Update on large-log resummation in `FeynHiggs`

Henning Bahl

KUTS Madrid
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- EFT calculations allow to resum large logarithms
  $\rightarrow$ should be accurate for high SUSY scale M_{Susy}
- misses however terms $\propto v/M_{Susy}$
- diagrammatic calculation expected to be more accurate for low M_{Susy} ($\lesssim$ few TeV)

Goal

Combine both approaches to get precise results for both regimes.

`FeynHiggs` already contains full 1-loop and partial 2-loop results

$$\Downarrow$$

Double counting has to be avoided:
- ⇒ Subtract logarithms from the diagrammatic result
- ⇒ Subtract non-logarithmic terms from the EFT result

EFT calculation in $\overline{\text{MS}}/\overline{\text{DR}}$, diagrammatic calculation in OS:
- ⇒ Conversion $\overline{\text{MS}}/\overline{\text{DR}} \leftrightarrow$ OS is mandatory

$$\Downarrow$$

$$\begin{aligned} M_h^2 = &(M_h^2)^{\text{FD}} + (\Delta M_h^2)^{\text{EFT}}(X_t^{\overline{\text{DR}}}) \\ &- (\Delta M_h^2)^{\text{EFT,non-log}}(X_t^{OS}) - (\Delta M_h^2)^{\text{FD,Logs}}(X_t^{OS}) \end{aligned}$$

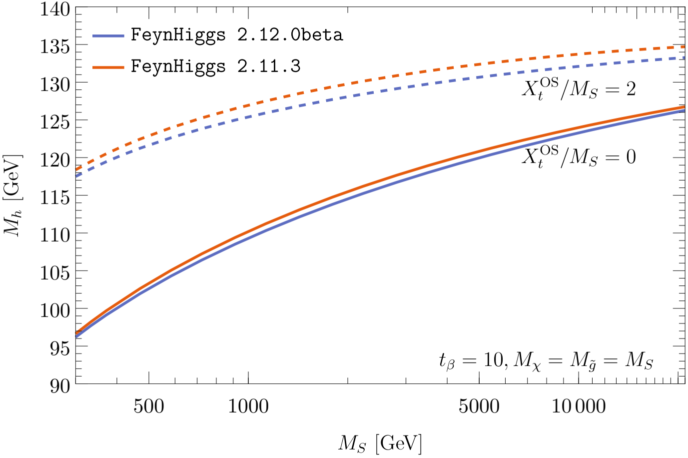
`FeynHiggs` resummation part - changelog

- `Version 2.10.0`:
  - LL+NLL resummation @ $\mathcal{O}(\alpha_s, \alpha_t)$ introduced
- `Version 2.11.3`:
  - NLO $\overline{\text{MS}}$ top mass ($\sim +1.8$ GeV)
  - Additional terms in $X_t^{\text{OS}} \to X_t^{\overline{\text{DR}}}$ (~ -1 GeV for $X_t/M_S = 2$)
- `Version 2.12.0 (new)`:
  - Full LL+NLL resummation (inclusive electroweak contributions)
  - EWino and gluino thresholds
  - NNLL resummation @ $\mathcal{O}(\alpha_s, \alpha_t)$
  - additonal terms in extraction of $\overline{\text{MS}}$ top mass/Yukawa coupling (inclusive electroweak corrections)

New resummation options controlled by new flag (not by `looplevel` anymore)

- `loglevel = 0`: no resummation
- `loglevel = 1`: $\mathcal{O}(\alpha_s, \alpha_t)$ LL+NLL
- `loglevel = 2`: full LL+NLL
- `loglevel = 3`: full LL+NLL and $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL

$\overline{\text{MS}}$ top mass (Yukawa coupling) automatically chosen accordingly



Main contribution → electroweak contributions to $\overline{\mathrm{MS}}$ top mass

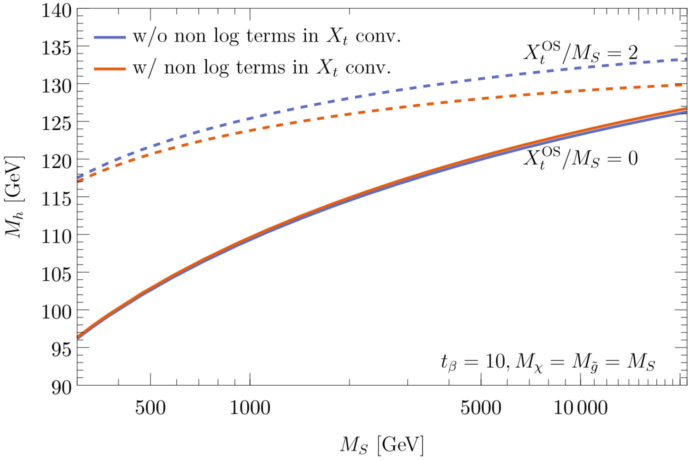
Changes in comparison to **KUTS Heidelberg**:

- EW corrections to $\overline{\text{MS}}$ top mass (Yukawa coupling)
- Changed $X_t^{\text{OS}} \to X_t^{\overline{\text{DR}}}$ conversion

Concept

Resum all logarithms in $\overline{\text{MS}}$ scheme of EFT and add it consistenly to diagrammatic result.

- To reproduce logs of diagrammatic result
  $\to$ 1L log terms in $X_t^{\text{OS}} \leftrightarrow X_t^{\overline{\text{DR}}}$ sufficient
  $\to$ M_S has not to be converted
- Non logarithmic terms, 2L terms, ... are omitted
  $\to$ in conversion, effects are of the order of unknown higher order corrections


w/o non log terms in X_t conv.
w/ non log terms in X_t conv.
$X_t^{\mathrm{OS}}/M_S = 2$
$X_t^{\mathrm{OS}}/M_S = 0$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
M_h [GeV]
M_S [GeV]
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- FeynHiggs
  $\rightarrow$ mixed OS/$\overline{\text{DR}}$ scheme
- other diagrammatic codes (SUSPECT, SoftSUSY, ...)
  $\rightarrow$ pure $\overline{\text{DR}}$ scheme
- EFT codes (SUSYHD, ...)
  $\rightarrow$ SUSY parameters in $\overline{\text{DR}}$ (i.e. X_t), rest in SM $\overline{\text{MS}}$

How to compare the different codes properly?

Two ways of comparison:

1. compare with $\overline{\text{DR}}$ input parameters
2. compare with OS input parameters

$\Rightarrow$ Conversion between $\overline{\text{DR}}$ and OS needed. But of which order?

Example 1

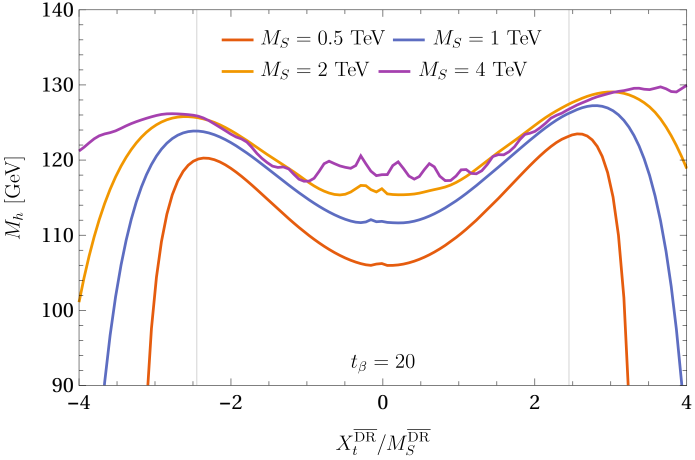
$\overline{\text{DR}}$ input parameters $\rightarrow$ compare 2L fixed-order calculations.

Most sensitive parameter: $X_t^{\overline{\mathrm{DR}}} \leftrightarrow X_t^{\mathrm{OS}}$

- X_t appears first at 1L order $\rightarrow$ 1L conversion is sufficient if comparing 2L fixed-order calculations

Use conversion routines built into `FeynHiggs`

- $\mathcal{O}(\alpha_s)$ (hep-ph/0105096), $\mathcal{O}(\alpha_t)$ (hep-ph/0112177), $\mathcal{O}(\alpha_b)$ (hep-ph/0206101)



- maxima expected at $\sim \pm\sqrt{6}$

Reason?

X_t conversion induces higher order terms, which shift maxima

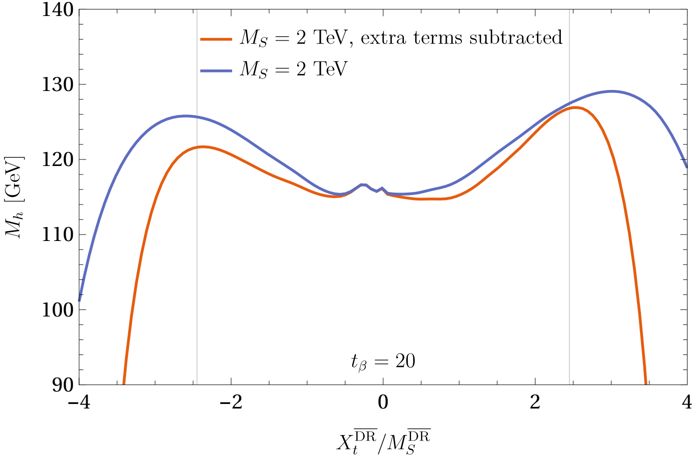
$$\hat{\Sigma}_{hh}(X_t^{\text{OS}}) = \hat{\Sigma}_{hh}^{(1)}(X_t^{\text{OS}}) + \hat{\Sigma}_{hh}^{(2)}(X_t^{\text{OS}})$$

$$\text{with } X_t^{\text{OS}} = X_t^{\overline{\text{DR}}} + \delta X_t \text{ yields}$$

$$= \underbrace{\hat{\Sigma}_{hh}^{(1)}(X_t^{\overline{\text{DR}}}) + \hat{\Sigma}_{hh}^{(2)}(X_t^{\overline{\text{DR}}}) + \left(\frac{\partial}{\partial X_t^{\text{OS}}}\hat{\Sigma}_{hh}^{(1)}\right)(X_t^{\overline{\text{DR}}}) \cdot \delta X_t}_{=\tilde{\Sigma}_{hh}^{(1)}(X_t^{\overline{\text{DR}}})+\tilde{\Sigma}_{hh}^{(2)}(X_t^{\overline{\text{DR}}})=\overline{\text{DR}}\text{ result}}$$

$$\underbrace{+\frac{1}{2}\left(\frac{\partial^2}{\partial^2 X_t^{\text{OS}}}\hat{\Sigma}_{hh}^{(1)}\right)(X_t^{\overline{\text{DR}}}) \cdot (\delta X_t)^2 + \ldots}_{\text{extra terms not present in pure }\overline{\text{DR}}\text{ calculation}}$$

Extra terms get significant for high M_S → subtract them



Case 2

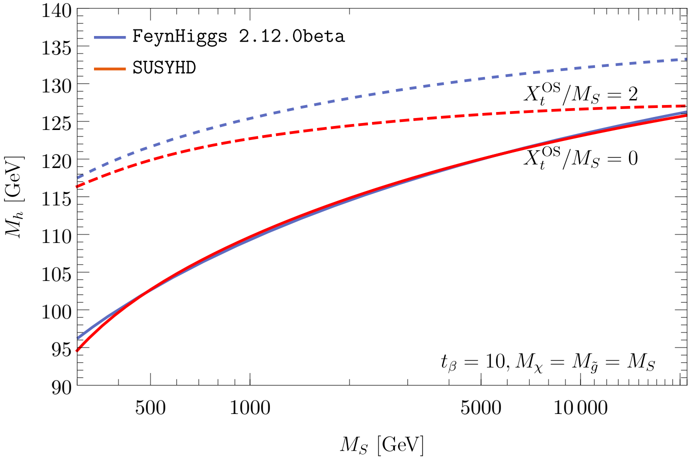
OS input parameters → compare 2L fixed-order calculations.

- same problem arises

With resummation: `FeynHiggs` vs. `SUSYHD` with OS input

How to get proper $\overline{\text{DR}}$ input for `SUSYHD`?

1. $X_t^{\text{OS}} \to X_t^{\overline{\text{DR}}}$ using full 1L conversion


FeynHiggs 2.12.0beta
SUSYHD
$X_t^{OS}/M_S = 2$
$X_t^{OS}/M_S = 0$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
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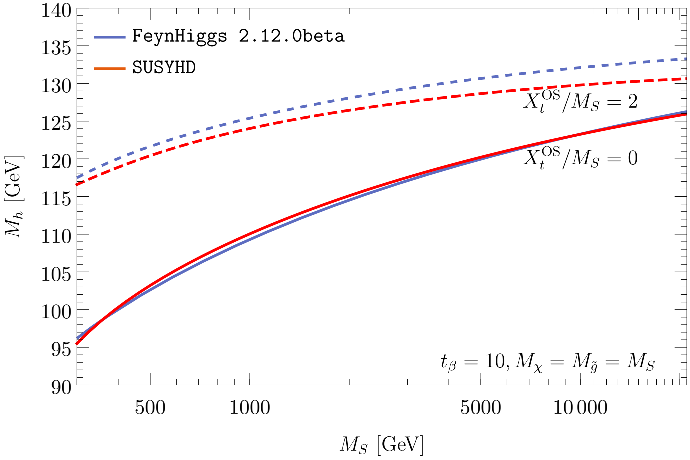
With resummation: `FeynHiggs` vs. `SUSYHD` with OS input

How to get proper $\overline{\text{DR}}$ input for `SUSYHD`?

1. $X_t^{\text{OS}} \to X_t^{\overline{\text{DR}}}$ using full 1L conversion
   - Different $X_t^{\overline{\text{DR}}}$ used as input for RGE procedure
     → large 3L terms induced in `SUSYHD`
2. $X_t^{\text{OS}} \to X_t^{\overline{\text{DR}}}$ using 1L conversion excluding non-log terms
   - missing non-logarithmic 2L terms in `SUSYHD`
     → add them by hand


FeynHiggs 2.12.0beta
SUSYHD
$X_t^{\mathrm{OS}}/M_S = 2$
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FeynHiggs

Full momentum dependence of 1L self-energies included

Determine pole mass by solving

$$\left(p^2 - m_h^2 + \hat{\Sigma}_{hh}(p^2)\right)\left(p^2 - m_H^2 + \hat{\Sigma}_{HH}(p^2)\right) - \left(\hat{\Sigma}_{hH}(p^2)\right)^2 = 0$$

For $M_A \gg M_Z$ by solving

$$p^2 - m_h^2 + \hat{\Sigma}_{hh}^{(1)}(p^2) + \hat{\Sigma}_{hh}^{(2)}(0) = 0.$$

Solve iteratively

$$M_h^2 = m_h^2 - \hat{\Sigma}_{hh}^{(1)}(m_h^2) - \hat{\Sigma}_{hh}^{(2)}(0) + \underbrace{\hat{\Sigma}_{hh}^{(1)}(m_h^2) \cdot \hat{\Sigma}_{hh}^{(1)\prime}(m_h^2)}_{\text{induced by } p^2 \text{ dependence of 1L self-energy}}$$

Are momentum dependent terms included in pure EFT calculations?

Explicit comparison:

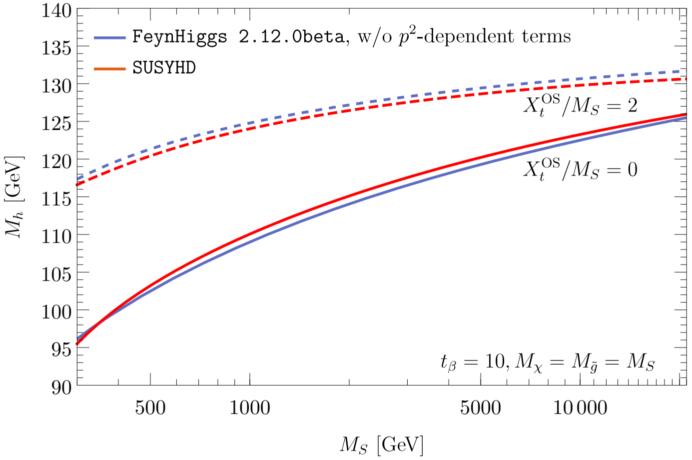
$$2\text{L } \mathcal{O}(\alpha_t^2) \text{ effective potential result} + \hat{\Sigma}_{hh}^{(1)}(0) \cdot \hat{\Sigma}_{hh}^{(1)\prime}(0)$$

(hep-ph/0003246)

$$\updownarrow$$

pure EFT result (2L running, 1L matching)

$\Rightarrow$ EFT gets same result


FeynHiggs 2.12.0beta, w/o p^2-dependent terms
SUSYHD
$X_t^{OS}/M_S = 2$
$X_t^{OS}/M_S = 0$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
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Issue discussed at KUTS Heidelberg

Lightest Higgs 4-point self-coupling:

$$\lambda_{\text{THDM}} = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5) c_\beta^2 s_\beta^2 + 4\lambda_6 c_\beta^3 s_\beta + 4\lambda_7 c_\beta s_\beta^3$$

Stop threshold corrections:

$$\Rightarrow \Delta_{\tilde{t}} \lambda_{\text{THDM}} = \Delta_{\tilde{t}}^{\text{Ver}} \lambda_1 c_\beta^4 + \Delta_{\tilde{t}}^{\text{Ver}} \lambda_2 s_\beta^4 + 2\Delta_{\tilde{t}}(\lambda_3 + \lambda_4 + \lambda_5) c_\beta^2 s_\beta^2 + 4\Delta_{\tilde{t}} \lambda_6 c_\beta^3 s_\beta + 4\Delta_{\tilde{t}} \lambda_7 c_\beta s_\beta^3$$

In the case $M_A = M_S$ we should recover threshold corrections of SM $\leftrightarrow$ MSSM.

$M_A \to M_S$ provides test of threshold corrections

$$\Delta_{\tilde{t}} \lambda_{\text{THDM}} \stackrel{!}{=} \Delta_{\tilde{t}} \lambda_{\text{SM}}$$

$\rightarrow$ naive calculation yields that condition is not fullfilled

Solved! (→ thanks to Pietro Slavich and Carlos Wagner)

Solution

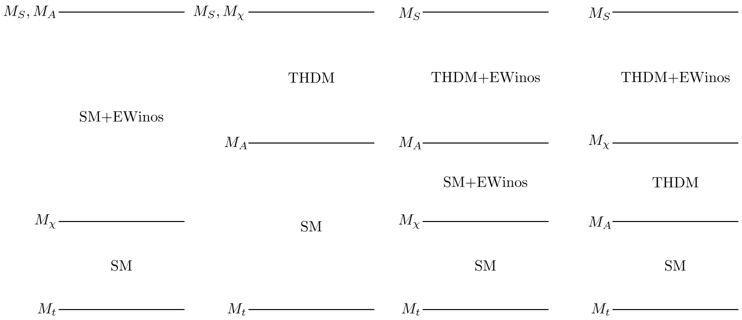
Also $\tan\beta$ gets treshold correction, i.e. $\beta_{\text{THDM}} \neq \beta_{\text{MSSM}}$.

For matching of derivative of 2-point function, fields have to be rescaled

$$\Phi_i^{\text{THDM}} = \left(1 + \frac{1}{2}\Sigma'_{ii}\right)\Phi_i^{\text{MSSM}} + \frac{1}{2}\Sigma'_{ij}\Phi_j^{\text{MSSM}}$$

$$\Rightarrow \beta^{\text{THDM}} = \beta^{\text{MSSM}} - \frac{1}{2}\Sigma'_{hH,\text{heavy}}(0) =$$
$$= \beta^{\text{MSSM}} + \frac{1}{4}kh_t^2 s_{2\beta}(\hat{A}_t - \hat{\mu}/t_\beta)(\hat{A}_t + \hat{\mu}t_\beta)$$

Low M_A extension of `FeynHiggs`



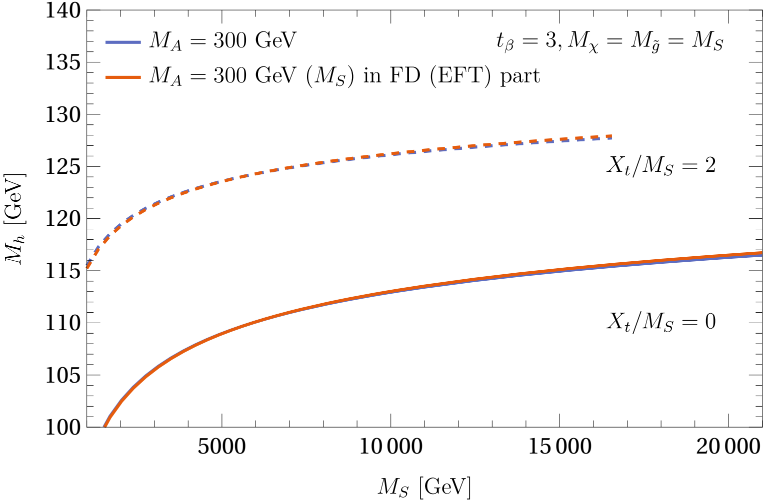
- Full dependence on effective couplings (thresholds and 2L RGEs)

- Running from M_S to $M_A \to \Delta\hat{\Sigma}_{11}, \Delta\hat{\Sigma}_{12}, \Delta\hat{\Sigma}_{22}$, e.g.

$$\Delta\hat{\Sigma}_{11} = v^2 \left(3\lambda_1 c_\beta^2 + (\lambda_3 + \lambda_4 + \lambda_5) s_\beta^2 + 6\lambda_6 s_\beta c_\beta\right) (Q = M_A)$$
$$- \text{1L,2L subtraction terms}$$

- Running from M_A to $m_t \to \Delta\hat{\Sigma}_{22} = \lambda(m_t) v^2 / s_\beta^2$ (as in high M_A case)
- still issue with definition of t_β: $\underbrace{t_\beta^{\text{MSSM}}(m_t)}_{\text{FH}} \leftrightarrow \underbrace{t_\beta^{\text{MSSM}}(M_S) \leftrightarrow t_\beta^{\text{THDM}}(M_A)}_{\text{EFT}}$
- so far: 1L running (also below $Q = M_A$ without thresholds)

First results (very preliminary)



`FeynHiggs 2.12.0`

- Full LL+NLL and $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation
- Downwards shift of ~ 1.5 GeV for $\hat{X}_t = 2$ in comparison to `FeynHiggs 2.11.3`

Comparison to other codes

- Simple 1L conversion between schemes
  $\rightarrow$ large discrepancies at high scales
- Alternative conversion and p^2 dependent terms have sizeable impact

Low M_A scenario

- First results seem to indicate neglible effects
- Issue with proper definition of $\tan\beta$

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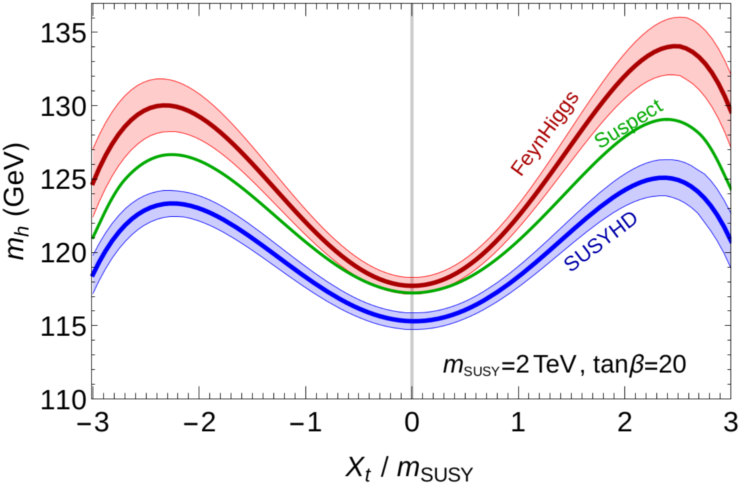
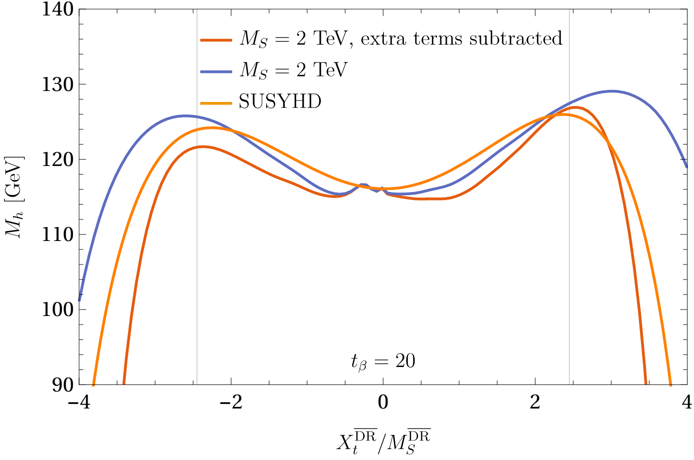
Conversion:

- X_t has to be converted respecting also non-logarithmic terms ($\propto \alpha_s, \alpha_t$) Espinosa & Zhang (2000)
- now also M_S has to be converted
- conversion of M_χ can be neglected

$\Rightarrow$ New subtraction terms needed:

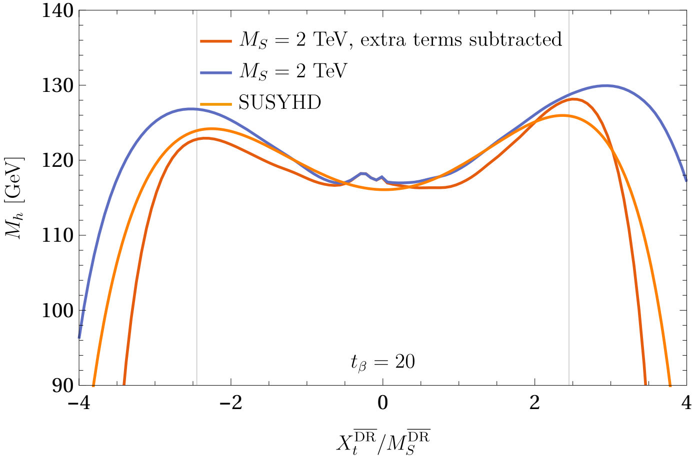
- subtract non-log terms generated by conversion of 1-loop threshold corrections
- subtract non-log terms originating from 2-loop threshold correction


135
130
125
120
115
110
m_h (GeV)
−3
−2
−1
0
1
2
3
X_t / m_{SUSY}
FeynHiggs
Suspect
SUSYHD
m_{SUSY}=2 TeV , tanβ=20



Note: no resummation for `FeynHiggs` curve used

With FeynHiggs $\mathcal{O}(\alpha_s, \alpha_t)$ LL+NLL resummation:



Stop-sector vertex corrections ($h_t = y_t/s_\beta$)

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_1 = -\frac{1}{2}kh_t^4\hat{\mu}^4 + \frac{3}{4}k\left(g^2+g'^2\right)h_t^2\hat{\mu}^2$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_2 = 6kh_t^4\hat{A}_t^2\left(1-\frac{1}{12}\hat{A}_t^2\right) - \frac{3}{4}k\left(g^2+g'^2\right)h_t^2\hat{A}_t^2$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_3 = \frac{1}{2}kh_t^4\hat{\mu}^2\left(3-\hat{A}_t^2\right) - \frac{3}{8}k\left(g^2-g'^2\right)h_t^2\left(\hat{A}_t^2-\hat{\mu}^2\right)$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_4 = \frac{1}{2}kh_t^4\hat{\mu}^2\left(3-\hat{A}_t^2\right) + \frac{3}{4}kg^2h_t^2\left(\hat{A}_t^2-\hat{\mu}^2\right)$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_5 = -\frac{1}{2}kh_t^4\hat{\mu}^2\hat{A}_t^2$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_6 = \frac{1}{2}kh_t^4\hat{\mu}^3\hat{A}_t - \frac{3}{8}k(g^2+g'^2)h_t^2\hat{\mu}\hat{A}_t$$

$$\Delta_{\tilde{t}}^{\rm Ver}\lambda_7 = \frac{1}{2}kh_t^4\hat{\mu}\hat{A}_t\left(\hat{A}_t^2-6\right) + \frac{3}{8}k(g^2+g'^2)h_t^2\hat{\mu}\hat{A}_t$$

Terms in red not present in Cheung et. al. (2015) and Lee & Wagner (2015), but in Haber & Hempfling (1993)

Lightest Higgs 4-point self-coupling:

$$\lambda_{\text{THDM}} = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5) c_\beta^2 s_\beta^2 + 4\lambda_6 c_\beta^3 s_\beta + 4\lambda_7 c_\beta s_\beta^3$$

$$\Rightarrow \Delta_{\tilde{t}}^{\text{Ver}} \lambda_{\text{THDM}} = \Delta_{\tilde{t}}^{\text{Ver}} \lambda_1 c_\beta^4 + \Delta_{\tilde{t}}^{\text{Ver}} \lambda_2 s_\beta^4 + 2\Delta_{\tilde{t}}^{\text{Ver}} (\lambda_3 + \lambda_4 + \lambda_5) c_\beta^2 s_\beta^2 + 4\Delta_{\tilde{t}}^{\text{Ver}} \lambda_6 c_\beta^3 s_\beta + 4\Delta_{\tilde{t}}^{\text{Ver}} \lambda_7 c_\beta s_\beta^3$$

In the case $M_A = M_S$ ($X_t = A_t - \mu/t_\beta$):

$$\Delta_{\tilde{t}}^{\text{Ver}} \lambda_{\text{SM}} = 6k y_t^2 \left\{ \left(y_t^2 + \frac{1}{8} \left(g^2 + g'^2 \right) c_{2\beta} \right) \hat{X}_t^2 - \frac{1}{12} y_t^2 \hat{X}_t^4 \right\}$$

$M_A \to M_S$ provides test of threshold corrections

$$\Delta_{\tilde{t}}^{\text{Ver}} \lambda_{\text{THDM}} \overset{!}{=} \Delta_{\tilde{t}}^{\text{Ver}} \lambda_{\text{SM}}$$

$\to$ only fullfilled if red terms are included

Higgs wavefunction renormalization:

- again Cheung et. al. (2015), Lee & Wagner (2015) $\neq$ Haber & Hempfling (1993)
- $\Delta_{\tilde{t}}^{\text{WFR}}\lambda_{\text{SM}} = -\frac{1}{4}y_t^2(g^2 + g'^2)c_{2\beta}^2\hat{X}_t^2$
- none of the results yields SM correction
- also $\Delta_{\tilde{t}}^{\text{Ver}}\lambda_{\text{SM}} + \Delta_{\tilde{t}}^{\text{WFR}}\lambda_{\text{SM}} \overset{!}{=} \Delta_{\tilde{t}}^{\text{Ver}}\lambda_{\text{THDM}} + \Delta_{\tilde{t}}^{\text{WFR}}\lambda_{\text{THDM}}$ (for $M_A \to M_S$) not fullfilled