Update on resummation in FeynHiggs

Henning Bahl
work in collaboration with Wolfgang Hollik

Max-Planck-Institut für Physik, München

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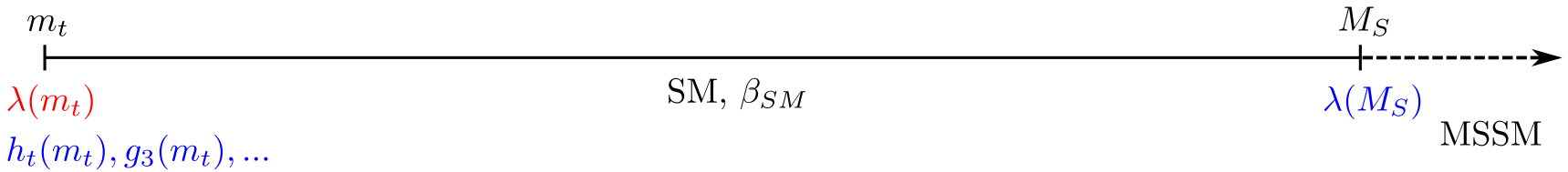


- EFT calculations allow to resum large logarithms
  $\rightarrow$ should be accurate for high stop mass scale M_S
- Misses however terms $\propto v/M_S$
- Diagrammatic calculation expected to be more accurate for low M_S ($\lesssim$ few TeV)
- Diagrammatic approach $\rightarrow$ full control over Higgs self-energies (decays, production,..)

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
- Only 1L log terms in X_t conversion needed to reproduce 1- and 2-loop logs in diagrammatic result
  $\rightarrow$ restrict conversion to 1L log terms
- non-log or higher order terms
  $\rightarrow$ unknown higher order corrections

So far: LL+NLL resummation of $\mathcal{O}(\alpha_s, \alpha_t)$

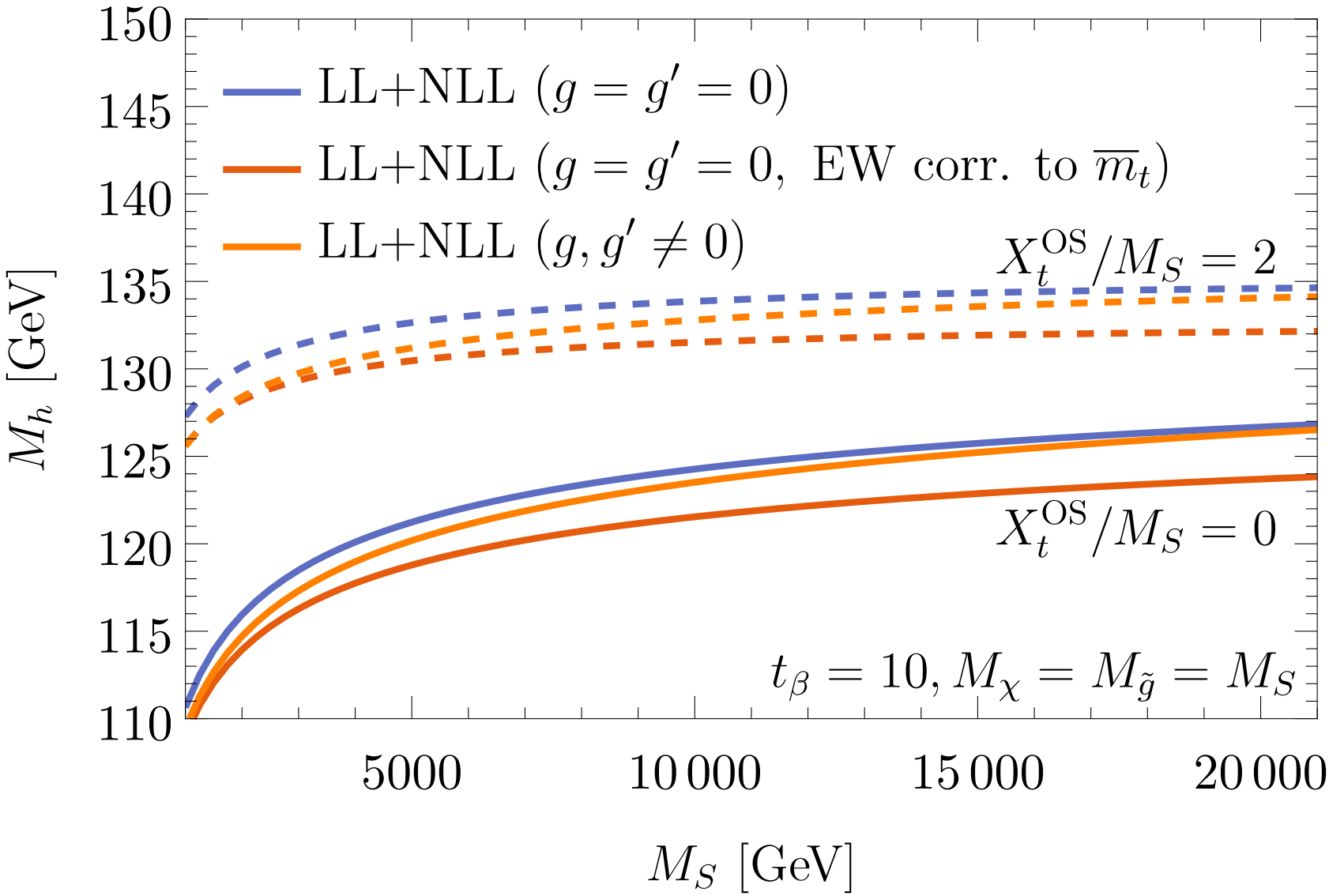
First improvement

Implementation of full LL+NLL resummation including electroweak contributions.

- Full SM 2L RGEs
- Full 1L thresholds [1108.6077,1407.4081]

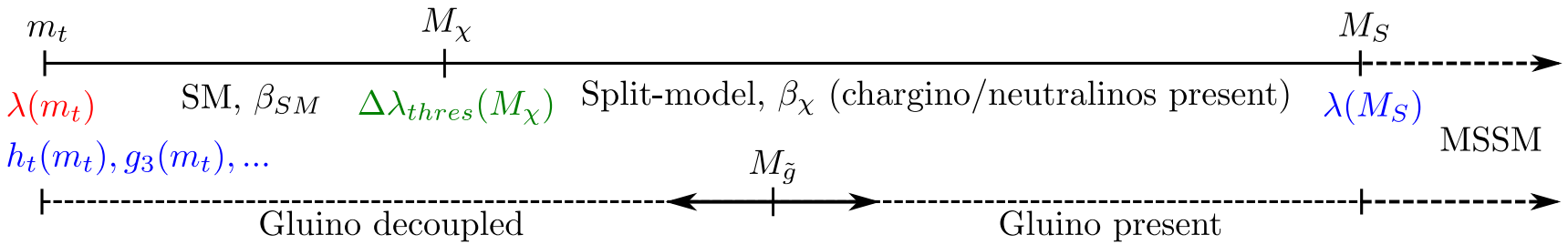
$$\Delta\lambda(M_S) = \Delta_{\text{stop}}\lambda + \Delta_{\text{heavyH}}\lambda + \Delta_{\text{EWino}}\lambda + \Delta_{\overline{\text{DR}}\to\overline{\text{MS}}}\lambda$$

- Avoid double-counting of 1L electroweak logarithms
- Include EW corrections into matching of top Yukawa coupling / $\overline{\text{MS}}$ top mass

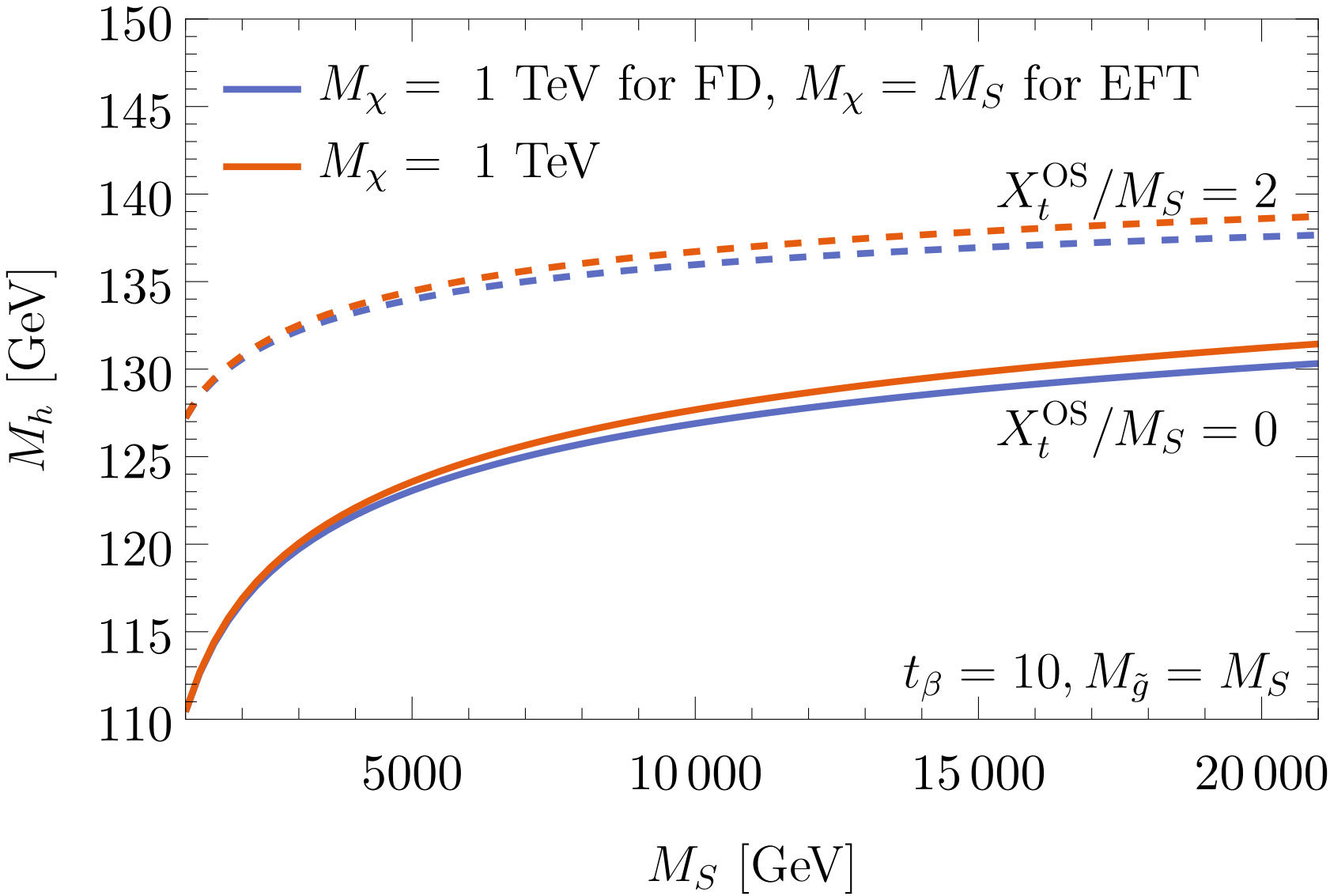

150
145
140
135
130
125
120
115
110
M_h [GeV]
LL+NLL $(g = g' = 0)$
LL+NLL $(g = g' = 0,$ EW corr. to $\overline{m}_t)$
LL+NLL $(g, g' \neq 0)$
$X_t^{\rm OS}/M_S = 2$
$X_t^{\rm OS}/M_S = 0$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
5000
10 000
15 000
20 000
M_S [GeV]

Second improvement

Implementation of electroweakino and gluino thresholds



- $M_\chi = M_1 = M_2 = \mu$ assumed
- EFTs:
  SM+EWino [1108.6077,1407.4081], SM+Gluino,
  SM+EWino+Gluino
- Resums $\ln(M_\chi^2/m_t^2)$



- Gluino threshold negligible (effects $\lesssim 20$ MeV)

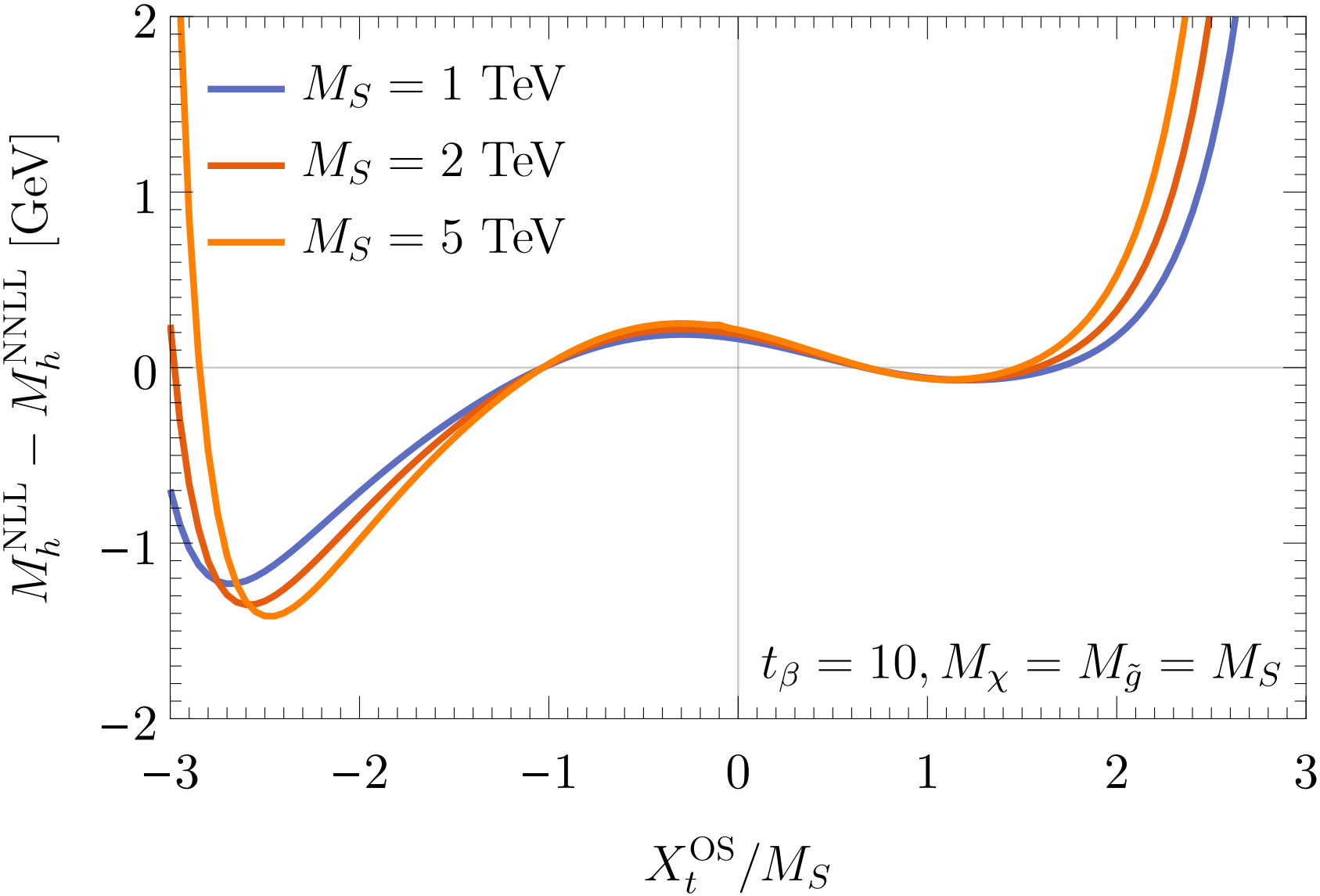
Third improvement

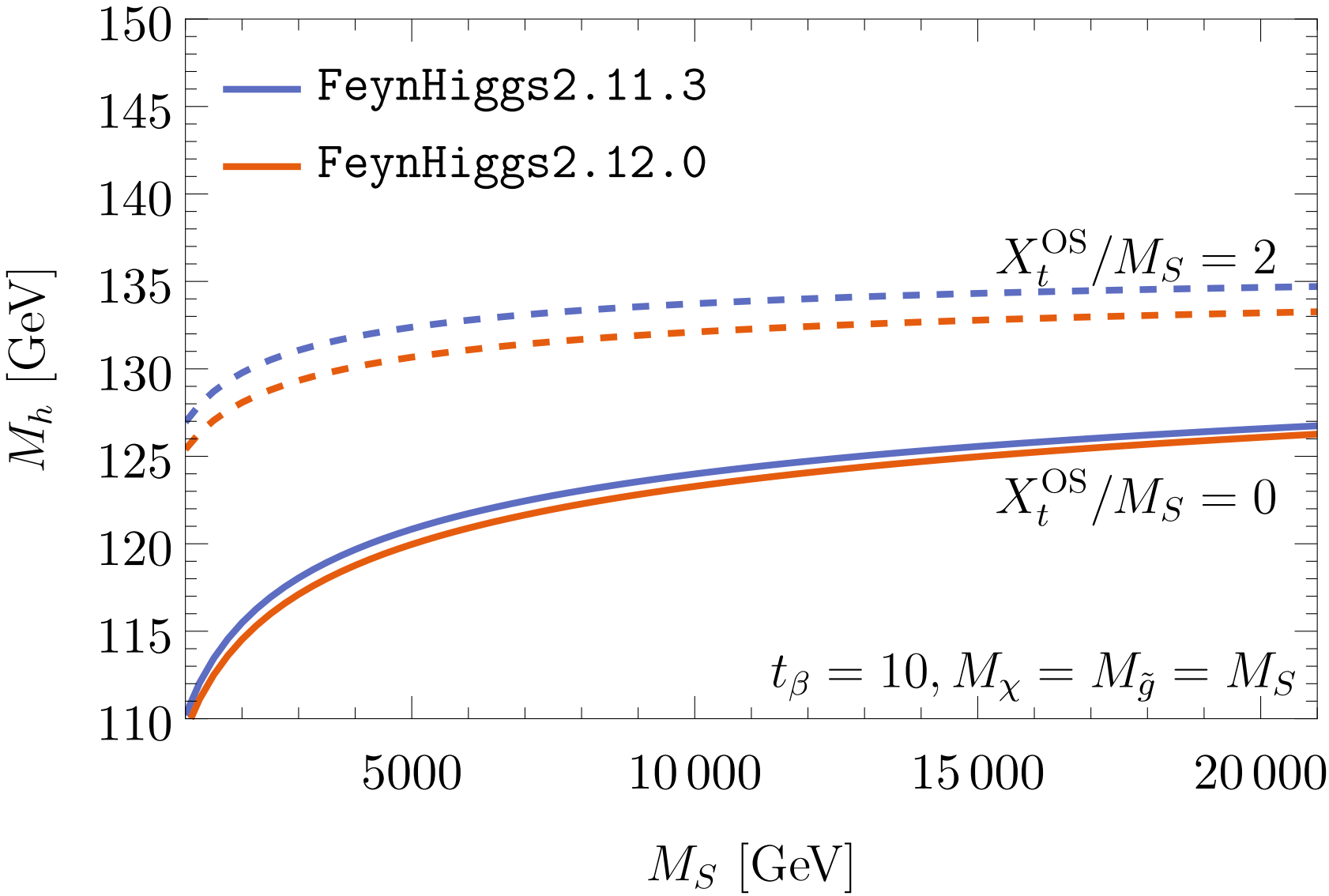
Implementation of NNLL resummation at $\mathcal{O}(\alpha_s, \alpha_t)$

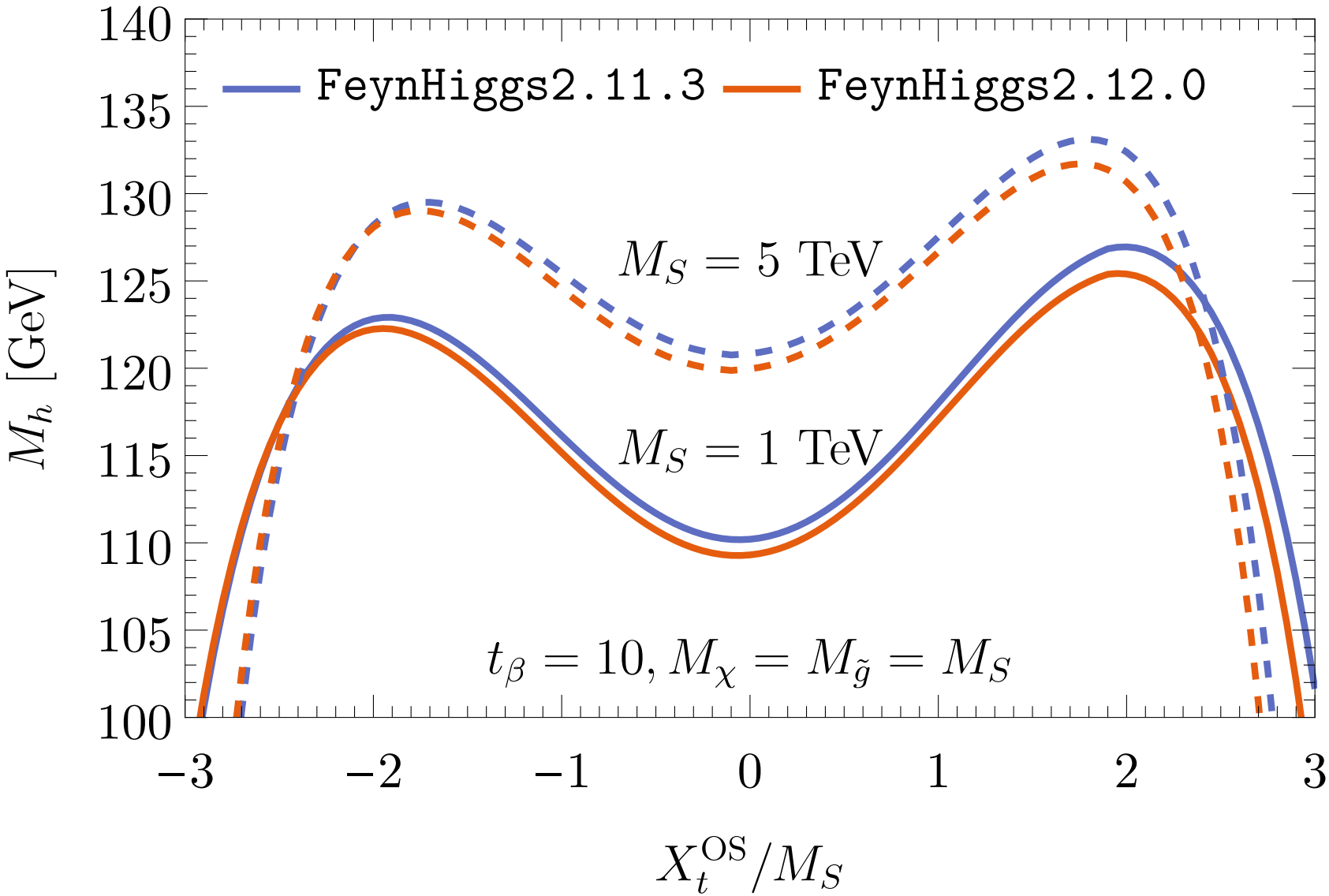
- 2L $\mathcal{O}(\alpha_s, \alpha_t)$ thresholds [1312.5743,1407.4081,1504.05200]

$$\Delta\lambda(M_S) = \Delta_{1L}\lambda + \Delta\lambda_{\alpha_s\alpha_t} + \Delta\lambda_{\alpha_t^2}$$

- 3L SM RGEs [1201.5868,1205.2892,...]
- restricted to $M_{\tilde{g}} = M_S$
- $\mathcal{O}(\alpha_s^2)$ corrections to top Yukawa coupling / top $\overline{\text{MS}}$ mass already included in `FeynHiggs 2.11.3`


$M_S = 1$ TeV
$M_S = 2$ TeV
$M_S = 5$ TeV
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
$M_h^{\rm NLL} - M_h^{\rm NNLL}$ [GeV]
$X_t^{\rm OS}/M_S$
2
1
0
−1
−2
−3
−2
−1
0
1
2
3


FeynHiggs2.11.3
FeynHiggs2.12.0
$X_t^{\rm OS}/M_S = 2$
$X_t^{\rm OS}/M_S = 0$
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
M_h [GeV]
M_S [GeV]
150
145
140
135
130
125
120
115
110
5000
10 000
15 000
20 000


FeynHiggs2.11.3
FeynHiggs2.12.0
$M_S = 5$ TeV
$M_S = 1$ TeV
$t_\beta = 10, M_\chi = M_{\tilde{g}} = M_S$
M_h [GeV]
$X_t^{\rm OS}/M_S$
140
135
130
125
120
115
110
105
100
−3
−2
−1
0
1
2
3

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

Pure EFT calculations

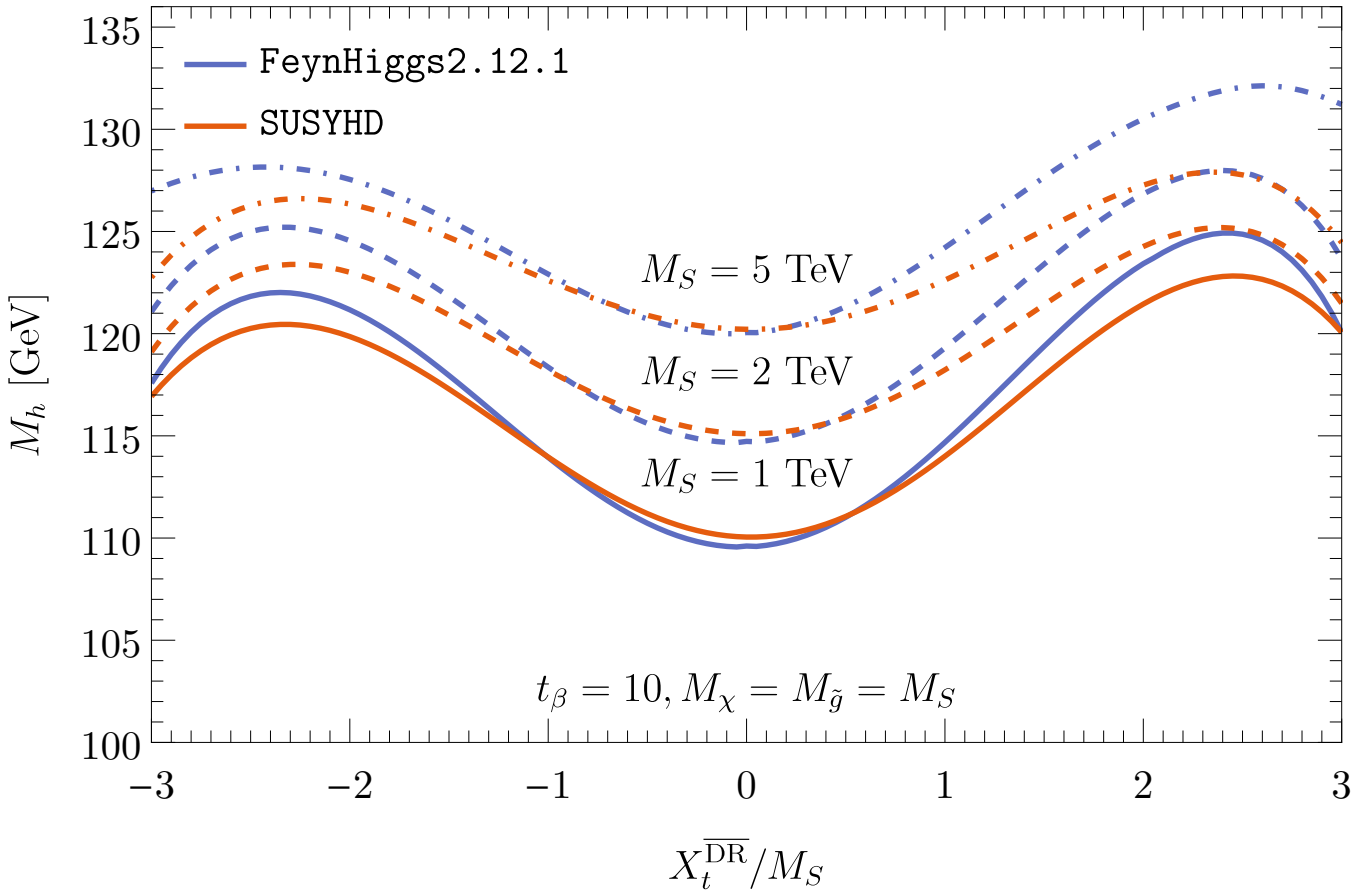
Expected to be accurate for high M_S

- `SUSYHD` is taken as example

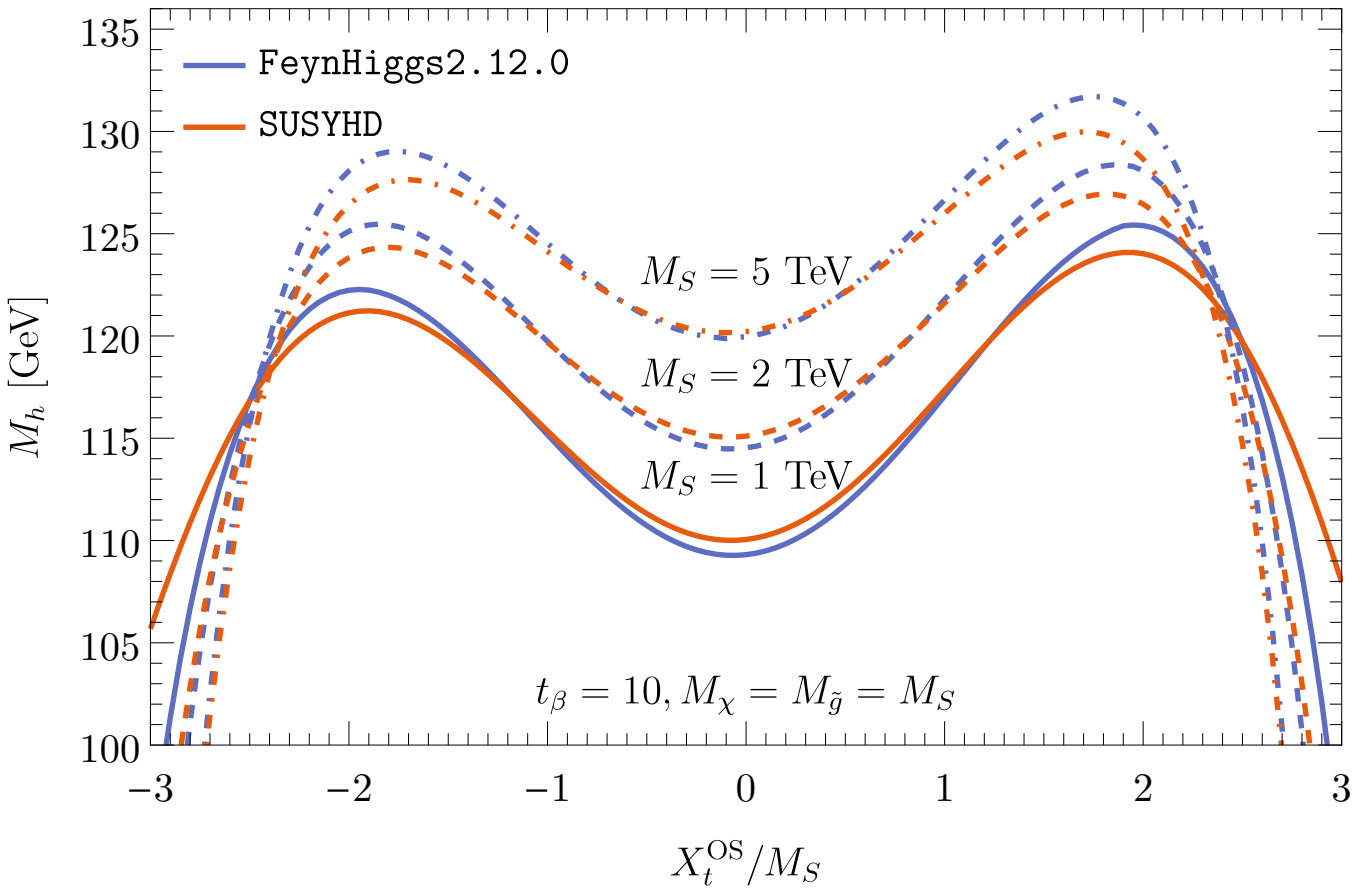
`FeynHiggs` vs. `SUSYHD`

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

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



- Different $X_t^{\overline{\rm DR}}$ in EFT calculation $\rightarrow$ different $\lambda(m_t)$
- Non-log terms in conversion induce higher-order terms, which can be significant for high $|X_t/M_S|$ ($\rightarrow$ 3L)



- Same $X_t^{\overline{\rm DR}}$ in EFT calculation $\rightarrow$ very similar $\lambda(m_t)$
- Missing 2L terms have to be added by hand
- Remaining differences: suppressed terms, p^2-dependence, ...

`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 pure EFT calculation (`SUSYHD`)

- Highly dependent on X_t conversion
- Agreement within 2 GeV for $M_S \lesssim 5$ TeV

Things to come soon:

- Improvements in $\overline{\text{DR}} \leftrightarrow$ OS conversion
- Stability fixes for high M_S
- Updated error estimate

Things to come later:

- `FeynHiggs` for NMSSM
- Diagrammatic $\mathcal{O}(\alpha_s \alpha)$ and $\mathcal{O}(\alpha_t \alpha_b, \alpha_b^2)$ (complex parameters) corrections
- Resummation in low M_A scenario

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:

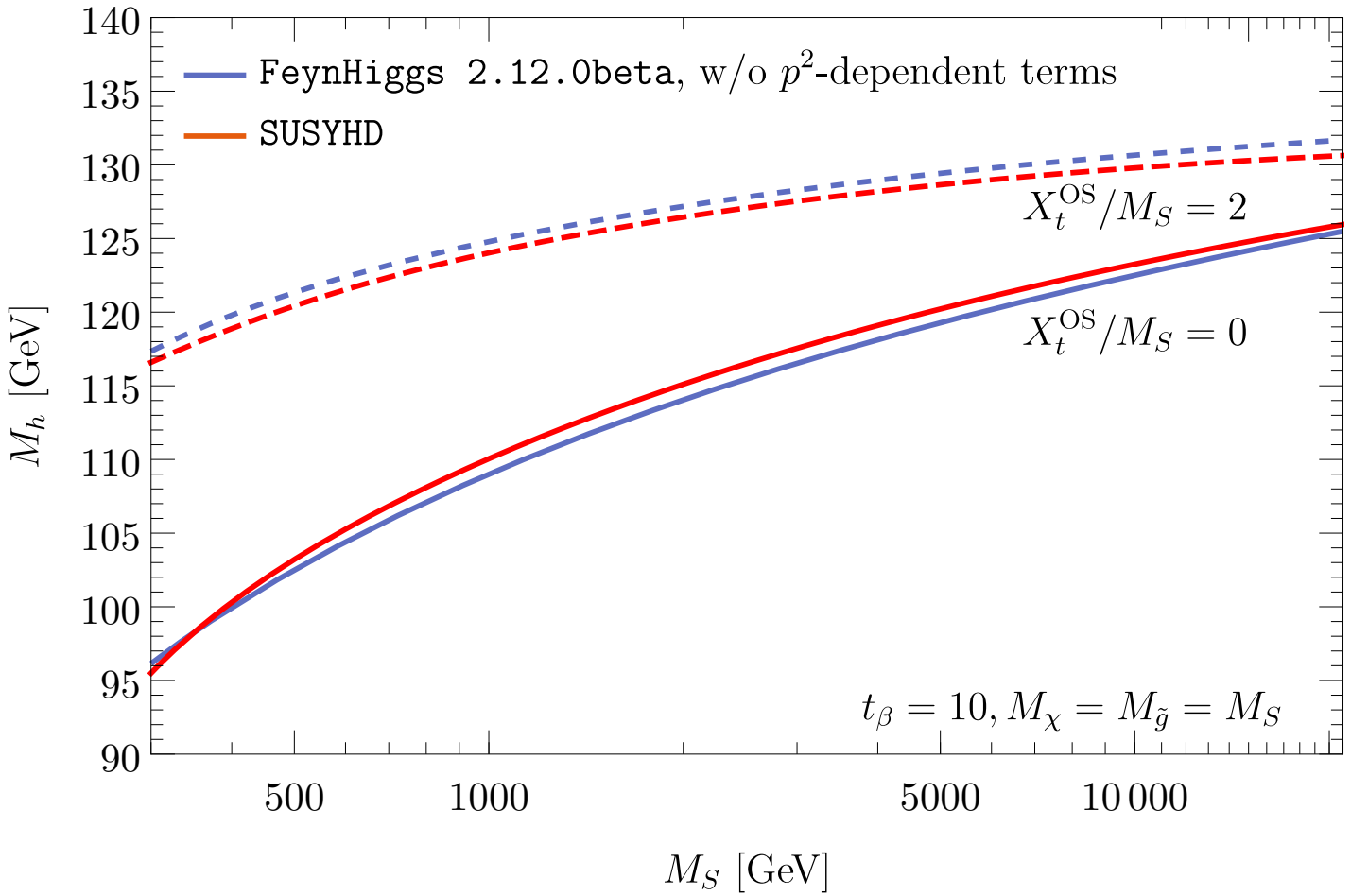
$$\text{2L } \mathcal{O}(\alpha_t^2) \text{ effective potential result} + \hat{\Sigma}^{(1)}_{hh}(0) \cdot \hat{\Sigma}^{(1)\prime}_{hh}(0)$$

(hep-ph/0003246)

$$\updownarrow$$

$$\text{pure EFT result (2L running, 1L matching)}$$

$\Rightarrow$ EFT gets same result


FeynHiggs 2.12.0beta, w/o p^2-dependent terms
SUSYHD
$X_t^{\rm OS}/M_S = 2$
$X_t^{\rm OS}/M_S = 0$
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