# Precise prediction of MSSM Higgs boson masses combining fixed-order and effective field theory calculations

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Current situation:

- Higgs discovery at LHC fixed last free parameter of the Standard Model (SM),

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

- However still open questions which can not be solved within the SM
  $\rightarrow$ Need beyond SM physics
- No direct evidence for beyond SM physics at LHC so far

Beyond SM models constrained by

- Direct searches
- Indirect constraints $\rightarrow$ precision observables

## One of the most common models of beyond the SM physics

**M**inimal **S**upersymmetric **S**tandard **M**odel

- Builds upon the concept of Supersymmetry (SUSY) relating bosons and fermions
- Each SM particle is associated with a superpartner
- Superpartner has same couplings but its spin is shift by 1/2

MSSM Higgs sector: 2 Higgs doublets

- Corresponds to a type II Two-Higgs-doublet model (THDM)
- Two Higgs doublets results in five physical Higgs states: $\mathcal{CP}$-even: $h$, $H$; $\mathcal{CP}$-odd: $A$; Charged: $H^\pm$
- SUSY reduces Higgs potential parameters to 2 non-SM parameters ($M_A$ 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 $\sim 100\%$)

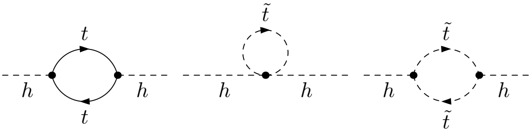
$\rightarrow$ Higher order calculations are essential

Two standard approaches:

- Fixed-order techniques
- Effective field theories

# Fixed-order approach

Calculate Higgs self-energy diagrams:

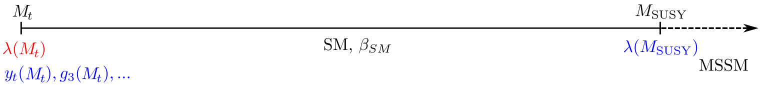



Status: full 1L, $\mathcal{O}(\alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2)$ 2L, partial 3L

→ 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 $\rightarrow$ SM as EFT
- Higgs self-coupling fixed at matching scale $\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g_y^2)\cos^2 2\beta + \ldots$
- Run $\lambda$ down to electroweak scale using SM RGEs
- Calculate Higgs mass in effective SM: $M_h^2 = 2\lambda(M_t)v^2 + \ldots$

Status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL

$\rightarrow$ Precise for high SUSY scales (logarithms resummed) ✓

But: Inaccurate for low scales (misses $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms) ✗

# How to deal with intermediary SUSY scales?

- For superpartners in the LHC range, both large logarithms and $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms might be relevant

↓

**Hybrid approach**

Combine both approaches to get precise results for both regimes

- First calculation based on existing state-of-the-art fixed-order result:
  - $\mathcal{O}(\alpha_s, \alpha_t)$ LL and NLL resummation [Hahn et. al. (2013)]
  - Implemented into public code `FeynHiggs`

# Hybrid approach

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

$$\hat{\Sigma}_{hh} \longrightarrow \hat{\Sigma}_{hh} + \Delta_{hh}^{\text{EFT}}$$

with

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

Additional complication:

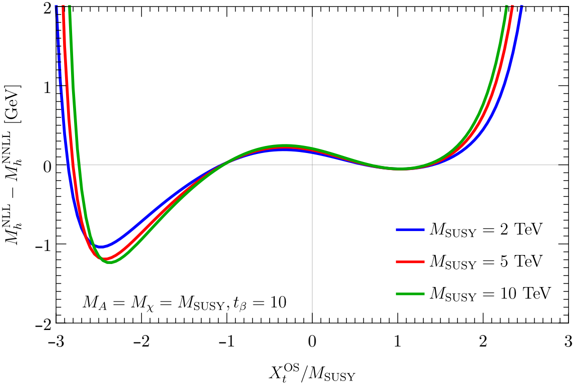
Fixed-order calculation uses mixed OS/$\overline{\text{DR}}$ scheme, for EFT calculation however $\overline{\text{DR}}$ parameters needed (i.e. $X_t^{\overline{\text{DR}}}$)

$\rightarrow$ 1L log only conversion of $X_t$ sufficient

# Improvement of EFT calculation

- Inclusion of electroweak contributions
  - Included at the LL+NLL level
    (full SM 2L RGEs, full 1L threshold corrections)
  - Include electroweak 1L corrections to SM $\overline{\text{MS}}$ top mass, used in the fixed-order calculation
- Separate thresholds for EWinos and gluino
- Inclusion of $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation
  - 2L threshold correction for $\lambda$, 3L RGEs

# Example result – Inclusion of NNLL resummation

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Same logarithmic accuracy as pure EFT calculations

# Comparison to pure EFT calculations

For large SUSY scales, suppressed terms are negligible
⇒ Expect to see agreement with EFT codes for high scales

✗ Large discrepancies could be observed

Two main origins found:

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

Focus on single scale scenario: $\tan\beta = 10, \;\; M_A = M_\chi = M_{\text{Susy}}$

Hybrid approach uses OS/$\overline{\text{DR}}$ scheme $\leftrightarrow$ EFT calculations $\overline{\text{DR}}$

$\rightarrow$ For comparison parameter conversion necessary

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

Conversion:

- $X_t^{\overline{\text{DR}}} \xrightarrow{1L} X_t^{\text{OS}}$
- Forget about $X_t^{\overline{\text{DR}}}$, use $X_t^{\text{OS}}$ as "new" input parameter

**Problem: result contains resummed logarithms**

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

$\Rightarrow$ Implemented optional $\overline{\text{DR}}$ ren. of fixed-order result

# Pole mass determination

In the decoupling limit $M_A \gg M_t$, we have to solve

$$p^2 - m_h^2 + \hat{\Sigma}_{hh}(p^2) + \Delta_{hh}^{\text{EFT}} = 0$$

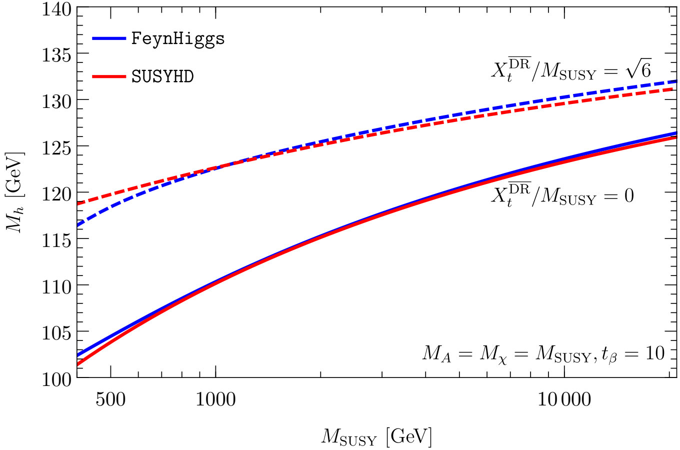
- Numerical solution induces terms beyond order of fixed-order calculation
- Part of these terms would cancel in a more complete calculation

$\downarrow$

Adapted determination of Higgs propagator pole to avoid these terms (truncate expansion around tree-level mass)

# Comparison to SUSYHD as exemplary EFT code

[J.P. Vega, G. Villadoro]




$\longrightarrow$ Good agreement for $M_{\mathrm{SUSY}} > 1$ TeV

# Resummation for low $M_A$

**Assumption so far**

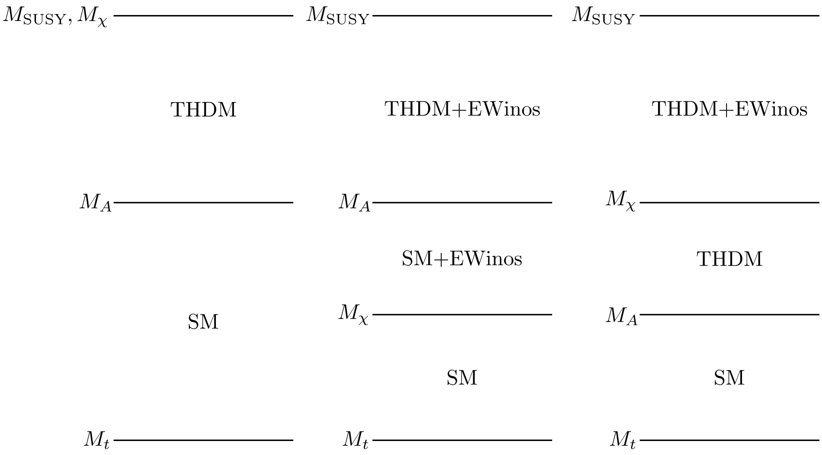
Fermion superpartners and heavy Higgs bosons share common mass scale

In case of $M_A \ll M_{\text{SUSY}}$, SM is not the right EFT anymore

$$\downarrow$$

Low-energy THDM is needed for full resummation of $\ln(M_{\text{SUSY}}/M_A)$

# 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 $\rightarrow$ 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 $\lambda_i$'s

$\rightarrow$ Most precise EFT calculation available

# Combination with fixed-order calculation

$\mathcal{CP}$-even Higgs masses are zeros of

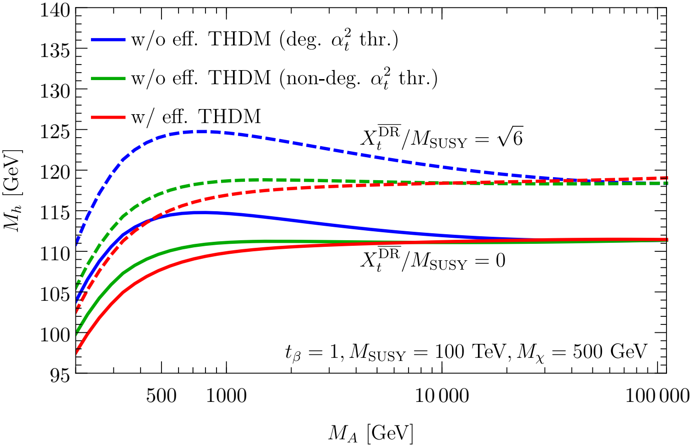
$$\Delta^{-1}_{\text{hybrid}}(p^2) =$$
$$= \begin{pmatrix} p^2 - m_h^2 + \hat{\Sigma}_{hh}(p^2) + \Delta^{\text{EFT}}_{hh} & \hat{\Sigma}_{hH}(p^2) + \Delta^{\text{EFT}}_{hH} \\ \hat{\Sigma}_{hH}(p^2) + \Delta^{\text{EFT}}_{hH} & p^2 - m_H^2 + \hat{\Sigma}_{HH}(p^2) + \Delta^{\text{EFT}}_{HH} \end{pmatrix}$$

with $\Delta^{\text{EFT}}_{ij} = \hat{\Sigma}^{\text{EFT}}_{ij} - \hat{\Sigma}^{\text{sub}}_{ij}$

Important: "Relative" normalization of Higgs doublets

- Combination of EFT result (THDM normalization) with fixed order result (MSSM renormalization) $\rightarrow$ Implemented by means of finite field renormalization
- Calculation of 1L and 2L subtraction terms

# Scan over $M_A$



w/o eff. THDM (deg. $\alpha_t^2$ thr.)
w/o eff. THDM (non-deg. $\alpha_t^2$ thr.)
w/ eff. THDM
$X_t^{\overline{\mathrm{DR}}}/M_{\mathrm{SUSY}} = \sqrt{6}$
$X_t^{\overline{\mathrm{DR}}}/M_{\mathrm{SUSY}} = 0$
$t_\beta = 1, M_{\mathrm{SUSY}} = 100$ TeV, $M_\chi = 500$ GeV
$M_h$ [GeV]
$M_A$ [GeV]
95
100
105
110
115
120
125
130
135
140
500
1000
10 000
100 000

# Conclusion

- SM-like Higgs mass is an important constraint on MSSM parameter space
- Precise prediction for low and high SUSY scales
  $\rightarrow$ Combine fixed-order and EFT calculations
- Improved accuracy of EFT calculation
  - Full LL, NLL and $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL corrections
  - Low-energy electroweakino and gluino thresholds
- Optional $\overline{\text{DR}}$ renorm. and improved pole determination
  $\rightarrow$ Good agreement with pure EFT codes
  found for high scales
- For low $M_A$, implemented effective THDM as EFT

$\rightarrow$ All results implemented into public code `FeynHiggs`