Constraining the MSSM Higgs sector at the LHC and beyond

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Theory seminar

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Motivation

Current situation:

- No direct evidence for BSM physics at LHC yet,
- most known particles studied intensively confirming SM predictions.

Where to look for new physics?

→ One promising place: the **Higgs sector**

- Higgs boson properties still leave room for deviations from SM,
- Higgs boson can be coupled easily to BSM particles,
- why should there be only one scalar particle?
  → Searches for additional Higgs bosons.

How much can we learn from current Higgs measurements about extended Higgs sectors?

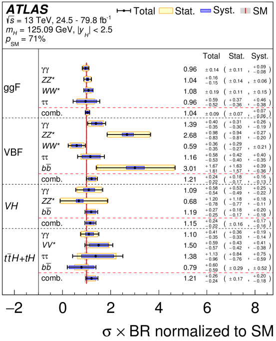
Higgs measurements: examples

- Higgs mass: [Aad et al.,1503.07589]

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

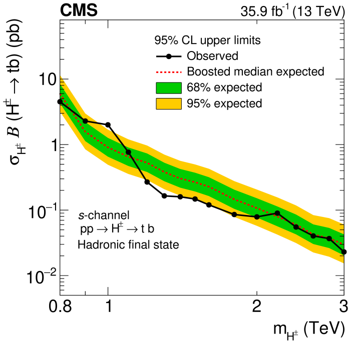
- Coupling measurements:

[1909.02845,ATLAS]



- Additional Higgs bosons:

[2001.07763,CMS]



Complementarity of the constraints

- The different measurements can not be compared directly.
- Need specific BSM model to explore the complementarity between the different constraints!

This talk:

Use MSSM as a benchmark model with a focus on collider phenomenology.

In addition, Higgs physics can also be constrained by

- flavour measurements,
- EDM measurements,
- ...

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

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

- 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

Diagonalizing the Higgs mass matrices yields mass eigenstates

$$\begin{pmatrix} h \\ H \end{pmatrix} = R(\alpha) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \begin{pmatrix} A \\ G \end{pmatrix} = R(\beta) \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}, \begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$\rightarrow$ five physical Higgs states: h, H, A, $H^\pm$

- Two non-SM input parameters: M_A and $\tan\beta = v_2/v_1$,
- tree-level relations:

$$m^2_{h,H} = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right),$$

$$m^2_{H^\pm} = M_A^2 + M_W^2,$$

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \tan 2\beta.$$

The MSSM Higgs sector – decoupling limit

Decoupling limit, $M_A \gg M_Z$, implies:

- masses:

$$m_h^2 \to M_Z^2 \cos^2(2\beta),$$
$$m_H^2 \to M_A^2 + M_Z^2 \sin^2(2\beta),$$

$\Rightarrow$ all Higgses, apart from h, decouple.

- couplings:

$$\alpha \to \beta - \pi/2$$

$\Rightarrow$ couplings of h boson SM-like

- Yukawa sector: THDM type II

$$g_{Hbb}/g_{hbb} \sim \tan\beta,\ g_{H\tau\tau}/g_{h\tau\tau} \sim \tan\beta,\ g_{Htt}/g_{htt} \sim 1/\tan\beta$$
$$g_{Abb}/g_{hbb} \sim \tan\beta,\ g_{A\tau\tau}/g_{h\tau\tau} \sim \tan\beta,\ g_{Att}/g_{htt} \sim 1/\tan\beta$$

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.

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

- Many tools on the market: `FeynHiggs`, `FlexibleSUSY`, `SARAH/SPheno`, `SOFTSUSY`, ...
- In this talk, I will focus on `FeynHiggs` [HB,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Sobolev,Weiglein].

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.

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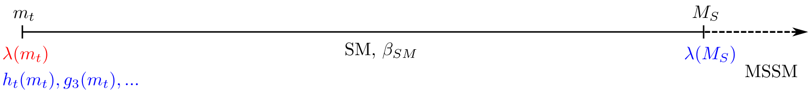
EFT calculation (simplest framework)



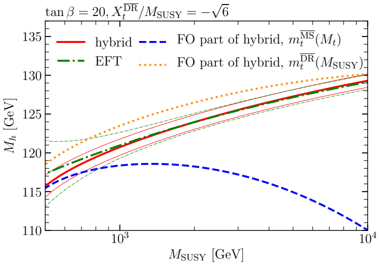
- Integrate out all SUSY particles → SM as EFT,
- Higgs self-coupling fixed at matching scale

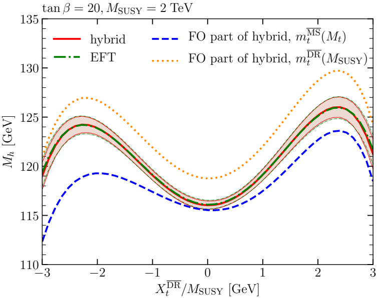
$$\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g_y^2) + \frac{6y_t^4}{(4\pi)^2}\left[\left(\frac{X_t}{M_{\text{SUSY}}}\right)^2 - \frac{1}{12}\left(\frac{X_t}{M_{\text{SUSY}}}\right)^4\right] + \ldots,$$

- run Higgs self-coupling down to electroweak scale,
- calculate Higgs mass: $M_h^2 = \lambda(M_t)v^2 + \ldots,$
- recent progress:
  - NNLL resummation beyond the gaugeless limit [1908.01670,Bagnaschi,Degrassi,Slavich,Paßehr],
  - partial N^3LL resummation [1910.03595,Harlander,Klappert,Voigt],
  - X_t resummation [2003.04639,Kwasnitza,Stöckinger,Voigt].

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

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





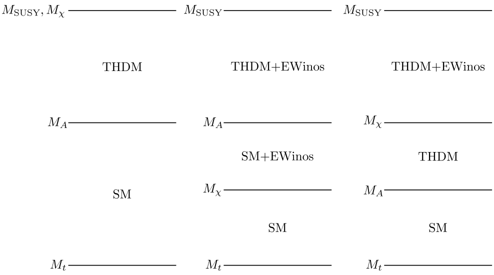
"Rule of thumb"

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.

What happens in non-degenerate scenarios?

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

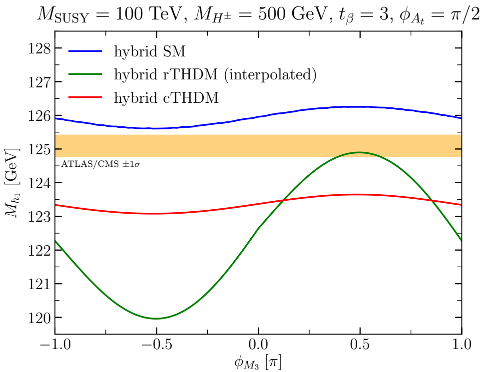
- For low M_A, the EFT of the MSSM is not the THDM type-II,
  $\rightarrow$ both Higgs doublets couple to e.g. top quarks,
- loop corrections induce non-zero (potentially complex) values for $\lambda_{5,6,7}$

$\Rightarrow$ 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



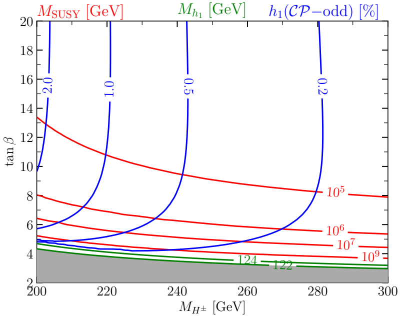
Including phase dependence fully in

- 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

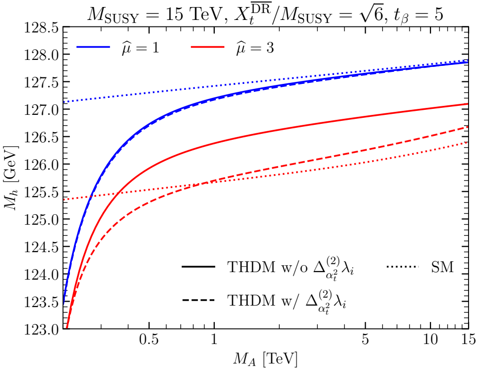
Sizeable $\mathcal{CP}$-odd component requires

- 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.

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.

Benchmark scenarios:

- M_h^{125} scenario $\rightarrow$ all SUSY particles at the TeV scale,
- $M_h^{125}(\tilde{\tau})$ scenario $\rightarrow$ light Stau, Bino and Winos,
- $M_h^{125}(\tilde{\chi})$ scenario $\rightarrow$ light Bino, Winos and Higgsinos,
- M_h^{125}(alignment) scenario $\rightarrow$ alignment without decoupling,
- M_H^{125} scenario $\rightarrow$ heavy $\mathcal{CP}$-even Higgs is SM-like,
- $M_{h_1}^{125}$(CPV) scenario $\rightarrow$ $\mathcal{CP}$-violation in the Higgs sector.

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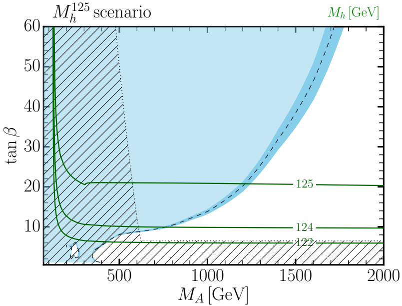
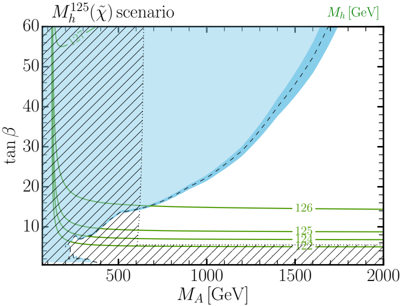
M_h^{125} and $M_h^{125}(\tilde{\chi})$ scenarios

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



$\mu = M_1 = M_2 = 1$ TeV

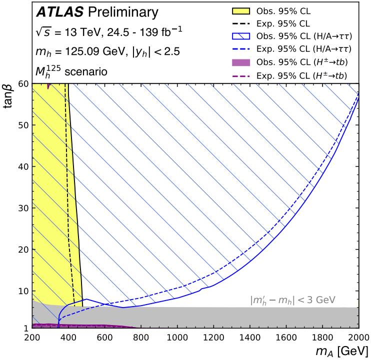


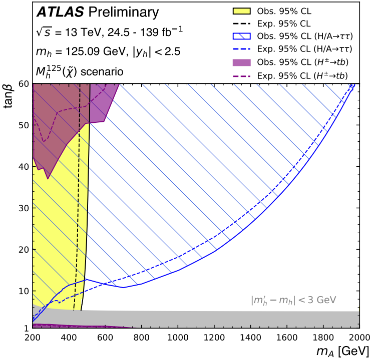
$\mu = M_2 = 180$ GeV, $M_1 = 160$ GeV

- 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 – experimental results

[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).

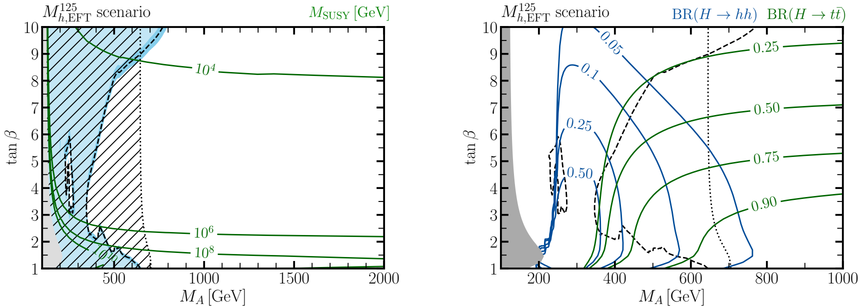
$\rightarrow$ large hierachy between M_A and M_{SUSY}
$\rightarrow$ using THDM as EFT crucial.

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.

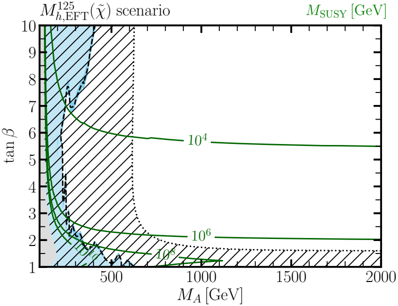
$M_{h,\text{EFT}}^{125}$ scenario

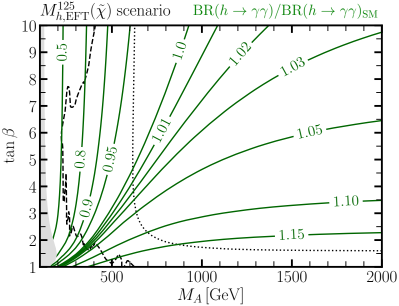
Similar to hMSSM scenario [1307.5205,1307.5205,...,Djouadi et al.]



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

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





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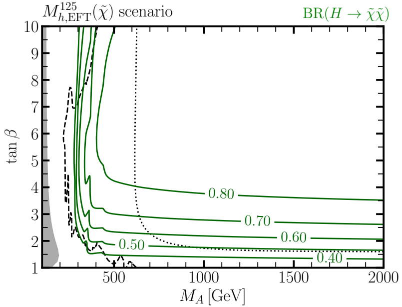
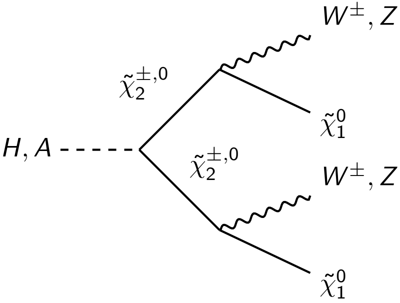
$M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario – $H, A, H^\pm \to \tilde{\chi}\tilde{\chi}$



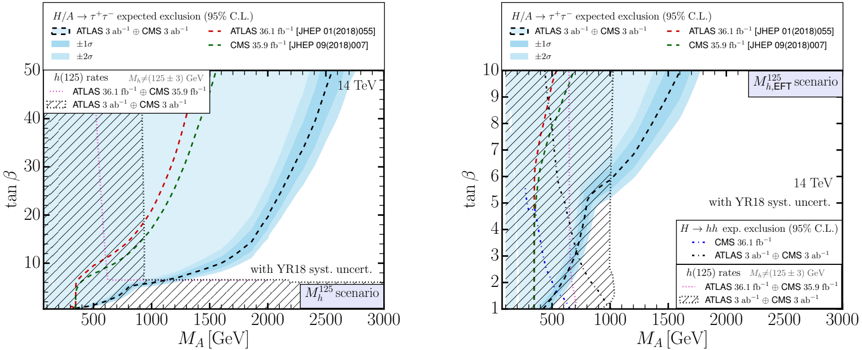


- Interesting $H, A \to \tilde{\chi}_i\tilde{\chi}_j \to E_{T,\text{miss}} + W^\pm, Z, h$ signatures,
- no experimental searches yet,
- EWino production via heavy Higgs can exceed direct production,
- particularly senstive for compressed EWino spectrum.

[Gori et al.,1811.11918;Wagner et al,2006.07389;...]

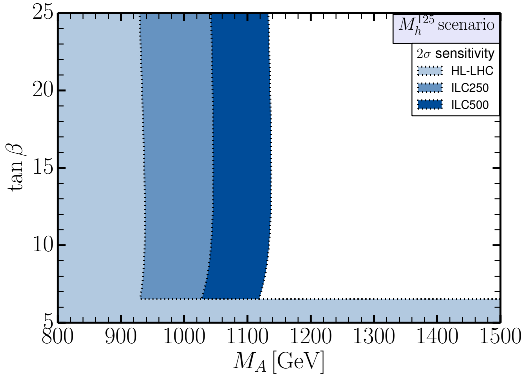
HL-LHC projections – M_h^{125} and $M_{h,\mathrm{EFT}}^{125}$ scenarios

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



- Assumption: discovered Higgs has SM-like couplings.

ILC projections – M_h^{125} scenario



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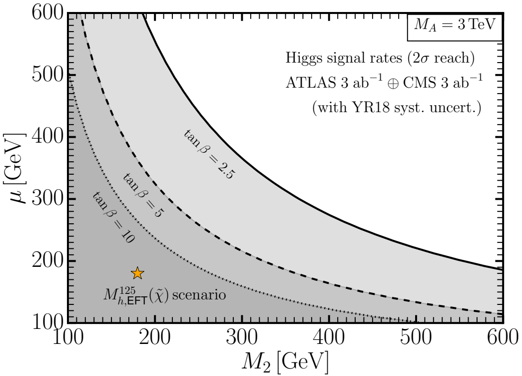
HL-LHC projections – $M_{h,\text{EFT}}^{125}(\chi)$ scenario



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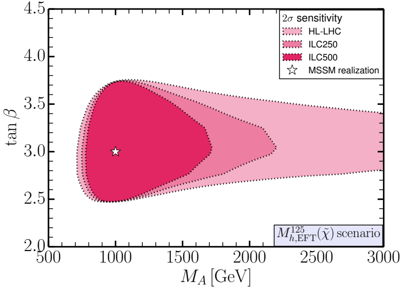
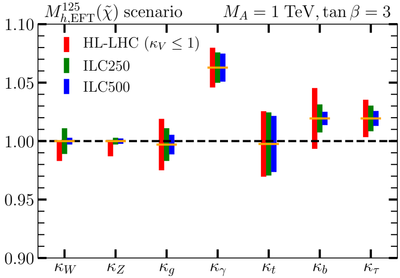
What if $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario is realized?





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

Conclusions

Higgs mass calculation:

- Unique observable directly sensitive to SUSY scale,
- theoretical uncertainty of $\lesssim 1$ GeV.

Higgs benchmark scenarios:

- Help to interpret LHC results,
- Higgs couplings $\rightarrow$ lower bound on M_A ($M_A \gtrsim 600$ GeV),
- Higgs searches $\rightarrow$ strong constraints for large $\tan\beta$,
- low $\tan\beta$ region challenging to probe at the LHC.

HL-LHC and ILC constraints:

- tightening constraints, $M_A \gtrsim 900$ GeV,
- ILC especially beneficial to pinpoint specific model in case of deviation.

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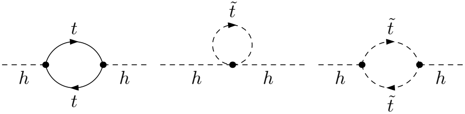
Thanks for your attention!

Fixed-order techniques



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

- Stop mass scale $M_{\tilde{t}} = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$,
- status: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2, \alpha_s^2 \alpha_t)$.

  [1708.05720,1802.09886,1901.03651,1910.02094,...]

Advantages and disadvantages:

+ Precise for low SUSY scales,
− but for high scales $\ln(M_{\tilde{t}}^2/M_t^2)$ terms spoil convergence of perturbative expansion.

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 → 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,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Weiglein;1312.4937,1608.01880,1706.0034,1812.06452]

other approaches: 1609.00371,1703.03267,1710.03760,1910.03595;

other codes: `FlexibleEFTHiggs`, `SARAH/SPheno`

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

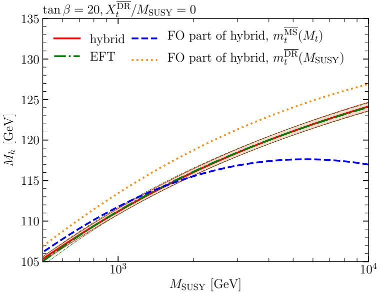
$$\hat{\Sigma}_{hh}(m_h^2) \longrightarrow \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{nolog}} - \left[v^2\lambda(M_t)\right]_{\text{log}}$$

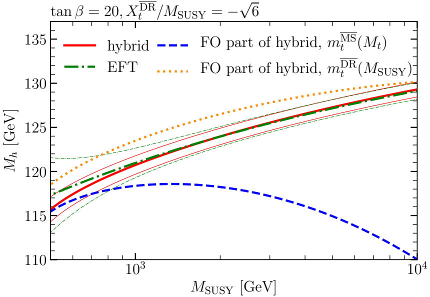
In practice, this is achieved by using subtraction terms.

Additional complication:
FH by default uses OS 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

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

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



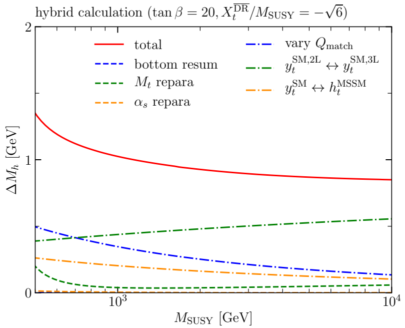


"Rule of thumb"

Remaining theoretical uncertainties (for $\overline{DR}$ stop input parameter):
$X_t/M_{SUSY} = 0 \;\rightarrow\; \Delta M_h \sim$ 0.5 GeV,
$X_t/M_{SUSY} = \sqrt{6} \;\rightarrow\; \Delta M_h \sim$ 1 GeV

Slightly higher for OS stop input parameters.

Remaining uncertainties – individual sources

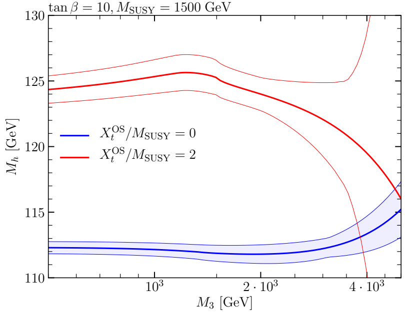


Uncertainty estimate dominated by:

- Uncertainty from higher order threshold corrections:
  - vary matching scale between SM and MSSM,
  - reexpress treshold correction in terms of h_t^{MSSM} instead of y_t^{SM}.
- Uncertainty of SM input couplings:
  - $y_t(M_t)$ extracted at the 2- or 3-loop level out of OS top mass.

One exception: $M_{\tilde{g}} \gg M_{\tilde{t}}$

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

Expressions for unknown so far ...

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

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

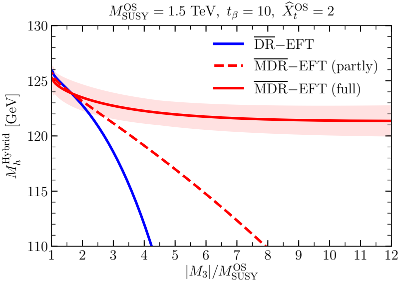
$$\left(m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}}\right)^2 = \left(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m_{\tilde{t}_{L,R}}^2} \left(1 + \ln \frac{Q^2}{|M_3|^2}\right)\right],$$

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

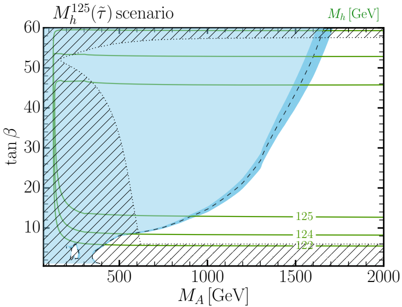
resums all $\mathcal{O}(\alpha_s^n M_3^{2n}, \alpha_s^n M_3^n)$ terms.

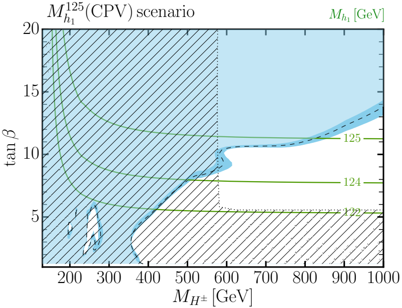
$\Downarrow$

Drastically reduced uncertainty.



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





M_h^{125}(alignment) and M_H^{125} scenarios