Vacuum stability and supersymmetry at high scales with two Higgs doublets

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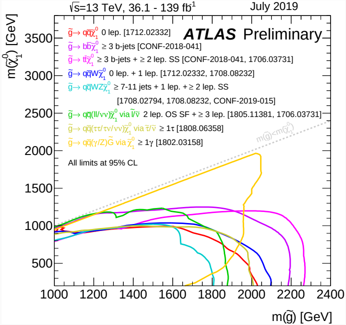
[EB, F. Brümmer, W. Buchmüller, A. Voigt, G. Weiglein, 1512.07761]

[EB, A. Voigt, G. Weiglein, WIP]

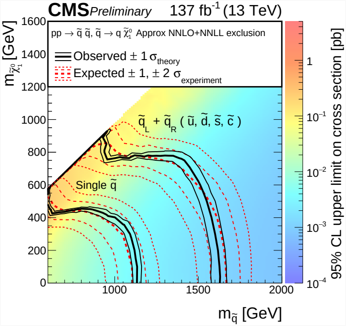
Introduction and motivations

Introduction and Motivations

- Let's assume, as a working hypothesis, that the LHC (or one of the next generation colliders) will *not* find SUSY and that we are left with the realistic possibility that the SUSY breaking scales is much higher than the EW scale.
- Then SUSY will *not* be a solution of the hierarchy problem, give a viable dark matter candidate or help gauge with coupling unification.
- However supersymmetry will *still* be a features of UV models (e.g. string inspired). Then the natural scale for SUSY breaking will be either around 10^{16}-10^{18}, with the UV-completion of the SUSY-field theory around $M_{\rm Pl}$.



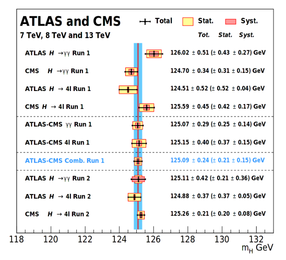
[ATL-PHYS-PUB-2019-022]



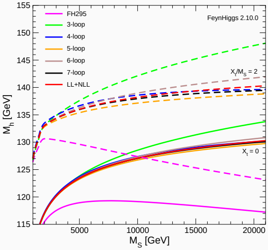
[1908.04722]

Introduction and Motivations

- Even if new SUSY states are well beyond the reach of collider physics, we can hope to derive some information (or constraint) from the Higgs sector, in first instance through the Higgs mass.
- The calculation of the Higgs for this class of SUSY spectra require the resummation of large logs $\log(M_S/Q_{EW})$ that otherwise spoil the accuracy of the calculation $\rightarrow$ sophisticated predictions required.
- The resummation is achieved by using a tower of effective field theories and by *matching and running*.



[PDG2018]



[1312.4937]

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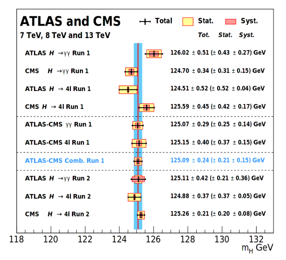
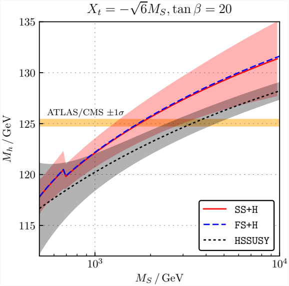
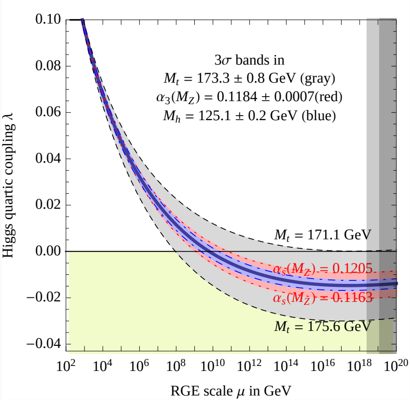


[PDG2018]

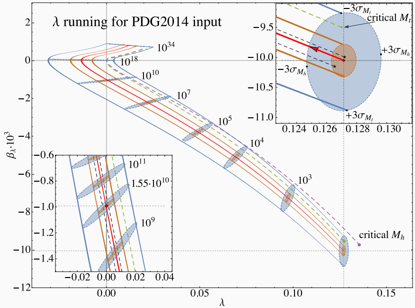


[1804.09410]

Is one doublet enough for this purpose?



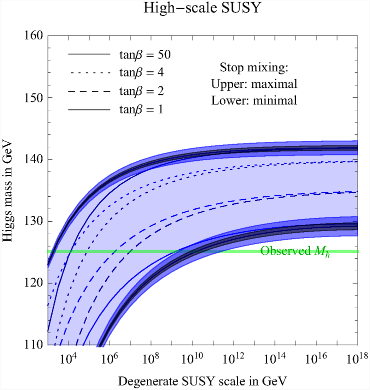
Buttazzo et al. [1307.3536]

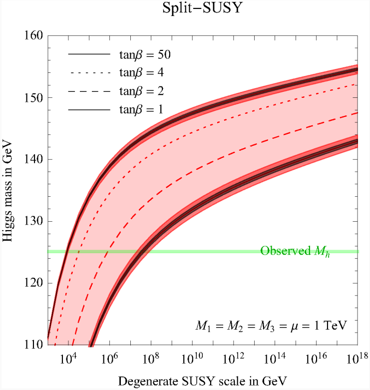


Bednyakov et al. [1507.08833]

- Running of λ in the SM is such that at around 10^{10}-10^{11} GeV the quartic coupling turns negative.
- Tree-level matching $\lambda = \frac{1}{4}(g^2 + g'^2)\cos^2(2\beta) \geq 0$.

In dire need of two doublets





EB et al. [1407.4081]

- Unable to match at very high-scales, the observed Higgs mass value lies below the theoretical prediction.
- Caveat: if the SUSY-completion is not minimal, this is not the case (e.g. NMSSM Zarate [1601.05946], Gabelmann et al. [1810.12326])
- Solution: assume a THDM at the low-scale.

Status

Single Higgs doublet

- Boundary conditions: full 1-loop + 2-loop strong and Yukawa EB, Giudice, Slavich and Strumia [1407.4081], EB, Pardo-Vega and Slavich [1703.08166], EB, Degrassi, Paßehr and Slavich [1908.01670]
- Dim-6 operators EB, Pardo-Vega and Slavich [1703.08166].
- RGEs: 3-loop (see Buttazzo et al. [1307.3536]).
- EW-scale matching: full 2-loop + higher order QCD corrections for g_t Buttazzo et al. [1307.3536], Kniehl et al. [1503.02138].
- Codes: `HSSUSY` [Bagnaschi, Voigt] , `SUSYHD` [Pardo-Vega, Villadoro].

"Hybrid" calculations

- `FlexibleEFTHiggs` Athron, Park, Steudner, Stöckinger, Voigt [1609.00371].
- `FeynHiggs` Bahl, Hahn, Heinemeyer, Hollik, Paßehr, Rzehak, Weiglein.

Two Higgs doublets

- Calculations: Lee and Wagner [1508.00576], EB, Brümmer, Büchmuller, Voigt and Weiglein [1512.07761], Bahl and Hollik [1805.00867] Murphy and Rzehak [1909.00726] (complex parameters)
- Codes: `MhEFT`, `FlexibleSUSY`, `FeynHiggs`.

Automatic/Generic matching

- `FlexibleEFTHiggs`
- `SARAH+Spheno` Gabelmann, Mühlleitner and Staub [1810.12326].
- Calculations: Braathen, Goodseel and Slavich [1810.09388]
- Functional methods: Wells and Zhang [1711.04774], [1908.04798].

[...]

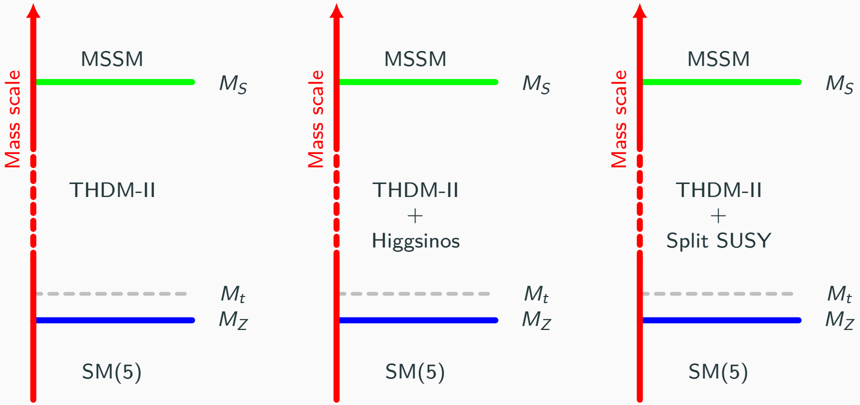
- *See D. Stockinger and H. Bahl* talks for a more in depth discussion of the current status of Higgs mass prediction in scenarios with heavy sparticles.

Outline of the study

- Correlate the low-scale Higgs sector phenomenology, specifically the Higgs mass, with the vacuum stability constraint of the THDM and the SUSY boundary conditions at high-scale, assumed to be from a UV completion.
- Means: match the MSSM onto THDM-like EFTs at lower scale

The study

THDM Hierarchies



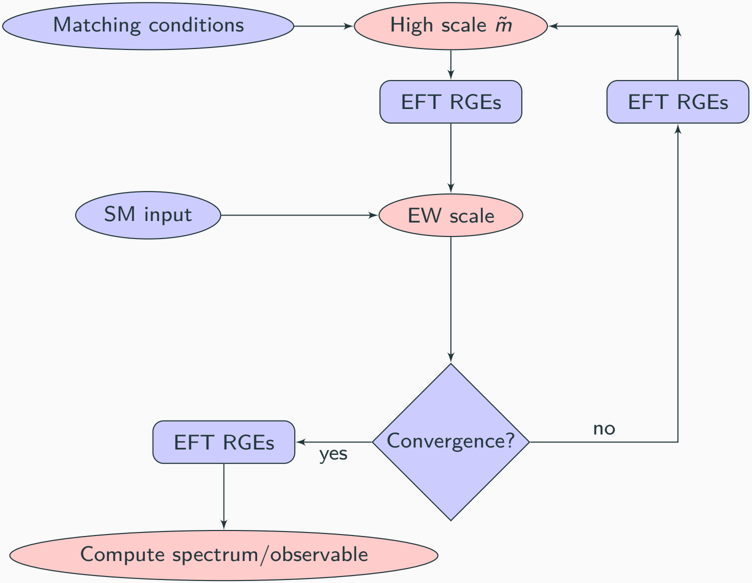
- THDM+higgsinos interesting because of gauge coupling unification around 10^{14} GeV.
- Available in `FlexibleSUSY` starting from version 1.4.0.

FlexibleSUSY and EFT towers

- Framework developed by Athron, Park, Stöckinger and Voigt [1406.2319, 1710.03760].
- Automatic generation of a SoftSUSY-like spectrum generator based for arbitrary models starting from a SARAH model file.
- SLHA input and output – easy interface with other codes and analysis pipelines.
- Native support for EFT towers. Boundary conditions can be specified in Mathematica code.

```
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),
[...]
```

Algorithm implementation



Perturbative content

$$\mathcal{L}_{\text{2HDM}} \supset - m_1^2|H_1|^2 + m_2^2|H_2|^2 - \lambda_1(H_1^\dagger H_1)^2 - \lambda_2(H_2^\dagger H_2)^2 - \lambda_3|H_1|^2|H_2|^2 - \lambda_4|H_2^\dagger H_1|^2$$
$$+ \left[m_{12}^2 H_1^\dagger H_2 - \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 - \lambda_6(H_1^\dagger H_1)(H_1^\dagger H_2) - \lambda_7(H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.}\right]$$

- 2 loop RGEs from `SARAH`, cross-checked by direct comparison with `PYR@TE`.
- Full 1-loop computation of the $\overline{MS}$ running parameters of the EFT; include also 2 loop QCD for the top Yukawa.
- Full 1-loop corrections to the Higgs mass matrix.

Perturbative content

$$\lambda_1(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\lambda_1^{1L} + \Delta\lambda_1^{2L}\ ,\ \lambda_2(M_S) = \frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \Delta\lambda_2^{1L} + \Delta\lambda_2^{2L}$$
$$\lambda_3(M_S) = -\frac{1}{4}\left(\frac{3}{5}g_1^2 + g_2^2\right) + \frac{g_2^2}{2} + \Delta\lambda_3^{1L} + \Delta\lambda_3^{2L}\ ,\ \lambda_4(M_S) = -\frac{g_2^2}{2} + \Delta\lambda_4^{1L} + \Delta\lambda_4^{2L}$$
$$\lambda_5(M_S) = 0 + \Delta\lambda_5^{1L} + \Delta\lambda_5^{2L}\ ,\ \lambda_6(M_S) = 0 + \Delta\lambda_6^{1L} + \Delta\lambda_6^{2L}$$
$$\lambda_7(M_S) = 0 + \Delta\lambda_7^{1L} + \Delta\lambda_7^{2L}$$

- Partial thresholds as in Lee et all (1-loop Haber et al. [hep-ph/9307201]) in the code.
- For the study we used tree-level conditions to avoid being too much dependent on a specific scenario.

EW-vacuum stability in the THDM

- Instability condition for the THDM [Deshpande/Ma '77].

$$
\begin{aligned}
\lambda_1 &> 0 \\
\lambda_2 &> 0 \\
\lambda_3 + (\lambda_1\lambda_2)^{1/2} &> 0 \\
\lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2} &> 0
\end{aligned}
$$

- At the matching scale the potential is stable (SUSY).
- These conditions have to be satisfied at all intermediate scales between M_S and Q_{EW}.
- Due to the matching with SUSY, only the fourth stability condition can be violated.

Metastability

- If the vacuum is unstable at some intermediate scale, there is preferred direction (the steepest) along which it will prefer to decay.
- Derive a metastability bound from the λ^4 potential at tree level.
- Choose a gauge and field basis such that the problem become one-dimensional.

$$\lambda = \frac{4\,(\lambda_1\lambda_2)^{1/2}\,\left(\lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2}\right)}{\lambda_1 + \lambda_2 + 2\,(\lambda_1\lambda_2)^{1/2}}\,.$$

- Tunneling probability for the decay of EW vacuum [Isidori et al. '10]

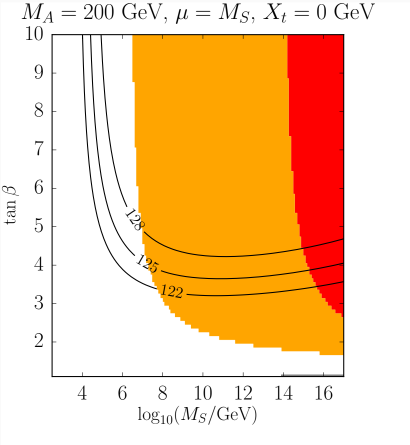
$$p \approx \max_Q (\tau Q)^4 \exp\left(-\frac{8\pi^2}{3|\lambda(Q)|}\right)$$

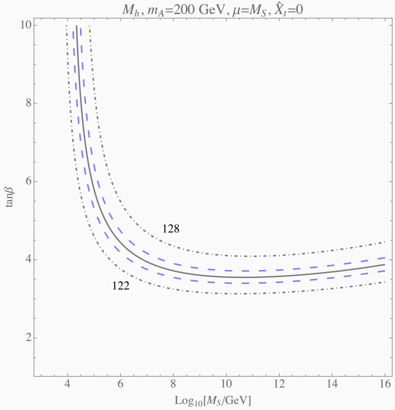
from which we derive

$$\lambda(\mu_r) \gtrsim -\frac{2.82}{41.1 + \log_{10}\frac{\mu_r}{\mathrm{GeV}}} \equiv \lambda_{meta}$$

Results

Comparison with Lee et al.

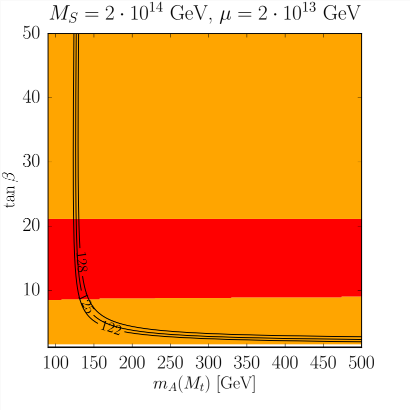


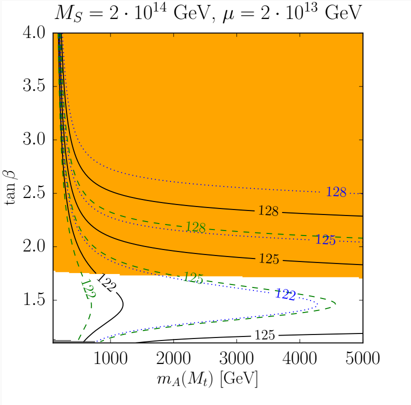


Lee et al. [1508.00576]

- Good qualitative agreement between the two results.
- In the meanwhile, a new calculation by Bahl and Hollik was published. [1805.00867]

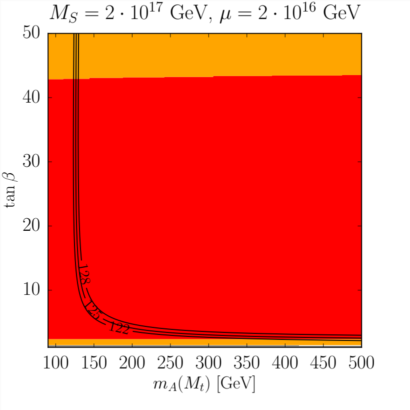
THDM with high-scale SUSY

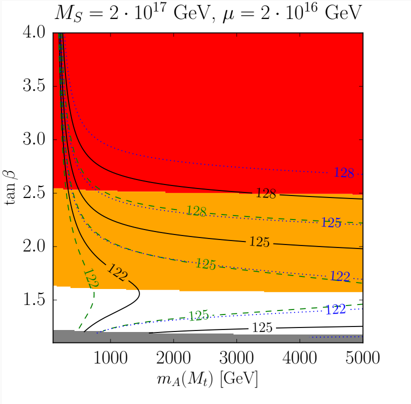




- Stable at very low $\tan\beta$, relatively large M_A.
- High sensitivity to the specific value used for the input top pole mass.

THDM with high-scale SUSY





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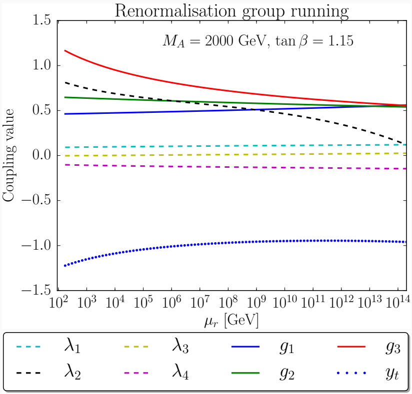
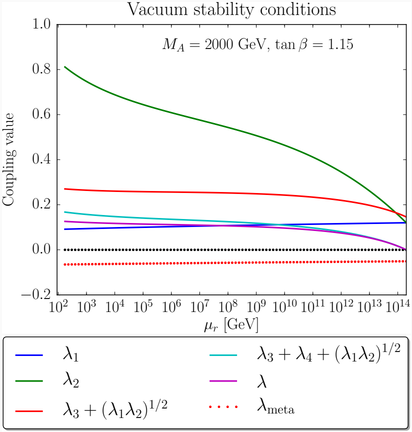
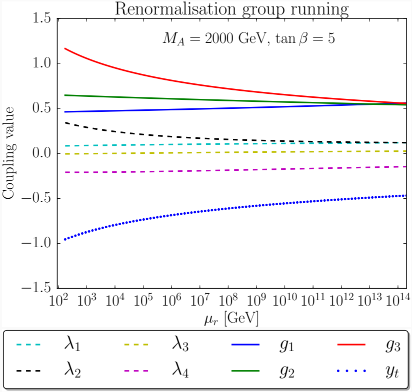
RG running and vacuum stability

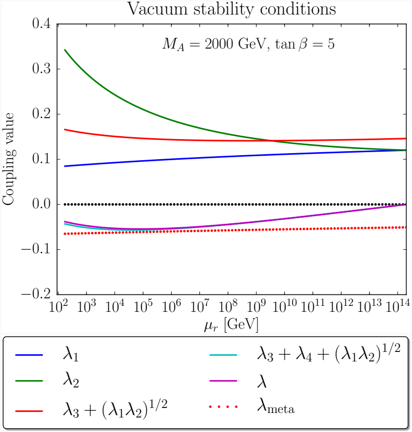




- At low $\tan\beta$, the large top Yukawa at the low scale drives high λ_2 to high values in the IR.
- At the high scale, gauge couplings approximately unify; λ_4 negative.
- $\lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2} > 0$.

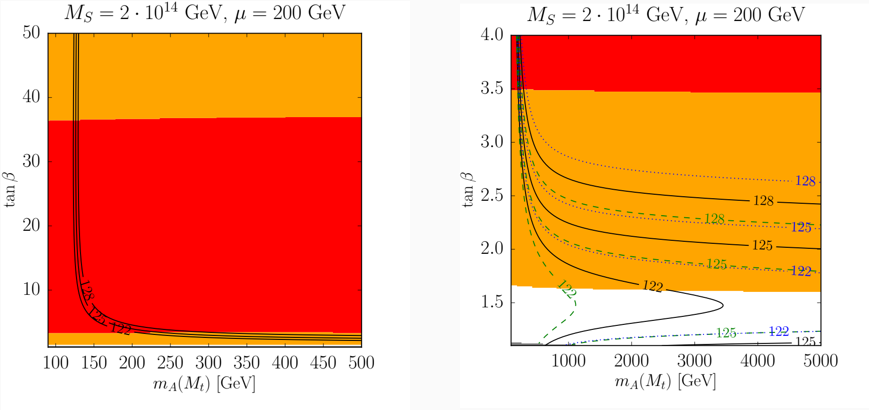
RG running and vacuum stability





- If $\tan\beta$ is large enough, the top Yukawa is unable to push λ_2.

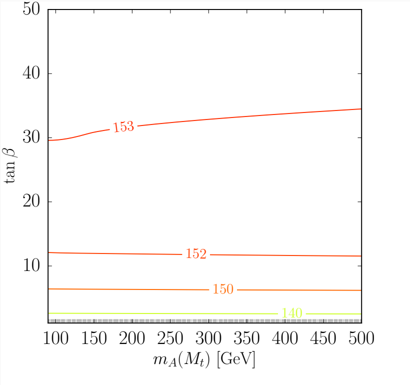
THDM+Higgsinos with high-scale SUSY

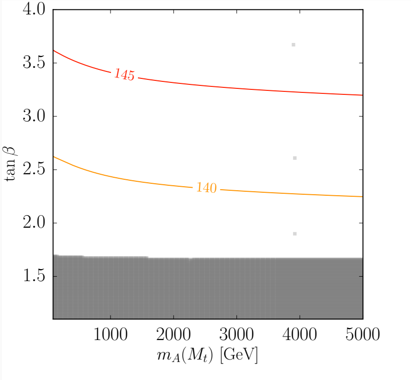


- Higgsinos have a minor effect on the Higgs mass.

THDM+Split with high-scale SUSY

$M_S = 2 \cdot 10^{16}$ GeV, $\mu = M_{1,2,3} = 2000$ GeV

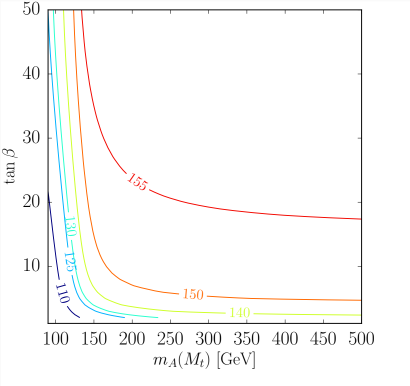


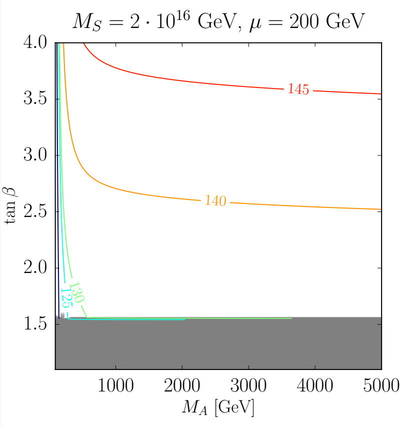


- Very large Higgs mass, impossible to agree with the observed light Higgs mass value.

THDM+Split with high-scale SUSY

$M_S = 2 \cdot 10^{16}$ GeV, $\mu = M_{1,2} = 200$ GeV, $M_3 = 2000$ GeV

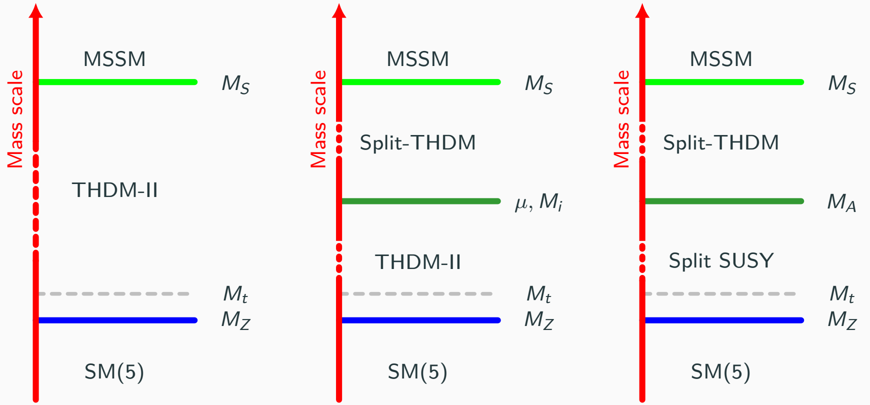




- Allowed only for low values of M_A, for which the scenario is excluded by $b \to s\gamma$.

New developments

New THDM Hierarchies



- Towers with intermediate thresholds are built using the 'addons' facility of `FlexibleSUSY`.
- We use the full 1-loop threshold corrections for the λs from [Gorbahn et al., 0901.2065].

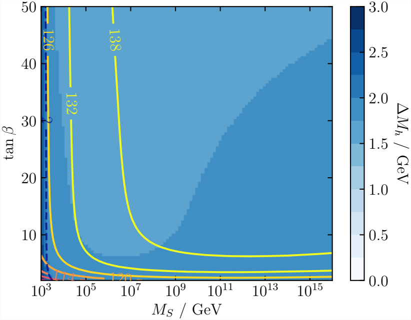
Uncertainty estimation

- Higher-order terms
  - **Low-energy EFT**:

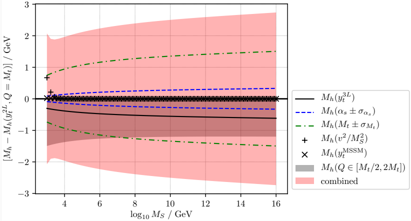
    $\Delta M_h^{(THDM)} = \left| M_h(y_t^{(2)}) - M_h(y_t^{(3)}) \right| +$
    $\max_{\lambda=\{2,1/2\}} \left| M_h(Q_{pole} = M_t) - M_h(Q_{pole} = \lambda M_t) \right|$
  - **EFT uncertainty**: $\Delta\lambda_i \to \Delta\lambda_i + \sum_k \left| \Delta\lambda_{ik} \frac{v^2}{\min\{m_k^2\}} \right|$.
  - **SUSY uncertainty**:

    $\Delta M_h^{(MSSM)} = \left| M_h(y_t^{THDM}) - M_h(y_t^{MSSM}) \right| +$
    $\max_{\lambda=\{2,1/2\}} \left| M_h(Q_S = M_S) - M_h(Q_S = \lambda M_S) \right|$.
- We also consider the parametric uncertainties coming from α_s and M_t.
- Automatic uncertainty delivered to the user through a Mathematica script, as in the single Higgs-doublet case.

THDM single scale

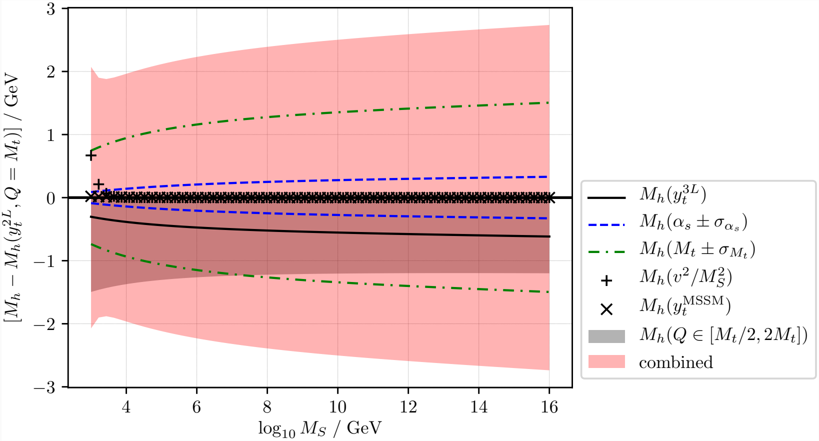


- $m_A = 400$ GeV, $X_t = \sqrt{6} M_S$.



- Uncertainty breakdown along the $m_h = 125.09$ GeV line.

THDM single scale



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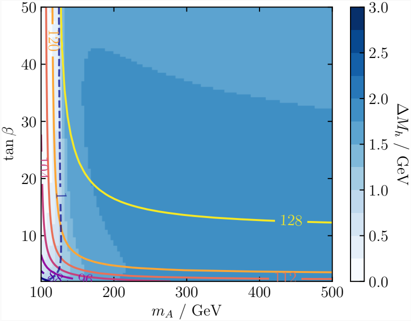
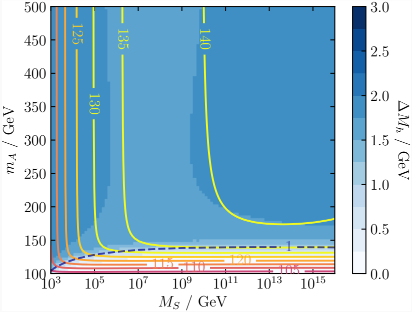
THDM single scale





- $M_S = 50$ TeV, $X_t = 0$.

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

Outlook and conclusions

Outlook

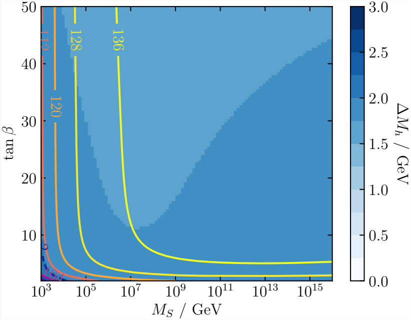
- Add the possibility of decoupling the gluino in the THDM+split.
- Complete matching to the THDM-III.
- Phenomenology in all these scenarios, uncertainty estimation for the prediction of the light Higgs mass at the low scale.
- Update/more in depth study of the vacuum stability constraint for the high-scale SUSY case.

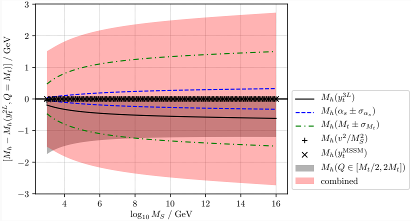
Conclusions

- We have studied vacuum stability with very high-scale Supersymmetry in the case of the matching of the MSSM with a THDM EFT (+higgsinos;+split).
- Large part of parameter space is constrained by vacuum stability constraints.
- Allowed region for the simplest THDM EFT is at low $\tan\beta$ and large M_A.
- We have several planned improvements for our computation to leverage new state-of-the-art perturbative results.

Backup slides

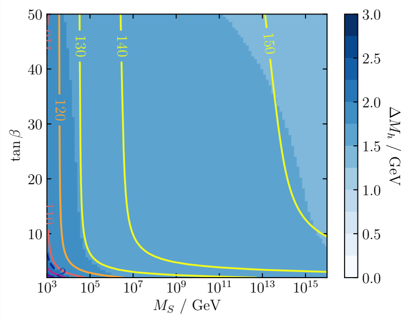
THDM single scale



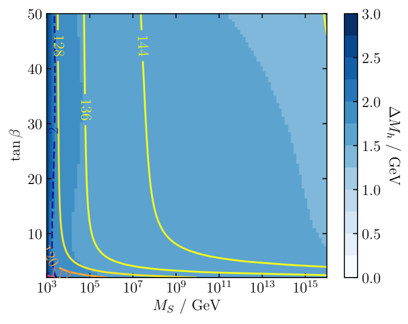


- $m_A = 400$ GeV, $X_t = 0$.

Intermediate gaugino/higgsinos

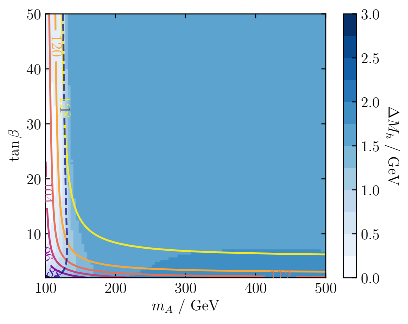


- $m_A = 400$ GeV, $X_t = 0$, $\mu = M_i = 2$ TeV.

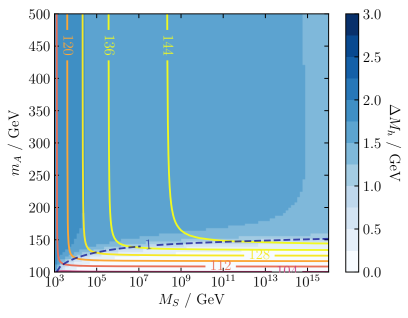


- $m_A = 400$ GeV, $X_t = \sqrt{6} M_S$, $\mu = M_i = 2$ TeV.

Intermediate gaugino/higgsinos

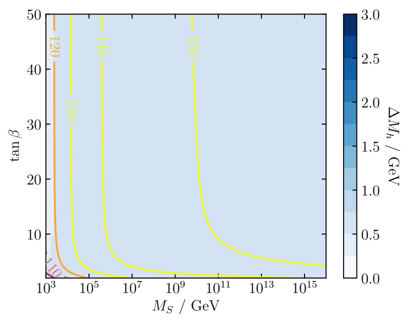


- $M_S = 50$ TeV, $X_t = 0$, $\mu = M_i = 2$ TeV.

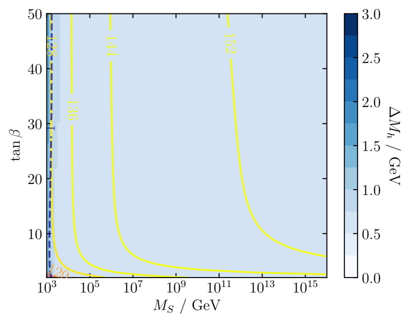


- $\tan\beta = 20$, $X_t = 0$, $\mu = M_i = 2$ TeV.

Intermediate m_A

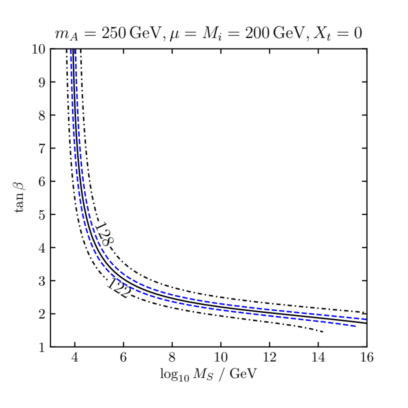


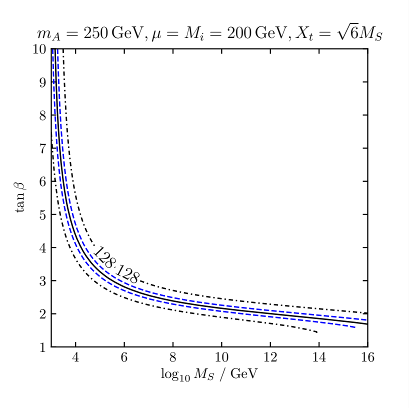
- $m_A = 5$ TeV, $X_t = 0$, $\mu = M_i = 1$ TeV.



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

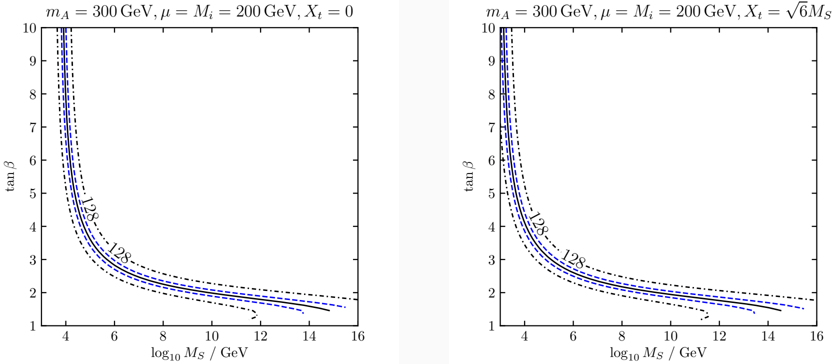
THDM+split and $m_h = 125$ GeV





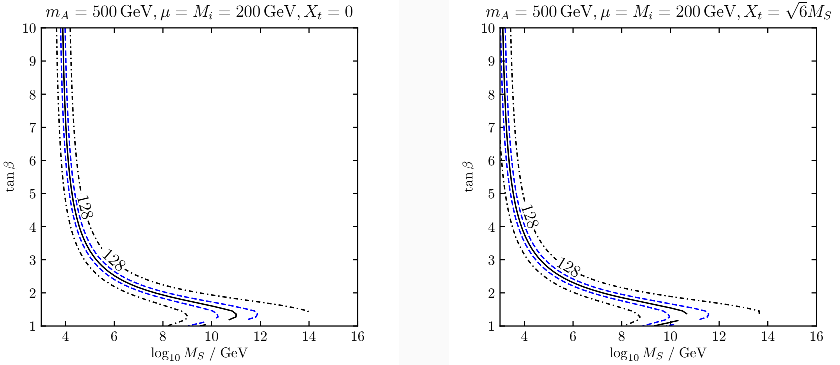
- Low-scale gauginos and Higgsinos, upcoming hierarchies.
- $m_A = 250$ GeV.

THDM+split and $m_h = 125$ GeV



- Low-scale gauginos and Higgsinos, upcoming hierarchies.
- $m_A = 300$ GeV.

THDM+split and $m_h = 125$ GeV



- Low-scale gauginos and Higgsinos, upcoming hierarchies.
- $m_A = 500$ GeV.