Resummation for low M_A & uncertainty estimates

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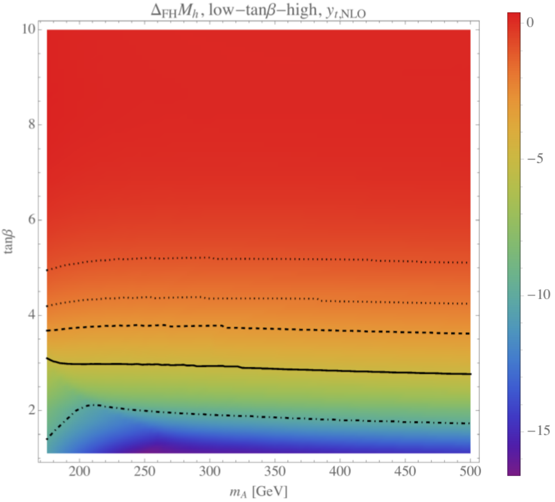
Low M_A: Current status

Resummation routines built into `FH` assume $M_A = M_{\text{SUSY}}$
$\rightarrow$ what if $M_{\text{SUSY}} \gg M_t$ but $M_A \sim M_t$?

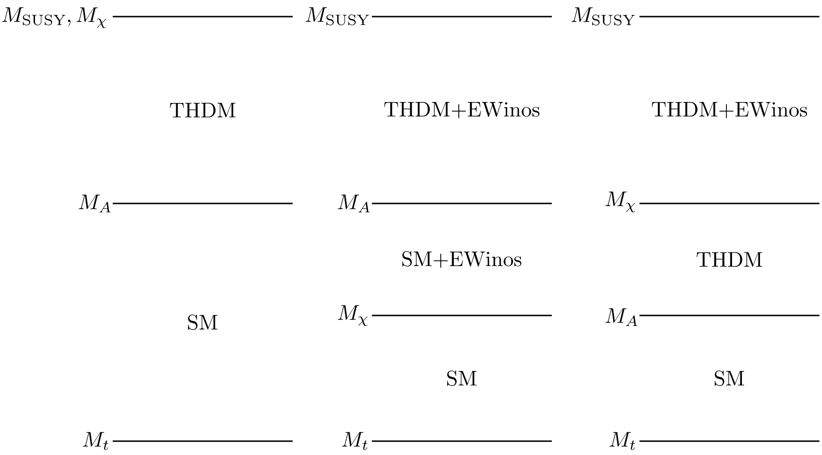
- Need to consider effective THDM for correct resummation
- Haber & Hempfling (1993), Lee & Wagner (2015), ...

Low-tanb-high scenario



$\mu = 1.5$ TeV, $M_2 = 2$ TeV, $A_{b,..} = 2$ TeV, M_{SUSY} and X_t chosen to get $M_h = 125$ GeV

EFTs for low M_A



+ gluino threshold (not shown), $M_\chi \sim M_1, M_2, \mu$

EFT calculation

- all possible hierarchies taken into account
  - THDM type III $\rightarrow$ 12 effective couplings $(\lambda_{1..7}, h_t, h_t')$
  - THDM type III + EWinos $\rightarrow$ 20 effective couplings $(\lambda_{1..7}, h_t, h_t'$ + gaugino-Higgsino-Higgs couplings)
- full 2L running for all effective couplings (RGEs via `SARAH`)
- full 1L threshold corrections for all effective couplings
- $\mathcal{O}(\alpha_s\alpha_t)$ threshold corrections for λ_i's

Matching to fixed order calculation

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

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

- Running from M_A to $M_t \to \Delta\hat{\Sigma}_{22} = \lambda(m_t) v^2 / c_\alpha^2$ (as done for $M_A = M_{\text{SUSY}}$)

Matching to fixed order calculation II

Normalization of Higgs doublets

MSSM and THDM Higgs doublets have not the same normalization

- LSZ theorem yields (at the 1L level)

$$\begin{pmatrix} \Phi_1^{\text{THDM}} \\ \Phi_2^{\text{THDM}} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 + \frac{1}{2}\Delta\Sigma'_{11} & \frac{1}{2}\Delta\Sigma'_{12} \\ \frac{1}{2}\Delta\Sigma'_{12} & 1 + \frac{1}{2}\Delta\Sigma'_{22} \end{pmatrix}}_{=U_{\Delta\Phi}} \begin{pmatrix} \Phi_1^{\text{MSSM}} \\ \Phi_2^{\text{MSSM}} \end{pmatrix}$$

with $\Delta\Sigma'_{ij} = \Sigma_{ij}^{\text{MSSM}\prime} - \Sigma_{ij}^{\text{THDM}\prime}$

$$\Rightarrow \Delta^{-1}_{\text{MSSM}}(p^2) = U^T_{\Delta\Phi}\Delta^{-1}_{\text{THDM}}(p^2)U_{\Delta\Phi}$$

- pole masses do not depend on absolute field normalization $\rightarrow$ not important for pure EFT calculation

Matching to fixed order calculation III

Hybrid calculation in `FeynHiggs`:

$$\Delta_{\mathtt{FH}}^{-1}(p^2) =$$
$$= \begin{pmatrix} p^2 - m_h^2 + \hat{\Sigma}_{hh}^{\text{FO}}(p^2) + \Delta\Sigma_{hh}^{\text{logs}} & \hat{\Sigma}_{hH}^{\text{FO}}(p^2) + \Delta\Sigma_{hH}^{\text{logs}} \\ \hat{\Sigma}_{hH}^{\text{FO}}(p^2) + \Delta\Sigma_{hH}^{\text{logs}} & p^2 - m_H^2 + \hat{\Sigma}_{HH}^{\text{FO}}(p^2) + \Delta\Sigma_{HH}^{\text{logs}} \end{pmatrix}$$

with $\Delta\Sigma_{ij}^{\text{logs}} = \Sigma_{ij}^{\text{EFT}} - \Sigma_{ij}^{\text{sub}}$

"Relative" normalization important for

- correct merging of EFT result (THDM normalization) with fixed order result (MSSM renormalization)
- calculation of 1L and 2L subtraction terms

Matching to fixed order calculation IV

How to implement different normalization?
→ finite field normalization in fixed-order calculation

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta^{(1)}Z_{11}+\frac{1}{2}\Delta^{(2)}Z_{11} & \frac{1}{2}\delta^{(1)}Z_{12}+\frac{1}{2}\Delta^{(2)}Z_{12} \\ \frac{1}{2}\delta^{(1)}Z_{12}+\frac{1}{2}\Delta^{(2)}Z_{12} & 1+\frac{1}{2}\delta^{(1)}Z_{22}+\frac{1}{2}\Delta^{(2)}Z_{22}\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix},$$

$$\Delta Z_{ij} = \delta^{(2)}Z_{ij} - \frac{1}{4}\left(\delta^{(1)}Z_{ij}\right)^2$$

- choose $\delta^{(1)}Z_{ij}\big|_{\text{fin}} = \Delta\Sigma'_{ij}$
- $\delta^{(2)}Z_{ij}$ drops out completely
  → 2L relation between Φ^{MSSM} and Φ^{THDM} not needed

Affect on $\tan\beta$

$$\delta^{(1)} t_\beta = \tfrac{1}{2} t_\beta \left(\delta Z_{22}^{(1)} - \delta Z_{11}^{(1)}\right) + \tfrac{1}{2}\left(1 - t_\beta^2\right)\delta Z_{12}^{(1)}$$

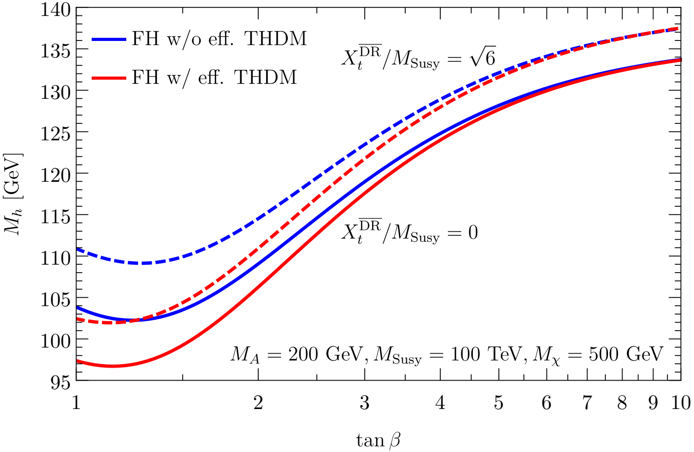
- finite field normalization changes definition of t_β
- renormalization scale of fixed-order calculation by default chosen to be M_t
- scale of THDM $\rightarrow M_A$

$\Rightarrow t_\beta^{\text{MSSM}}(M_t) \xrightarrow{\delta Z\big|_{\text{fin}}} t_\beta^{\text{THDM}}(M_A)$ in fixed-order calculation

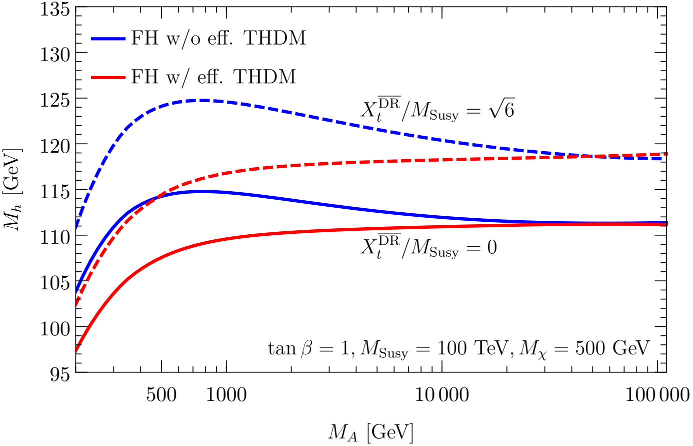
$$\downarrow$$

$$t_\beta^{\text{MSSM}}(M_t) = t_\beta^{\text{THDM}}(M_A) \cdot \\ \cdot \left[1 - \frac{y_t^2}{(4\pi)^2 s_\beta^2}\left(\frac{3}{2}\ln\frac{M_A^2}{M_t^2} + \frac{1}{4}(\hat{A}_t - \hat{\mu}/t_\beta)(\hat{A}_t + \hat{\mu} t_\beta)\right)\right]$$

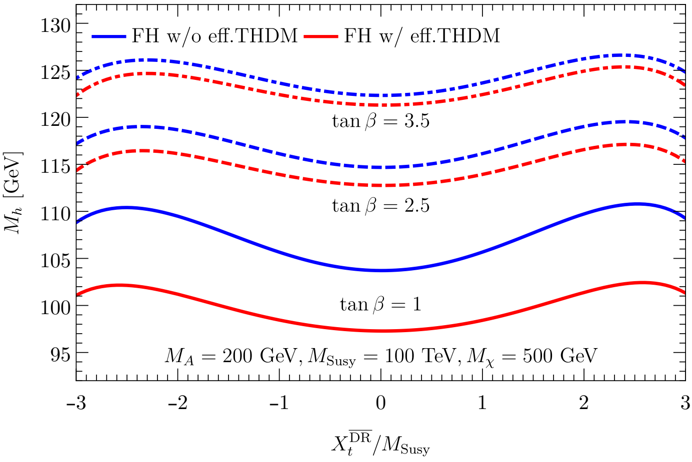
Comparison with FH w/o eff. THDM: $\tan\beta$ scan



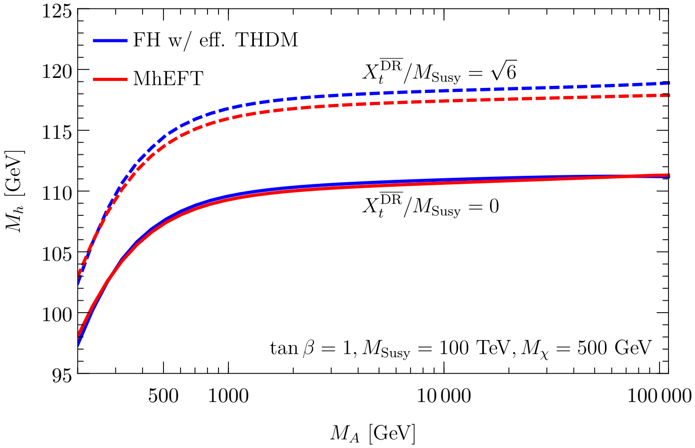
Comparison with FH w/o eff. THDM: M_A scan



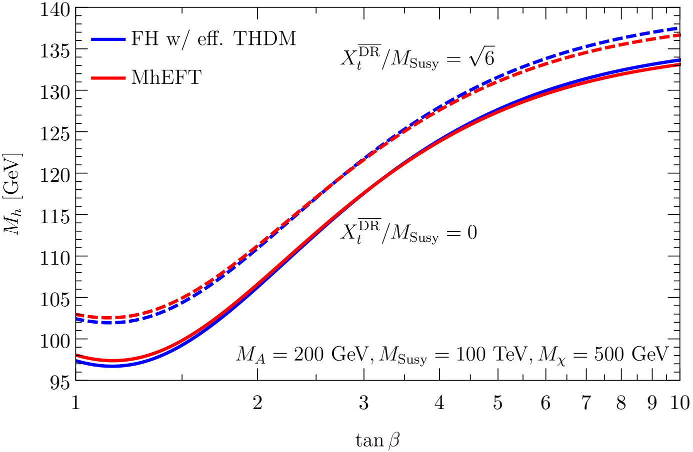
Comparison with FH w/o eff. THDM: $X_t^{\overline{\mathrm{DR}}}$ scan



Comparison with MhEFT: M_A scan



Comparison with MhEFT: $X_t^{\overline{\mathrm{DR}}}$ scan



Differences observed in Lee & Wagner?

- In `FH 2.10.2` log resummation was not very advanced (no EW contributions, no NNLL, ...).
- Resummation assumed $M_A = M_{\text{Susy}}$
- Lee & Wagner used OS parameters as input, but set $M_A = M_{\text{SUSY}}$ in conversion

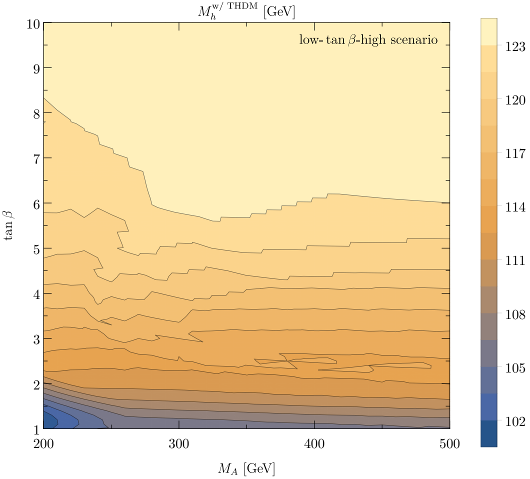
$$X_t^{\overline{\text{DR}}}(M_{\text{SUSY}}) = X_t^{\text{OS}} \left\{ 1 + \left[\frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi}\left(1 - \hat{X}_t^2\right)\right] \ln \frac{M_{\text{SUSY}}^2}{M_t^2} - \frac{3}{16\pi}\frac{\alpha_t}{t_\beta^2}\left(1 - \hat{Y}_t^2\right) \ln \frac{M_{\text{SUSY}}^2}{M_A^2} + \ldots \right\}$$

low-tanb-high scenario

LHCHXSWG benchmark scenario defined by

- $\hat{X}_t^{\text{OS}} = \begin{cases} 2 & \tan\beta \leq 2 \\ 0.0375\tan^2\beta - 0.7\tan\beta + 3.25 & 2 < \tan\beta \leq 8.6 \\ 0 & 8.6 < \tan\beta \end{cases}$
- $\mu = 1.5$ TeV, $M_2 = 2$ TeV, $M_1 \approx 0.5 M_2$, $M_3 = M_{\text{SUSY}}$
- $A_{b,c,s,u,d} = 2$ TeV
- M_{SUSY} chosen such that $M_h \sim 125$ GeV (and $M_{\text{SUSY}} \lesssim 100$ TeV)
- defined using using `FH 2.10.4`

low-tanb-high scenario ($\overline{\text{DR}}$)

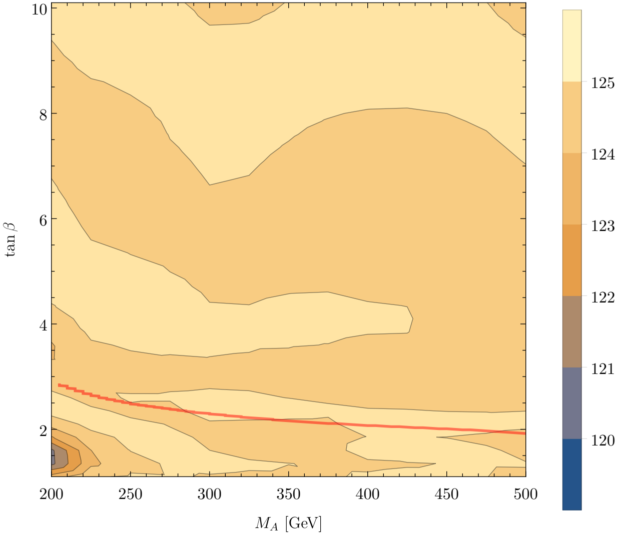


⇒ need to define new benchmark scenario

new proposal (a)

- $$\hat{X}_t^{\overline{\text{DR}}} = \begin{cases} \sqrt{6} & \tan\beta \le 3 \\ \frac{\sqrt{6}}{49}(\tan\beta - 10) & 3 < \tan\beta \le 10 \\ 0 & 10 < \tan\beta \end{cases}$$
- $\mu = 300$ GeV, $M_2 = 600$ GeV, $M_1 \approx 0.5 M_2$, $M_3 = M_{\text{SUSY}}$
- $A_{b,c,s,u,d} = 0$ TeV
- M_{SUSY} chosen such that $M_h \sim 125$ GeV (and $M_{\text{SUSY}} \lesssim 10^{16}$ GeV)
- defined at the moment by using using `FH` with eff. THDM and `MhEFT`

new proposal (a)

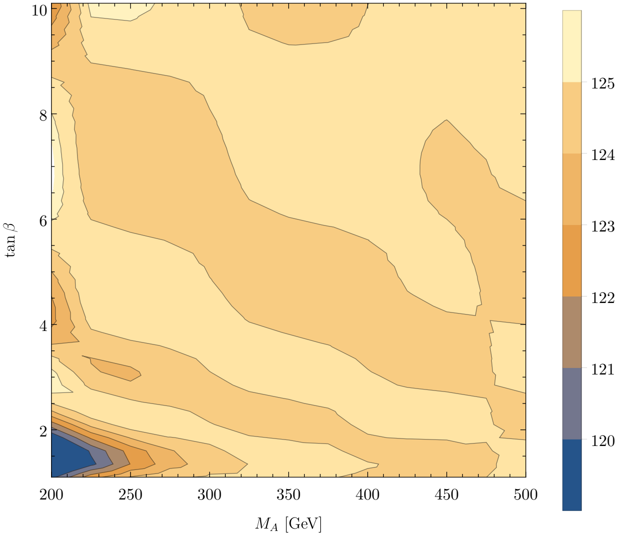


above red line `FH` is used, below `MhEFT`

new proposal (b)

- $A_t^{\overline{\mathrm{DR}}} = 0$
- $\mu = 300$ GeV, $M_2 = 600$ GeV, $M_1 \approx 0.5 M_2$, $M_3 = 3$ TeV
- $A_{b,c,s,u,d} = 0$ TeV
- M_{SUSY} chosen such that $M_h \sim 125$ GeV (and $M_{\mathrm{SUSY}} \lesssim 10^{16}$ GeV)
- defined at the moment by using using `FH` with eff. THDM and `MhEFT`

new proposal (b)



Uncertainties - status up to now

FeynHiggs

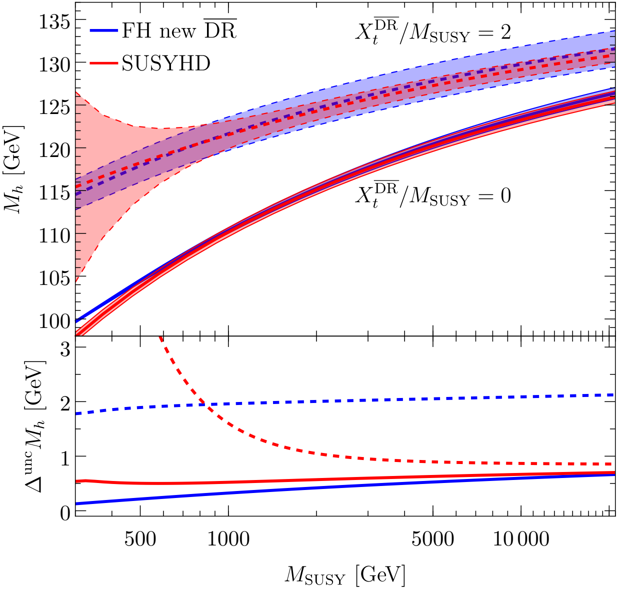
- variation of renormalization scale between $M_t/2$ and $2M_t$
- change of renormalization scheme; switch between OS top mass and SM $\overline{\text{MS}}$ top mass
- deactivating the resummation of bottom Yukawa coupling

SUSYHD

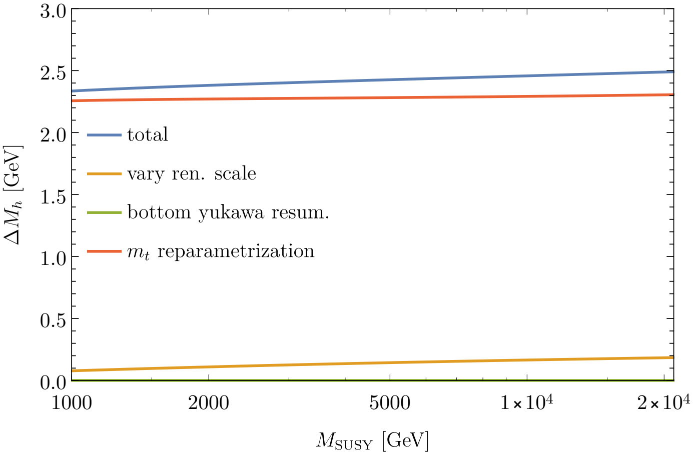
- variation of matching scale between $M_{\text{SUSY}}/2$ and $2M_{\text{SUSY}}$
- switching between NNLO and NNNLO top Yukawa coupling
- estimate of suppressed terms, $\mathcal{O}(M_t/M_{\text{SUSY}})$

Discussion so far restricted to single scale scenario ($\tan\beta = 10$)

Last KUTS: tons of discussions about



FeynHiggs: different contributions for $\hat{X}_t^{\overline{\text{DR}}} = \sqrt{6}$



Missing piece in FeynHiggs

No estimate of logarithmic uncertainty so far

$$\underbrace{g(M_{\text{SUSY}})^8}_{\text{estimated in EFT calc.}} = \underbrace{g(M_t)^8}_{\text{estimated in FH}} + \text{logs}$$

- $g(M_{\text{SUSY}})$ typically decreases with rising M_{SUSY}
- logarithms increase
- $g(M_t)$ stays constant

↓

compensation between logarithms and non-logarithmic piece not taken into account in FeynHiggs

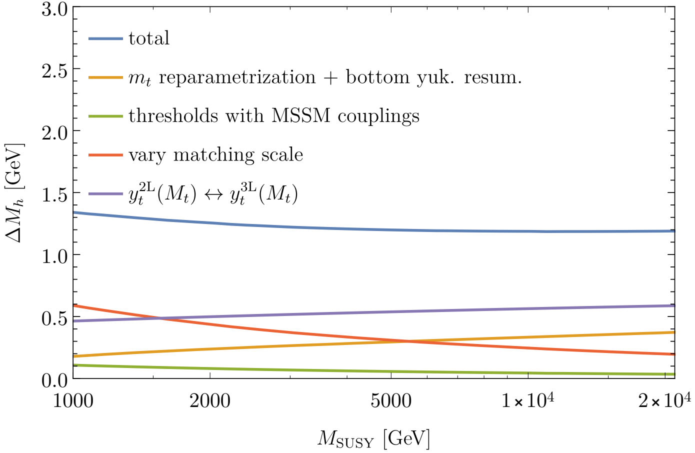
One idea under discussion:
Build upon uncertainty estimate of pure EFT calculation

Uncertainty based on EFT estimate

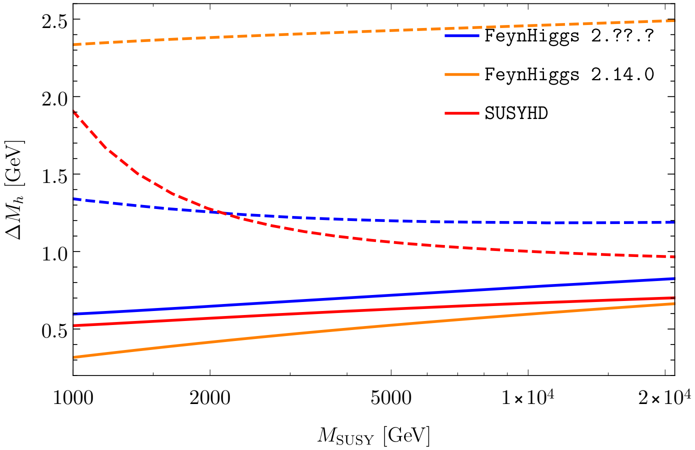
Estimate uncertainty in two step procedure:

1. uncertainty of EFT calculation
   - change between $y_t^{\overline{\mathrm{MS}},2\mathrm{L}} \leftrightarrow y_t^{\overline{\mathrm{MS}},3\mathrm{L}}$
   - variation of matching scale between $M_{\mathrm{SUSY}}/2$ and $2M_{\mathrm{SUSY}}$
   - reparametrization of threshold in terms of MSSM couplings
2. uncertainty of suppressed terms and SM contributions
   - change of renormalization scheme; switch between OS top mass and SM $\overline{\mathrm{MS}}$ top mass
   - deactivating the resummation of bottom Yukawa coupling

Uncertainty based on EFT estimate for $\hat{X}_t^{\overline{\text{DR}}} = \sqrt{6}$



Comparison to SUSYHD



solid: $X_t^{\overline{\text{DR}}} = 0$; dashed: $X_t^{\overline{\text{DR}}}/M_{\text{SUSY}} = \sqrt{6}$

Conclusion

Low M_A scenario:

- upcoming extension of `FH` with effective THDM
- important to take different normalizations of Higgs doublets into account
- eff. THDM only relevant for very low $\tan\beta$
- time to update low-tanb-high scenario

Uncertainty estimate:

- no estimate of logarithmic uncertainty in `FH` so far
- compensation between logarithmic and non-logarithmic terms leads to reduce uncertainty

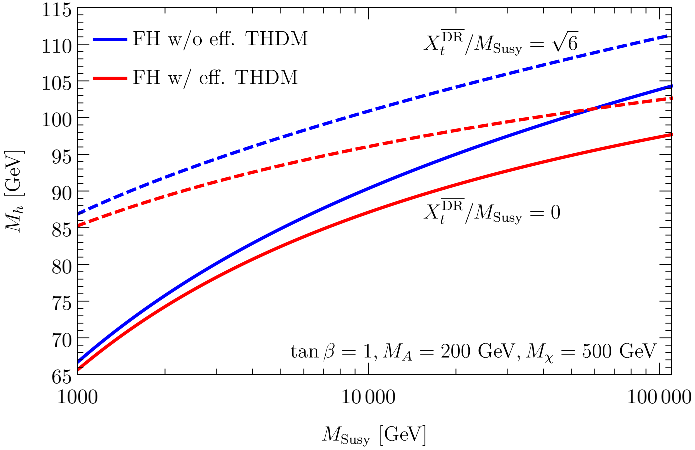
Matching to fixed order calculation V

$$\hat{\Sigma}^{(2)}_{hh}(0)\Big|_{\delta Z} = \Sigma^{(2),\text{sub}}_{hh}(0)\Big|_{\delta Z} - \frac{e}{2 s_W M_W}\left(T^{(2),\text{sub}}_{h}\Big|_{\delta Z} + \frac{1}{2} s_\beta^2 T^{(1)}_{h} \delta^{(1)} Z_{hh}\right)$$

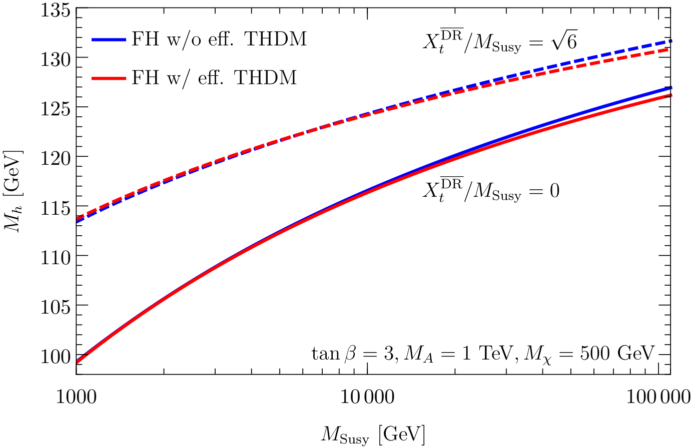
$$\hat{\Sigma}^{(2)}_{hH}(0)\Big|_{\delta Z} = \Sigma^{(2),\text{sub}}_{hH}(0)\Big|_{\delta Z} - \frac{e}{2 s_W M_W}\left(T^{(2),\text{sub}}_{H}\Big|_{\delta Z} + \frac{1}{2} s_\beta^2 T^{(1)}_{H} \delta^{(1)} Z_{hh}\right)$$

$$\hat{\Sigma}^{(2)}_{HH}(0)\Big|_{\delta Z} = \Sigma^{(2),\text{sub}}_{HH}(0)\Big|_{\delta Z} - \Sigma^{(2),\text{sub}}_{AA}(0)\Big|_{\delta Z},$$

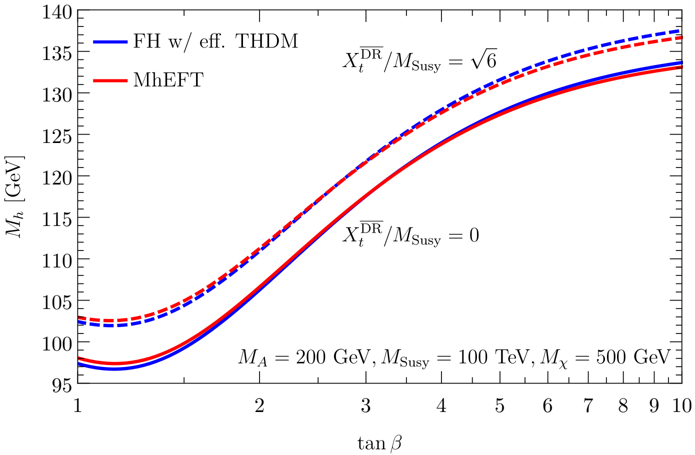
Results for M_H: $\tan\beta$ scan



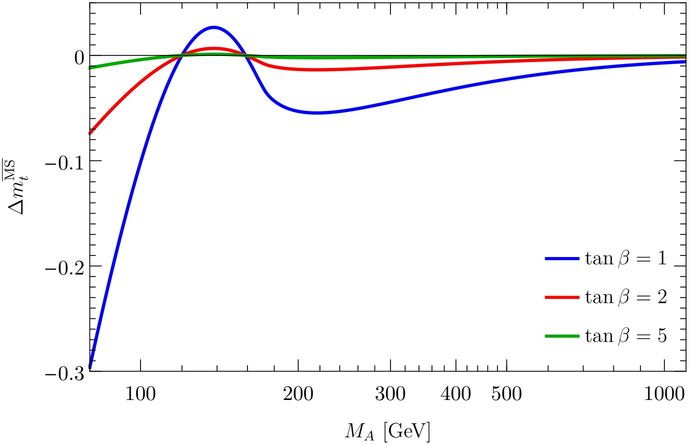
Results for M_H: M_A scan



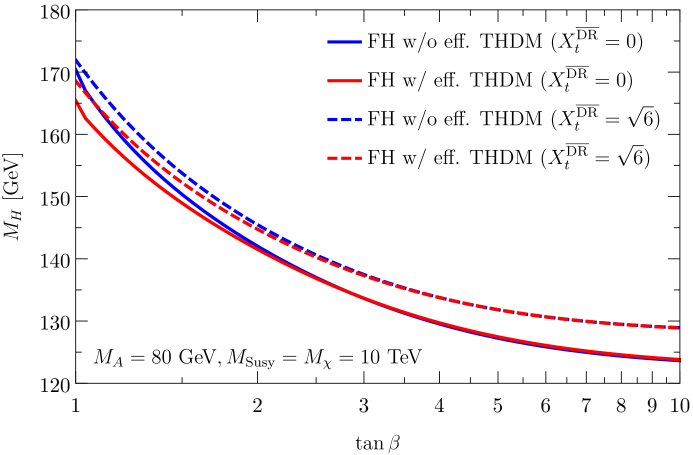
Comparison with MhEFT: tan β scan



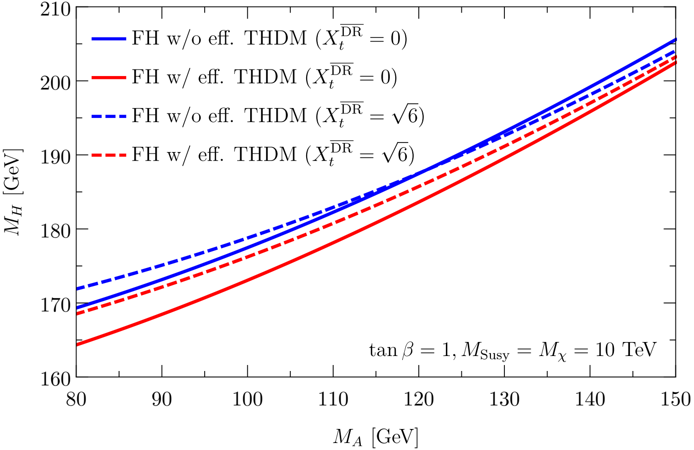
Influence of low M_A on extraction of top Yukawa coupling



Results for M_H: $\tan\beta$ scan



Results for M_H: M_A scan



shift in low-tanb-high scenario ($\overline{\text{DR}}$)