Constraining the MSSM Higgs sector using precise Higgs mass predictions

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The MSSM Higgs sector

- SM Higgs sector enlarged by adding additional Higgs doublets
  → corresponds to type-II THDM at the tree-level
- Five physical Higgs bosons:
  \( \mathcal{CP} \)-even \( h \) and \( H \), \( \mathcal{CP} \)-odd \( A \), and charged \( H^\pm \)
- SUSY fixes Higgs potential parameters
  → only two non-SM parameters: \( M_A \) and \( \tan \beta = v_2/v_1 \)

Tree-level prediction

SM-like \( h \) boson mass: \( M_h^2 \leq M_Z^2 \cos^2 2\beta \leq M_Z^2 \)

- But: Large loop corrections shift Higgs mass up.
Fixed-order approach

- Most direct approach: evaluate self-energy diagrams
- Status: $O$(full 1L, $\alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2$) + 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 approach

Integrate out all SUSY particles $\rightarrow$ SM as EFT

Higgs self-coupling fixed at matching scale

$$\lambda(M_{\text{SUSY}}) = \frac{1}{4} (g^2 + g'^2) c_{2\beta}^2 + ...$$

Use RGEs to run $\lambda$ down to electroweak scale
$\rightarrow$ resummation of large logarithms

Status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL, partial $N^3$LL

$\rightarrow$ precise for high SUSY scales (logs resummed),
but for low scales $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms are missed
How to deal with intermediary SUSY scales?

For sparticles in the TeV 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 ...

↓

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

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

In practice, this is achieved by using subtraction terms.
Hybrid approach of **FeynHiggs** - history

- $O(\alpha_s, \alpha_t)$ LL+NLL resummation
  $\Delta M_h \sim +3$ GeV for $M_{SUSY} \sim 1$ TeV [Hahn et al.,1312.4937]

- Full LL+NLL and $O(\alpha_s, \alpha_t)$ NNLL resummation
  $\Delta M_h \sim -1$ GeV for $M_{SUSY} \sim 1$ TeV [HB&Hollik,1608.01880]

- Comparison to EFT approach
  $\Delta M_h \sim -0.5$ GeV for $M_{SUSY} \sim 1$ TeV
  [HB,Heinemeyer,Hollik,Weiglein,1706.00346]

- THDM as EFT
  $\Delta M_h \sim -2$ GeV for $M_A \ll M_{SUSY}$, $\tan \beta \lesssim 5$ [HB&Hollik,1805.00867]

- Improved pole determination close if $M_A \sim M_t$
  $\Delta M_h \sim \pm 3$ GeV if second Higgs has almost same mass
  [HB,1812.06452]
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Hybrid approach - comparison to EFT approach

\[ \tan \beta = 20, \frac{X_{\text{DR}}}{M_{\text{SUSY}}} = -\sqrt{6} \]

Uncertainty bands → [HB, Heinemeyer, Hollik, Weiglein, 19xx.xxx]
Hybrid approach - THDM as EFT

- Implemented EFTs:
  SM, SM+EWinos, SM+EWinos+Gluino,
  THDM, THDM+EWinos, THDM+EWinos+Gluino
- Full LL+NLL resummation and partial NNLL resummation
Application to MSSM Higgs benchmark scenarios – why do we need them?

- Large number of free parameters
- Interpretation of measured Higgs properties and searches for additional Higgs bosons would require parameter scans → impractical

Downarrow

Focus on benchmark scenarios with only two free parameters

- Typically presented in $M_A$-$\tan \beta$ plane (or $M_{H^\pm}$-$\tan \beta$)
- Other parameters chosen such that one neutral Higgs is SM-like
- Each scenario has a different phenomenology
New Higgs benchmark scenarios

Original benchmark scenarios presented in

Since then:

- Improved prediction of SM-like Higgs boson mass
  (see first part of the talk)
- Improved calculation of Higgs production cross-sections
- Updated SM input parameters
- More stringent limits on SUSY particles

New scenarios defined using publicly available tools

- **FeynHiggs** → Higgs masses and branching ratios
- **SusHi** → Higgs production cross-sections
- **HiggsBounds** → direct searches for extra Higgs bosons
- **HiggsSignals** → SM-like Higgs signal strengths
Six new scenarios with fixed $M_{\text{SUSY}} \sim 1.5$ TeV

[HB,Fuchs,Hahn,Heinemeyer,Liebler,Patel,Slavich,Stefaniak,Wagner,Weiglein,1808.07542]

- $M_{h}^{125}$ scenario → all SUSY particles at the TeV scale
- $M_{h}^{125}(\tilde{\tau})$ scenario → light Stau, Bino and Winos
- $M_{h}^{125}(\tilde{\chi})$ scenario → light Bino, Winos and Higgsinos
- $M_{h}^{125}$ (alignment) scenario → alignment without decoupling
- $M_{H}^{125}$ scenario → heavy $\mathcal{CP}$-even Higgs is SM-like
- $M_{h_{1}}^{125}$ (CPV) scenario → $\mathcal{CP}$-violation in the Higgs sector

Two new scenarios valid for low $\tan \beta$

[HB,Liebler,Stefaniak, 1901.05933]

- $M_{h,EFT}^{125}$ scenario resembling $M_{h}^{125}$ scenario
- $M_{h,EFT}(\tilde{\chi})^{125}$ scenario resembling $M_{h}^{125}(\tilde{\chi})$ scenario
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$M_h^{125}(\tilde{\chi})$ and $M_{h,EFT}^{125}(\tilde{\chi})$ scenarios

\[
M_{Q3} = M_{U3} = M_{D3} = M_{L3} = M_{E3} = M_{SUSY},
\]
\[
\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},
\]
\[
A_b = A_{\tau} = A_t.
\]

$M_h^{125}(\tilde{\chi})$:

- $M_{SUSY} = 1.5 \text{ TeV}, \ X_t = 2.8 \text{ TeV}$
- Use SM+EWinos as EFT

$M_{h,EFT}^{125}(\tilde{\chi})$:

- Adjust $M_{SUSY}$ at every point such that $M_h \sim 125$ GeV (upper limit: $10^{16}$ GeV, $A_t = 0$)
- Need THDM+EWinos as EFT
$M_{h}^{125}(\tilde{\chi})$ scenario

- Blue: Excluded by direct searches for heavy Higgs bosons
- Hashed: Excluded by Higgs signal strengths / Higgs mass

$M_{h}$ [GeV]

$tan\beta$

$M_{A}$ [GeV]

$122$

$124$

$125$

$126$

$127$
$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario

$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario

- Gray: $M_h < 122$ GeV
- Potentially interesting signature: $H, A, H^\pm \rightarrow$ leptons + $\not{E}_T$
Calculation of SM-like Higgs mass

► Fixed-order approach precise for low SUSY scales
► EFT approach precise for high SUSY scales
► Hybrid approach merges fixed-order and EFT approaches → precise also for intermediary scales

Application: new MSSM Higgs benchmark scenarios

► Existing scenarios outdated
► Proposed set of new scenarios based on state-of-the-art calculations
\[ M_{h,\text{EFT}}^{125}(\tilde{\chi}) \rightarrow h \rightarrow \gamma\gamma \text{ enhancement} \]