Light-THDM scenarios matched with heavy SUSY in the FlexibleSUSY framework: recent developments and results

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In collaboration with W. Buchmüller, F. Brümmer, A. Voigt and G. Weiglein

[1512.07761]

Talk structure

Introduction and motivations

The EW-scale scenarios

Framework

Results

Outlook and conclusions

Introduction and Motivations

- Along the same lines as Lee et al [1508.00576], with the idea of improving/extending the computation.
- Possible richer phenomenology than Split-SUSY due to the presence of a second Higgs doublet at the low scale.
- Study of EW-vacuum stability in the context of a THDM matched with SUSY.
- No extensive studies of uncertainties have been performed.

At the EW scale | Much above the EW scale

THDM

Chiral supermultiplets

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

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	$\widetilde{W}^\pm$ $\widetilde{W}^0$	$W^\pm$ W^0	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

At the EW scale | Much above the EW scale

THDM + Higgsinos

Chiral supermultiplets

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

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bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

At the EW scale | Much above the EW scale

THDM + Split SUSY

Chiral supermultiplets

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

Gauge supermultiplets

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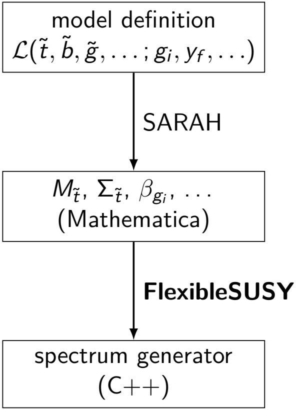
gluino,gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \; \widetilde{W}^0$	$W^\pm \; W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Generating a spectrum generator



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Slide from Alexander Voigt's (DESY) talk at KUTS2016

Available models with MSSM high-scale origin

Model	RGEs	h self-energy contributions	matching conditions to the MSSM
MSSM ("full model")	3L	1L + 2L $O((\alpha_t+\alpha_b)\alpha_s)$ + 2L $O((\alpha_t+\alpha_b)^2)$	–
THDM	2L	1L	1L λ_i $O((\alpha_t+\alpha_b+\alpha_\tau)\alpha_i)$ + 2L λ_i $O(\alpha_t^2\alpha_s)$ [1508.00576]
THDM + $\tilde{h}_i$	2L	1L	1L λ_i $O((\alpha_t+\alpha_b+\alpha_\tau)\alpha_i)$ + 2L λ_i $O(\alpha_t^2\alpha_s)$ [1508.00576]
THDM + split	2L	1L	1L λ_i $O((\alpha_t+\alpha_b+\alpha_\tau)\alpha_i)$ + 2L λ_i $O(\alpha_t^2\alpha_s)$ [1508.00576]
SM + split	2L	1L + 2L $O(\alpha_t(\alpha_s+\alpha_t))$ + 3L gluino $O(\alpha_t\alpha_s^2)$	1L $\tilde{g}_{ij}$ $O(\alpha_t+\alpha_i)$ + 1L λ $O((\alpha_t+\alpha_i)^2)$ + 2L λ $O(\alpha_s\alpha_t^2)$ [1407.4081]
SM ("EFT")	3L	1L + 2L $O(\alpha_t(\alpha_s+\alpha_t))$	1L λ $O((\alpha_t+\alpha_i)^2+\alpha_b^2+\alpha_\tau^2)$ + 2L λ $O((\alpha_s+\alpha_t)\alpha_t^2)$ [1407.4081, 1504.05200]
SM ("automatic EFT")	3L	1L	1L λ + $O(p^2/M_S^2)$ terms

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Slide from Alexander Voigt's (DESY) talk at KUTS2016

FlexibleSUSY and EFT towers

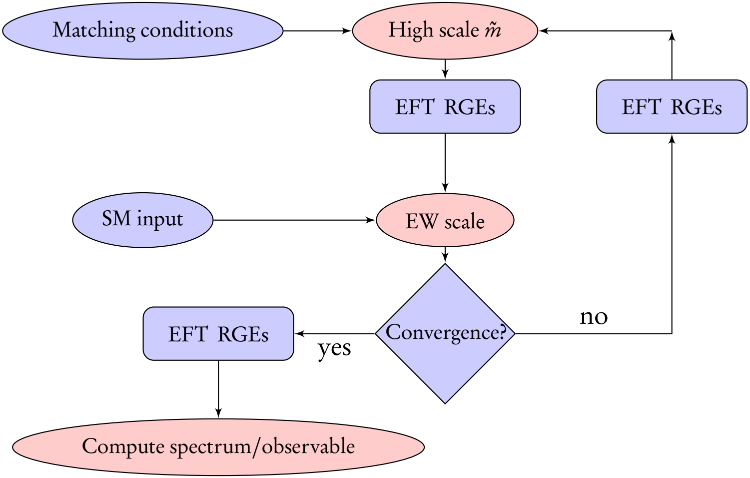
- Framework developed by Athron, Park, Stöckinger and Voigt [1406.2319].
- Automatic generation of a SoftSUSY-like spectrum generator based for arbitrary models starting from a SARAH model file.
- SLHA input and output – easy interface with other codes and analysis pipelines.
- Native support for EFT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

Perturbative content of the current implementation

- 2 loop RGEs from `SARAH-4.6.0`, verified 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.
- For the moment same (partial) thresholds as in Lee et all (1-loop Haber et al[hep-ph/9307201]). We will recompute and include all the thresholds from Nierste et al [0901.2065] in the matching of the MSSM to THDM.
- Assume moreover that $\lambda_6 = \lambda_7 = 0$.
- Just one threshold for the moment.

Algorithm implementation



EW-vacuum stability in the THDM

- Published study on the EW stability of the THDM with GUT scale SUSY [1512.07761].
- Instability condition for the THDM

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

- Due to the matching with SUSY, only the fourth stability condition can be violated.

Metastability

- 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.

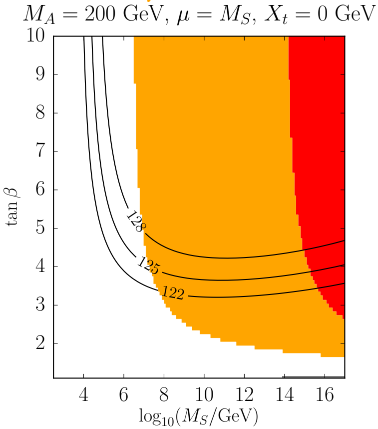
$$\lambda(\mu_r) \gtrsim -\frac{2.82}{41.1 + \log_{10} \frac{\mu_r}{\text{GeV}}}$$

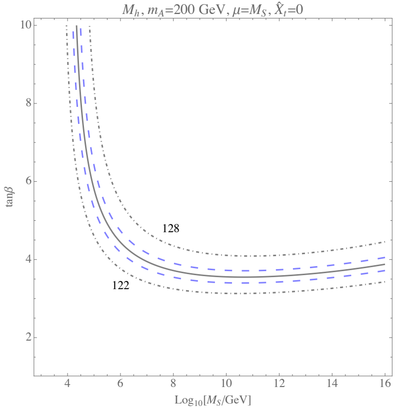
with

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

Comparison with Wagner et al

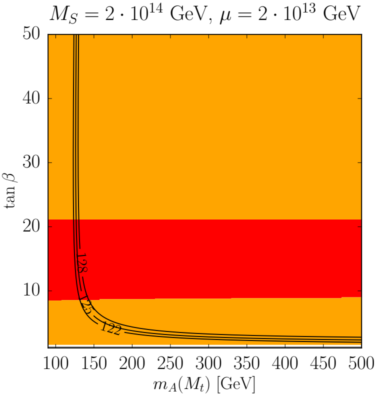
Preliminary

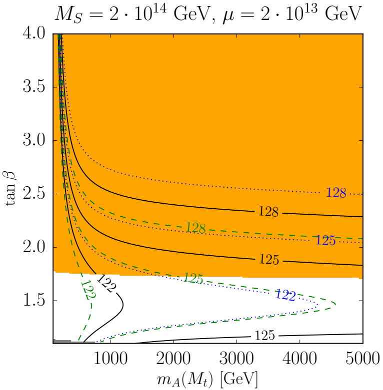




- Good qualitative agreement for the THDM. Looking forward for a more thorough comparison of the implementations.

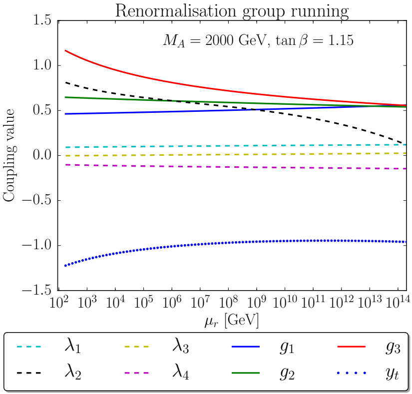
THDM with GUT-scale SUSY

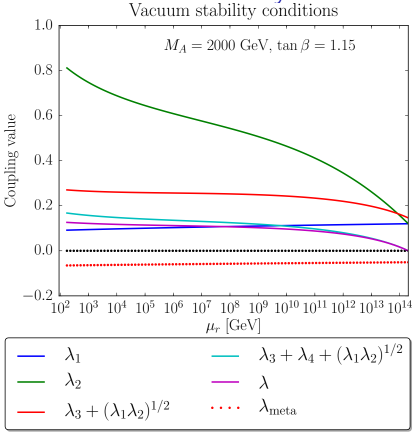




- Match the THDM instead of the SM. [Lee et al, Bagnaschi et al]

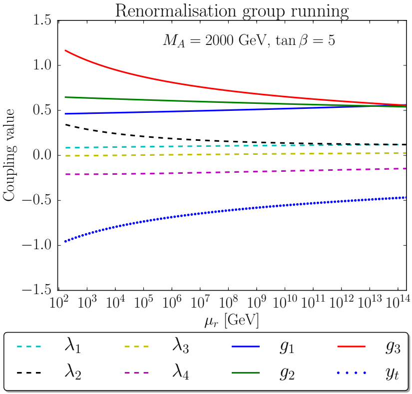
RG running and vacuum stability

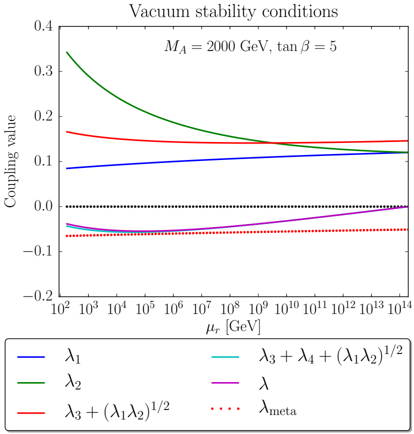




- At low $\tan\beta$, the large top Yukawa at the low scale drives high λ_2 to high values in the IR.
- At the high scale, gauge couplings approximately unify; λ_4 negative.
- $\lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2} > 0$.

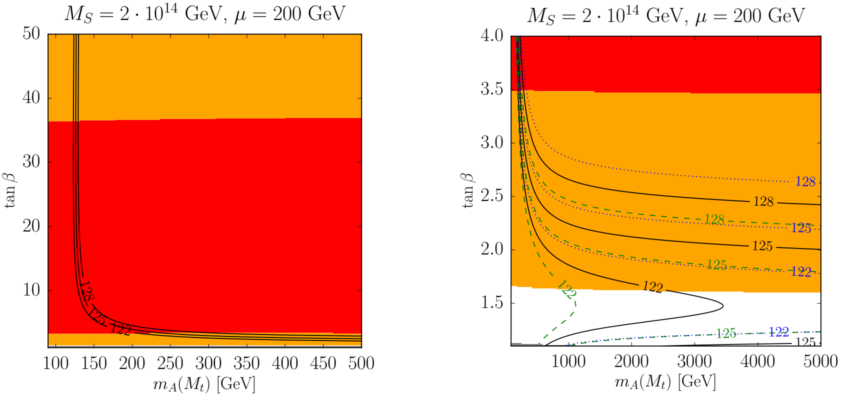
RG running and vacuum stability





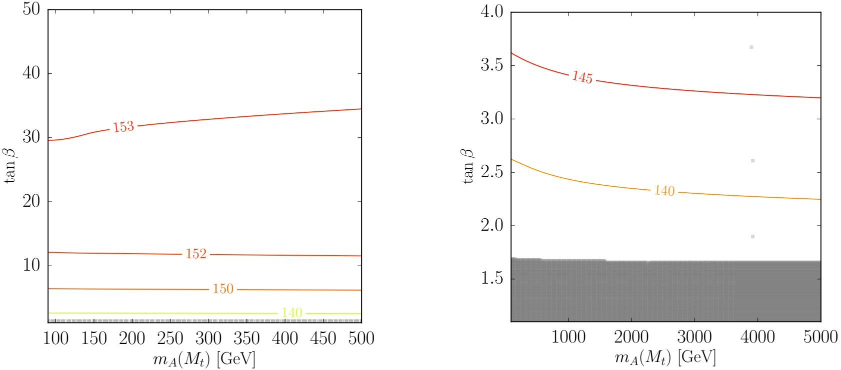
- If $\tan\beta$ is large enough, the top Yukawa is unable to push λ_2

THDM+Higgsinos with GUT-scale SUSY



- Higgsinos have a minor effect on the Higgs mass since they couple only through gauge interactions (no gauginos in the spectrum).

THDM+Split with GUT-scale SUSY



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

Outlook

- Compute the gauge contribution to the thresholds as a cross-check for Nierste et al and include them in `FlexibleSUSY`.
- Include all the missing thresholds.
- Add the possibility of decoupling the pseudoscalar (in all three scenarios) and the gluino in the THDM+split.
- Complete matching to the THDM, include λ_6 and λ_7 and all the Yukawas and split-Yukawa coupling.
- Phenomenology in all these scenarios, uncertainty estimation for the prediction of the light Higgs mass at the low scale.

Conclusions

- We have implemented in `FlexibleSUSY`the matched computation of the MSSM to a single-Higgs-doublet (not shown in the talk) and two-Higgs-doublet models (with various gaugino/higgsinos hierarchy).
- We have studied vacuum stability with GUT scale Supersymmetry in the case of the matching of the MSSM with a THDM EFT (+higgsinos;+split).
- Planned improvements for our computation.

Backup slides