Precise Higgs mass predictions for multi-scale hierarchies with FeynHiggs

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The SM-like Higgs mass as a precision observable

Special feature of the 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 $M_h^2 \simeq M_Z^2 \cos^2(2\beta) \leq M_Z^2$,
- M_h is, however, heavily affected by loop corrections,
- directly sensitive to the SUSY scale.

Experimentally measured mass: [Aad et al.,1503.07589]

$$M_h^{\text{exp}} = 125.08 \pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{sys.})\ \text{GeV}$$

To fully profit from experimental precision, higher order calculations are crucial!

FeynHiggs

Main purpose: precise calculation of Higgs mass spectrum in the MSSM.

[Authors: HB,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Weiglein]

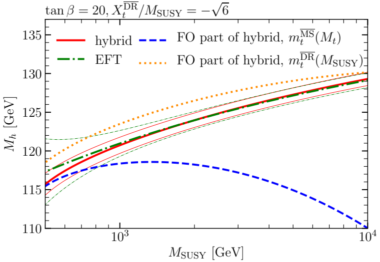
Higgs mass calculation II

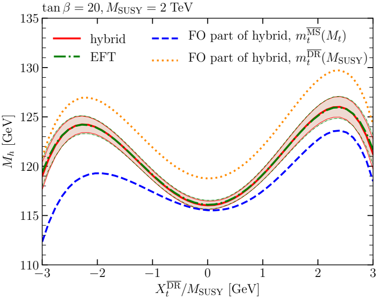
Three approaches are used:

- Fixed-order (FO) approach:
  - \+ Precise for low SUSY scales,
  - − but for high scales $\ln(M_{\text{SUSY}}^2/M_t^2)$ terms spoil convergence of perturbative expansion.
- effective field theory (EFT) approach:
  - \+ Precise for high SUSY scales (logs resummed),
  - − but for low scales $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms are missed if higher-dimensional operators are not included.
- hybrid approach combining FO and EFT approaches:
  - ++ Precise for low and high SUSY scales.

Current status for single-scale scenarios [HB,Heinemeyer,Hollik,Weiglein,1912.04199]

Single-scale scenario with all non-SM particles at M_{SUSY} (SM as EFT)





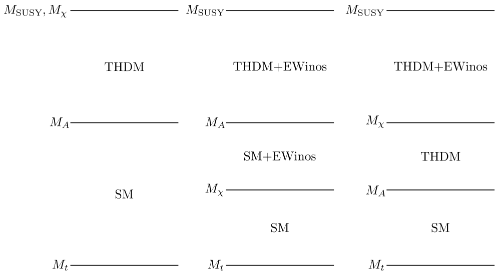
"Rule of thumb"

Remaining theoretical uncertainties (for $\overline{\text{DR}}$ stop input parameter):
$X_t/M_{\text{SUSY}} = 0 \;\rightarrow\; \Delta M_h \sim$ 0.5 GeV,
$X_t/M_{\text{SUSY}} = \sqrt{6} \;\rightarrow\; \Delta M_h \sim$ 1 GeV

Slightly higher for OS stop input parameters.

Multi-scale hierarchies

Large hierarchy between SUSY particles → EFT tower needed.



EFTs implemented in `FeynHiggs`:

- SM (resums $\ln(M_{\tilde t}/M_t)$),
- SM+EWinos (resums $\ln(M_{\tilde t}/M_{\tilde\chi})$),
- SM+Gluino (resums $\ln(M_{\tilde t}/M_{\tilde g})$ if $M_{\tilde g} < M_{\tilde t}$),
- SM+EWinos+Gluino,
- THDM (resums $\ln(M_{\tilde t}/M_A)$),
- THDM+EWinos,
- THDM+EWinos+Gluino.

THDM as EFT

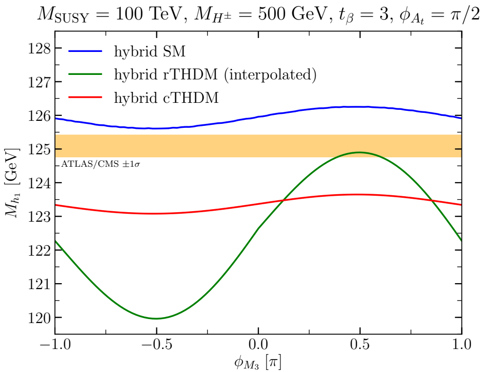
- For low M_A, the EFT of the MSSM is not the THDM type-II, $\rightarrow$ both Higgs doublets couple to e.g. top quarks,
- loop corrections induce non-zero (potentially complex) values for $\lambda_{5,6,7}$

$\Rightarrow$ Large number of EFT parameters complicating the calculation.

Recent progress:

- complex THDM as EFT [HB,Murphy,Rzehak,1909.00726,2010.04711],
- calculation of $\mathcal{O}(\alpha_t^2)$ threshold corrections [HB,Sobolev, 2010.01989].

Complex THDM as EFT



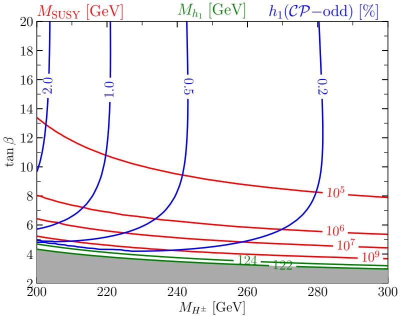
Including phase dependence fully in

- 2L RGEs,
- one-loop threshold corrections,
- $\mathcal{O}(\alpha_t\alpha_s)$ λ_i-threshold corrections.

Application: the $\mathcal{CP}$-odd component of the SM-like Higgs boson

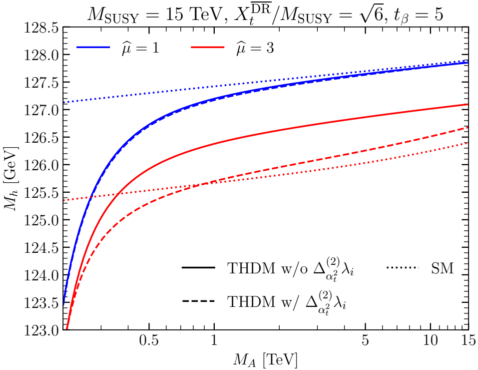
Sizeable $\mathcal{CP}$-odd component requires

- large mixing with $\mathcal{CP}$-odd A boson
  - imaginary parts of couplings have to be large ($\phi_{A_t} = 2\pi/3, \phi_{M_3} = \pi/4$)
  - $\tan\beta$ and $M_{H^\pm}$ must be small
- large SUSY scale required to ensure $M_h \sim 125$ GeV $\rightarrow \mathcal{CP}$-mixing decouples



Potential discovery of $\mathcal{CP}$-odd component at the LHC has potential to exclude the MSSM.

$\mathcal{O}(\alpha_t^2)$ threshold corrections to λ_i



- compared different calculation methods,
- easiest method: calculate 2L 4-point functions in the unbroken phase,
- calculation fully includes CP-violating phases.

⇒ similar precision level as for single-scale hierarchy: theoretical uncertainty for low M_A should be under control!

Introduction

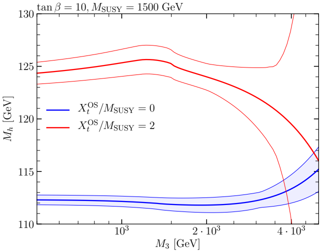
Multi-scale hierarchies: low-mass BSM Higgs bosons

Multi-scale hierarchies: high-mass gluino

Conclusions

The heavy gluino limit: $M_{\tilde{g}} \gg M_{\tilde{t}}$

Increasingly relevant due to tightening LHC gluino limits.



Large uncertainty due to M_3 power-enhanced terms appearing at the two-loop level in $\overline{\rm DR}$ EFT calculation (do not appear in OS scheme).

Needed EFT: MSSM without gluino

Has not been worked out yet...

(available in `FeynHiggs` since version 2.18.0)

Solution: Absorb power-enhanced terms into renormalization scheme [HB,Sobolev,Weiglein,1912.10002]

Use $\overline{\text{MDR}}$ instead of $\overline{\text{DR}}$ in EFT ($\overline{\text{DR}}$ ill-defined for $Q < |M_3|$),

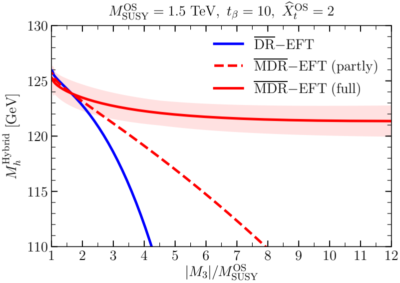
$$\left(m^{\overline{\text{MDR}}}_{\tilde{t}_{L,R}}\right)^2 = \left(m^{\overline{\text{DR}}}_{\tilde{t}_{L,R}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m^2_{\tilde{t}_{L,R}}} \left(1 + \ln \frac{Q^2}{|M_3|^2}\right)\right],$$

$$X_t^{\overline{\text{MDR}}}(Q) = X_t^{\overline{\text{DR}}}(Q) - \frac{\alpha_s}{\pi} C_F M_3 \left(1 + \ln \frac{Q^2}{|M_3|^2}\right),$$

resums all $\mathcal{O}(\alpha_s^n M_3^{2n}, \alpha_s^n M_3^n)$ terms.

$\Downarrow$

Drastically reduced uncertainty.



(coming to `FeynHiggs` soon)

Introduction

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Multi-scale hierarchies: high-mass gluino

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- The SM-like Higgs mass is a unique observable in the MSSM directly sensitive to the SUSY scale,
- most precise prediction available for single-scale scenario (SM as EFT).

What about multi-scale hierarchies?

- Low-mass BSM Higgs bosons (THDM as EFT):
  - have now reached similar precision level as for single-scale hierarchy,
  - $\mathcal{CP}$ violating phases are fully taken into account.
- High-mass gluino:
  - large uncertainty if gluino is heavier than stops in the $\overline{\text{DR}}$ scheme,
  - large corrections can be absorbed by modifying the renormalization scheme.

Conclusions

- The SM-like Higgs mass is a unique observable in the MSSM directly sensitive to the SUSY scale,
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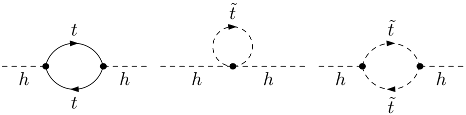
Thanks for your attention!

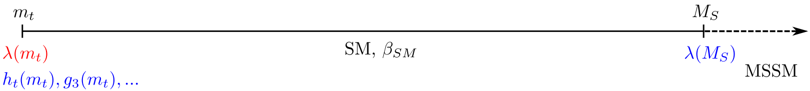
Fixed-order techniques



$$M_h^2 = m_h^2 + \frac{6y_t^4}{(4\pi)^2} v^2 \left[\ln \frac{M_{\tilde{t}}^2}{M_t^2} + \left(\frac{X_t}{M_{\tilde{t}}} \right)^2 - \frac{1}{12} \left(\frac{X_t}{M_{\tilde{t}}} \right)^4 \right] + \ldots$$

- Stop mass scale $M_{\tilde{t}} = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$,
- large logarithms spoil perturbative convergence if $M_{\tilde{t}} \gg M_t$,
- status in `FeynHiggs`: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2)$.

EFT calculation (simplest hierarchy)



- Integrate out all SUSY particles $\rightarrow$ SM as EFT,
- Higgs self-coupling fixed at matching scale

$$\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g_y^2) + \frac{6y_t^4}{(4\pi)^2}\left[\left(\frac{X_t}{M_{\text{SUSY}}}\right)^2 - \frac{1}{12}\left(\frac{X_t}{M_{\text{SUSY}}}\right)^4\right] + \ldots,$$

- run Higgs self-coupling down to electroweak scale,
- calculate Higgs mass: $M_h^2 = \lambda(M_t)v^2 + \ldots,$
- status in `FeynHiggs`: full LL + NLL resummation, NNLL resummation in gaugeless limit, partial N^{3}LL resummation; similar precision for multi-scale hierarchies.

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 $\rightarrow$ need to calculate more three- and two-loop corrections,
- EFT calculation $\rightarrow$ need to include higher-dimensional operators into calculation.

or ...

$$\downarrow$$

Hybrid approach

Combine both approaches to get precise results for both regimes!

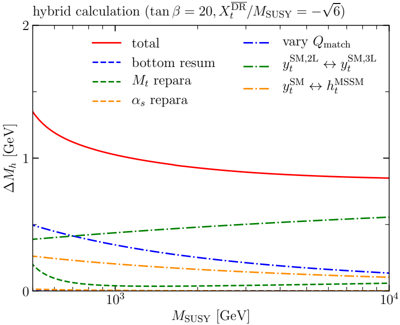
Procedure in FeynHiggs

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

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

In practice, this is achieved by using subtraction terms.

Remaining uncertainties – individual sources



Uncertainty estimate dominated by:

- Uncertainty from higher order threshold corrections:
  - vary matching scale between SM and MSSM,
  - reexpress threshold correction in terms of $h_t^{\rm MSSM}$ instead of $y_t^{\rm SM}$.
- Uncertainty of SM input couplings:
  - $y_t(M_t)$ extracted at the 2- or 3-loop level out of OS top mass.

$\rightarrow$ `FeynHiggs` provides point-by-point uncertainty estimate.