Precise MSSM Higgs mass prediction combining diagrammatic and EFT calculations

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Current situation:

- no direct evidence for BSM physics at LHC yet

BSM models constrained by

- direct searches
- indirect constraints → precision observables

One of the most common BSM models: MSSM

- Higgs sector of MSSM corresponds to a THDM type II
- Two Higgs doublets results in five physical Higgs states: h, H, A, $H^{\pm}$
- A gneral THDM type II has 9 free parameters
  → SUSY reduces these to 2 (M_A and $\tan\beta = v_2/v_1$)

Special feature of MSSM

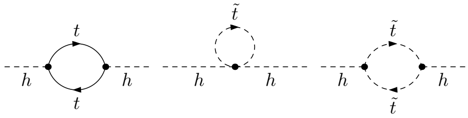
Mass of lightest $\mathcal{CP}$-even Higgs M_h is calculable in terms of model parameters $\Rightarrow$ can be used as a precision observable

- at tree-level $M_h^2 \simeq M_Z^2 \cos(2\beta)^2 \leq M_Z^2$
- M_h is however heavily affected by loop corrections (up to $\sim 100\%$)

To fully profit from experimental precision, higher order calculations are needed. Two standard approaches:

- Fixed-order techniques
- Effective field theories

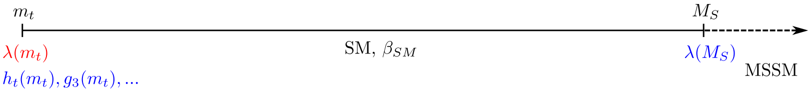
Fixed-order techniques



- diagrammatic approach
  status: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2)$
- effective potential approach
  status: same + partial three-loop results

→ precise for low SUSY scales,
but for high scales large logarithms appear, $\ln(M_{\text{SUSY}}/M_t)$,
spoiling convergence of perturbative expansion

EFT calculation



- integrate out all SUSY particles → SM as EFT
- Higgs self-coupling fixed at matching scale $\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g_y^2) + ...$
- status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL

→ precise for high SUSY scales (logs resummed), but for low scales $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms are important

How to deal with intermediary SUSY scales?

For sparticles in the LHC range, both logs and suppressed terms might be relevant. We could try to improve

- fixed-order calculation → need to calculate more three- and two-loop corrections,
- EFT calculation → need to include higher-dimensional operators into calculation.

or ...

↓

Hybrid approach

Combine both approaches to get precise results for both regimes

Such an approach is implemented e.g. in `FeynHiggs`
[HB, T. Hahn, S. Heinemeyer, W. Hollik, S. Paßehr, H. Rzehak, G. Weiglein]

Procedure in FeynHiggs

1. Calculation of diagrammatic fixed-order self-energies $\hat{\Sigma}_{hh}$
2. Calculation of EFT prediction $2\lambda(M_t)v^2$
3. Add non-logarithmic terms contained in fixed-order result and the logarithms contained in EFT result

$$\hat{\Sigma}_{hh}(m_h^2) \longrightarrow \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{nolog}} - \left[2v^2\lambda(M_t)\right]_{\text{log}}$$

   In practice, this is achieved by using subtraction terms.

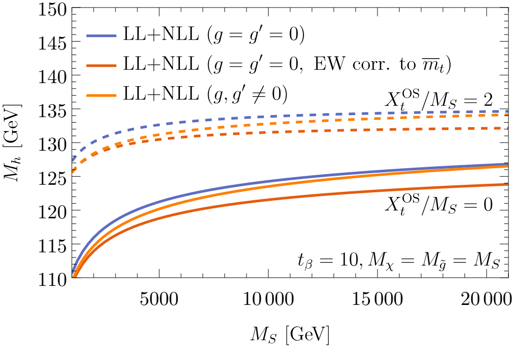
Additional complication:
FH by default uses OS scheme, for EFT calculation however $\overline{\text{DR}}$ parameters needed (i.e. $X_t^{\overline{\text{DR}}}$)
$\rightarrow$ 1L log only conversion of X_t sufficient

Development history (and talk outline)

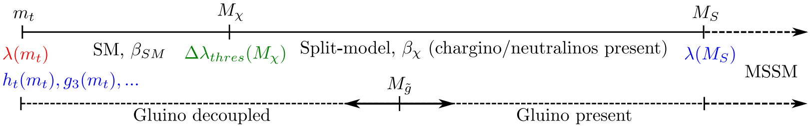
- First implementation:
  $\mathcal{O}(\alpha_s, \alpha_t)$ LL and NLL resummation [Hahn et. al. (2013)]
- Improvement of EFT calculation:
  full LL and NLL and $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation, gaugino thresholds [HB & W. Hollik (2016)]
- Comparison to pure EFT calculations:
  handling of $\overline{\text{DR}}$ input, improved pole mass determination
  [HB, S. Heinemeyer, W. Hollik, G. Weiglein (2017)]
- More complicated mass hierarchies:
  THDM as low-energy EFT [HB & W. Hollik (in preparation)]

Inclusion of electroweak contributions

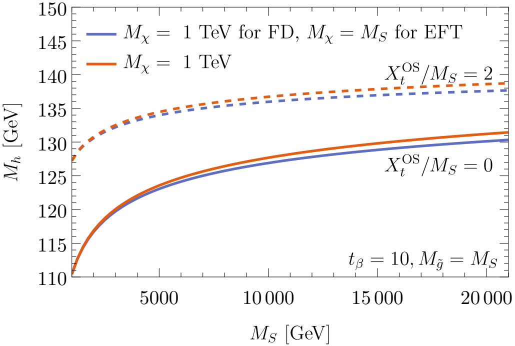
- included at the LL+NLL level
  (full SM 2L RGEs, full 1L thresholds)
- include electroweak 1L corrections to SM $\overline{\text{MS}}$ top mass, used in the diagrammatic calculation



Separate gaugino thresholds

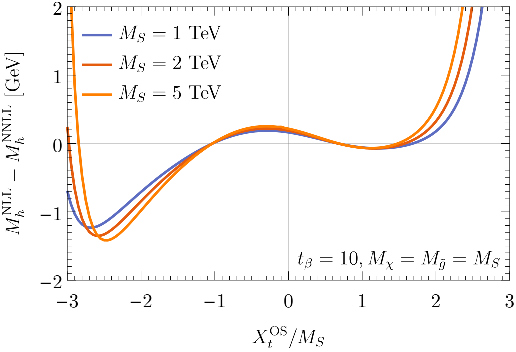


- Separate threshold for EWinos (neutralinos/charginos) and gluino



Inclusion of NNLL resummation

- 2L threshold for λ, 3L RGEs



↓

This work brought EFT calculation in `FeynHiggs` to same level of accuracy as pure EFT calculations

Next step: Comparison to pure EFT calculations

$\Rightarrow$ expected to see agreement with EFT codes for high scales, but at this time large discrepancies could be observed

Two main origins found

- $\overline{\text{DR}} \leftrightarrow$ OS conversion
- determination of Higgs propagator pole

We focused on single scale scenario:

$\tan\beta = 10, \;\; M_{\text{soft}} = \mu = M_A \equiv M_{\text{Susy}}, \;\; A_{b,c,s,e,\mu,\tau} = 0$

`FeynHiggs` mixed OS/$\overline{\text{DR}}$ scheme ↔ EFT codes typically $\overline{\text{DR}}$

→ for comparison parameter conversion necessary

Especially relevant: stop mixing parameter X_t
(large impact on Higgs mass, large logarithms in conversion)

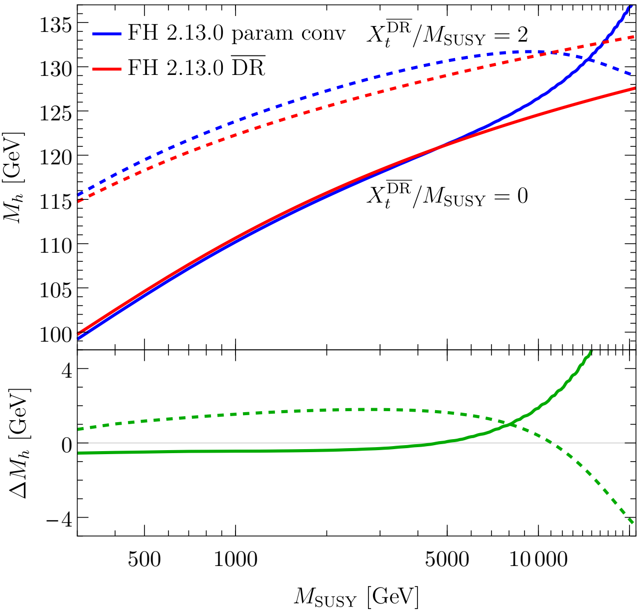
Procedure at this time

- $X_t^{\overline{\text{DR}}} \xrightarrow{\mathcal{O}(\alpha_s,\alpha_t,\alpha_b)} X_t^{\text{OS}}$
- Forget about $X_t^{\overline{\text{DR}}}$, use X_t^{OS} as 'new' input parameter

Problem: result contains resummed logarithms

→ conversion induces additional logarithms not present in a genuine $\overline{\text{DR}}$ calculation

→ solution: optional $\overline{\text{DR}}$ renormalization of fixed-order result



How is the pole mass determined?

EFT calculation

$$p^2 - 2\lambda(M_t)v^2 + \hat{\Sigma}_{hh}^{\text{SM}}(p^2) = 0$$
$$\rightarrow (M_h^2)_{\text{EFT}} = 2\lambda(M_t)v^2 - \hat{\Sigma}_{hh}^{\text{SM}}(m_h^2) - \hat{\Sigma}_{hh}^{\text{SM}\prime}(m_h^2)\left[2\lambda(M_t)v^2 - \hat{\Sigma}_{hh}^{\text{SM}}(m_h^2) - m_h^2\right] + \ldots$$

Hybrid calculation

In limit $M_A \gg M_Z$ Higgs pole mass is determined by

$$p^2 - m_h^2 + \hat{\Sigma}_{hh}^{\text{MSSM}}(p^2) - \left[2v^2\lambda(M_t)\right]_{\text{log}} - \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{log}} = 0$$
$$\rightarrow (M_h^2)_{\text{FH}} = m_h^2 + \left[2v^2\lambda(M_t)\right]_{\text{log}} - \left[\hat{\Sigma}_{hh}^{\text{MSSM}}(m_h^2)\right]_{\text{nolog}} - \hat{\Sigma}_{hh}^{\text{MSSM}\prime}(m_h^2)\left(\left[2v^2\lambda(M_t)\right]_{\text{log}} - \left[\hat{\Sigma}_{hh}^{\text{MSSM}}(m_h^2)\right]_{\text{nolog}}\right) + \ldots$$

Comparison of logarithmic terms

In decoupling limit, we can split up MSSM self-energy

$$\hat{\Sigma}_{hh}^{\text{MSSM}}(m_h^2) = \hat{\Sigma}_{hh}^{\text{SM}}(m_h^2) + \hat{\Sigma}_{hh}^{\text{nonSM}}(m_h^2).$$

We straightforwardly obtain

$$\begin{aligned}\Delta^{\log} &\equiv (M_h^2)^{\log}_{\text{FH}} - (M_h^2)^{\log}_{\text{EFT}} \\ &= \left[\hat{\Sigma}_{hh}^{\text{nonSM}\prime}(m_h^2)\right]_{\log}\left[\hat{\Sigma}_{hh}^{\text{MSSM}}(m_h^2)\right]_{\text{nolog}} \\ &\quad - \hat{\Sigma}_{hh}^{\text{nonSM}\prime}(m_h^2)\left[2v^2\lambda(M_t)\right]_{\log} + \ldots\end{aligned}$$

Very similar for non-logarithmic terms.

Observation

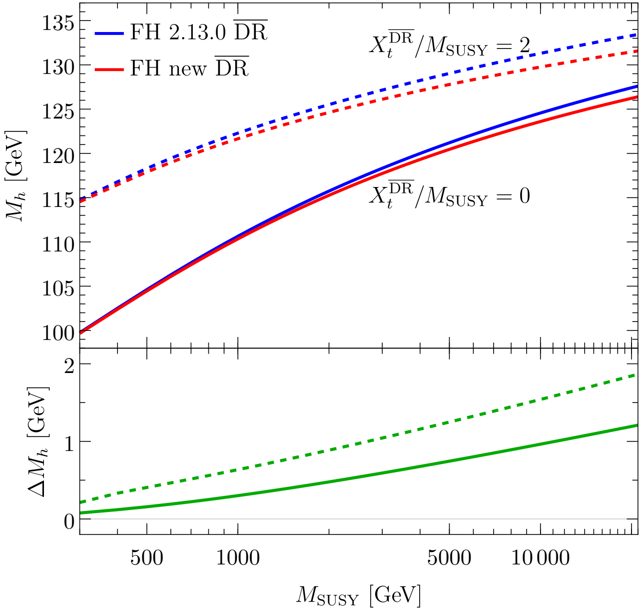
vev counterterm appearing in 2L subloop-renormalization cancels 2L terms in $\Delta^{\log}$

$$\frac{(\delta v^2)^{\text{MSSM}}}{v^2} = \frac{(\delta v^2)^{\text{SM}}}{v^2} - \hat{\Sigma}_{hh}^{\text{nonSM},(1)\prime}(m_h^2) + \mathcal{O}(v/M_{\text{SUSY}})$$

- Argument holds for all 2L contributions
- Full 2L calculation however not available
  $\rightarrow$ induced terms of e.g. $\mathcal{O}(\alpha_t\alpha)$ are not compensated
- Likely also holds for higher loop orders

$\downarrow$

adapted determination of Higgs propagator pole to avoid these terms (truncate expansion around tree-level mass)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$X_t^{\overline{\mathrm{DR}}}/M_{\mathrm{SUSY}} = 2$
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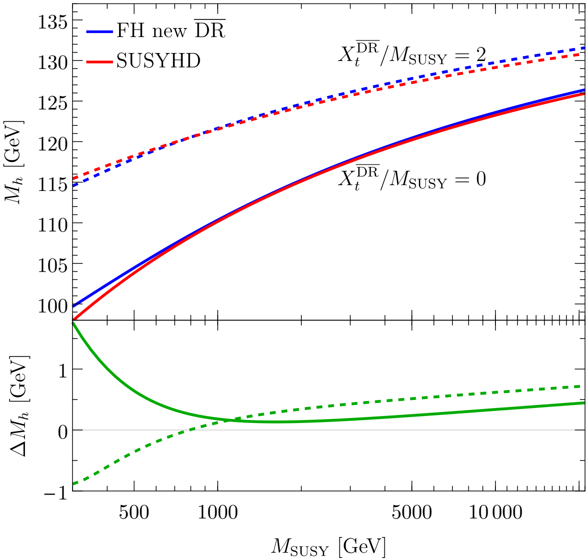
M_h [GeV]
135
130
125
120
115
110
105
100
ΔM_h [GeV]
2
1
0
500
1000
5000
10 000
M_{SUSY} [GeV]

Comparison to SUSYHD as exemplary EFT code

[J.P. Vega, G. Villadoro]



$\longrightarrow$ **overall very good agreement**

Remaining differences

- derivation for small scales due to suppressed terms not captured in EFT framework
- constant shift due to different parametrizations of non-logarithmic terms (i.e. top mass and vev)

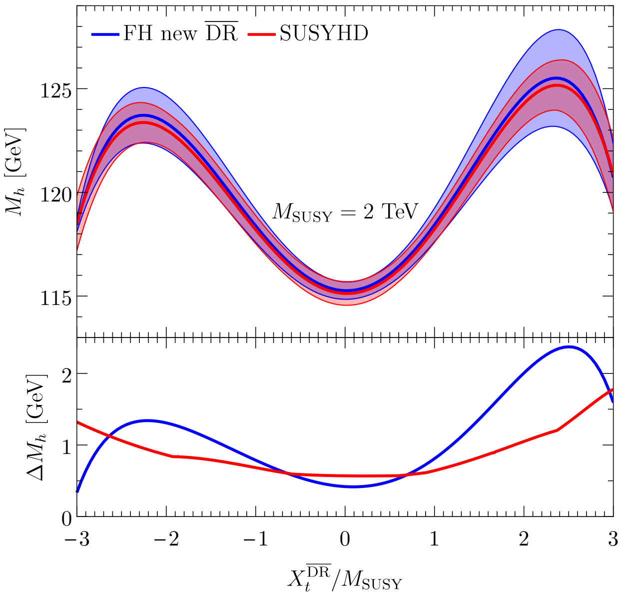
Comparison of uncertainty estimates

`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, $\mathcal{O}(M_t/M_{\text{SUSY}})$


FH new $\overline{\text{DR}}$
SUSYHD
$M_{\text{SUSY}} = 2$ TeV
M_h [GeV]
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115
ΔM_h [GeV]
2
1
0
−3
−2
−1
0
1
2
3
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}}$

What is about more complicated hierarchies?

Assumption so far

All sfermions and non-SM Higgs share common mass scale

Therefore, prediction might be unreliable e.g. if

- one stop is much lighter than the other
  [Espinosa & Navarro (2001)]
- non SM Higgs are much lighter than sfermions
  [Haber & Hempfling (1993), Lee & Wagner (2015)]
- ...

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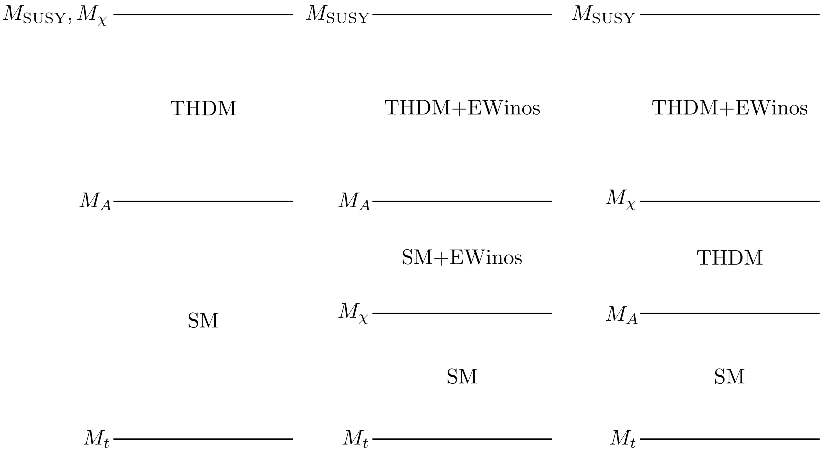
→ Low-energy THDM is needed for correct resummation

EFTs for low M_A



$M_\chi = M_1 = M_2 = \mu$;
additional freely variable gluino threshold not shown

EFT calculation

- all possible hierarchies taken into account
  - THDM type III → 12 effective couplings ($\lambda_{1..7}, h_t, h'_t$)
  - THDM type III + EWinos → 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

→ most precise EFT calculation available

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`:

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

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

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

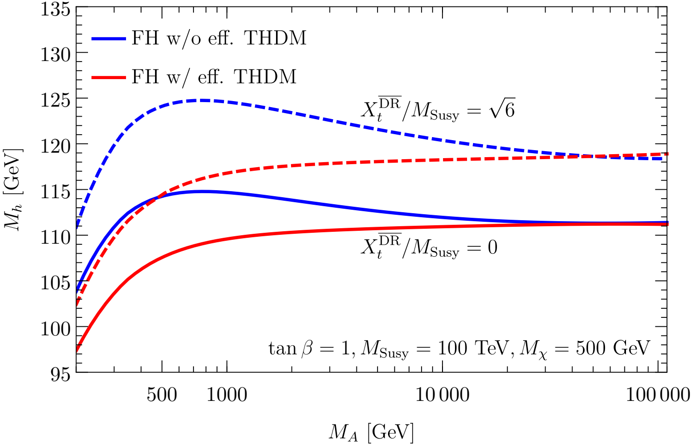
$$\Delta Z_{ij} = \delta^{(2)}Z_{ij} - \frac{1}{4}\left(\delta^{(1)}Z_{ij}\right)^2$$

- 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

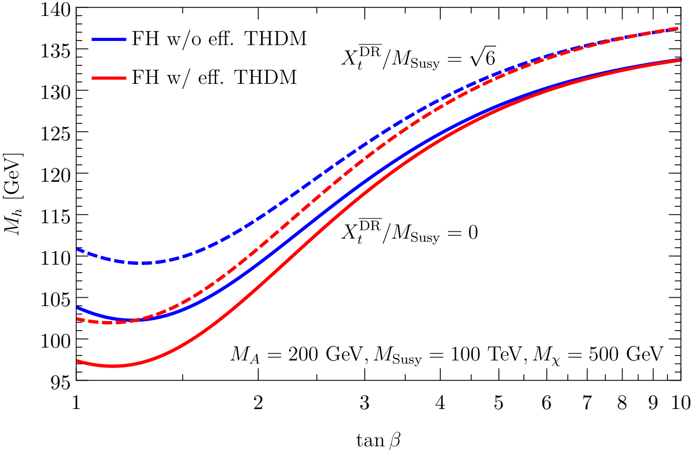
→ definition of $\tan\beta$ is changed

$$t_\beta^{\text{MSSM}}(M_t) \xrightarrow{\delta Z|_{\text{fin}}} t_\beta^{\text{THDM}}(M_A)$$

Results I: M_A scan

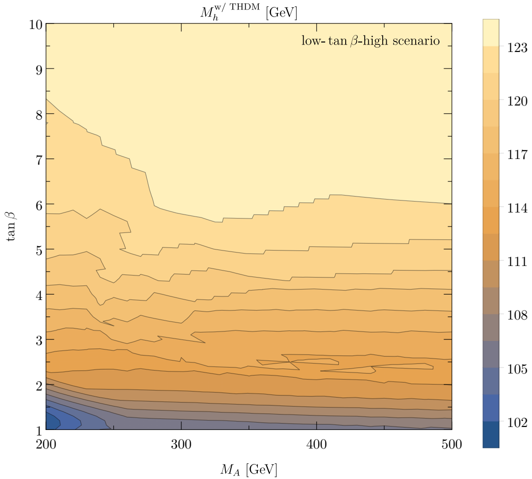


Results II: $\tan\beta$ scan

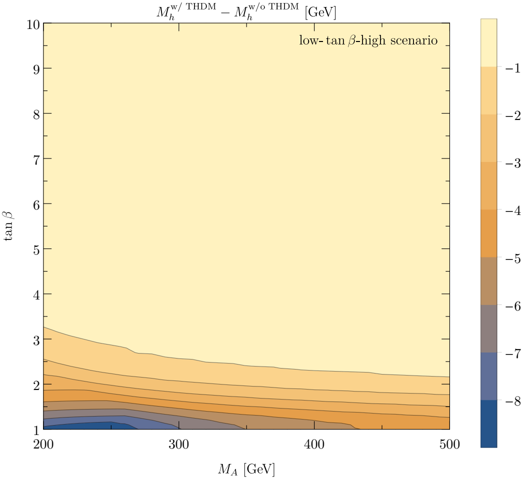


Results III: low-tanb-high scenario ($\overline{\text{DR}}$)

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



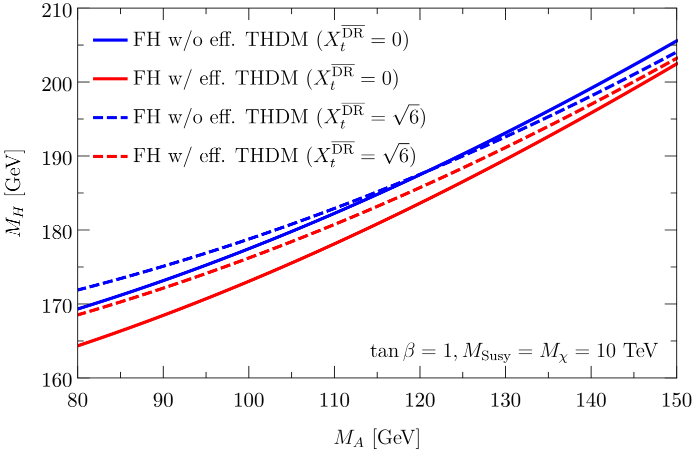
Results IV: shift in low-tanb-high scenario ($\overline{\text{DR}}$)



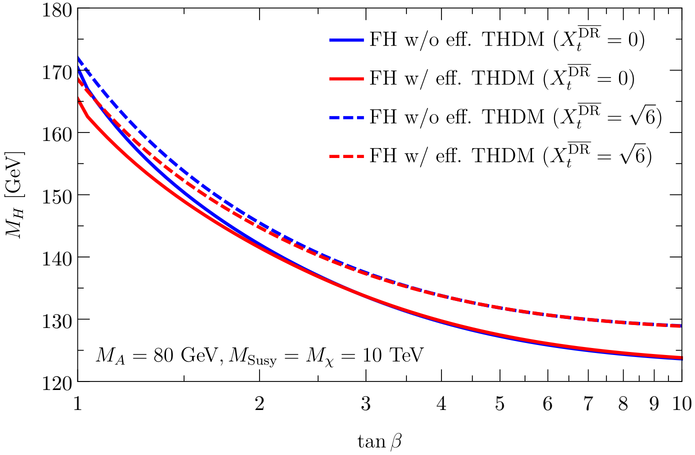
→ need to define new benchmark scenario (LHCHXSWG)

Results for M_H I

How important is the eff. THDM, when H plays role of SM Higgs?



Results for M_H II



→ negligible in these scenarios

Conclusion

- SM-like Higgs mass is an important constraint on MSSM parameter space
- To gain precise prediction for all SUSY scales, we combined
  - state-of-the-art fixed-order calculation
  - state-of-the-art EFT calculation
- Optional $\overline{\text{DR}}$ renorm. and improved pole determination
  $\rightarrow$ excellent agreement of `FeynHiggs` with pure EFT codes found for high scales
- For low M_A, implemented effective THDM as EFT
  $\rightarrow$ Large numerical effects

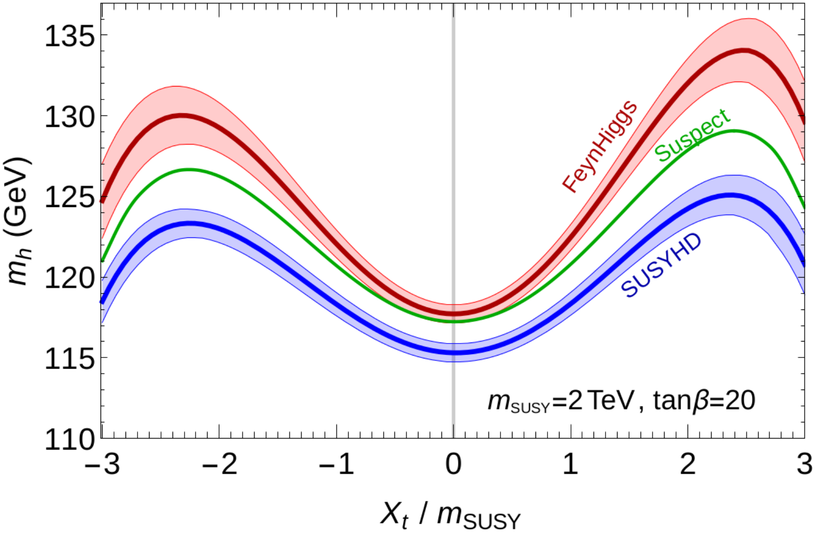
$$\Downarrow$$

For multi-scale scenarios, proper EFT treatment is essential

Outlook

- For each hierarchy the same steps are always repeated:
  - define EFTs
  - calculate RGEs and threshold corrections
  - merge with diagrammatic calculation (calculate subtraction terms)

  → automatizing these steps would allow for a precise predicition for arbitrary hierarchies
- application to other observable and models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m_h (GeV)
X_t / m_{SUSY}
FeynHiggs
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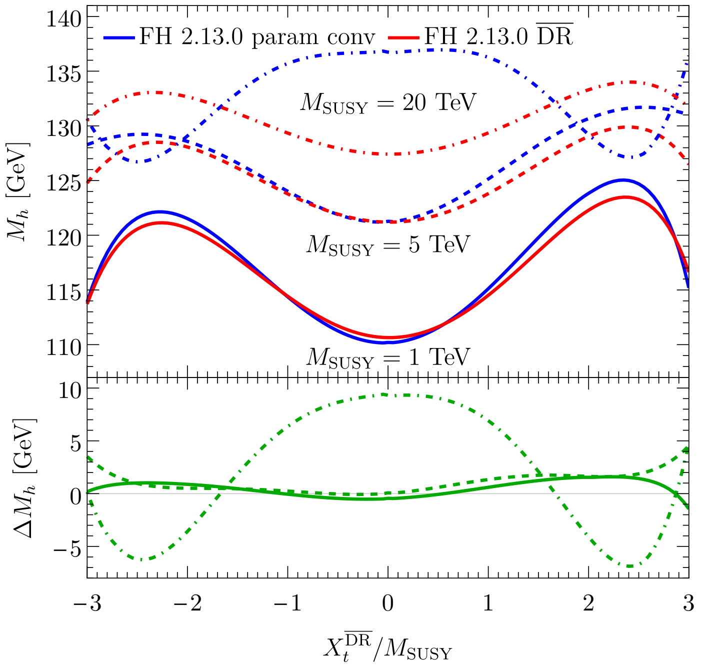
FH 2.13.0 param conv
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Need to determine poles of inverse propagator matrix

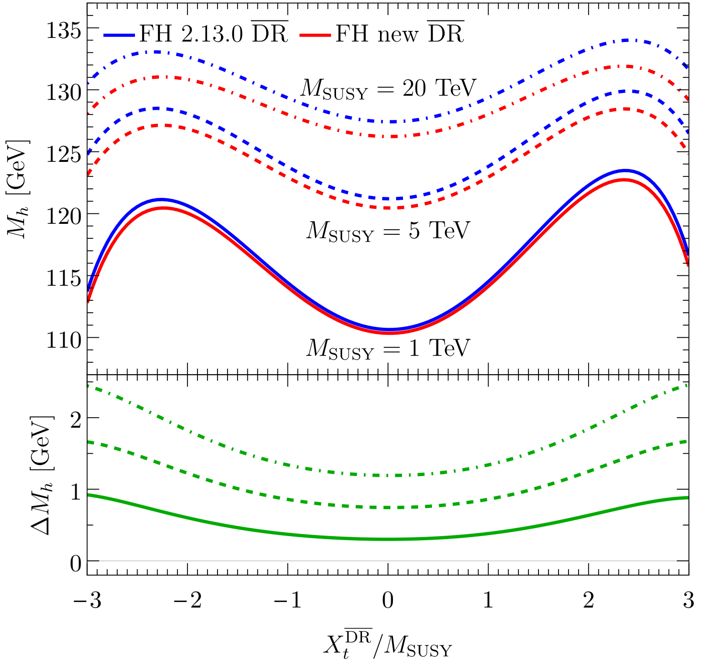
$$\Delta^{-1}(p^2) =$$
$$= \begin{pmatrix} p^2 - m_h^2 + \hat{\Sigma}^{(1)}_{hh}(p^2) + \hat{\Sigma}^{(2)}_{hh}(0) & \hat{\Sigma}^{(1)}_{hH}(p^2) + \hat{\Sigma}^{(2)}_{hH}(0) \\ \hat{\Sigma}^{(1)}_{hH}(p^2) + \hat{\Sigma}^{(2)}_{hH}(0) & p^2 - m_H^2 + \hat{\Sigma}^{(1)}_{HH}(p^2) + \hat{\Sigma}^{(2)}_{HH}(0) \end{pmatrix}$$

At 1L level $M_h^2 = m_h^2 - \hat{\Sigma}^{(1)}_{hh}(m_h^2) \rightarrow$ expand around 1L solution

$\Rightarrow$ determine poles of

$$\Delta^{-1}_{hh}(p^2) = p^2 - m_h^2 \quad + \hat{\Sigma}^{(1)}_{hh}(m_h^2) \quad + \hat{\Sigma}^{(2)}_{hh}(0) \quad - \left[\hat{\Sigma}^{(1)\prime}_{hh}(m_h^2)\hat{\Sigma}^{(1)}_{hh}(m_h^2)\right]_{g=g_Y=0}$$
$$\Delta^{-1}_{hH}(p^2) = \quad + \hat{\Sigma}^{(1)}_{hH}(m_h^2) \quad + \hat{\Sigma}^{(2)}_{hH}(0) \quad - \left[\hat{\Sigma}^{(1)\prime}_{hH}(m_h^2)\hat{\Sigma}^{(1)}_{hh}(m_h^2)\right]_{g=g_Y=0}$$
$$\Delta^{-1}_{HH}(p^2) = p^2 - m_H^2 \quad + \hat{\Sigma}^{(1)}_{HH}(m_h^2) \quad + \hat{\Sigma}^{(2)}_{HH}(0) \quad - \left[\hat{\Sigma}^{(1)\prime}_{HH}(m_h^2)\hat{\Sigma}^{(1)}_{hh}(m_h^2)\right]_{g=g_Y=0}$$

For determination of M_H expand around $M_H^2 = m_H^2 - \hat{\Sigma}^{(1)}_{HH}(m_H^2)$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ΔM_h [GeV]
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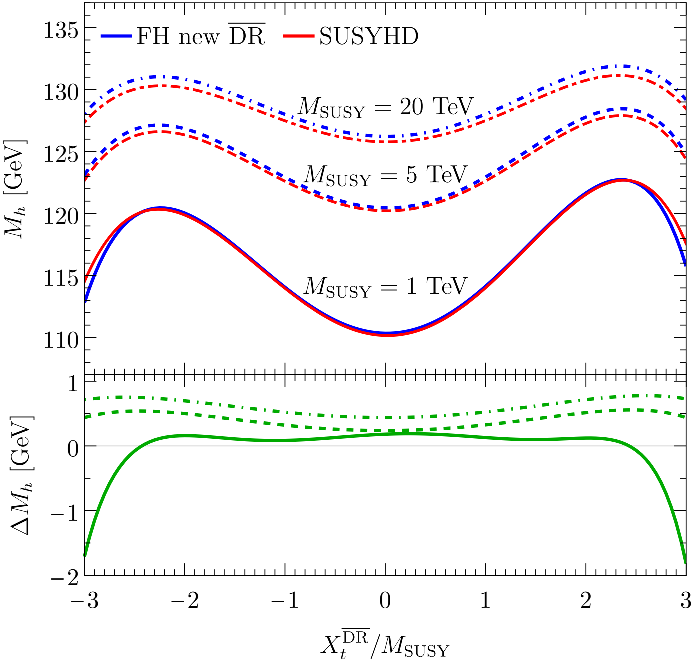

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M_h [GeV]
ΔM_h [GeV]
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}}$
135
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1
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1
2
3

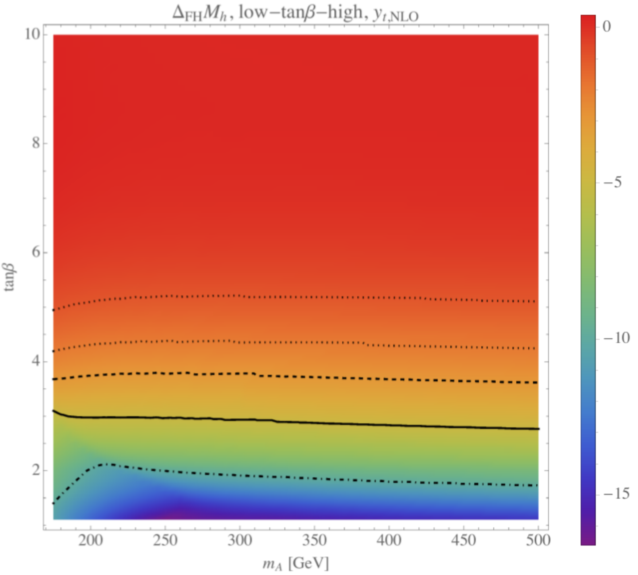
Effective Lagrangians

$$\mathcal{L}_{\text{THDM}} = ... - V_{\text{THDM}}(H_u, H_d) - h_t \epsilon_{ij} \bar{t}_R Q_L^i H_u^j - h_t' \bar{t}_R Q_L H_d$$

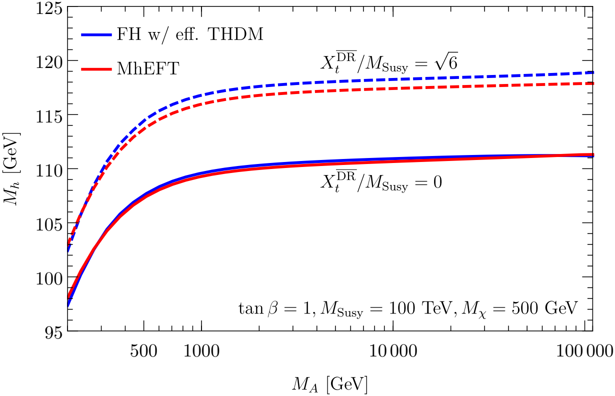
$\rightarrow$ 12 effective couplings $(\lambda_{1..7}, h_t, h_t')$

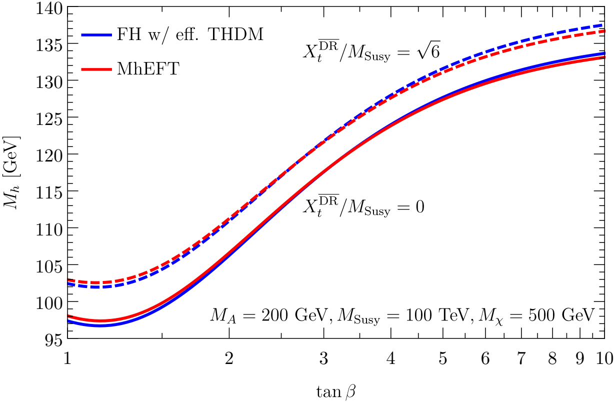
$$\begin{aligned}
\mathcal{L}_{\text{THDM+EWinos}} = ... &- \frac{1}{\sqrt{2}} H_u^\dagger \left(\hat{g}_{2uu} \sigma^a \tilde{W}^a + \hat{g}_{1uu} \tilde{B} \right) \tilde{\mathcal{H}}_u \\
&- \frac{1}{\sqrt{2}} H_d^\dagger \left(\hat{g}_{2dd} \sigma^a \tilde{W}^a - \hat{g}_{1dd} \tilde{B} \right) \tilde{\mathcal{H}}_d \\
&- \frac{1}{\sqrt{2}} (-i H_d^T \sigma_2) \left(\hat{g}_{2du} \sigma^a \tilde{W}^a + \hat{g}_{1du} \tilde{B} \right) \tilde{\mathcal{H}}_u \\
&- \frac{1}{\sqrt{2}} (-i H_u^T \sigma_2) \left(\hat{g}_{2ud} \sigma^a \tilde{W}^a - \hat{g}_{1ud} \tilde{B} \right) \tilde{\mathcal{H}}_d \\
&+ h.c. - V_{\text{THDM}}(H_u, H_d),
\end{aligned}$$

$\rightarrow$ 20 effective couplings



$\Delta_{\rm FH} M_h$, low−tanβ−high, $y_{t,\rm NLO}$
10
8
6
4
2
tanβ
200
250
300
350
400
450
500
m_A [GeV]
0
−5
−10
−15


FH w/ eff. THDM
MhEFT
$X_t^{\overline{\mathrm{DR}}}/M_{\mathrm{Susy}} = \sqrt{6}$
$X_t^{\overline{\mathrm{DR}}}/M_{\mathrm{Susy}} = 0$
$\tan\beta = 1, M_{\mathrm{Susy}} = 100$ TeV, $M_\chi = 500$ GeV
M_h [GeV]
M_A [GeV]
125
120
115
110
105
100
95
500
1000
10 000
100 000


FH w/ eff. THDM
MhEFT
$X_t^{\overline{\text{DR}}}/M_{\text{Susy}} = \sqrt{6}$
$X_t^{\overline{\text{DR}}}/M_{\text{Susy}} = 0$
$M_A = 200$ GeV, $M_{\text{Susy}} = 100$ TeV, $M_\chi = 500$ GeV
M_h [GeV]
$\tan\beta$
140
135
130
125
120
115
110
105
100
95
1
2
3
4
5
6
7
8
9
10