

# Towards high-precision for high-scale SUSY: status and perspectives on the EFT Higgs-mass computation in FlexibleSUSY

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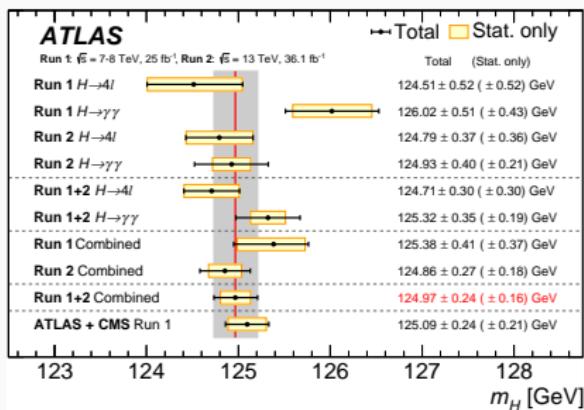
24 July 2018  
SUSY 2018  
Barcelona, Spain

# Introduction

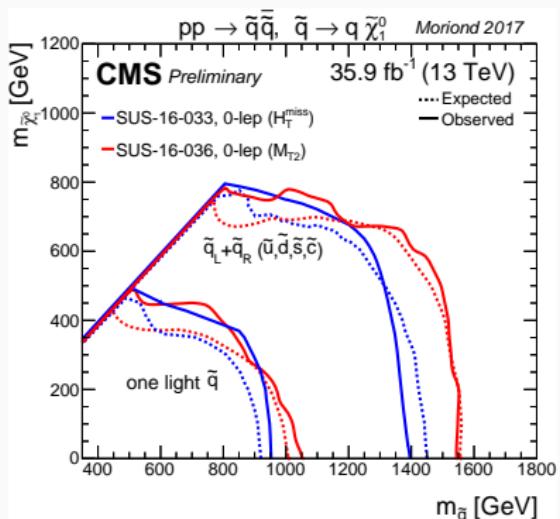
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# Motivations

- No signs of supersymmetric particles at the LHC renew the interest for the study of scenarios where part/all of these new states lie far above the EW scale.
- In these scenarios, the value of the (light) Higgs mass is the only (the main) handle that we have to gather information on the spectrum at the higher scales.
- Radiative corrections for this quantity are known to be large; need to perform the resummation of large  $\log(M_S/Q_{EW}) \rightarrow$  sophisticated predictions required.
- See the talk by P. Slavich for a review of the current status of the field.



[1806.00242]



# FlexibleSUSY and EFT towers

- Automatic generation of SoftSUSY-like spectrum generators using SARAH.
- SLHA input and output – easy interface with other codes and analysis pipelines.
- Native support for EFT towers.
- See the talk by A. Voigt for an overview of the recent results obtained with FlexibleSUSY.

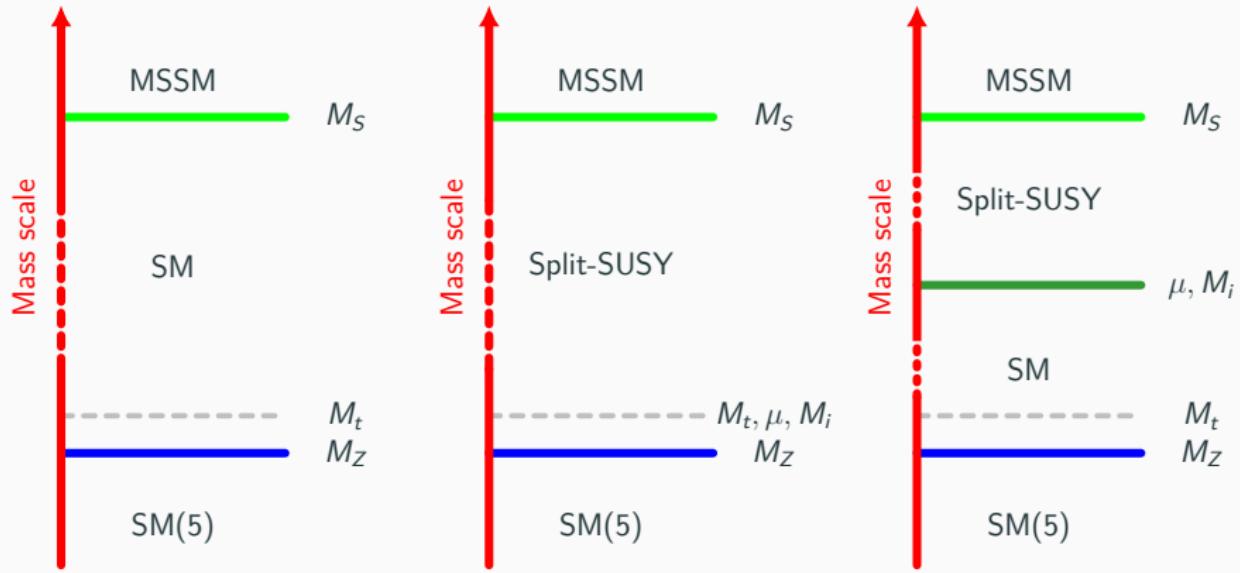


```
FSmodelName = "THDM";
FSEigenstates = SARAH'EWSB;
AutomaticInputAtMSUSY = False;
FSDefaultSARAHModel = "THDM-II";
MINPAR = {
    {3, TanBeta}
};
EXTPAR =
    {0, MSUSY},{1, MEWSB},
    {2, MuInput},{6, MAInput},
    {7, AtInput},{8, AbInput},
    {9, AtauInput},{100, LambdaLoopOrder}
];
EWSBOutputParameters = { M112, M222 };
(* The high scale where we match to the MSSM *)
HighScale = MSUSY;
HighScaleFirstGuess = MSUSY;
HighScaleInput = {
    {Lambda1, 1/2 (1/4 (
        (GUTNormalization[g1] g1)^2 + g2^2)
    + UnitStep[THRESHOLD-1]
        UnitStep[LambdaLoopOrder-1]
        (deltaLambda1th1L + deltaLambda1Phi1L)
    + UnitStep[THRESHOLD-2]
        UnitStep[LambdaLoopOrder-2]
        deltaLambda1th2L),
    [...]
```

# **One Higgs doublet at the EW scale**

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# Hierarchies



# Accuracy of the prediction

## Perturbative content

- 1-loop matching condition for the  $\lambda$ : complete.
- 2-loop matching condition for the  $\lambda$ : [1407.4081, 1703.08166]
  - $\mathcal{O}(g_3^2 g_t^4 + g_3^2 g_b^4)$
  - $\mathcal{O}(g_t^6 + g_b^6 + g_\tau^6 + g_t^4 g_t^2 + g_b^2 g_t^4 + g_b^2 g_\tau^4 + g_b^4 g_\tau^2).$
- Split-SUSY  $\tilde{g}$  couplings matched at 1-loop [1407.4081].
- 3-loop SM RGEs ([1307.3536]) and 2-loop RGEs from SARAH for the other hierarchies.
- At the low scale:
  - 3-loop corrections SM  $y_t$  extraction [9911434, 9912391], 3-loop SM-QCD thresholds to  $\alpha_s$  [0004189].
  - 3- and 4-loop SM Higgs mass corrections [1407.4336, 1508.00912].
  - 4-loop SM beta functions [arxiv:1508.00912, arXiv:1604.00853, 1508.02680].

# Theoretical uncertainty estimation

- For the MHOUs, we improve the prescription developed by the community over the past few years ([[1407.4081](#)], [[1504.05200](#)]).

- Low-energy EFT:**

$$\Delta M_h^{SM} = \left| M_h(y_t^{(2)}) - M_h(y_t^{(3)}) \right| + \max_{\lambda=\{2,1/2\}} |M_h(Q_{pole} = M_t) - M_h(Q_{pole} = \lambda M_t)|$$

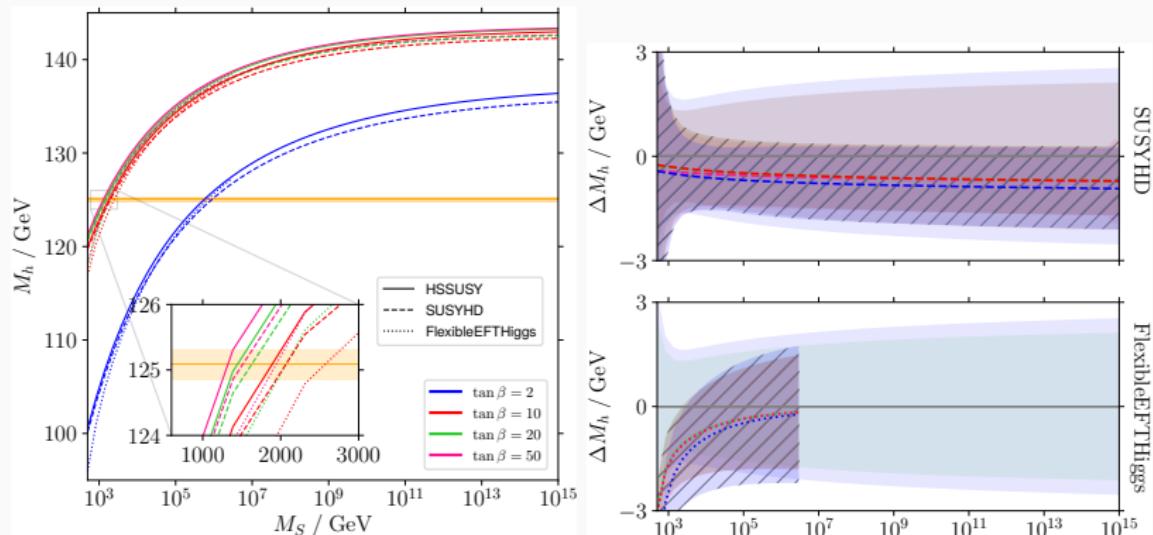
- EFT uncertainty:**  $\Delta\lambda_i \rightarrow \Delta\lambda_i + \sum_k \left| \Delta\lambda_{ik} \frac{v^2}{\min\{m_k^2\}} \right|$ .

- SUSY uncertainty:**

$$\Delta M_h^{(MSSM)} = \left| M_h(y_t^{SM}) - M_h(y_t^{MSSM}) \right| + \max_{\lambda=\{2,1/2\}} |M_h(Q_S = M_S) - M_h(Q_S = \lambda M_S)|.$$

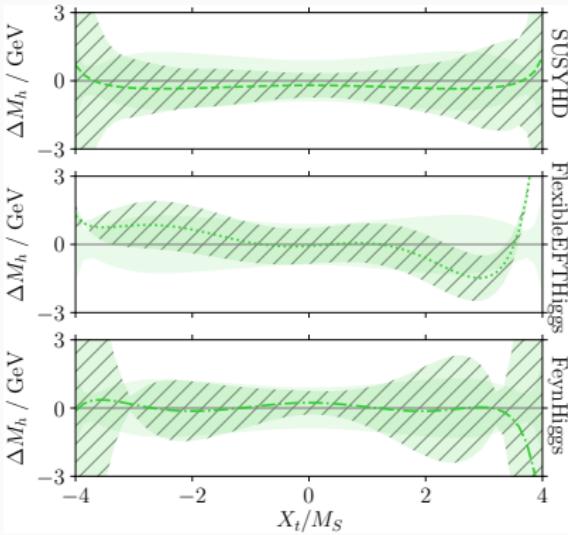
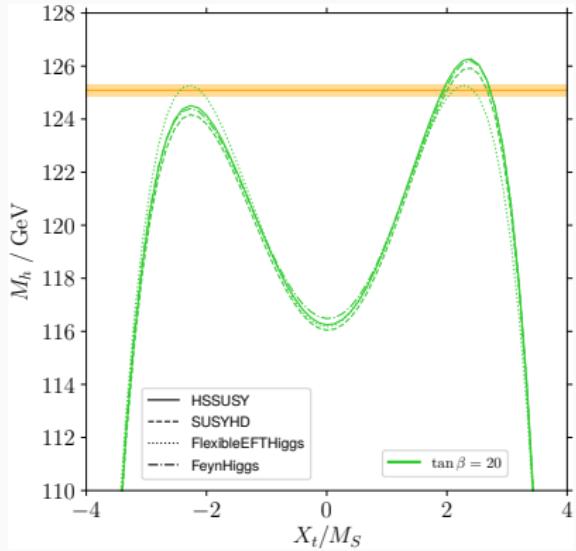
- We also consider the parametric uncertainties coming from  $\alpha_s$  and  $M_t$ .
- Uncertainties are combined linearly.
- Automatic uncertainty estimation delivered to the user through a Mathematica script.

# $m_H$ vs $M_S$ , high-scale SUSY scenario



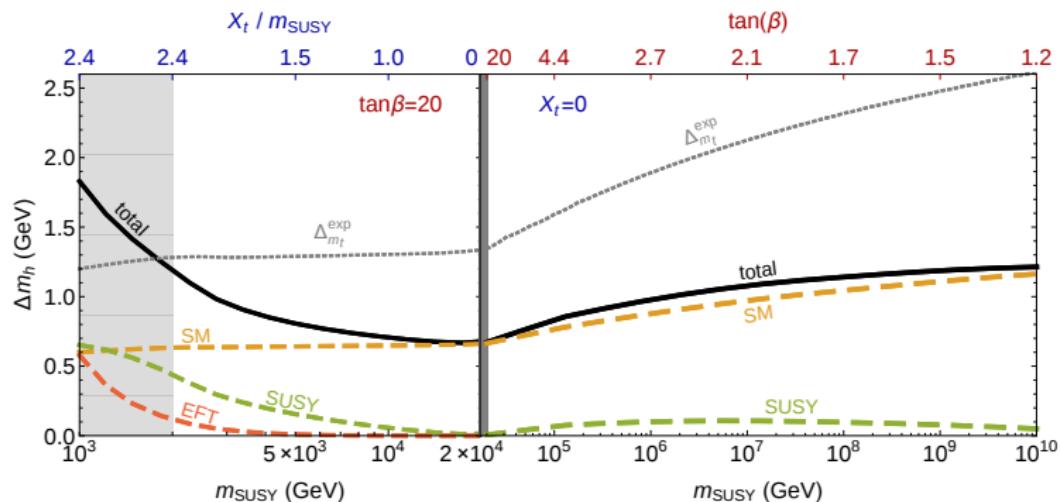
- $X_t = \sqrt{6}M_S$ ,  $X_b = X_\tau = 0$ .
- Compatibility between the codes at the level of the uncertainty bands.

# $m_H$ vs $X_t$ , high-scale SUSY scenario



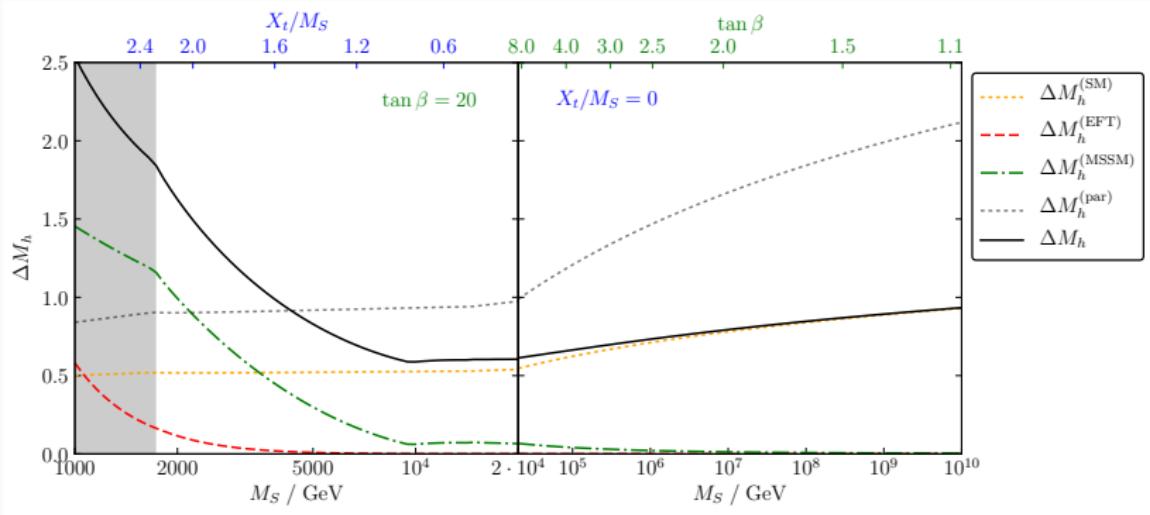
- $\tan \beta = 20, M_S = 2$  TeV.

# Theoretical uncertainty discussion



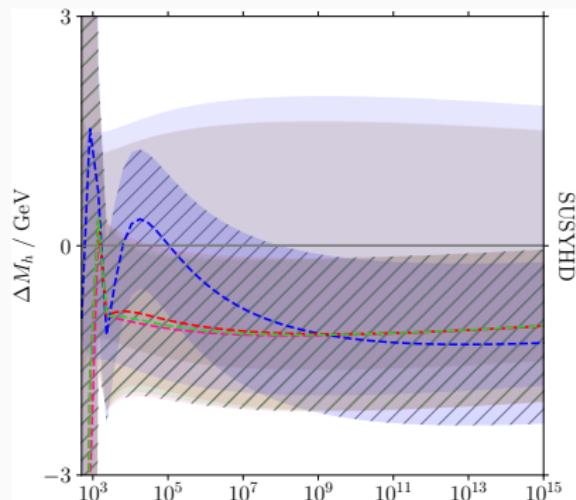
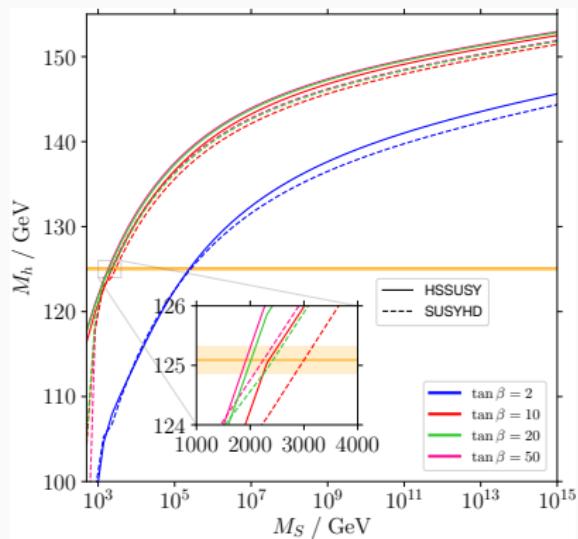
- SUSYHD [1504.05200].

# Theoretical uncertainty discussion



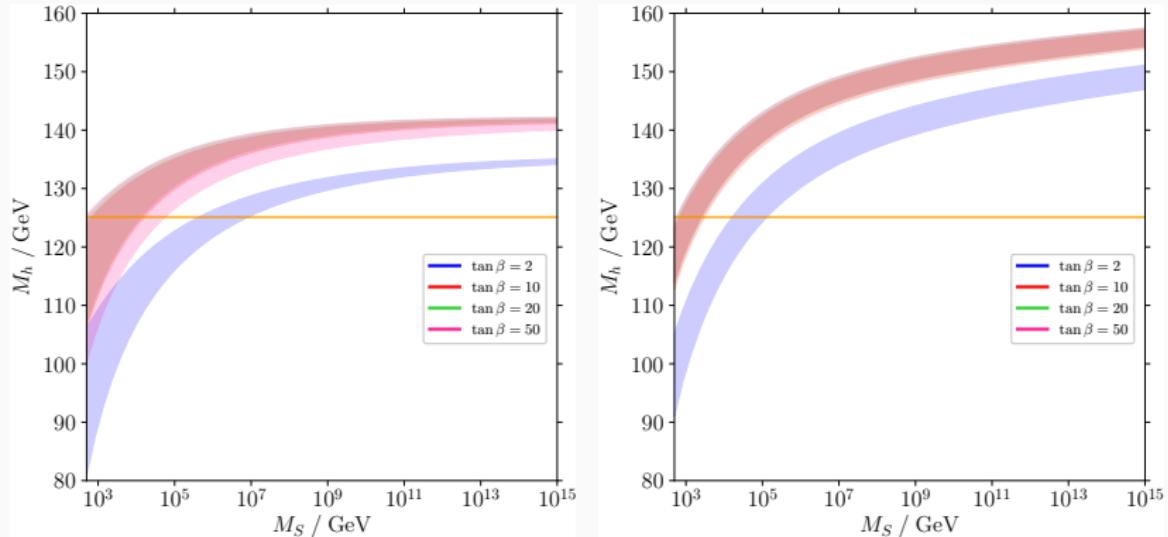
- HSSUSY.

# $m_H$ vs $M_S$ , split-SUSY scenario



- $\mu(Q_{split}) = M_i(Q_{split}) = 2$  TeV,  $X_t = \sqrt{6}M_S$ ,  $X_b = X_\tau = 0$ .

# Dependence on the degeneracy hypothesis



- Variation of the soft SUSY-breaking mass terms in the range  $[M_S/2, 2M_S]$ .
- $X_t = \sqrt{6} \sqrt{M_{Q_3}(M_S)M_{U_3}(M_S)}$ ,  $X_b = X_\tau = 0$ .
- Split-SUSY (right)  $\mu(Q_{\text{split}}) = M_i(Q_{\text{split}}) = 2 \text{ TeV}$ .

# Two-Higgs-doublets at the EW scale

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## THDM

## Chiral supermultiplets

Name	Symbol	spin 0	spin 1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks,quarks ( $\times 3$ families)	$Q$ $\bar{u}$ $\bar{d}$	$(\tilde{u}_L, \tilde{d}_L)$ $\tilde{u}_R^*$ $\tilde{d}_R^*$	$(u_L, d_L)$ $u_R^\dagger$ $d_R^\dagger$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ $(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$ $(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons,leptons ( $\times 3$ families)	$L$ $\bar{e}$	$(\tilde{\nu}, \tilde{e}_L)$ $\tilde{e}_R^*$	$(\nu, e_L)$ $e_R^\dagger$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ $(\mathbf{1}, \mathbf{1}, \mathbf{1})$
Higgses, Higgsinos	$H_u$ $H_d$	$(H_u^+, H_u^0)$ $(H_d^0, H_d^-)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$ $(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$ $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

## Gauge supermultiplets

Name	spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon	$\tilde{g}$	$g$	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm$	$W^\pm$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	$B^0$	$(\mathbf{1}, \mathbf{1}, 0)$

# THDM + Split SUSY

## Chiral supermultiplets

Name	Symbol	spin 0	spin 1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks,quarks ( $\times 3$ families)	$Q$ $\bar{u}$ $\bar{d}$	$(\tilde{u}_L, \tilde{d}_L)$ $\tilde{u}_R^*$ $\tilde{d}_R^*$	$(u_L, d_L)$ $u_R^\dagger$ $d_R^\dagger$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ $(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$ $(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons,leptons ( $\times 3$ families)	$L$ $\bar{e}$	$(\tilde{\nu}, \tilde{e}_L)$ $\tilde{e}_R^*$	$(\nu, e_L)$ $e_R^\dagger$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ $(\mathbf{1}, \mathbf{1}, \mathbf{1})$
Higgses, Higgsinos	$H_u$ $H_d$	$(H_u^+, H_u^0)$ $(H_d^0, H_d^-)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$ $(\tilde{H}_d^0, \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$ $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

## Gauge supermultiplets

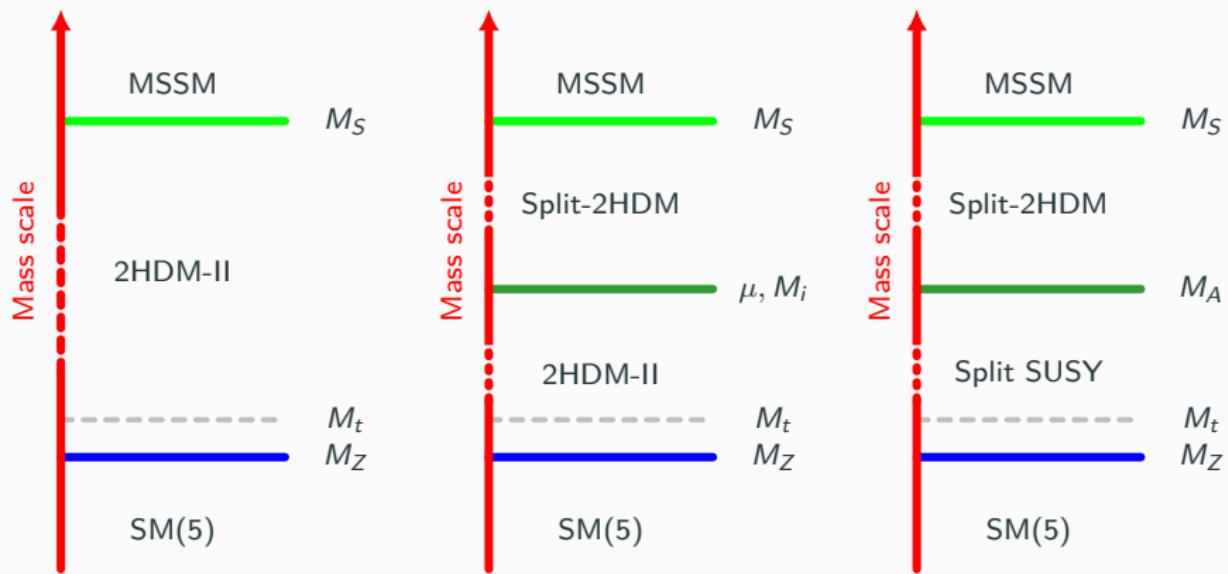
Name	spin 1/2	spin 1	$(SU(3)_C, SU(2)_L, U(1)_Y)$
gluino,gluon	$\tilde{g}$	$g$	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm$	$W^\pm$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	$B^0$	$(\mathbf{1}, \mathbf{1}, 0)$

# Matching to a THDM

$$\begin{aligned}-\mathcal{L}_{\text{Yuk}} = & \frac{\tilde{g}_d}{\sqrt{2}} H_1 \tilde{W} \tilde{h}_d + \frac{\tilde{g}'_d}{\sqrt{2}} H_1 \tilde{B} \tilde{h}_d + \frac{\tilde{g}_u}{\sqrt{2}} H_2^\dagger \tilde{W} \tilde{h}_u + \frac{\tilde{g}'_u}{\sqrt{2}} H_2^\dagger \tilde{B} \tilde{h}_u \\& + \frac{\tilde{\gamma}_d}{\sqrt{2}} H_2 \tilde{W} \tilde{h}_d + \frac{\tilde{\gamma}'_d}{\sqrt{2}} H_2 \tilde{B} \tilde{h}_d + \frac{\tilde{\gamma}_u}{\sqrt{2}} H_1^\dagger \tilde{W} \tilde{h}_u + \frac{\tilde{\gamma}'_u}{\sqrt{2}} H_1^\dagger \tilde{B} \tilde{h}_u \\& + h_b \bar{b}_R H_1^* Q_L + h_t \bar{t}_R Q_L H_2 + \tilde{\eta}_b \bar{b}_R H_2^* Q_L + \tilde{\eta}_t \bar{t}_R Q_L H_2 \\& + \text{h.c.}\end{aligned}$$

- “Wrong” Yukawas  $\tilde{\gamma}_i = \tilde{\eta}_j = 0$  at tree level.
- Ignored for now for simplicity, we consider a type-II THDM as the scalar-sector of the low-energy EFT.
- Other tools and results: MhEFT (public, [\[1508.00576\]](#)) and FeynHiggs (still private, [\[1805.00867\]](#)).
- We also had released less accurate versions of our FlexibleSUSY-based generators with FS-1.4.0 (see also [\[1512.07761\]](#)).

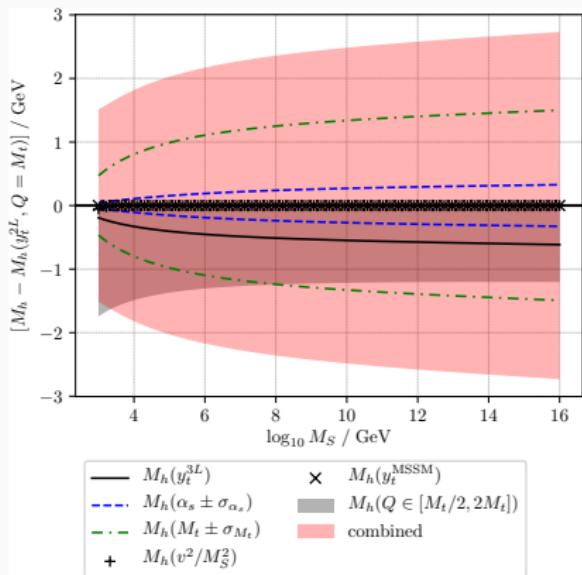
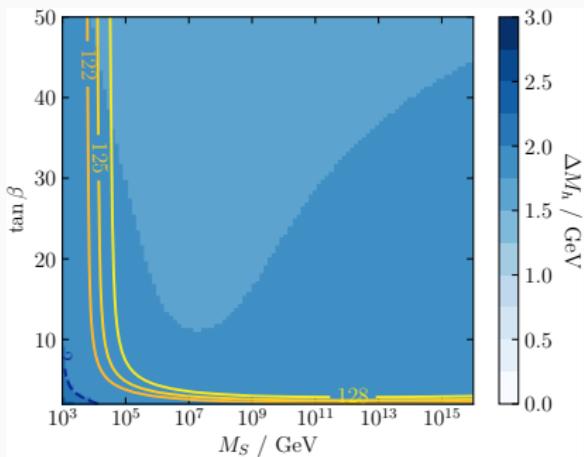
# Hierarchies



# Perturbative accuracy

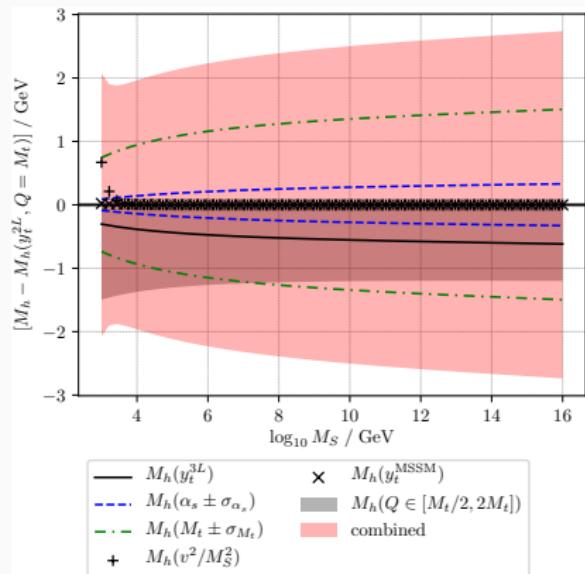
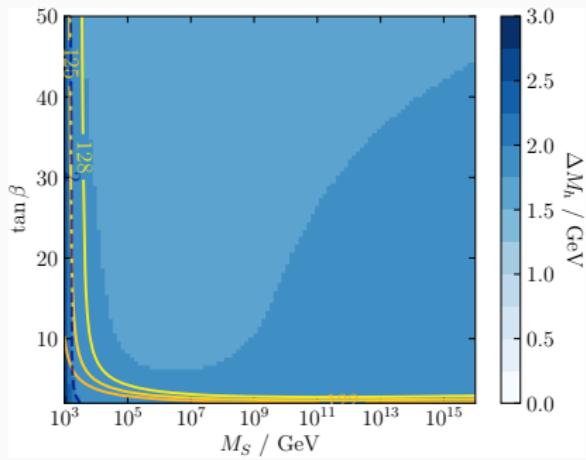
- 2 loop RGEs from SARAH, verified by direct comparison with PYR@TE.
- Full 1-loop computation of the  $\overline{MS}$  running parameters of the EFT; include also 2(3) loop SM-QCD for the top Yukawa.
- Full 1-loop corrections to the Higgs mass matrix.
- Full 1-loop thresholds for the  $\lambda$ s from Gorbahn et al. [\[0901.2065\]](#).
- 2-loop corrections  $\mathcal{O}(g_3^2 g_t^4)$  from [\[1508.00576\]](#).

# THDM single scale



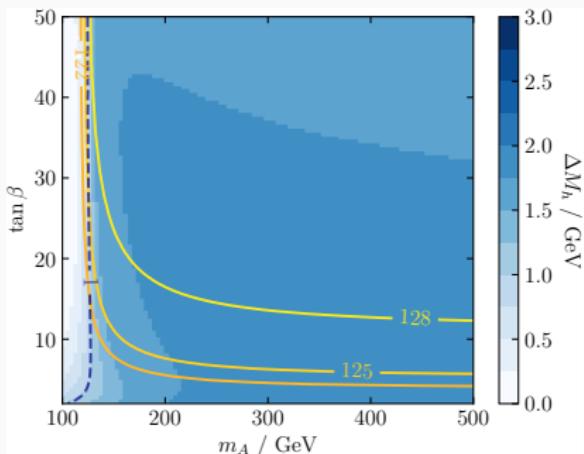
- $m_A = 400$  GeV,  $X_t = 0$ .

# THDM single scale

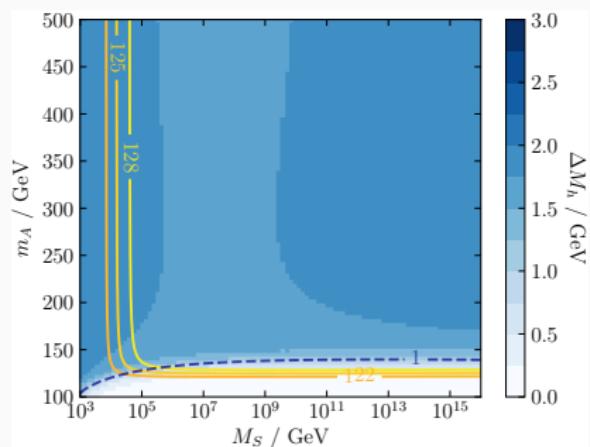


- $m_A = 400 \text{ GeV}$ ,  $X_t = \sqrt{6}M_S$ .

# THDM single scale

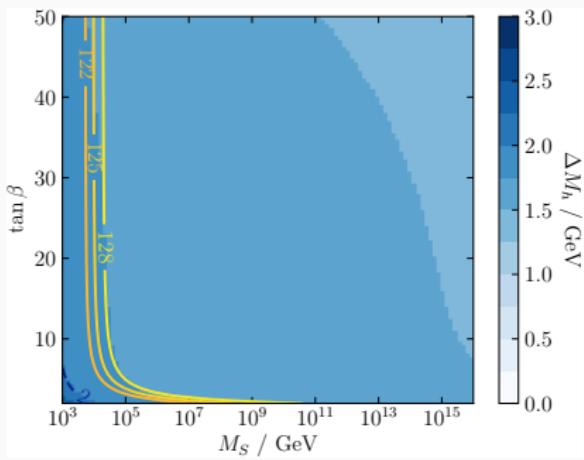


- $M_S = 50 \text{ TeV}, X_t = 0.$

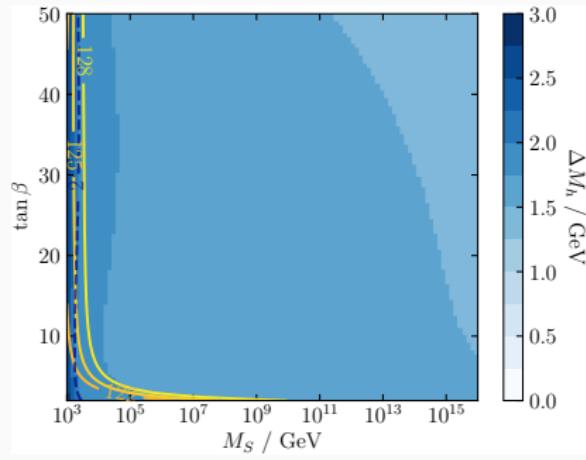


- $\tan \beta = 20, X_t = 0.$

# Intermediate gaugino/higgsinos

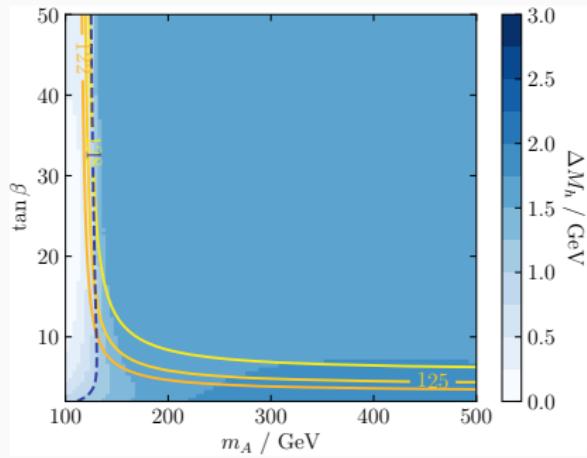


- $m_A = 400 \text{ GeV}, X_t = 0, \mu = M_i = 2 \text{ TeV}.$

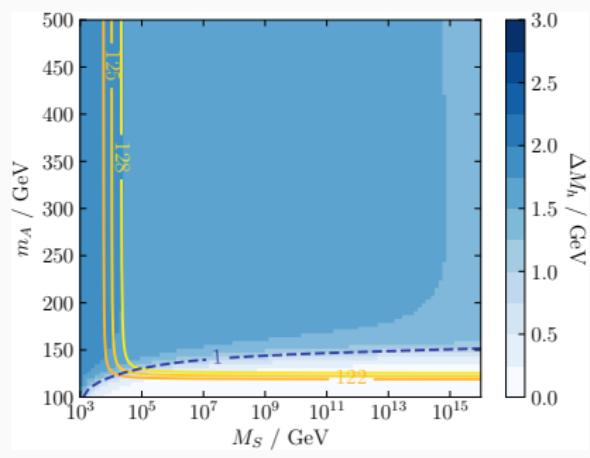


- $m_A = 400 \text{ GeV}, X_t = \sqrt{6}M_S, \mu = M_i = 2 \text{ TeV}.$

# Intermediate gaugino/higgsinos

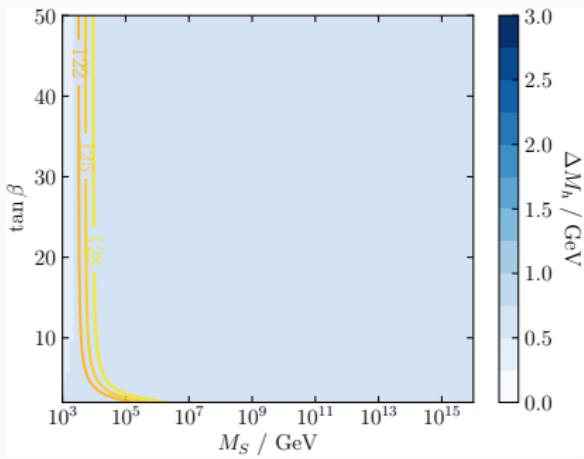


- $M_S = 50$  TeV,  $X_t = 0$ ,  $\mu = M_i = 2$  TeV.

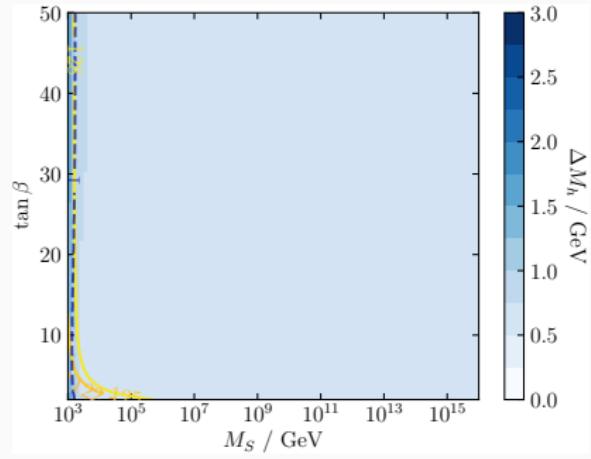


- $\tan \beta = 20$ ,  $X_t = 0$ ,  $\mu = M_i = 2$  TeV.

# Intermediate $m_A$

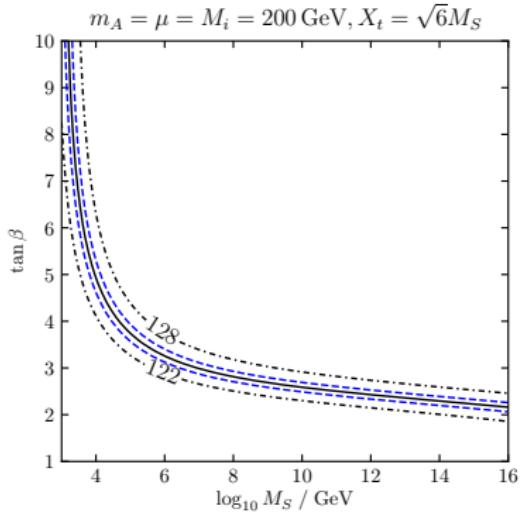
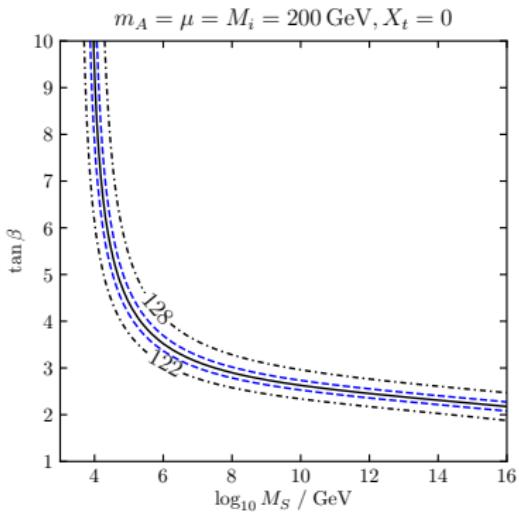


- $m_A = 5 \text{ TeV}, X_t = 0, \mu = M_i = 1 \text{ TeV}.$



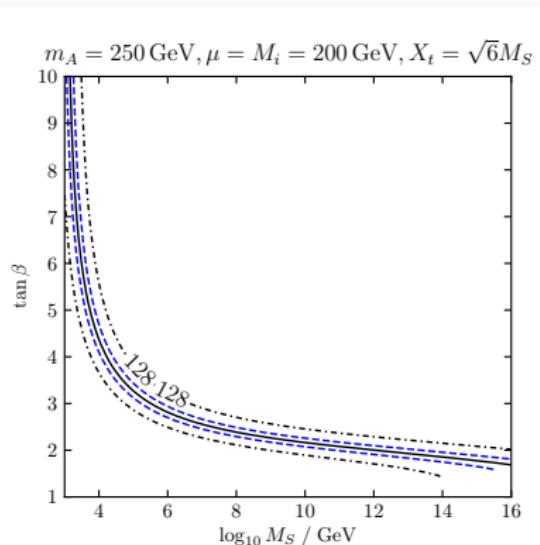
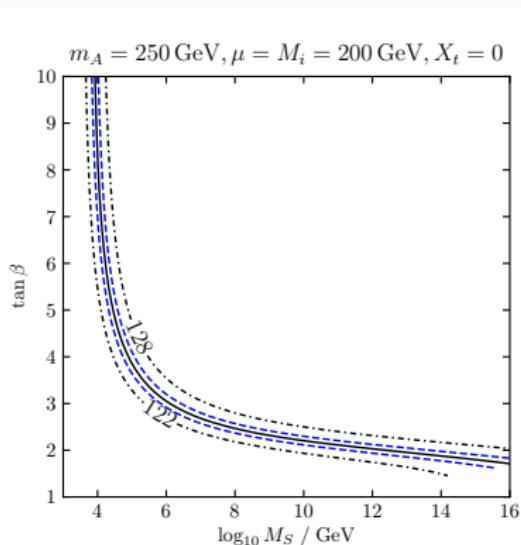
- $m_A = 2 \text{ TeV}, X_t = \sqrt{6}M_S, \mu = M_i = 1 \text{ TeV}.$

# How low can we go with $m_A$ to have $m_h = 125$ GeV Higgs at low $\tan \beta$ ?



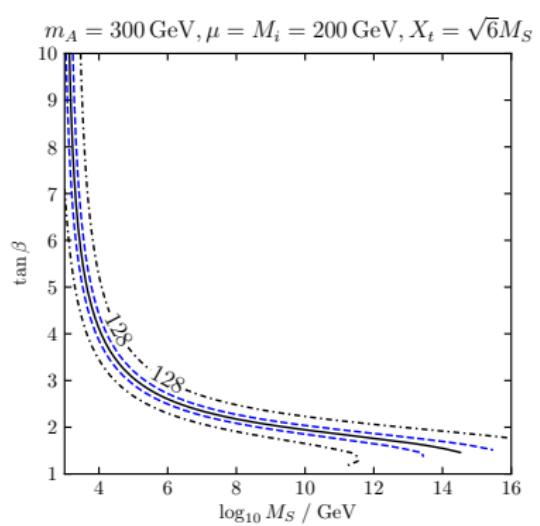
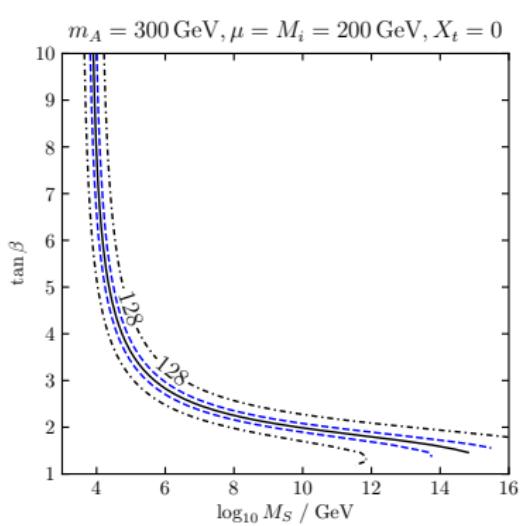
- Low-scale gauginos and Higgsinos.

# Pushing $m_A$ a bit higher



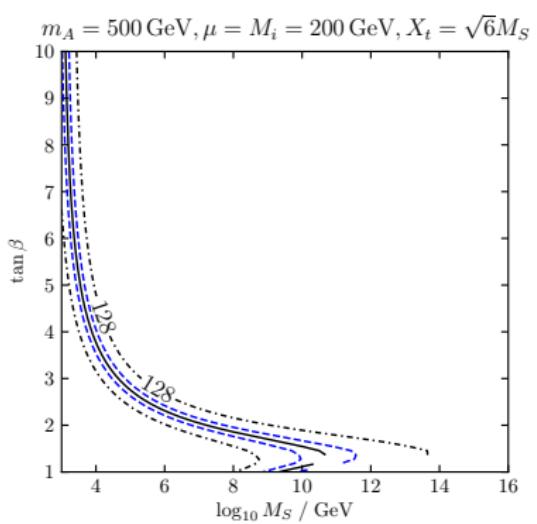
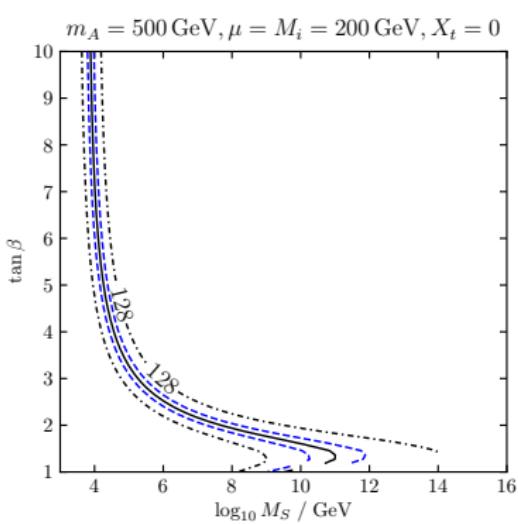
- Low-scale gauginos and Higgsinos.
- $m_A = 250 \text{ GeV}$ .

# Pushing $m_A$ a bit higher



- Low-scale gauginos and Higgsinos.
- $m_A = 300 \text{ GeV}$ .

# Pushing $m_A$ a bit higher



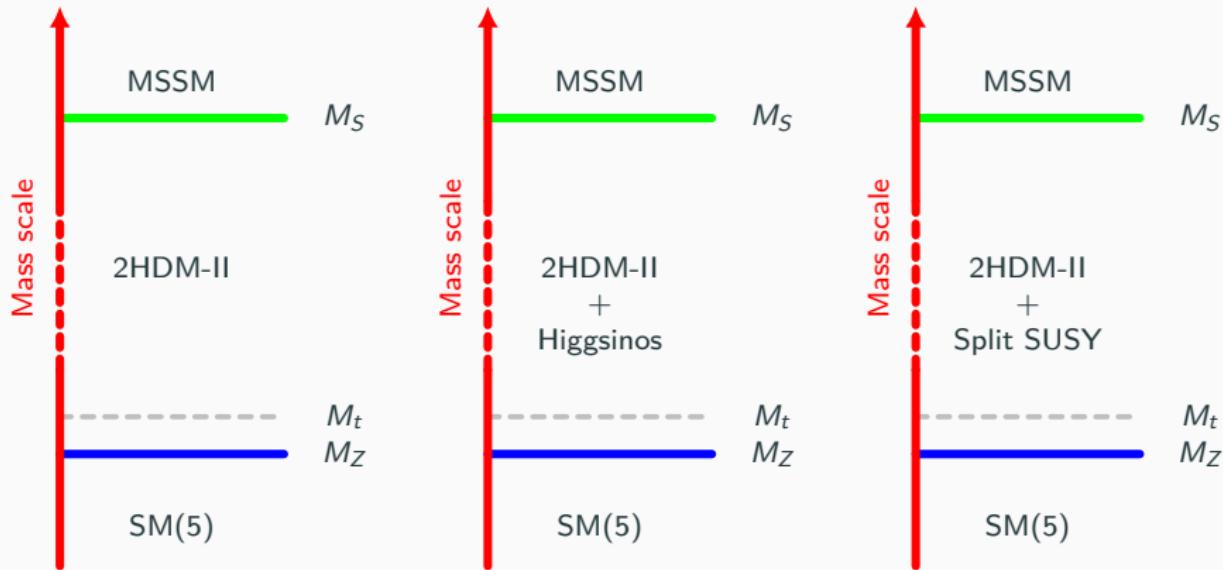
- Low-scale gauginos and Higgsinos.
- $m_A = 500 \text{ GeV}$ .

# Conclusions

- We have implemented and studied in FlexibleSUSY several different hierarchical SUSY spectra.
- For each one of them we studied the prediction of the Higgs mass and its theoretical uncertainties.
- The code will be released publicly in the near future. A script will be provided so that the users will be able to obtain a prediction of the uncertainty on a point-by-point basis.
- Looking forward to a complete comparison with the newest versions of MhEFT and FeynHiggs.

# Backup slides

# Old THDM Hierarchies



# Input parameters

## High-scale SUSY

$$\tan \beta^{\overline{\text{DR}}}(\textcolor{red}{M}_S), A_t^{\overline{\text{DR}}}(\textcolor{red}{M}_S), m_A^{\overline{\text{DR}}}(\textcolor{red}{M}_S), \mu^{\overline{\text{DR}}}(\textcolor{red}{M}_S), M_i^{\overline{\text{DR}}}(\textcolor{red}{M}_S), (m_f^2)_{ij}^{\overline{\text{DR}}}(\textcolor{red}{M}_S)$$

$$\lambda(\textcolor{red}{M}_S) = \frac{1}{4} \left( \frac{3}{5} g_1^2 + g_2^2 \right) \cos^2 2\beta + \Delta \lambda^{HSS,1L} + \Delta \lambda^{HSS,2L}$$

## Split-SUSY

$$\tan \beta^{\overline{\text{DR}}}(\textcolor{red}{M}_S), A_t^{\overline{\text{DR}}}(\textcolor{red}{M}_S), m_A^{\overline{\text{DR}}}(\textcolor{red}{M}_S), (m_f^2)_{ij}^{\overline{\text{DR}}}(\textcolor{red}{M}_S), \mu^{\overline{\text{MS}}}(M_Z), M_i^{\overline{\text{MS}}}(M_Z)$$

$$\tilde{\lambda}(\textcolor{red}{M}_S) = \frac{1}{4} \left( \frac{3}{5} g_1^2 + g_2^2 \right) \cos^2 2\beta + \Delta \tilde{\lambda}^{1L} + \Delta \tilde{\lambda}^{2L}$$

$$\tilde{g}_{1u}(\textcolor{red}{M}_S) = \sqrt{\frac{3}{5}} g_1 \sin \beta + \Delta \tilde{g}_{1u}^{1L}, \quad \tilde{g}_{1d}(\textcolor{red}{M}_S) = \sqrt{\frac{3}{5}} g_1 \cos \beta + \Delta \tilde{g}_{1d}^{1L}$$

$$\tilde{g}_{2u}(\textcolor{red}{M}_S) = g_2 \sin \beta + \Delta \tilde{g}_{2u}^{1L}, \quad \tilde{g}_{2d}(\textcolor{red}{M}_S) = g_2 \cos \beta + \Delta \tilde{g}_{2d}^{1L}$$