Reconciling EFT and hybrid calculations of the light MSSM Higgs-boson mass

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Current situation:

- no direct evidence for BSM physics at LHC yet

BSM models constrained by

- direct searches
- indirect constraints $\rightarrow$ precision observables

One of the most common BSM models: MSSM

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

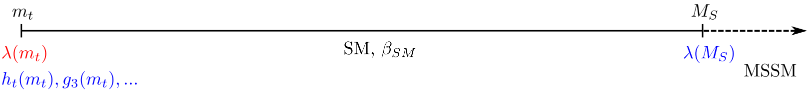
- M_h is however heavily affected by loop corrections (up to $\sim 100\%$)

To fully profit from experimental precision, higher order calculations are needed:

- 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, $\ln \frac{M_{\text{SUSY}}}{M_t}$,
spoiling convergence of perturbative expansion

Alternative: EFT calculation



- integrate out all SUSY particles → SM as EFT
  status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL

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

Solution: Hybrid approach

Combine both approaches to get precise results for both regimes → **FeynHiggs** (and FlexibleSUSY)

[HB, T. Hahn, S. Heinemeyer, W. Hollik, S. Paßehr, H. Rzehak, G. Weiglein]

Procedure in FeynHiggs:

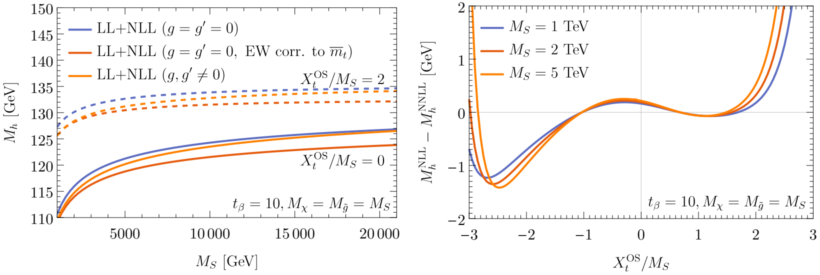
1. Calculation of diagrammatic fixed-order self-energies $\hat{\Sigma}_{hh}$
2. Calculation of EFT prediction $2\lambda(M_t)v^2$
3. Combine both

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

Current status

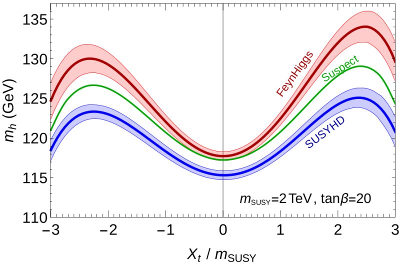
`FeynHiggs` includes state of the art EFT calculation
(and state of the art fixed-order calculation)

- Full LL+NLL resummation
- $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation [HB & W. Hollik '16]
- Possibility for seperate EWino and Gluino thresholds



⇒ expected to see agreement with EFT codes for high scales, but so far still large discrepancies could be observed

(e.g. J.V. Vega & G. Villadoro '15)



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 $\leftrightarrow$ EFT codes typically $\overline{\text{DR}}$

$\rightarrow$ for comparison parameter conversion necessary

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

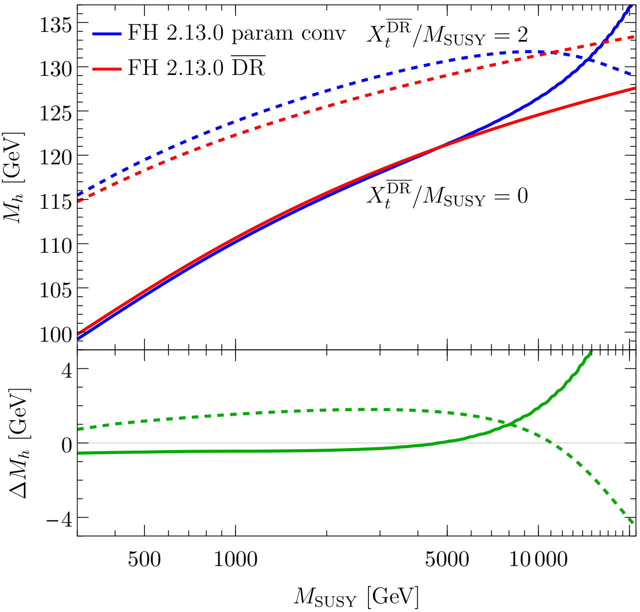
Procedure so far

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

Problem: result contains resummed logarithms

$\rightarrow$ 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

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

Very similar for non-logarithmic terms.

Observation

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

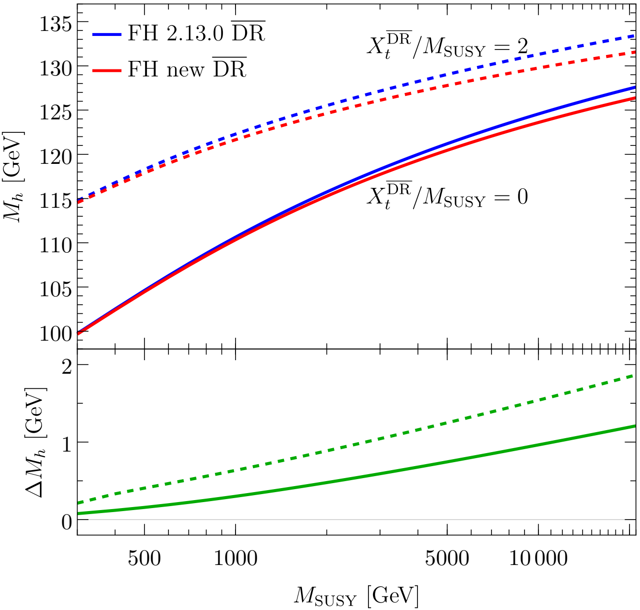
$$\frac{(\delta v^2)^{\text{MSSM}}}{v^2} = \frac{(\delta v^2)^{\text{SM}}}{v^2} - \hat{\Sigma}_{hh}^{\text{nonSM},(1)\prime}(m_h^2) + \mathcal{O}(v/M_{\text{SUSY}})$$

- 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

$\downarrow$

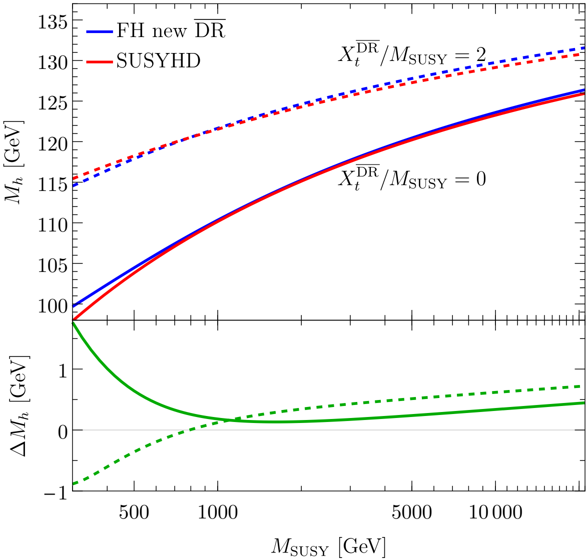
adapted determination of Higgs propagator pole to avoid these terms

→ built into new `FeynHiggs` version (will appear soon)



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)

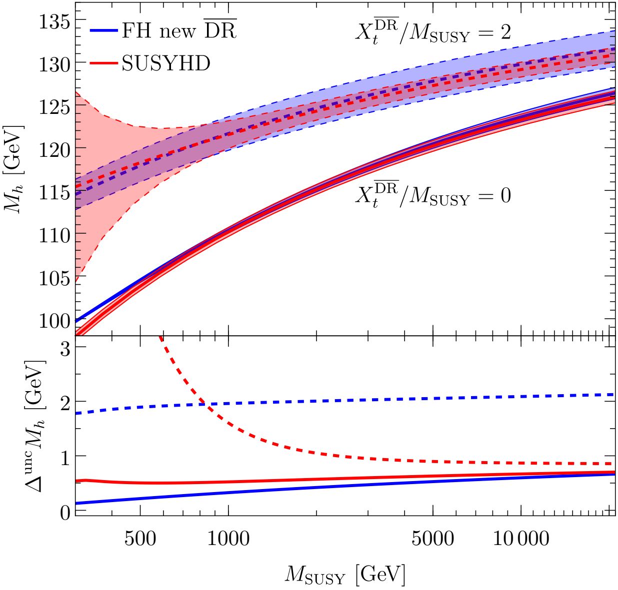
Comparison of uncertainty estimates

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
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}} = 2$
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}} = 0$
M_h [GeV]
$\Delta^{\text{unc}} M_h$ [GeV]
M_{SUSY} [GeV]
135
130
125
120
115
110
105
100
3
2
1
0
500
1000
5000
10 000

Uncertainty estimates

- comparable for vanishing stop mixing
- `FeynHiggs`'s estimate larger for large stop mixing
  $\rightarrow$ due to reparametrization of top mass (non-logarithmic terms)
- estimate of `SUSYHD` of higher order non-logarithmic terms probably too low

Rule of thumb

- uncertainty of ~ 0.5 GeV for vanishing stop mixing
- uncertainty of $\sim 2 - 2.5$ GeV for large stop mixing

$\downarrow$

more precise fixed-order calculation
(or higher order threshold corrections)
needed to further reduce uncertainty

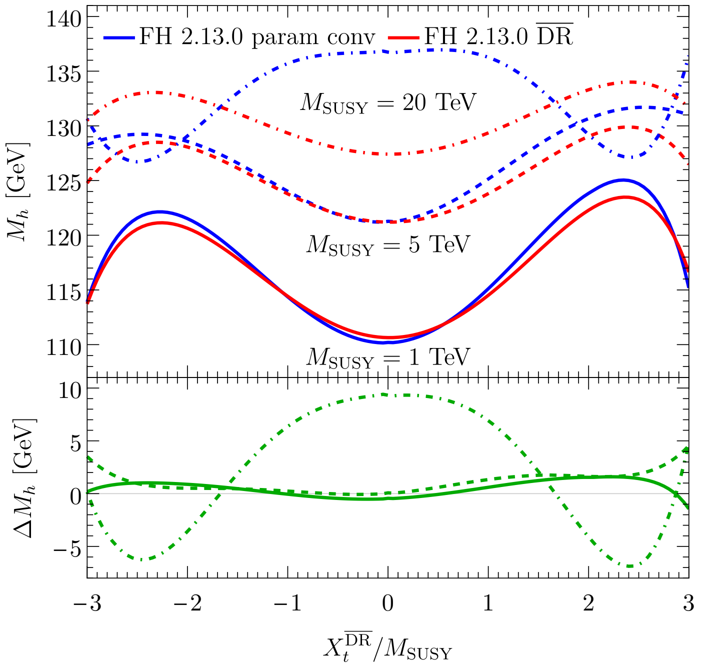
Conclusion

- $\overline{\text{DR}} \to$ OS parameter conversion induces large higher order terms when result contains large logarithms
- Observed cancellation of non-SM terms arising through the determination of the propagator pole with contributions of subloop-renormalization
- Taking into account these effects
  $\to$ excellent agreement of `FeynHiggs` with pure EFT codes found for high scales

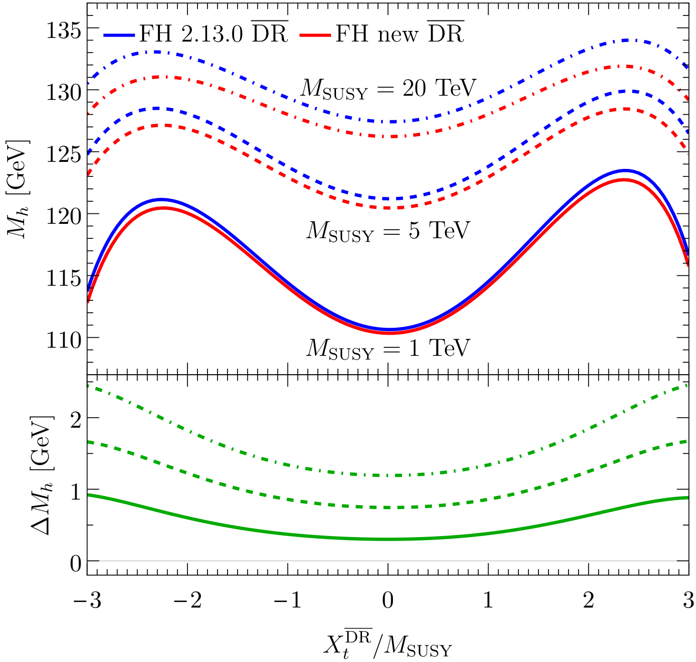
$\Downarrow$

Shows that `FeynHiggs` provides precise predictions of M_h for both low and high SUSY scales

Future work: Investigation of more complicated scenarios with multiple scales



FH 2.13.0 param conv
FH 2.13.0 $\overline{\text{DR}}$
$M_{\text{SUSY}} = 20$ TeV
$M_{\text{SUSY}} = 5$ TeV
$M_{\text{SUSY}} = 1$ TeV
M_h [GeV]
ΔM_h [GeV]
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}}$
140
135
130
125
120
115
110
10
5
0
−5
−3
−2
−1
0
1
2
3


FH 2.13.0 $\overline{\text{DR}}$
FH new $\overline{\text{DR}}$
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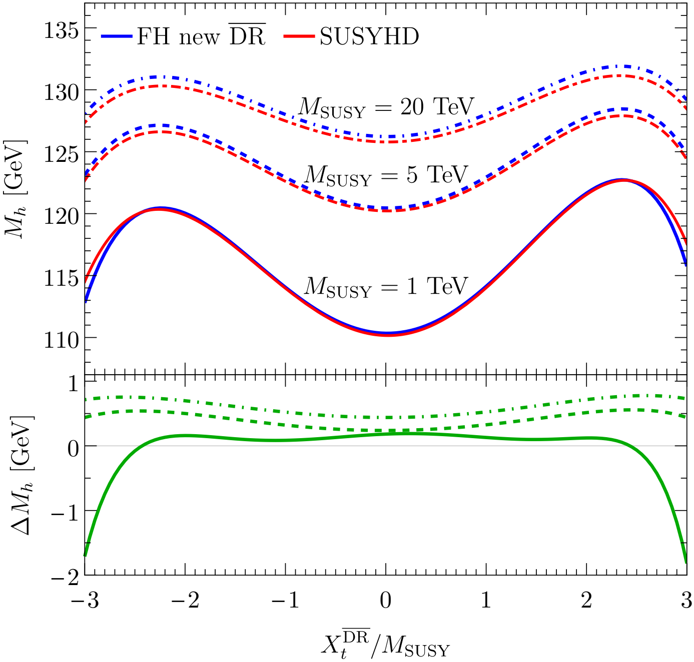
FH new $\overline{\text{DR}}$
SUSYHD
$M_{\text{SUSY}} = 20$ TeV
$M_{\text{SUSY}} = 5$ TeV
$M_{\text{SUSY}} = 1$ TeV
M_h [GeV]
ΔM_h [GeV]
$X_t^{\overline{\text{DR}}}/M_{\text{SUSY}}$
135
130
125
120
115
110
1
0
−1
−2
−3
−2
−1
0
1
2
3