Precision calculations in the MSSM Higgs sector with FeynHiggs

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Current situation in particle physics

- We have a well-established and well-tested model $\rightarrow$ Standard Model (SM),
- but SM must be extended to explain Dark Matter, hierarchy problem, ...,
- no direct evidence for beyond SM physics at the LHC yet,
- most known particles studied intensively confirming SM predictions,
- but discovered SM-like Higgs boson at the LHC.

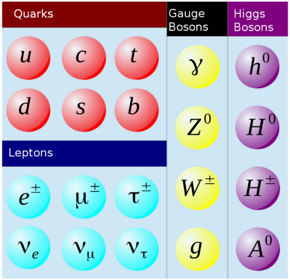
Where to look for new physics?

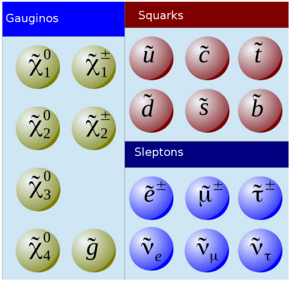
$\rightarrow$ One promising place: the **Higgs sector**

- Higgs boson properties still leave room for deviations from SM,
- Higgs boson can be coupled easily to beyond SM particles,
- why should there be only one scalar particle?

The Minimal Supersymmetric Standard Model (MSSM)

- The MSSM addresses many of the open issues of the SM,
- each SM degree of freedom is associated with a superpartner,
- in addition, the SM Higgs sector is extended by an additional doublet $\rightarrow$ five physical Higgses (h, H, A, $H^{\pm}$)





FeynHiggs

How can we learn the most about the MSSM Higgs sector from current Higgs measurements?

→ Theoretical uncertainty should ideally be smaller than the experimental precision.

⇓

The code FeynHiggs

FeynHiggs provides precision predictions for many Higgs-related observables.

- Higgs masses,
- Higgs decay widths,
- Higgs production cross sections,
- electroweak precision observables,
- basically a Fortran code,
- but a lot of code generated with Mathematica,
- C++ and Mathematica interfaces.

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FeynHiggs — short history

- 1998: original publication in CPC
  "FeynHiggs: a program for the calculation of the masses of the neutral CP-even Higgs bosons in the MSSM",
- since then many FeynHiggs related publications,
- 2018: CPC 50th anniversary article
  "Precision calculations in the MSSM Higgs-boson sector with FeynHiggs 2.14"

Authors:

- HB,
- Thomas Hahn,
- Sven Heinemeyer,
- Wolfgang Hollik,
- Sebastian Paßehr,
- Heidi Rzehak,
- Georg Weiglein.

Former members:

- Karina Williams,
- Ivan Sobolev.

The MSSM Higgs sector – potential

- Two Higgs doublets

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \phi_i + i\chi_i) \end{pmatrix},$$

- general THDM Higgs potential has 9 non-SM parameters

$$\begin{aligned} V_{\text{THDM}}(\Phi_1,\Phi_2) &= m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) \\ &+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \left(\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right), \end{aligned}$$

- SUSY reduces these to 2

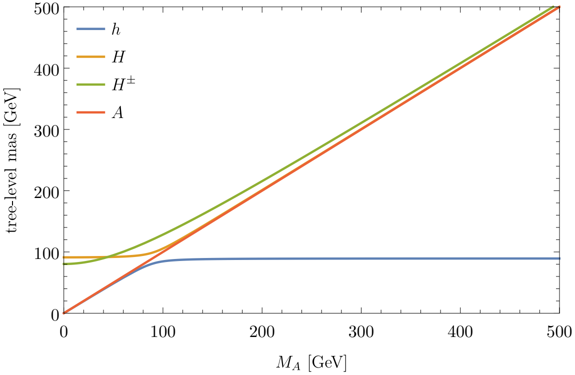
$$\lambda_1 = \lambda_2 = \frac{1}{4}(g^2 + g_y^2), \lambda_3 = \frac{1}{4}(g^2 - g_y^2), \lambda_4 = -\frac{1}{2}g^2, \lambda_{5,6,7} = 0$$

$\rightarrow$ predictive model!

The MSSM Higgs sector – mass eigenstates

Two Higgs doublets → five physical Higgs states: h, H, A, $H^\pm$

- Two non-SM input parameters: M_A and $\tan\beta = v_2/v_1$.



→ Decoupling limit: $M_A \gg M_Z$.

Introduction

The MSSM Higgs sector

Higgs mass calculation

Higgs mass: multi-scale hierarchies

Exemplary phenomenology applications

Conclusions

Higgs mass calculation I

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

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

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

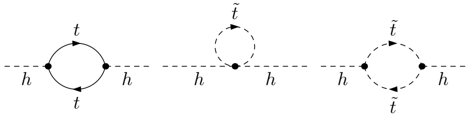
To fully profit from experimental precision, higher order calculations are crucial!

Higgs mass calculation II

Three approaches are used:

- Fixed-order (FO) approach:
  - \+ Precise for low SUSY scales,
  - − but for high scales $\ln(M_{\tilde{t}}^2/M_t^2)$ 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:
  - ++ Precise for low and high SUSY scales.

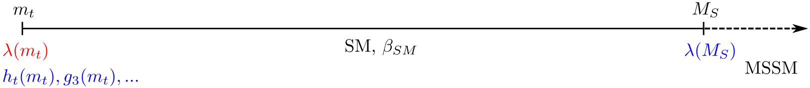
Fixed-order techniques



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

- 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 $\to$ 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

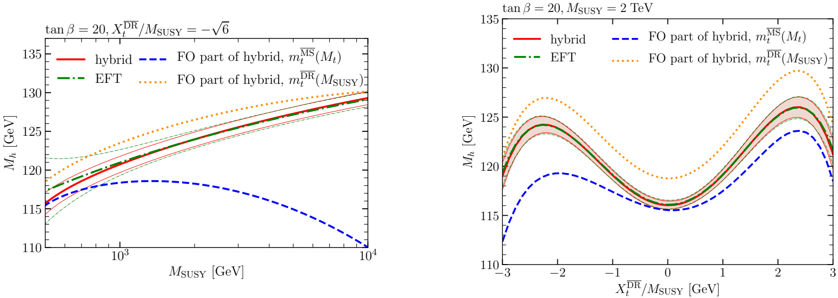
1. Calculation of diagrammatic fixed-order self-energies $\hat{\Sigma}_{hh}$
2. Calculation of EFT prediction $\lambda(M_t)v^2$
3. Add non-logarithmic terms contained in fixed-order result and the logarithms contained in EFT result

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

In practice, this is achieved by using subtraction terms.

Comparison of approaches [HB,Heinemeyer,Hollik,Weiglein,1912.04199]

Single-scale scenario with all non-SM particles at M_{SUSY}

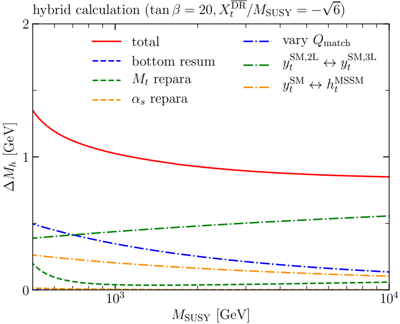


"Rule of thumb"

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.

Remaining uncertainties – individual sources



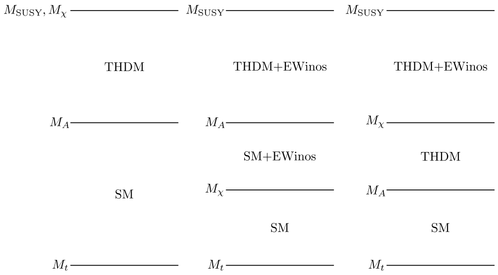
Uncertainty estimate dominated by:

- Uncertainty from higher order threshold corrections:
  - vary matching scale between SM and MSSM,
  - reexpress treshold 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.

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

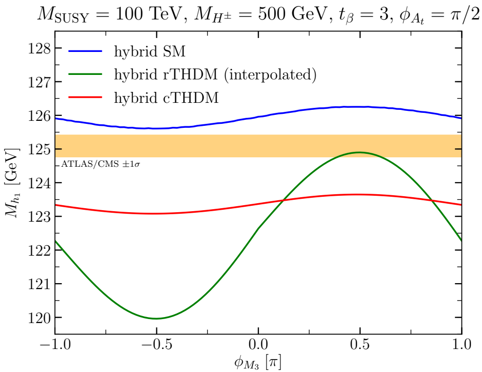
- For low M_A, the EFT of the MSSM is not the THDM type-II, $\rightarrow$ both Higgs doublets couple to e.g. top quarks,
- loop corrections induce non-zero (potentially complex) values for $\lambda_{5,6,7}$

$\Rightarrow$ 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



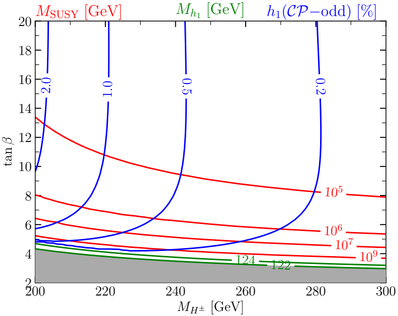
Including phase dependence fully in

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

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

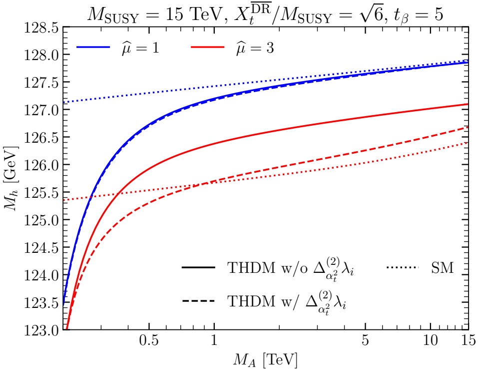
Sizeable $\mathcal{CP}$-odd component requires

- 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 would probably exclude the MSSM.

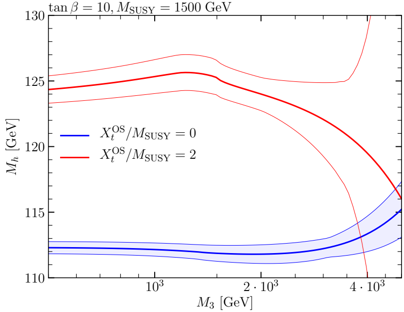
$\mathcal{O}(\alpha_t^2)$ threshold corrections to λ_i



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

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 $\overline{\text{DR}}$ EFT calculation (do not appear in OS scheme).

Needed EFT: MSSM without gluino

Has not been worked out yet...

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

Use $\overline{\text{MDR}}$ instead of $\overline{\text{DR}}$ in EFT,

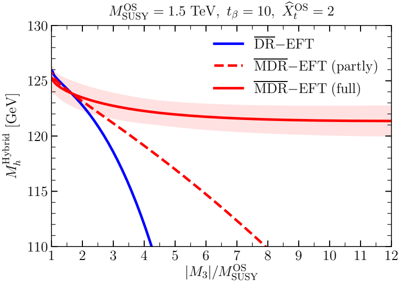
$$\left(m^{\overline{\text{MDR}}}_{\tilde{t}_{L,R}}\right)^2 = \left(m^{\overline{\text{DR}}}_{\tilde{t}_{L,R}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m^2_{\tilde{t}_{L,R}}} \left(1 + \ln\frac{Q^2}{|M_3|^2}\right)\right],$$

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

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

$\Downarrow$

Drastically reduced uncertainty.



(not yet usable with the public `FeynHiggs` version)

Higgs benchmark scenarios – why do we need them?

- MSSM has large number of free parameters,
- interpretation of Higgs properties and searches for additional Higgs bosons would require large parameter scans.

$$\Downarrow$$

Focus on benchmark scenarios with only two free parameters:

- Typically presented in M_A-$\tan\beta$ plane (or $M_{H^\pm}$-$\tan\beta$),
- fix stop mass scale and other parameters such that SM-like Higgs with mass of ~ 125 GeV exists,
- each scenario has a different phenomenology,
- provide interpretation frameworks for experiments.

Six scenarios with sfermion mass scale $M_{\text{SUSY}} \sim 1.5$ TeV

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

Defined using:

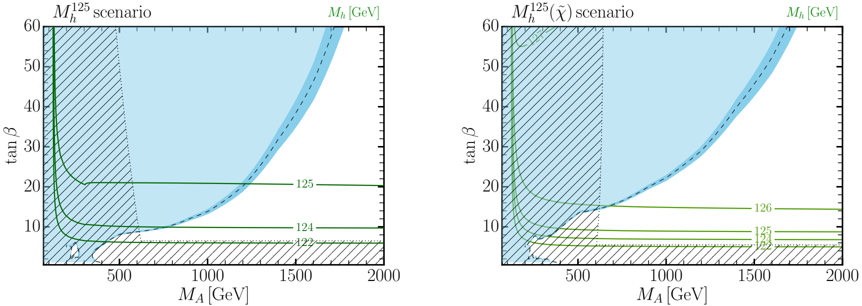
- `FeynHiggs` $\rightarrow$ Higgs masses and branching ratios,
- `SusHi` $\rightarrow$ Higgs production cross-sections,
- `HiggsBounds` $\rightarrow$ direct searches for extra Higgs bosons,
- `HiggsSignals` $\rightarrow$ SM-like Higgs signal strengths.

Exemplary benchmark scenarios:

- M_h^{125} scenario $\rightarrow$ all SUSY particles at the TeV scale,
- $M_h^{125}(\tilde{\chi})$ scenario $\rightarrow$ light Bino, Winos and Higgsinos.

M_h^{125} and $M_h^{125}(\tilde{\chi})$ scenarios

$$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5\text{ TeV}, \quad M_{L_3} = M_{E_3} = 2\text{ TeV},$$
$$M_3 = 2.5\text{ TeV}, \quad X_t = 2.8\text{ TeV}, \quad A_b = A_\tau = A_t\,.$$



$\mu = M_1 = M_2 = 1$ TeV $\qquad$ $\mu = M_2 = 180$ GeV, $M_1 = 160$ GeV

- Blue: excluded by direct searches for heavy Higgs bosons,
- hashed: excluded by SM-like Higgs signal strengths / mass.

M_h^{125} and $M_h^{125}(\tilde{\chi})$ scenarios

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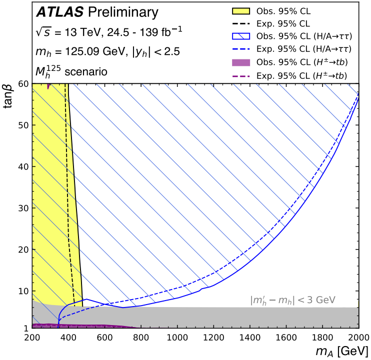
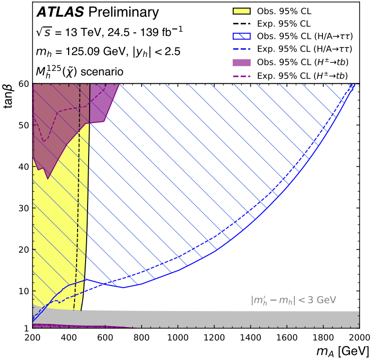




[ATLAS-CONF-2020-053]

Benchmark scenarios for the low $\tan\beta$ region

[HB,Liebler,Stefaniak,1901.05933]

In scenarios with $M_{\text{SUSY}} \sim 1.5$ TeV, region of $\tan\beta \lesssim 8$ excluded, since mass $M_h < 125 \pm 3$ GeV:
$M_{h,\text{tree}} \xrightarrow{t_\beta \to 1} 0 \Rightarrow$ need to raise M_{SUSY} to push M_h upwards.

Concept

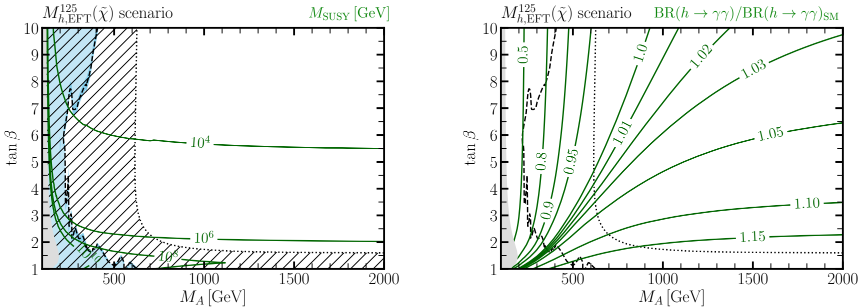
Take existing scenarios and raise M_{SUSY} at every point such that $M_h \sim 125$ GeV (upper limit: $M_{\text{SUSY}} \leq 10^{16}$ GeV).

$\rightarrow$ large hierachy between M_A and M_{SUSY}
$\rightarrow$ using THDM as EFT crucial.

Two low-$\tan\beta$ benchmark scenarios:

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

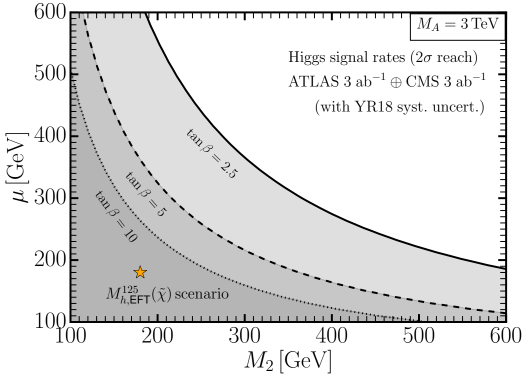
$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario



- Gray: $M_h < 122$ GeV,
- blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by Higgs signal strengths.

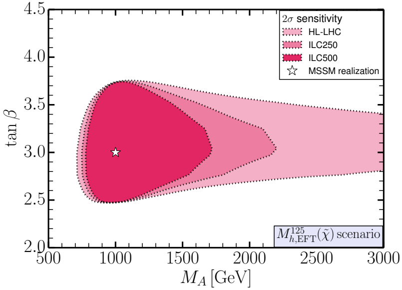
HL-LHC projections – $M_{h,\mathrm{EFT}}^{125}(\chi)$ scenario

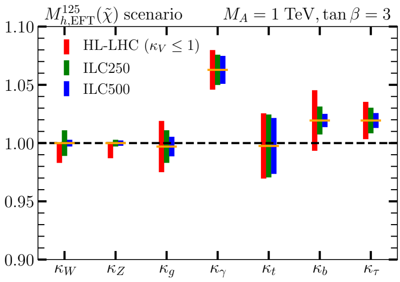
[HB,Bechtle,Heinemeyer,Liebler,Stefaniak,Weiglein,2005.14536]



- Assumption: discovered Higgs has SM-like couplings.

What if $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario is realized in nature?





- Assumption: discovered Higgs has couplings as predicted for $M_A = 1$ TeV and $\tan\beta = 3$.

Conclusions

- Higgs sector is a promising place to look for new physics,
- need precise prediction to fully profit from experimental precision.

→ FeynHiggs provides these for the MSSM.

Higgs mass calculation:

- Unique observable directly sensitive to SUSY scale,
- theoretical uncertainty of $\lesssim 1$ GeV,
- many recent updates for multi-scale hierarchies.

Exemplary phenomenology applications: Higgs benchmark scenarios

- Help to interpret LHC results,
- Higgs couplings → lower bound on M_A ($M_A \gtrsim 600$ GeV),
- Higgs searches → strong constraints for large $\tan\beta$.

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Thanks for your attention!