# Progress and remarks on MSSM Higgs boson mass calculations

## results from hybrid calculation including 3-loop corrections, 4-loop running, NNNLL- and $X_t$-resummation using FlexibleEFTHiggs


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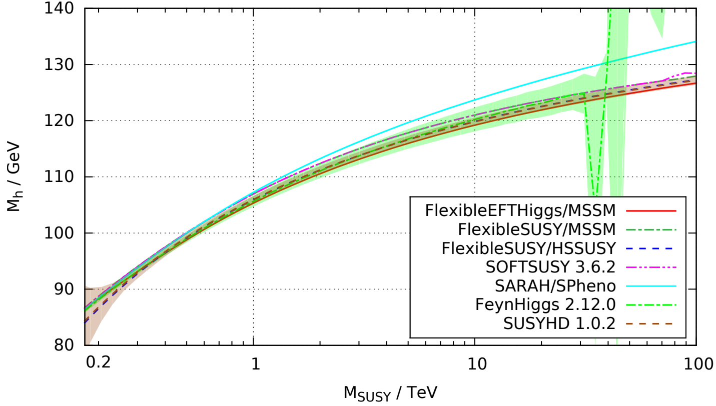
$$M_h^{\text{Exp}} = 125.18 \pm 0.16\text{GeV}$$

vs

MSSM theory 2016:



In SM:

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

MSSM tree-level relation

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

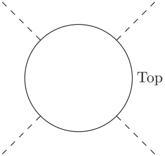
gives rise to $m_{h,\text{tree}} \leq M_Z$ and huge loop corrections!

# Overview of talk

- overview of contributions to $M_h$
- overview of calculations
- remarks on fixed order
- remarks on EFT+RGE
- Subtleties — $X_t$ “resummation”
- general theme: relationships between calculations, uncertainty estimates
- our calculation

# Outline

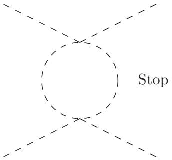
## SM top-loop contribution




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

- prefactor corresponds to the SM beta function of $\lambda$!

## $+$SUSY stop-loop contribution

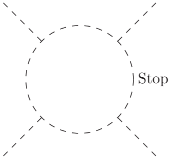



$$\Delta\lambda^{\rm eff} = y_{t_{\rm SM}}^4 \kappa_L \left[ 12 \log\left( m_{\tilde t}/m_t \right) \right]$$

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

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 $v^2/M^2_{\text{SUSY}}$

Full expression including those terms from self energy and tadpoles:

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

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

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

# Resulting 3-fold expansion of Higgs mass calculation

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

- Loops $\kappa_L = \frac{1}{16\pi^2}$, $L = \log(M_{\text{SUSY}}/M_{\text{weak}})$, mass suppression

Coefficients $c_{nmk}$ depend on all SUSY parameters

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

# Overview: Two basic approaches: Fixed order or EFT+RGE

$$
\begin{array}{llllll}
m_h^2 = m_{h,\text{tree}}^2 + & \kappa_L L & \kappa_L & & & + \\
& \kappa_L^2 L^2 & \kappa_L^2 L & \kappa_L^2 & & + \\
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Fixed order (explicit $n$-loop self energy/tadpole diagrams/eff.pot.) standard:

2-loop gaugeless limit, $p = 0$

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

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]

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Hybrid: resummed logs + full $M_{\text{SUSY}}$-dependence at fixed order (FeynHiggs, FlexibleEFTHiggs)

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]

# Remarks on fixed-order calculations

- Need $n$-loop self energies (on-shell)/tadpoles $\rightsquigarrow$ full $(v/M_{\text{SUSY}})$ and $X_t$ dependence at this order
- Not sufficient for $M_{\text{SUSY}} \gg 1$ TeV $\rightsquigarrow$ hybrid FeynHiggs [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein + Bahl]
- Progress beyond 2-loop gaugeless limit 3-loop gaugeless limit [Harlander, Kant, Mihaila, Steinhauser; Fazio, Reyes]; 2-loop beyond gaugeless limit [Borowka et al, Degrassi, Slavich, Passehr et al]; Check DRED is SUSY [DS, Unger]
- Different parametrizations possible
  - Theory uncertainty from missing higher-order leading logs
  - Scale variation only estimates missing subleading logs $\rightsquigarrow$ insufficient!

# Fixed order: choose parametrization and truncate

in terms of low-scale SM parameters $\hat{y}_t, \ldots$: e.g. FeynHiggs

$$M_h^2 = m_h^2 + \hat{v}^2 \hat{y}_t^4 \Big( 12 L \kappa_L - 192 \hat{g}_3^2 L^2 \kappa_L^2 \Big)$$

in terms of SUSY-scale MSSM parameters $\tilde{y}_t, \ldots$: e.g. SPheno, Softsusy/FlexibleSUSY

$$M_h^2 = m_h^2 + \tilde{v}^2 \tilde{y}_t^4 \Big( 12 L \kappa_L + 192 \tilde{g}_3^2 L^2 \kappa_L^2 \Big)$$

where $\tilde{y}_t$ can be determined in two ways

$$m_t^{\text{FS,SPheno}} = M_t + \Sigma_t^{(1)} \left( \left\{ \begin{array}{l} M_t{}^{\text{FS}} \\ m_t{}^{\text{SPheno}} \end{array} \right\} \right)$$

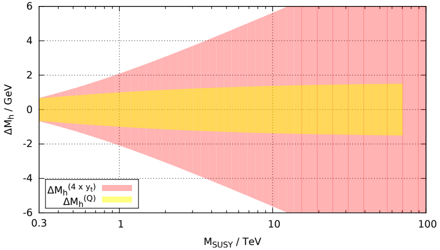
Compare

$$M_h^2 = m_h^2 + \hat{v}^2 \hat{y}_t^4 \left[ 12 L \kappa_L - 192 \hat{g}_3^2 L^2 \kappa_L^2 + 4 \hat{g}_3^4 L^3 \kappa_L^3 \left\{ \begin{array}{l} 0_{\text{FH}} \\ \frac{736}{3}\text{FS} \\ \frac{992}{3}\text{SPh} \\ 736_{\text{correct}} \end{array} \right\} + \cdots \right]$$

# Comments on uncertainty estimates

- very difficult in theories with many parameters
- important: clarify which types of missing terms are estimated

2-loop FO uncertainties [Athron,Park,Steudtner,DS,Voigt'16]:




FO scale variation: $\sim$ missing subleading logs, terms related to all parameters;
FO change Yukawa parametrization: $\sim$ missing leading logs related to $y_t$, missing $X_t$-terms

# Outline

# Remarks on EFT+RGE calculations

- Need $n$-loop matching, $n+1$-loop running
  1-loop [Casas et al '95]
  2-loop [Martin '07]
  3-loop [HSSUSY (Harlander et al)]
  3-loop hybrid [FlexibleEFTHiggs]
- typically neglects $v/M_{\text{SUSY}}$-terms at all orders; 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 ⇝impact negligible: [Bagnaschi,Vega,Slavich'17] ⇝ hybrid approach
- Can go beyond gaugeless limit more easily since $v/M_{\text{SUSY}}$ is neglected [Bagnaschi,Degrassi,Passehr,Slavich '19]
- Different parametrizations possible
  - technical subtleties and opportunities
  - full-model parametrization ⇝ $X_t$ resummation

# FlexibleEFTHiggs calculation ingredients

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 $\Sigma_t$, $\Sigma_h$

[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:

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

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.

# 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]

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Solution: need to consistently expand everything in terms of some parameter set and truncate at fixed order

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

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

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

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Correct option 2: Full model-parametrization
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$$\left[ \tilde{\Sigma}_h^{\text{SM}}((M_h^{\text{SM}})^2) \right]^{3\text{L}} = \left[ \tilde{\Sigma}_h^{\text{SM}}(0) \right]^{3\text{L}} + \sum_{n \cdot q + m = 3} \frac{\partial^n}{\partial P^n} \left[ \tilde{\Sigma}_h(0) \right]^{m-\text{L}} (\Delta P^{(q-\text{L})})^n$$

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

What's the point?

- difference is estimate of theory uncertainty
- 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 ("$\Delta m_b$ corrections" [Carena, Garcia, Nierste, Wagner'99...])

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

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

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

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Similarly we can prove that: *one-loop relation for $\lambda$ 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" e.g.

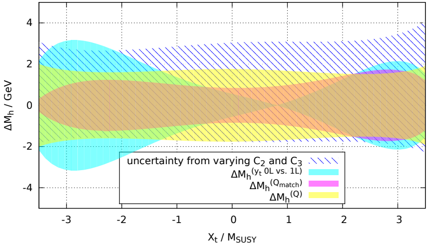
$$\alpha_t \alpha_g \alpha_s \hat{X}_t^3 \text{ (2L)},\ \alpha_t \alpha_g \alpha_s^2 \hat{X}_t^4 \text{ (3L)},\ \alpha_t^2 \alpha_s^3 \hat{X}_t^7 \text{ (4L)}$$

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

# Comments on uncertainty estimates

- very difficult in theories with many parameters
- important: clarify which types of missing terms are estimated

EFT+RGE (1-loop) uncertainties [Athron,Park,Steudtner,DS,Voigt'16]:




1-loop FEFTH

EFT matching scale variation: estimates missing h.o.-terms with UV divs ($\rightarrow$ misses $X_t$-terms) related to all couplings

EFT different parametrizations: estimates missing h.o.-terms related to specific parameters such as $X_t$

# 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]

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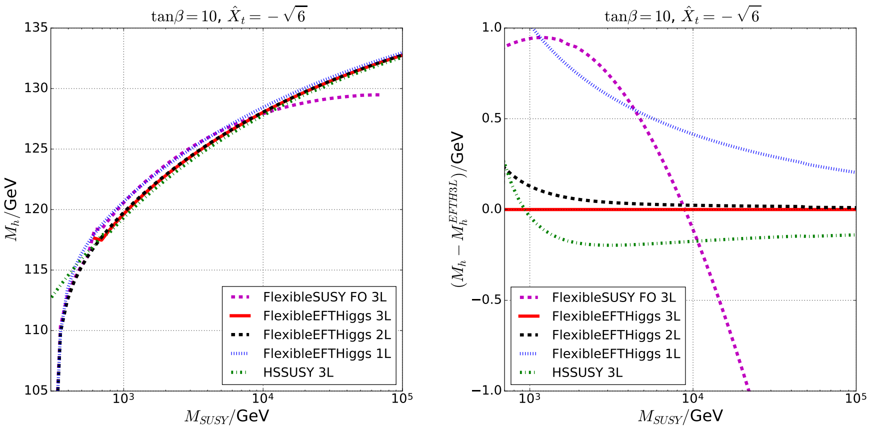
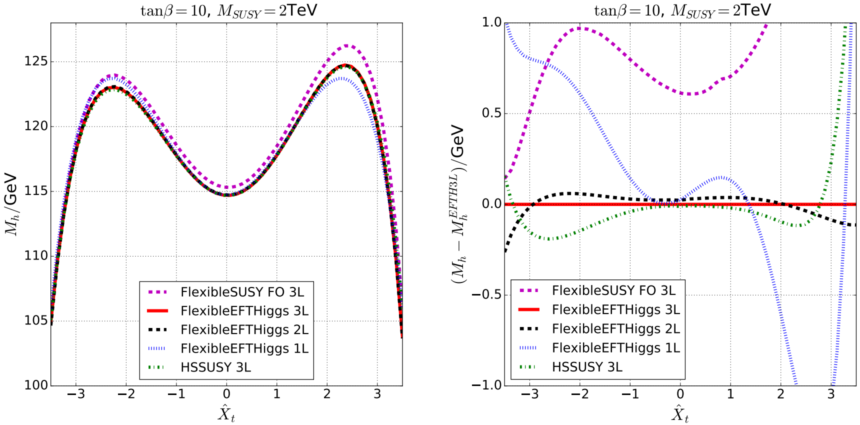


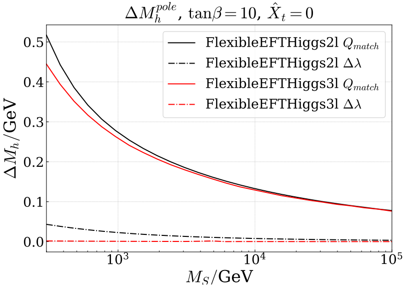

- fixed-order unreliable above 1 TeV
- pure EFT unreliable below 1 TeV
- hybrid reliable at all scales
- 1L*, 2L, 3L converges well * even better for 1L with full-model parametrization
- HSSUSY $\rightarrow \neq$ hybrid because of different parametrization/truncation

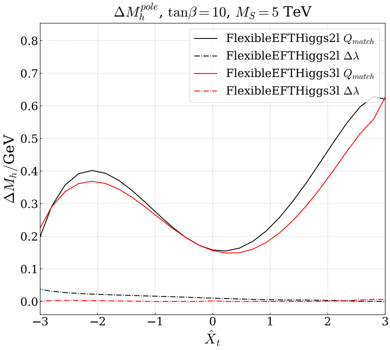



- matching corrections enhanced by $X_t$
- 1L*, 2L, 3L converges well   * even better for 1L with full-model parametrization
- HSSUSY and 1L* deviates at very large $X_t$ because of missing leading higher-order $X_t$-terms

# Uncertainty estimates

Preliminary result for 3-loop FlexibleEFTHiggs

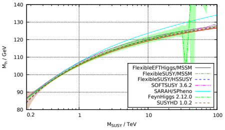


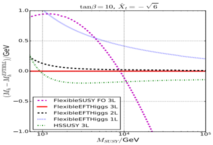

- uncertainty very small, does not shrink from 2L→3L
- Note: 3L was only $\mathcal{O}(y_t^4 \alpha_s^2)$—other types of terms now important

# Conclusions

- Huge recent progress in $M_h^{\mathrm{MSSM}}$
  - FO progress beyond 2-loop g-less limit
  - EFT+RGE/hybrid calculations available
  - FlexibleSUSY 3L codes: FO, HSSUSY, FlexibleEFTHiggs




- Many subtleties in EFT/hybrid codes
  - Parametrization in terms of EFT or full?
  - Double counting of logs?
  - Here: win-win situation! $\to X_t$-resummation!




- Uncertainty estimates
  - Clarify which missing terms are estimated!
  - scale variation? reparametrization? differences between codes?

- Outlook FlexibleEFTHiggs:
  - uncertainty analysis, nontrivial spectra
  - generalizable to other models