Constraining the MSSM Higgs sector at the LHC and beyond

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Séminaire théorie

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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? Obvious candidate: the **Higgs boson**

- 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?
  $\rightarrow$ Searches for additional Higgs bosons.

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

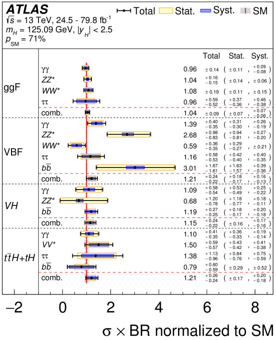
Higgs measurements: examples

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

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

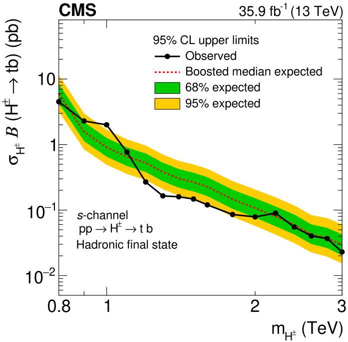
- Coupling measurements:

[1909.02845,ATLAS]



- Additional Higgs bosons:

[2001.07763,CMS]



⇒ Interpret constraints in specific model. Discussed today: MSSM

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

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

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

Special feature of MSSM

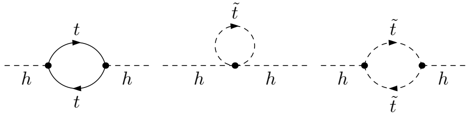
Mass of lightest $\mathcal{CP}$-even Higgs, M_h, is calculable in terms of model parameters $\Rightarrow$ can be used as a precision observable

- 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 (up to $\sim 100\%$)

To fully profit from experimental precision, higher order calculations are needed. Three approaches are used:

- Fixed-order (FO) approach,
- effective field theory (EFT) approach,
- hybrid approach.

Fixed-order techniques



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

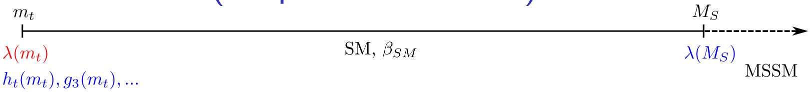
- Stop mass scale $M_{\tilde{t}} = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$,
- status: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2, \alpha_s^2\alpha_t)$.

  [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.

EFT calculation (simplest framework)



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

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

- run Higgs self-coupling down to electroweak scale,
- calculate Higgs mass: $M_h^2 = \lambda(M_t)v^2 + \ldots,$
- status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL, partial N^{3}LL.

  [1703.08166,1807.03509,1807.03509,1908.01670,...]

Advantages and disadvantages:

\+ Precise for high SUSY scales (logs resummed),

− but for low scales $\mathcal{O}(M_t/M_{\rm SUSY})$ terms are missed if higher-dimensional operators are not included.

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

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

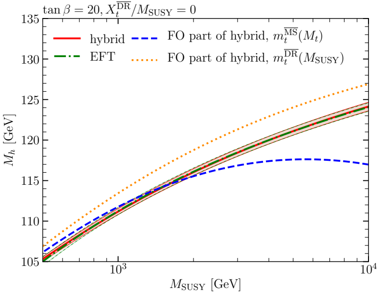
$$\hat{\Sigma}_{hh}(m_h^2) \longrightarrow \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{nolog}} - \left[v^2\lambda(M_t)\right]_{\text{log}}$$

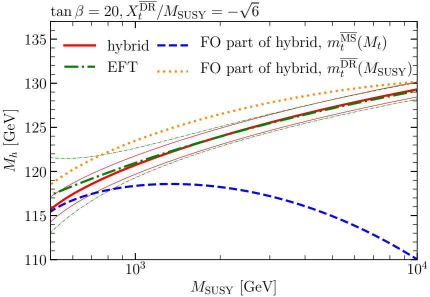
In practice, this is achieved by using subtraction terms.

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}



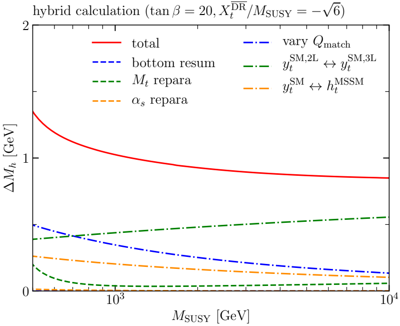


"Rule of thumb"

Remaining theoretical uncertainties (for $\overline{\text{DR}}$ 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^{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.

What happens in non-degenerate scenarios?

Large hierarchy between SUSY particles $\rightarrow$ EFT tower needed.

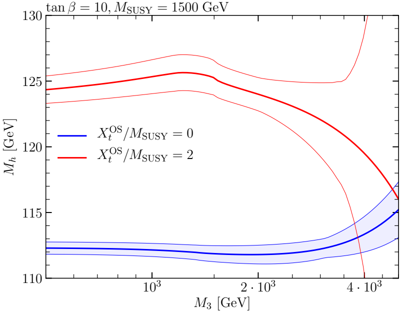
EFTs (NNLL accuracy) implemented in `FeynHiggs`:

- 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.

For most phenomenological interesting scenarios, all large logs are resummed $\Rightarrow$ theoretical uncertainty under control.

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 $\overline{\rm DR}$ 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,

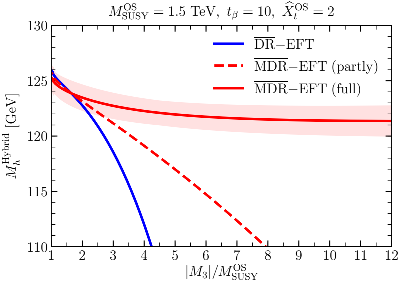
$$\left(m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}}\right)^2 = \left(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m_{\tilde{t}_{L,R}}^2}\left(1 + \ln\frac{Q^2}{|M_3|^2}\right)\right],$$

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

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

$\Downarrow$

Drastically reduced uncertainty.



Introduction

Higgs mass calculation

Higgs benchmark scenarios

Accessing the low tan β region

HL-LHC and ILC projections

Conclusions

Constraints on the MSSM Higgs sector

Considered constraints:

- properties of the Higgs boson discovered at the LHC:
  - mass,
  - couplings.
- searches for additional Higgs bosons.

$\rightarrow$ Evaluate constraints in Higgs benchmark scenarios.

Additional constraints not considered here:

- flavour constraints,
- vacuum stability,
- EWPOs,
- ...

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 125 GeV exist,
- each scenario has a different phenomenology.

Existing benchmark scenarios outdated $\rightarrow$ define new scenarios.

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

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

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

Defined using:

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

Benchmark scenarios:

- 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.

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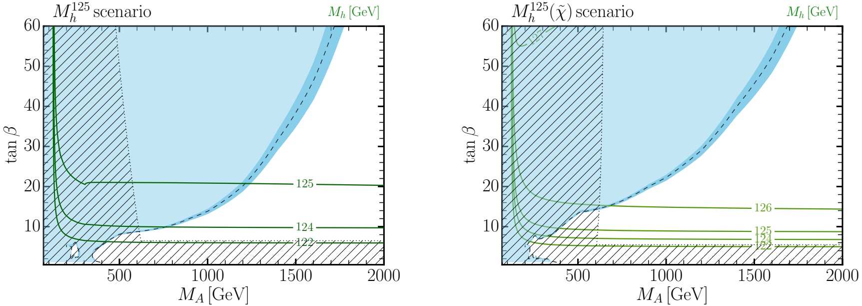
M_h^{125} and $M_h^{125}(\tilde{\chi})$ scenarios

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



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

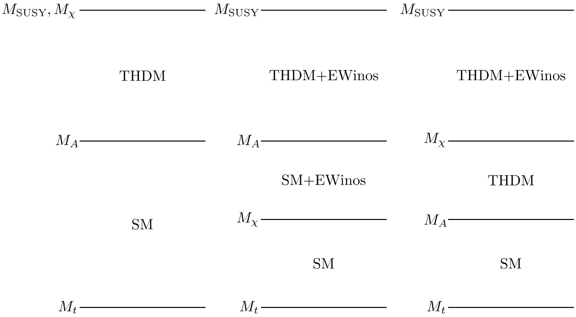
- Blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by SM-like Higgs signal strengths / mass.

Low tan β region?!

Region of tan $\beta \lesssim 8$ excluded, since mass $M_h < 125 \pm 3$ GeV:
$m_h^2 \xrightarrow{t_\beta \to 1} 0 \Rightarrow$ need to raise M_{SUSY} to push M_h upwards.

$\Downarrow$

Large hierarchy between heavy Higgs scale and SUSY scale.
Predictions should be evaluated in EFT framework!



[1805.00867,HB&Hollik]

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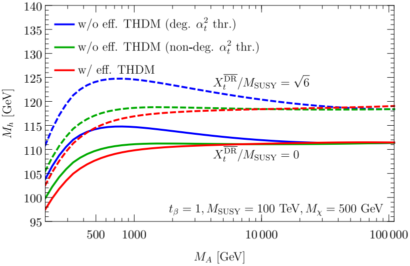


[1805.00867,HB&Hollik]

Benchmark scenarios for the low tan β region

[HB,Liebler,Stefaniak,1901.05933]

Use THDM-EFT calculation to define low-tan β benchmark scenarios.

Concept

Take existing scenarios and adjust M_{SUSY} at every point such that $M_h \sim 125$ GeV.

(upper limit: $M_{\text{SUSY}} \leq 10^{16}$ GeV)

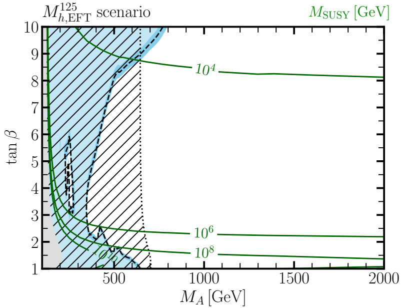
Two low-tan β benchmark scenarios:

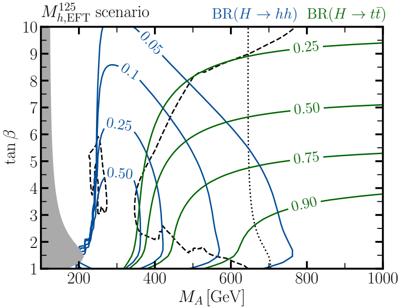
- $M_{h,\text{EFT}}^{125}$ scenario resembling M_h^{125} scenario,
- $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario resembling $M_h^{125}(\tilde{\chi})$ scenario.

Only differences: M_{SUSY} and X_t (set to zero for EFT scenarios)

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

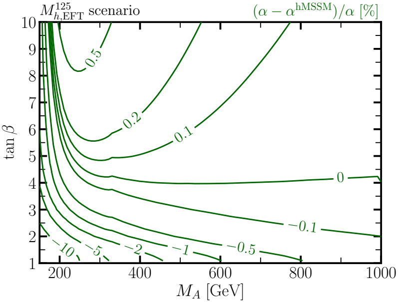
Similar to hMSSM scenario [1307.5205,1307.5205,...,Djouadi et al.]

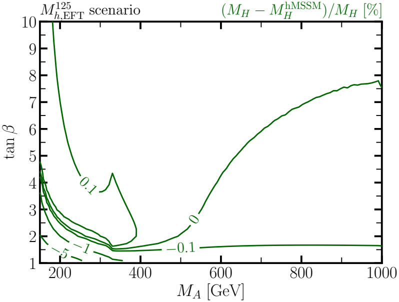




- Gray: $M_h < 122$ GeV,
- blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by Higgs signal strengths.

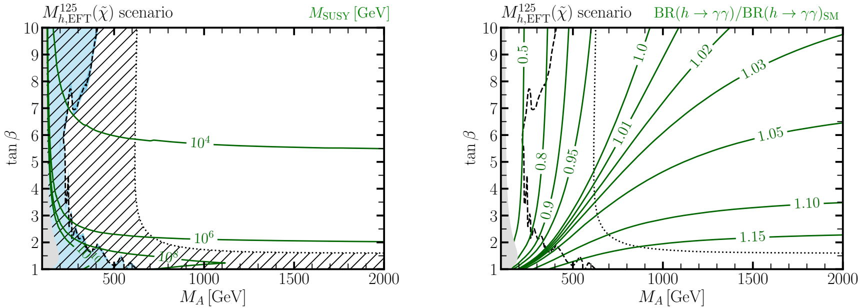
hMSSM comparison





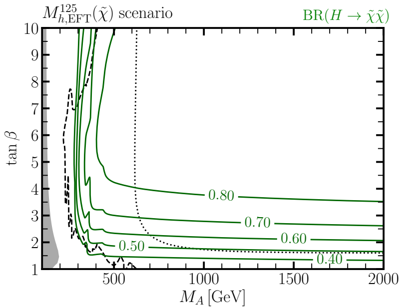
- Discrepancies for low M_A and $\tan\beta$,
- on-going effort to understand origin.

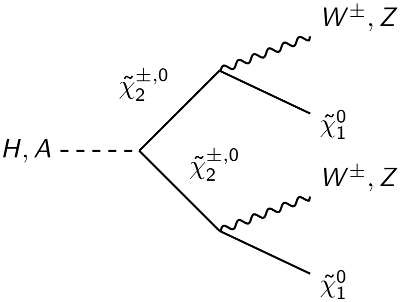
$M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario



- Gray: $M_h < 122$ GeV,
- blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by Higgs signal strengths,
- interesting $H, A \to \tilde{\chi}\tilde{\chi} \to W^{\pm}, Z$ signatures.

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



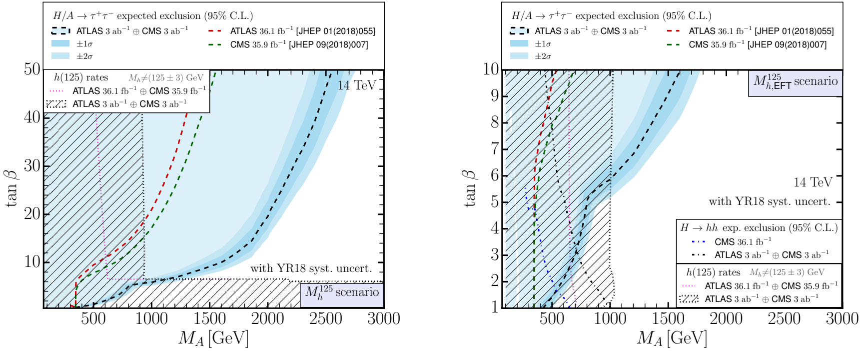


- Interesting multilepton signatures,
- no experimental searches yet,
- electroweakino production via heavy Higgs can exceed direct production.

[Gori et al.,1811.11918]

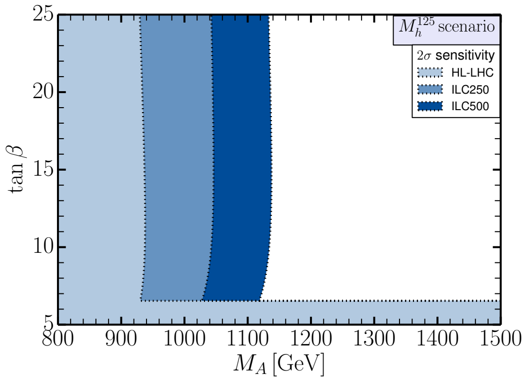
HL-LHC projections – M_h^{125} and $M_{h,\text{EFT}}^{125}$ scenarios

[HB,Bechtle,Heinemeyer,Liebler,Stefaniak,Weiglein,to appear]



- Assumed discovered Higgs to have SM couplings.

ILC projections – M_h^{125} scenario



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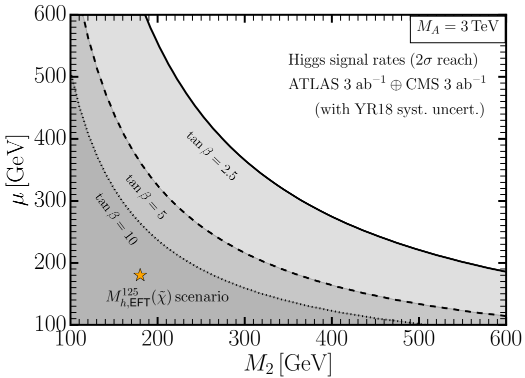
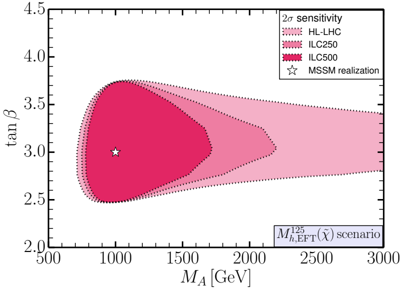
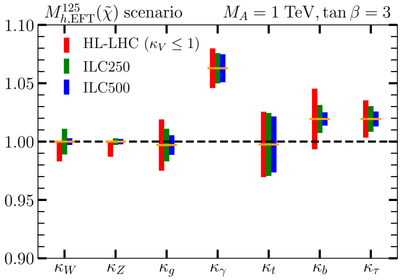
HL-LHC projections – $M_{h,\text{EFT}}^{125}(\chi)$ scenario



- Assumed discovered Higgs to have SM couplings.

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





- Assumed discovered Higgs to have couplings as predicted for $M_A = 1$ TeV and $\tan\beta = 3$.

Conclusions

Higgs mass calculation:

- Hybrid approach combines fixed-order and EFT approaches $\rightarrow$ precise prediction for all SUSY scales,
- 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.

HL-LHC and ILC constraints:

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

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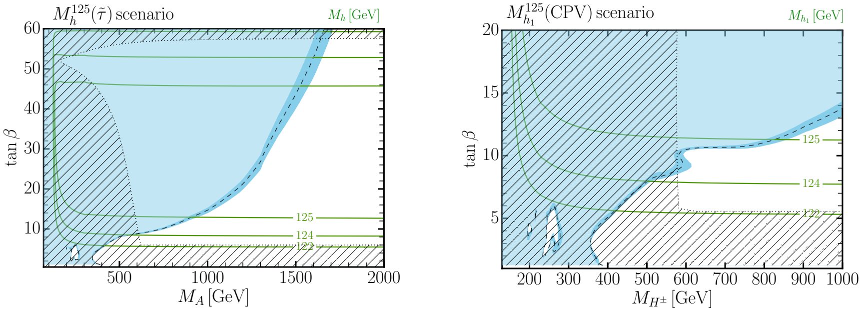
Thanks for your attention!

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



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