Higgs mass calculation in FeynHiggs

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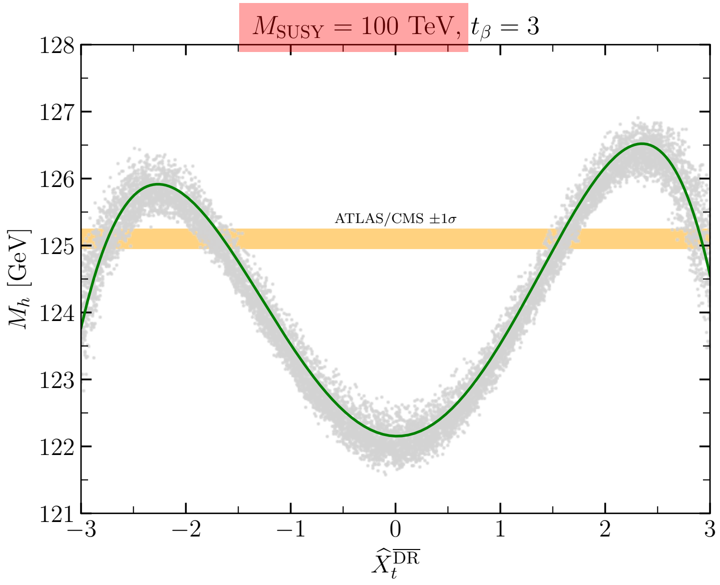
The SM-like Higgs mass as a precision observable

Special feature of the MSSM:
Mass of the lightest CP-even Higgs M_h is calculable in terms of model parameters
⇒ can be used as a precision observable.

- At the 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,
- unique sensitivity to SUSY parameters (even for very heavy SUSY scales).



[HB,Braathen,Weiglein, to appear]

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!

This is the main purpose of **FeynHiggs**.

[Authors: HB, Thomas Hahn, Sven Heinemeyer, Wolfgang Hollik, Sebastian Paßehr, Heidi Rzehak, Georg Weiglein]

Calculation of the Higgs boson masses

Three approaches are used:

- Fixed-order (FO) approach:
  - \+ precise for low SUSY scales,
  - – but for high scales large logarithms $\ln(M_{\text{SUSY}}^2/m_t^2)$ terms spoil convergence of perturbative expansion.
- Effective field theory (EFT) approach:
  - \+ precise for high SUSY scales (since logarithms are resumed),
  - – but for low scales $\mathcal{O}(m_t/M_{\text{SUSY}})$ terms are missed if higher-dimensional operators are not included.
- Hybrid approach combing FO and EFT approaches:
  - ++ precise for low and high SUSY scales.

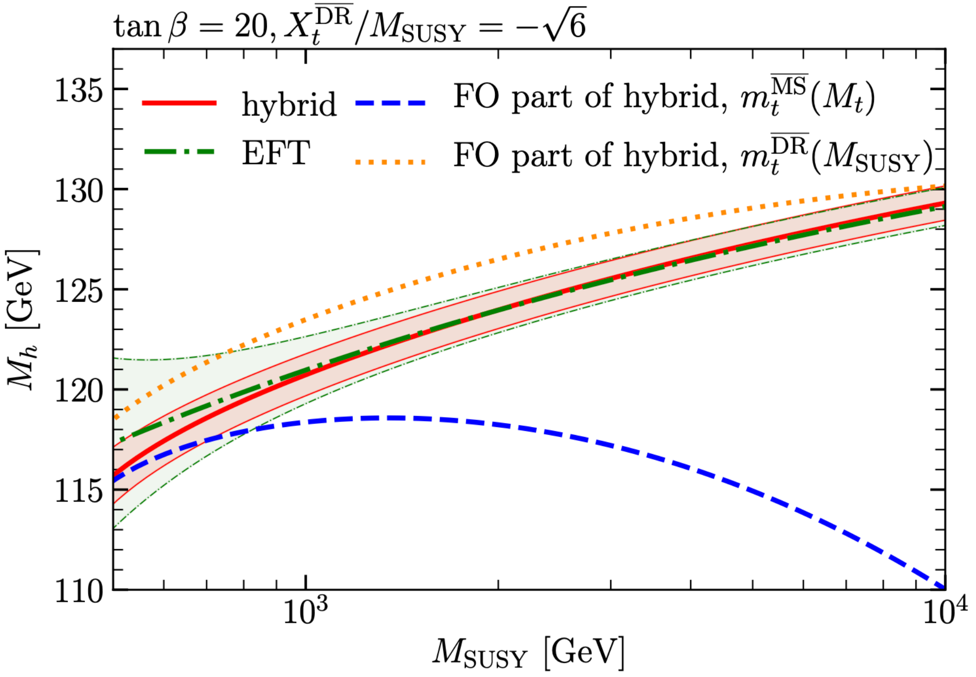
Current status:

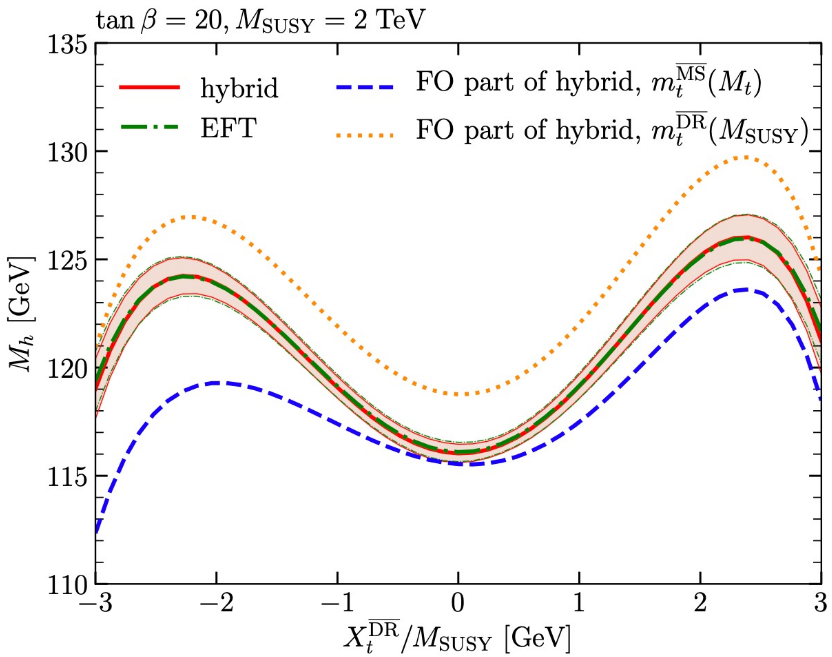
→ FO: (full 1L) + (2L in gaugeless limit),

→ EFT: (full LL + NLL) + (NNLL + partial $\mathrm{N}^3\mathrm{LL}$ in gaugeless limit).

Remaining theoretical uncertainty for single-scale scenario [HB,Heinemeyer,Hollik,Weiglein,1912.04199]

(single-scale scenario: all non-SM particles at M_{SUSY})





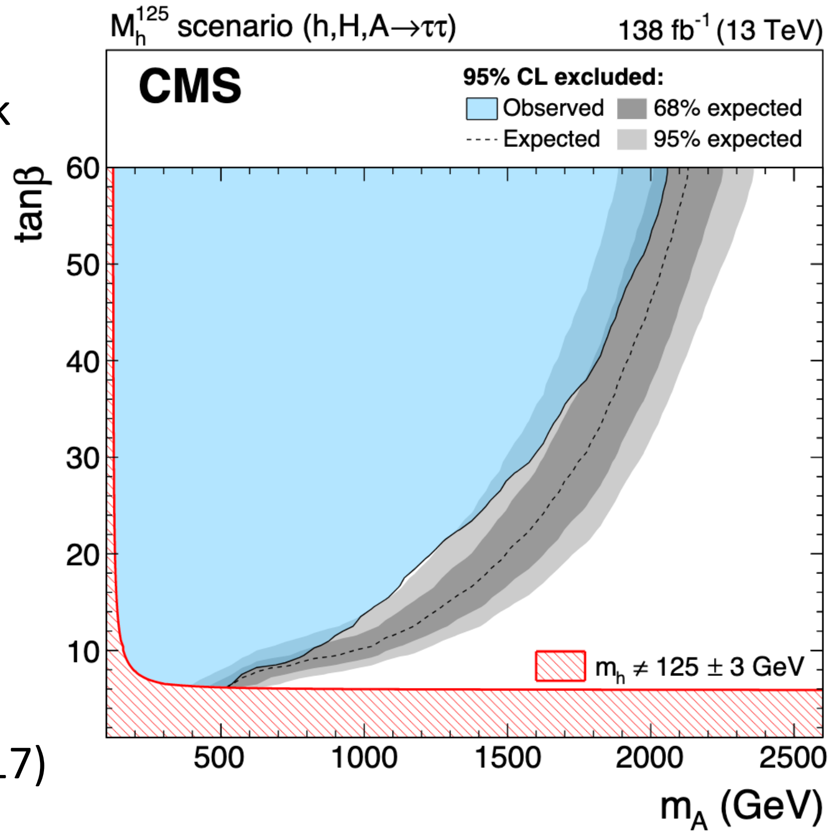
Approximate remaining theory uncertainty (for $\overline{\text{DR}}$ stop sector):

- Small stop mixing: $\Delta M_h \sim 0.5$ GeV
- Large stop mixing: $\Delta M_h \sim 1.0$ GeV

(slightly larger for OS stop sector)

Exemplary pheno application

- Higgs mass calculation has been used to define MSSM Higgs benchmark scenarios.
  [Bagnaschi et al.,1808.07542; HB et al.,1901.05933,2005.14536; Bagnaschi et al.,LHCHWG-2021-001]
  → see also Emanuele Bagnaschi's talk later today!
- These scenarios are used by the experimental collaborations for interpretation.
- These scenarios have been defined using FeynHiggs 2.14.
- Updates since then have
  - improved theoretical uncertainty estimate (v2.15)
  - added real THDM as EFT (v2.16)
  - added partial $\mathrm{N}^3\mathrm{LL}$ resummation + phase dependence in EFT (v2.17)
  - added complex THDM as EFT (v2.18)
  - introduced the $\overline{\mathrm{MDR}}$ scheme + reimplemented of FO 2L corrections (v2.19)

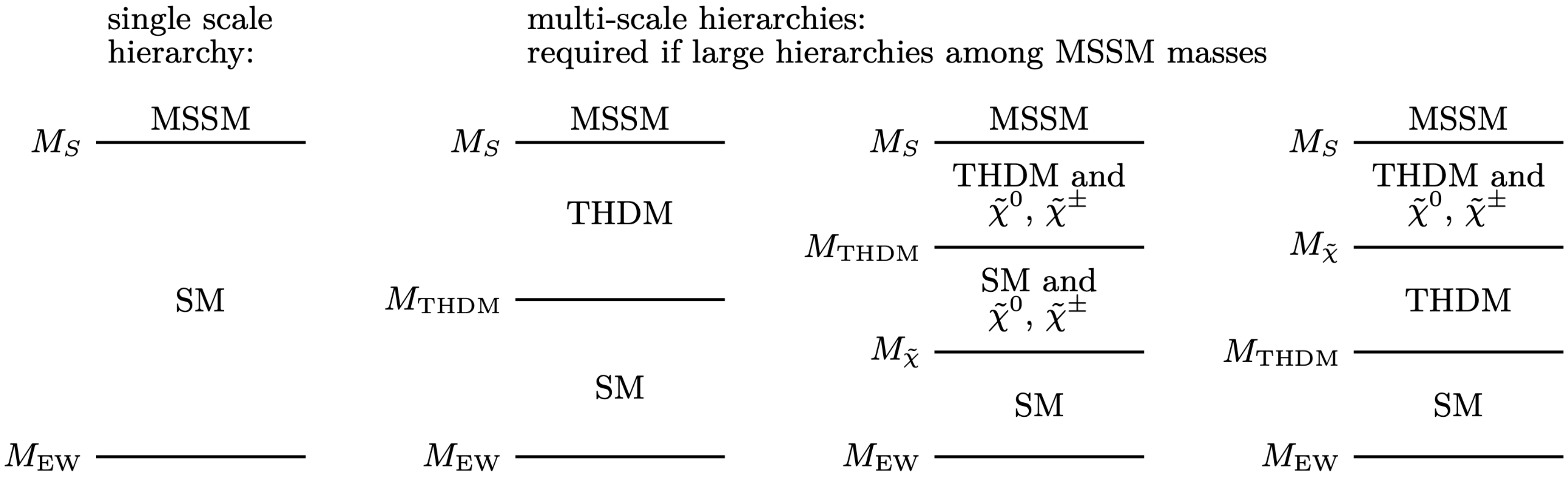


[CMS, 2208.02717]

Focus of FH updates: multi-scale hierarchies

- Experimental searches for colored SUSY particles push mass scale to the TeV range.
- Uncolored particles can, however, be lighter.

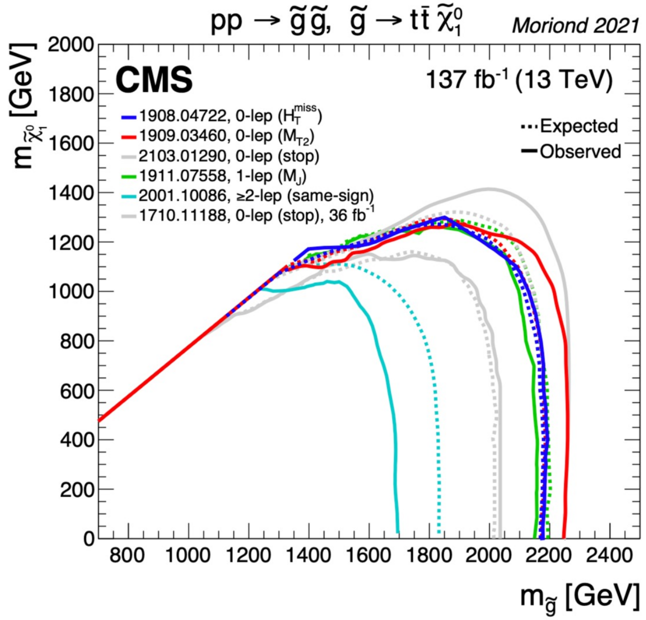
Large hierarchy between non-SM particles → tower of EFTs needed to resum all large logarithms.



- All these EFT towers are implemented in FeynHiggs.

Missing case so far: heavy gluino $(M_{\tilde{g}} = |M_3| \gg M_{\tilde{t}})$

- Increasingly relevant due to tightening LHC gluino limits.



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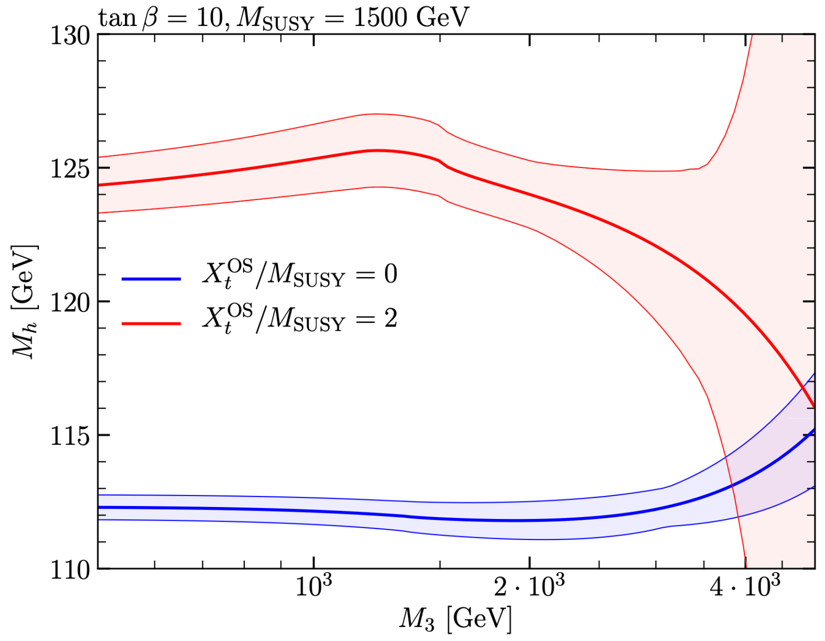

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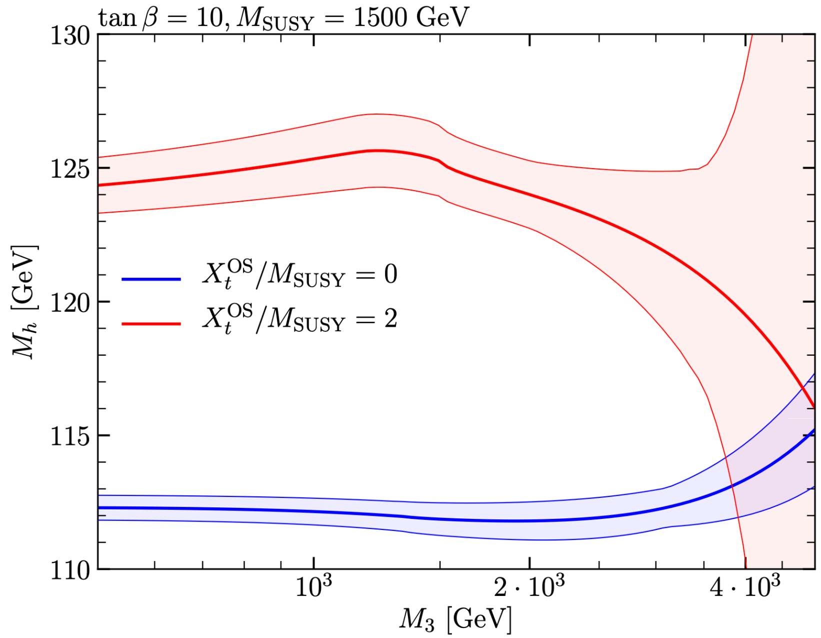
- OS renormalization of the stop sector avoids this issue. This, however, spoils the resummation of large logarithms.



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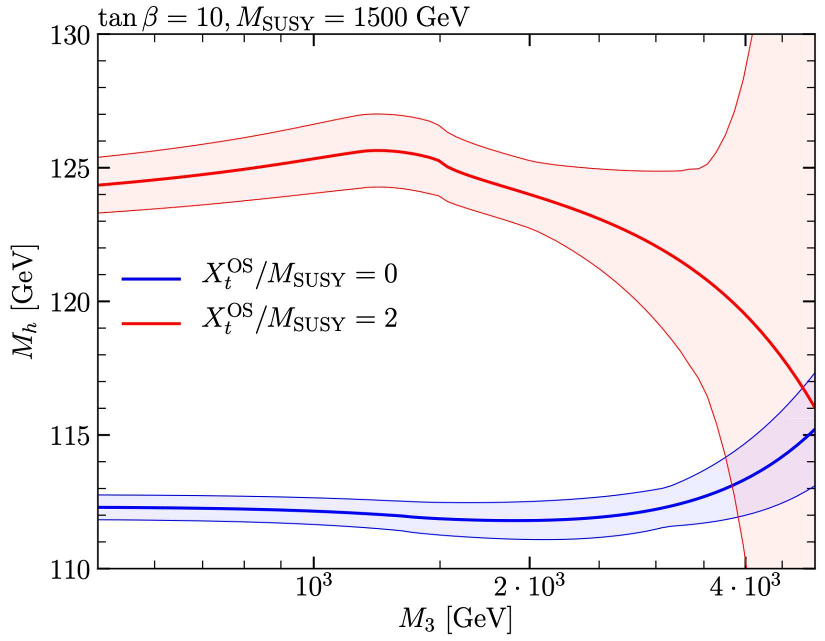
- While this is a known issue in the literature, it was not resolved in the context of Higgs mass calculations.
  [Mühlleitner et al., 0812.3815, Aebischer et al., 1703.08061; Krämer et al., 1908.04798; Deppisch et al., 1908.01222]



Solution: Absorb power-enhanced terms into renormalization scheme

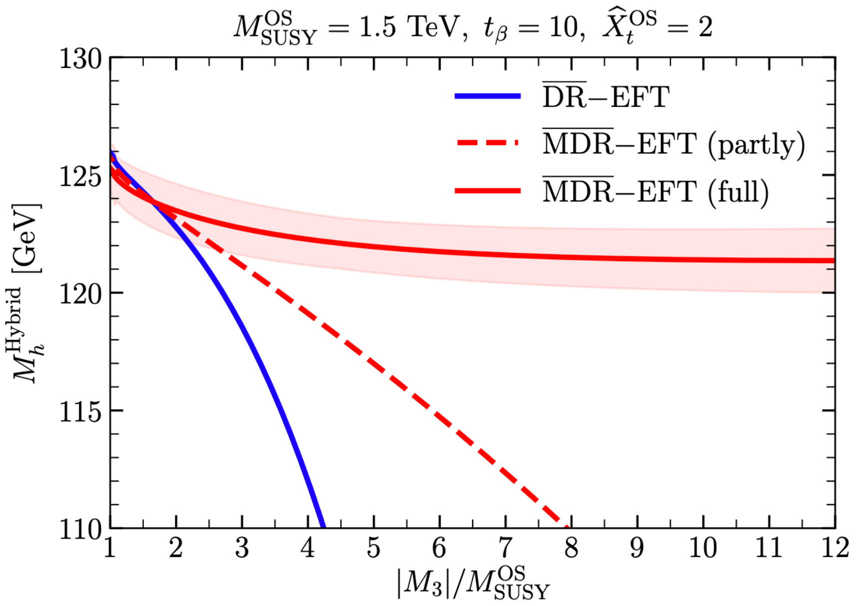
[HB,Sobolev,Weiglein,1912.10002]

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

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

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

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



Drastically reduced theoretical uncertainty.

$\overline{\text{MDR}}$ scheme in FeynHiggs 2.19

- FeynHiggs now uses $\overline{\text{MDR}}$ scheme in EFT part by default.

- OS stop input parameters → OS scheme is used in FO calculation and $\overline{\text{MDR}}$ scheme in EFT part.

- $\overline{\text{DR}}$ stop input parameters → conversion to $\overline{\text{MDR}}$ scheme → $\overline{\text{MDR}}$ scheme used in FO and EFT calculation.
  - ➢ Renormalization scale should not be below M_3 → otherwise no precise prediction possible.

- Alternatively, $\overline{\text{MDR}}$ stop input parameters can be used directly as input.

⇨ First precise Higgs mass prediction for scenarios with $M_{\tilde{g}} \gg M_{\tilde{t}}$!

Reimplementation of 2L FO corrections

(based on [Goodsell & Paßehr, arXiv:1910.02094])

- Code for 2L FO corrections was divided in several pieces, which were based on multiple publications:
  - corrections in real MSSM,
    [Brignole et al., hep-ph/0206101,hep-ph/0112177]
  - corrections in complex MSSM.
    [Heinemeyer et al., hep-ph/0411114, hep-ph/0705.0746, Paßehr & Hollik, 1404.7074]
- Code became increasingly difficult to maintain, making it difficult to implement new features like the $\overline{\text{MDR}}$ scheme.

Complete reimplementation of 2L FO corrections in FeynHiggs 2.19.0:

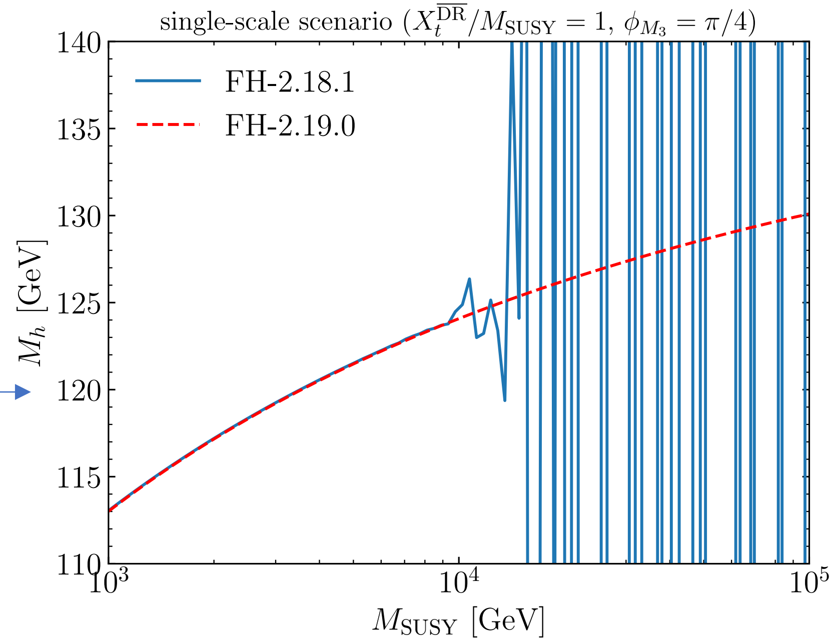
- sum over generalized couplings:
  - ✓ reduced algebraic size,
  - ✓ improved readability;
- easier implementation of different schemes:
  - ✓ $\overline{\text{MDR}}$ for stop sector,
  - ✓ $\overline{\text{DR}}$ for sbottom sector;
- full phase dependence for 2L $\alpha_b\alpha_s, \alpha_b\alpha_t, \alpha_b^2$ corrections;
- improved numerical stability.

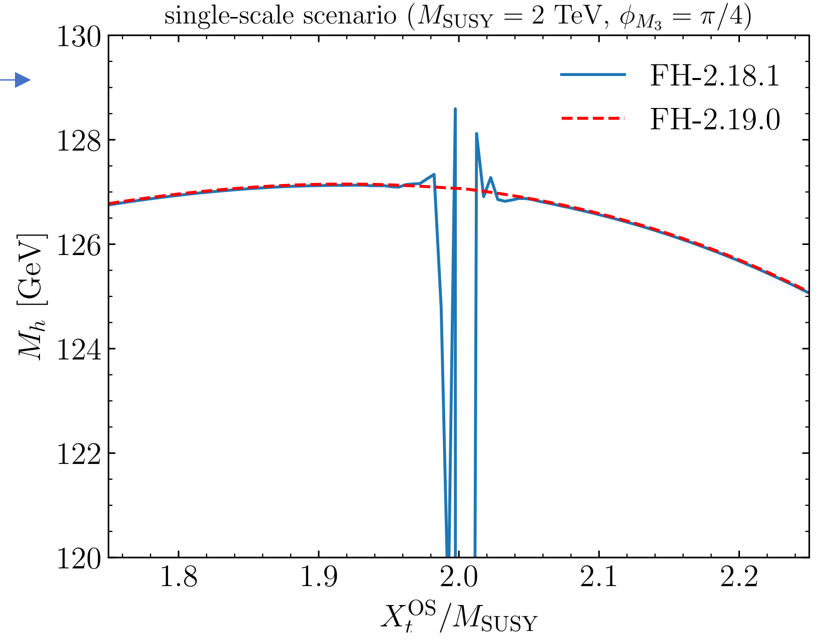
FeynHiggs-2.18.0	FeynHiggs-2.19.0
$\mathcal{O}\big(\alpha_t\,\alpha_s\big)$: 2.9 MB	$\mathcal{O}\big(\alpha_{t,b}\,\alpha_s\big)$: 224 KB
$\mathcal{O}\big(\alpha_t^2\big)$: 364 KB	$\mathcal{O}\Big(\big(\alpha_t+\alpha_b\big)^2\Big)$: 364 KB

Improved numerical stability

Old implementation was plagued by numerical instabilities

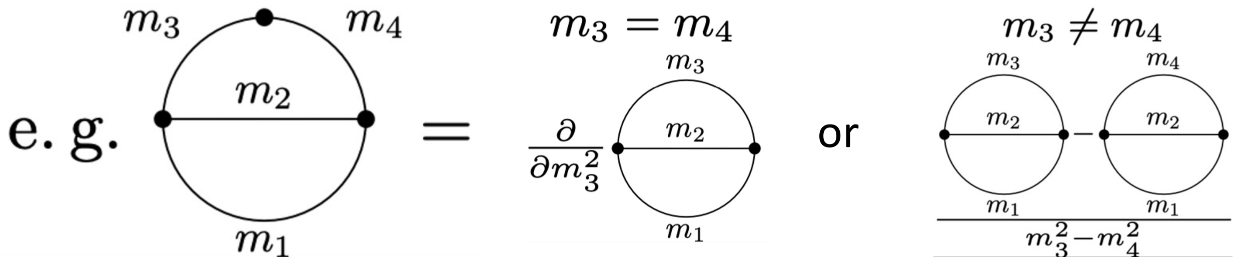
- if two masses were close to each other (e.g. $m_{\tilde{t}_1} \simeq m_{\tilde{t}_2}$),
- close to kinematic thresholds (e.g. $X_t \sim 2M_{SUSY} \to m_{\tilde{t}_{1,2}} \simeq M_{SUSY} \pm m_t$).
- origin: integral reduction resulting in terms like $1/(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2})$





Solution: delayed integral reduction. [Goodsell & Paßehr, arXiv:1910.02094]

- Integrals are reduced at runtime depending on given mass spectrum.



Conclusions

- The SM-like Higgs boson mass is a unique in the MSSM, which is directly sensitive to the SUSY scale.
- Precision predictions in the MSSM Higgs sector are the main purpose of FeynHiggs.
- Recent updates of FeynHiggs are mainly focused on improving the precision for multi-scale hierarchies.

- **New version FeynHiggs 2.19.0**
  - allows the user to obtain precise predictions for scenarios with a heavy gluino,
  - features a complete reimplementation of the fixed-order 2L corrections with a significantly improved numerical stability.

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Thanks for your attention!

- M_h^{125} scenario,
- $M_h^{125}(\tilde{\tau})$ scenario,
- $M_h^{125}(\tilde{\chi})$ scenario,
- $M_h^{125}(\text{alignment})$ scenario,
- M_H^{125} scenario,
- $M_{h_1}^{125}(\text{CPV})$ scenario,
- $M_{h,\text{EFT}}^{125}$ scenario,
- $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario,
- $M_h^{125\mu_i-}$ scenario.