}^2 +$$

$$\begin{array}{lllll}
\kappa_L L & \kappa_L & & & + \\
\kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\
\kappa_L^3 L^3 & \kappa_L^3 L^2 & \kappa_L^3 L & \kappa_L^3 & + \\
\kappa_L^4 L^4 & \kappa_L^4 L^3 & \kappa_L^4 L^2 & \kappa_L^4 L & + \ldots
\end{array}$$

$\rightarrow$ Goal

Outline

FlexibleEFTHiggs calculation

1. integrate out heavy sparticles at high scale, 3-loop matching to SM*

   [0105096, 0112177, 0212132, 0206101, 0305127, 0803.0672, 1005.5709 1205.6497, 1407.4336, 1708.05720, new]

$$\lambda(Q_{\text{match}}) = \frac{1}{v^2}\left[(m_h^{\text{MSSM}})^2 - \tilde{\Sigma}_h^{\text{MSSM}}((M_h^{\text{MSSM}})^2) + \tilde{\Sigma}_h^{\text{SM}}((M_h^{\text{SM}})^2)\right]$$

2. then RGE running to low scale with 4-loop SM beta functions

   [1201.5868, 1205.2892, 1212.6829, 1303.4364, 1604.00853]

$$\frac{\mathrm{d}\lambda(\mu)}{\mathrm{d}\ln\mu} = \beta_\lambda^{\text{SM}}(\mu)$$

3. compute Higgs mass at low scale in SM with 3-loop SM Σ_t, Σ_h

   [9912391, 0507139, 9912391][1205.6497, 1508.00912,1407.4336]

$$M_h^2 = \lambda(M_{\text{weak}})v^2 + \hat{\Sigma}_h$$

* and similar for all parameters such that m_h is correct at $\mathcal{O}(y_{t,b}^2\alpha_s, y_{t,b}^6, y_t^4\alpha_s^2)$

Subtleties 1 — Hybrid approach

Master formula for matching:

$$\lambda = \frac{1}{v^2}\left[(m_h^{\mathrm{MSSM}})^2 - \tilde{\Sigma}_h^{\mathrm{MSSM}}((M_h^{\mathrm{MSSM}})^2) + \tilde{\Sigma}_h^{\mathrm{SM}}((M_h^{\mathrm{SM}})^2)\right]$$

standard "pure" EFT matching: [Casas, Espinosa, Quiros, Riotto. . . Martin. . . SUSYHD, HSSUSY]

- evaluate in limit $M_{\mathrm{SUSY}} \to \infty$, neglect terms v/M_{SUSY}

  Not good in region around 1 TeV — Could be improved by taking into account dim=6 operators in EFT. Then even logs proportional to power-suppressed terms can be resummed $\rightsquigarrow$impact negligible: Bagnaschi,Vega,Slavich'17]

Hybrid approach: take into account power-suppressed terms at fixed-order

- FlexibleEFTHiggs approach: evaluate master formula exactly
  [Athron, Park, Steudtner, DS, Voigt '16]

  combines fixed-order calculation with resummed logs of $(v/M_{\mathrm{SUSY}})^0$ terms. Alternative hybrid approach in FeynHiggs

  [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein + Bahl]

Subtleties 2 — parametrization issues

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \gamma_1 {y_{t_{\text{MSSM}}}}^4 L + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

$$-\gamma_1 \left(\frac{y_{t_{\text{SM}}}}{s_\beta} \right)^4 L$$

$$y_{t_{\text{MSSM}}} (1 + \kappa_L \Delta\tilde{y}_t) = \frac{y_{t_{\text{SM}}}}{s_\beta}$$

Evaluate literally, e.g. numerically in a code?

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Evaluate literally, e.g. numerically in a code?

Generates two-loop single large log $\kappa_L^2 \Delta \tilde{y}_t {y_{t_{\text{MSSM}}}}^4 L$!

Bad and incorrect! Messes up log-resummation by RGE! [FlexibleSUSY 2, 2017]

Subtleties 2 — parametrization issues

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \gamma_1 {y_{t_{\text{MSSM}}}}^4 L + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

$$-\gamma_1 \left(\frac{y_{t_{\text{SM}}}}{s_\beta} \right)^4 L$$

$$y_{t_{\text{MSSM}}} (1 + \kappa_L \Delta \tilde{y}_t) = \frac{y_{t_{\text{SM}}}}{s_\beta}$$

Solution: need to consistently expand everything in terms of full model parameters and truncate at fixed order

Subtleties 2 — parametrization issues

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \cancel{\gamma_1 {y_{t_{\text{MSSM}}}}^4 L} + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

$$\cancel{-\gamma_1 \left(\frac{y_{t_{\text{SM}}}}{s_\beta} \right)^4 L}$$

$$y_{t_{\text{MSSM}}} (1 + \kappa_L \Delta \tilde{y}_t) = \frac{y_{t_{\text{SM}}}}{s_\beta}$$

Correct option 1: EFT-parametrization
Eliminate MSSM-Yukawa within MSSM self energy, expand/truncate in terms of SM-Yukawa

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \left(\frac{y_{t_{\text{SM}}}}{s_\beta} \right)^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

Subtleties 2 — parametrization issues

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \gamma_1 {y_{t_{\text{MSSM}}}}^4 L + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

$$-\gamma_1 \left(\frac{y_{t_{\text{SM}}}}{s_\beta} \right)^4 L$$

$$y_{t_{\text{MSSM}}} (1 + \kappa_L \Delta \tilde{y}_t) = \frac{y_{t_{\text{SM}}}}{s_\beta}$$

Correct option 2: Full model-parametrization
Eliminate SM-Yukawa within the SM self energy, expand/truncate in terms of MSSM-Yukawa

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6 \left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12} \right) \right]$$

Subtleties 2 — parametrization issues

$$\lambda^{\text{match 1L}} = \lambda^{\text{MSSM, tree}} + \gamma_1 {y_{t_{\text{MSSM}}}}^4 L + {y_{t_{\text{MSSM}}}}^4 \kappa_L \left[6\left(\hat{X}_t^2 - \frac{\hat{X}_t^4}{12}\right)\right]$$

$$-\gamma_1\left(\frac{y_{t_{\text{SM}}}}{s_\beta}\right)^4 L$$

$$y_{t_{\text{MSSM}}}(1+\kappa_L\Delta\tilde{y}_t) = \frac{y_{t_{\text{SM}}}}{s_\beta}$$

- The two options are equivalent but differ once p.t. is truncated

What's the point?

- previous codes use EFT-, but we will use full-model parametrization
- First advantage: technically easier
- Second advantage: "resums" leading X_t-contributions

Subtleties 2 — X_t "resummation"

Yukawa coupling ("Δm_b corrections" [Carena, Garcia, Nierste, Wagner'99...])

$$y_{t_{\mathrm{MSSM}}}(1+\Delta_y) = y_{t_{\mathrm{SM}}} \qquad\qquad \Delta_{y_t} \propto \kappa_L \alpha_s \hat{X}_t$$

this relation is exact wrt $\alpha_s^n \hat{X}_t^n$ (similar in b-sector)

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this relation is exact wrt $\alpha_s^n \hat{X}_t^n$ (similar in b-sector)

Invert: $$y_{t_{\text{MSSM}}} = \frac{y_{t_{\text{SM}}}}{1+\Delta_y}$$ "resummed" relation

Subtleties 2 — X_t “resummation”

Yukawa coupling (“Δm_b corrections” [Carena, Garcia, Nierste, Wagner'99...])

$$y_{t_{\text{MSSM}}}(1+\Delta_y) = y_{t_{\text{SM}}} \qquad \Delta_{y_t} \propto \kappa_L \alpha_s \hat{X}_t$$

this relation is exact wrt $\alpha_s^n \hat{X}_t^n$ (similar in b-sector)

Similarly we can prove that: *one-loop relation for λ in full-model parametrization is exact wrt X_t-dependence in all orders of $\alpha_t^2 \alpha_s^n$, $\alpha_t \alpha_g \alpha_s^n$.*

Converting to the EFT-parametrization this generates/"resums" terms

$$\alpha_t \alpha_g \alpha_s \hat{X}_t^3 \text{ (2L)},\ \alpha_t \alpha_g \alpha_s^2 \hat{X}_t^4 \text{ (3L)},\ \alpha_t^2 \alpha_s^3 \hat{X}_t^7 \text{ (4L)}$$

These terms are correctly taken into account in the full-model parametrization but would be neglected in a 3-loop EFT-parametrization.

FlexibleEFTHiggs properties

- 3-loop matching, 4-loop running of relevant quantities
- fixed-order results: 1L full, 2L gaugeless limit, 3L $\mathcal{O}(y_t^4\alpha_s^2)$
- RGE+EFT: NNNLL resummed
- Full-model parametrization: "resums" leading X_t-terms
- hybrid: power-suppressed terms kept at fixed order

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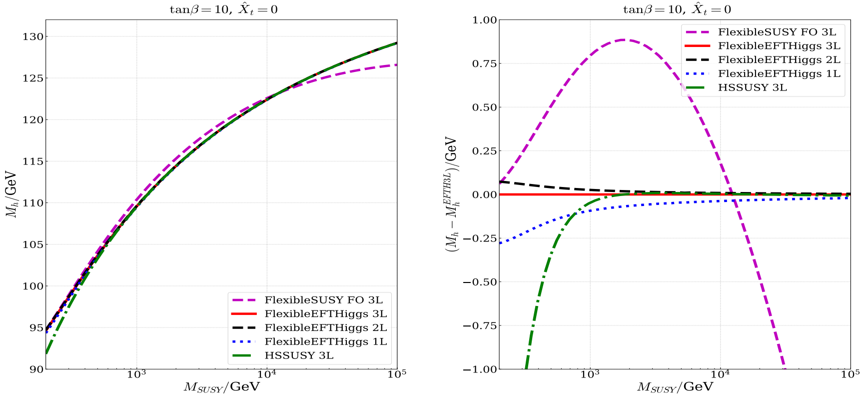
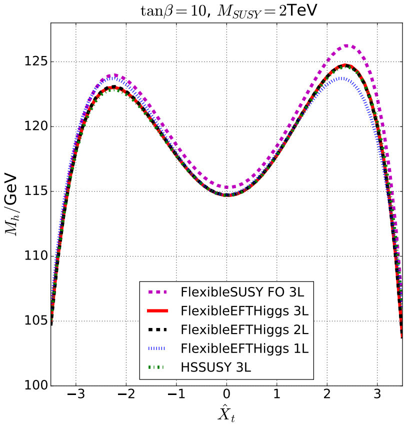
Compare to:

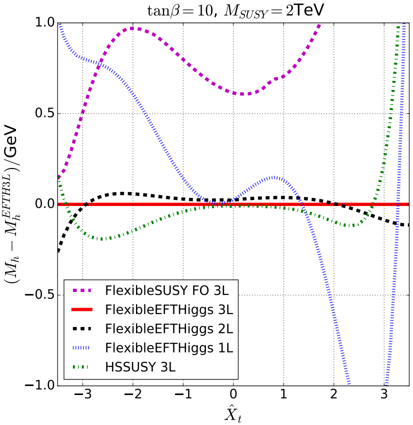
- HSSUSY: "pure EFT" calculation (3-loop) in EFT-parametrization
  [Harlander, Klappert, Franco, Voigt '18]
- FlexibleSUSY FO (+Himalaya): standard fixed-order computation in $\overline{\text{DR}}$ scheme [Harlander, Klappert, Voigt '18]

Outline

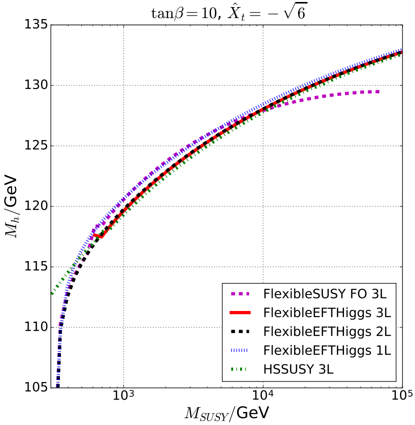


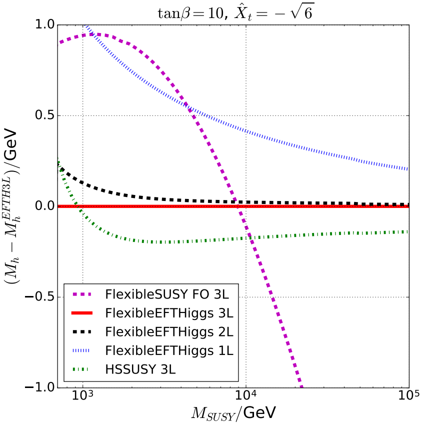
- simplest case: loop corrections to matching are very small
- fixed-order very unreliable above 1 TeV
- pure EFT unreliable below 1 TeV
- hybrid reliable at all scales





- matching corrections enhanced by X_t
- 1L, 2L, 3L converges well
- HSSUSY deviates at very large X_t because of missing leading higher-order X_t-terms

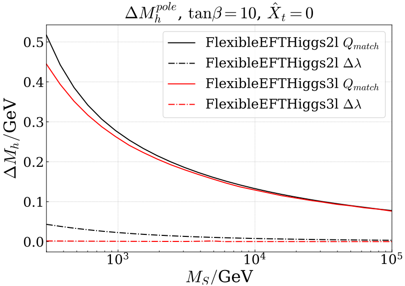


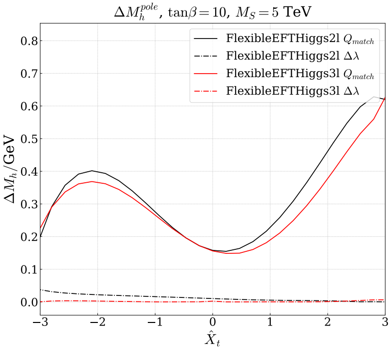


- 1L, 2L, 3L converges well
- HSSUSY does not converge towards hybrid because of different parametrization/truncation

Uncertainty estimates

Preliminary result for 3-loop FlexibleEFTHiggs

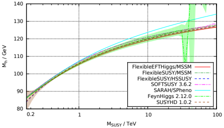




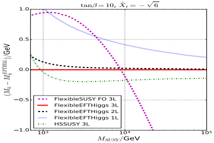
- uncertainty very small, does not shrink from 2L$\to$3L
- Note: 3L was only $\mathcal{O}(y_t^4\alpha_s^2)$—other types of terms now important

Conclusions

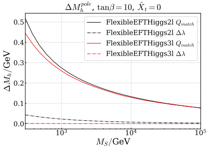
- Huge recent progress in M_h^{MSSM}
  - resummation now standard, hybrid available



- Three codes based on FlexibleSUSY incorporate 3-loop [Harlander, Kant et al]
  - FlexibleSUSY FO+Himalaya [Harlander,Klappert,Voigt]
  - HSSUSY [Harlander,Klappert,Franco,Voigt]
  - FlexibleEFTHiggs [Kwasnitza,DS,Voigt, in progress]



- Many subtleties in EFT/hybrid codes (see FeynHiggs [Bahl et al])
  - Parametrization in terms of EFT or full?
  - Double counting of logs?
  - Here: win-win situation! $\to$ X_t-resummation!



- Outlook:
  - uncertainty analysis, nontrivial spectra
  - code will be public MSSM spectrum generator
  - generalizable to other models