Constraining the MSSM Higgs sector using precise Higgs mass predictions

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The MSSM Higgs sector

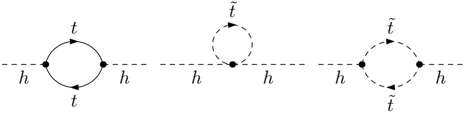
- SM Higgs sector enlarged by adding additional Higgs doublets
  → corresponds to type-II THDM at the tree-level
- Five physical Higgs bosons:
  $\mathcal{CP}$-even h and H, $\mathcal{CP}$-odd A, and charged $H^{\pm}$
- SUSY fixes Higgs potential parameters
  → only two non-SM parameters: M_A and $\tan\beta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

Tree-level prediction

SM-like h boson mass: $M_h^2 \le M_Z^2 \cos^2 2\beta \le M_Z^2$

- But: Large loop corrections shift Higgs mass up.

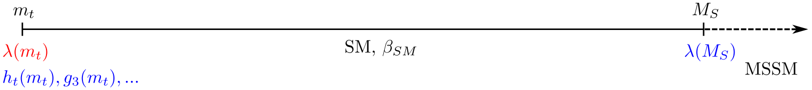
Fixed-order approach



- Most direct approach: evaluate self-energy diagrams
- Status: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2)$
  $+$ partial three-loop results

$\rightarrow$ 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 $\to$ 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 λ down to electroweak scale
  $\to$ resummation of large logarithms
- Status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL, partial N^{3}LL

$\to$ 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 → 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

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

In practice, this is achieved by using subtraction terms.

Hybrid approach of `FeynHiggs` - history

- $\mathcal{O}(\alpha_s, \alpha_t)$ LL+NLL resummation
  $\Delta M_h \sim +3$ GeV for $M_{\text{SUSY}} \sim 1$ TeV [Hahn et al.,1312.4937]
- Full LL+NLL and $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL resummation
  $\Delta M_h \sim -1$ GeV for $M_{\text{SUSY}} \sim 1$ TeV [HB&Hollik,1608.01880]
- Comparison to EFT approach
  $\Delta M_h \sim -0.5$ GeV for $M_{\text{SUSY}} \sim 1$ TeV
  [HB,Heinemeyer,Hollik,Weiglein,1706.00346]
- THDM as EFT
  $\Delta M_h \sim -2$ GeV for $M_A \ll M_{\text{SUSY}}$, $\tan\beta \lesssim 5$ [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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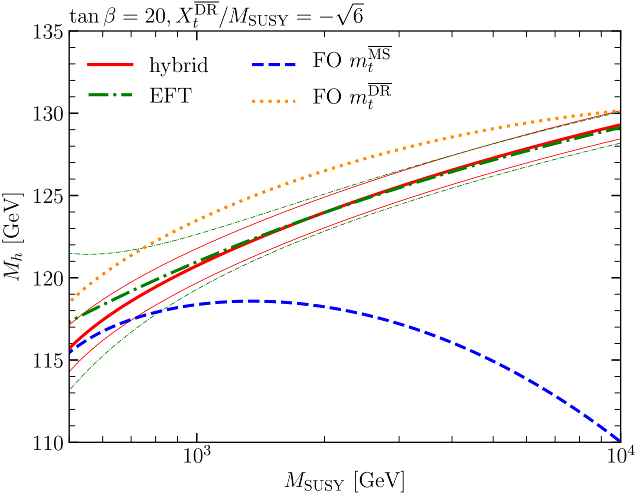
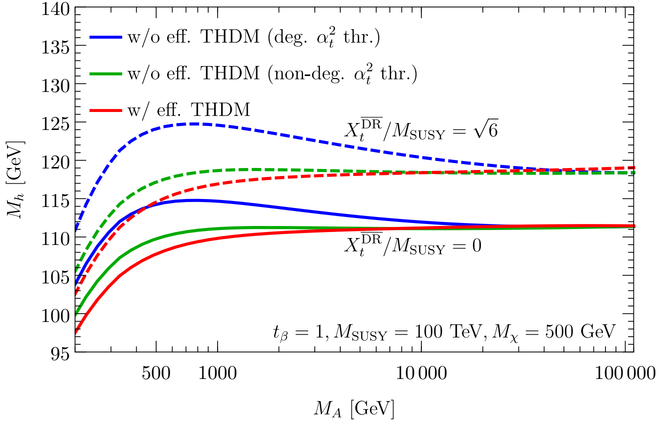
Hybrid approach - comparison to EFT approach



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 $\rightarrow$ 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
[hep-ph/9912223,hep-ph/0202167,hep-ph/0009212,1302.7033,1512.00437]

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]

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

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

$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = M_{\text{SUSY}},$$

$$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$A_b = A_\tau = A_t\,.$$

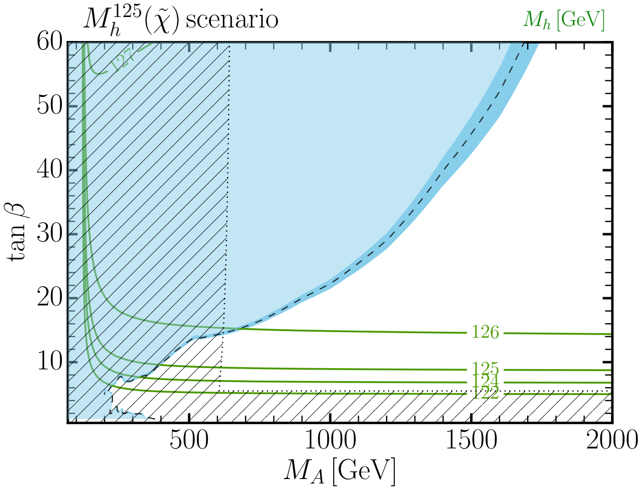
$M_h^{125}(\tilde{\chi})$:

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

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

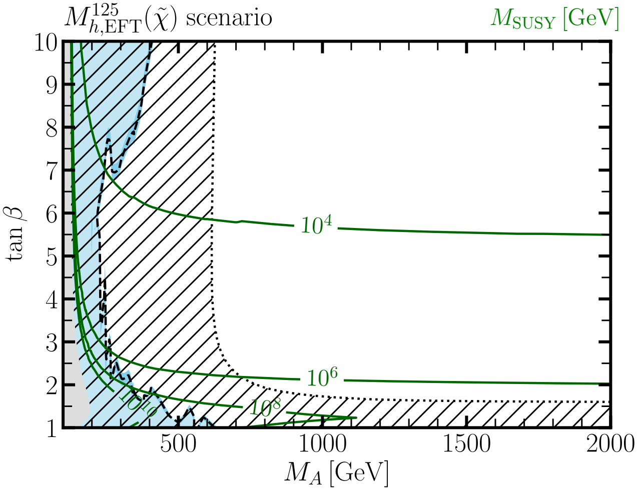
- Adjust M_{SUSY} at every point such that $M_h \sim 125$ GeV (upper limit: 10^{16} GeV, $A_t = 0$)
- Need THDM+EWinos as EFT

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



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

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



- Gray: $M_h < 122$ GeV
- Potentially interesting signature: $H, A, H^{\pm} \to$ 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
  $\rightarrow$ 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

$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ — $h \to \gamma\gamma$ enhancement