Higgs mass computation in BSM physics

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Talk structure

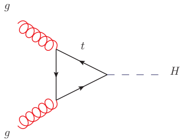
The Large Hadron Collider (LHC)

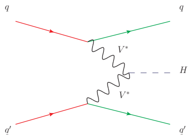
Fact sheet

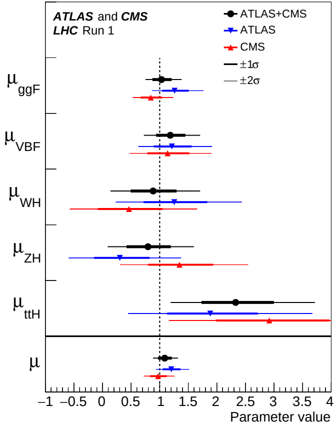
- 26.7 km LEP tunnel
- p-p collision up to 13/14 TeV
- $\mathscr{L}_{pp} = 10^{34} cm^{-2} s^{-1}$
- heavy ions collisions with up 2.8 TeV/nucleon
- $\mathscr{L}_{HI} = 10^{27} cm^{-2} s^{-1}$
- 4 interaction points
- 2 general purpose experiments, ATLAS and CMS
- 2 dedicated experiments, LHCb and ALICE
- LHC Computing GRID

The Higgs after LHC Run1 and Run2

- Higgs properties as measured by the LHC with the current dataset point to compatibility with the SM.
- No other BSM signatures appearead at the LHC up to now.
- The Higgs mass is a free parameter in the SM, however this could not be the case in in models beyond the SM, as in Supersymmetry.
- Can we use the Higgs mass as an handle for heavy BSM physics?



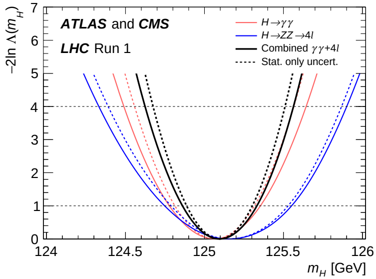


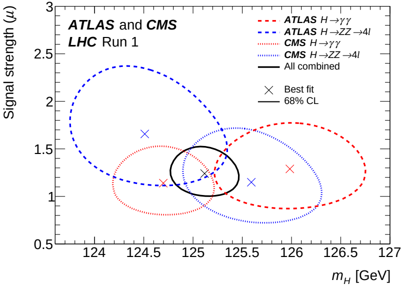


ATLAS+CMS combination [1606.02266]

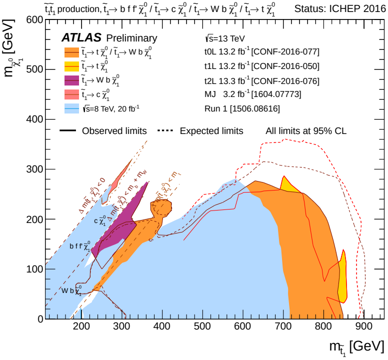
The Higgs after LHC Run1 and Run2

- Most important results from LHC Run-1 is the discovery a SM-like Higgs boson.
- Mass measured with high-accuracy (ATLAS+CMS combination , [hep-ex/1503.07589]) during the first run of the LHC.
- High-precision measurement not yet available with Run-2 data.

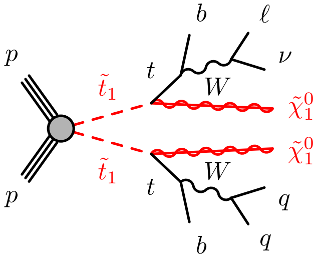




SUSY with heavy sparticles



- Negative searches for SUSY particles at the LHC have renewed interest in unnatural SUSY models, where superpartners are much above the EW scale.



Light scalars particle could lead the following issues:

- Quite light Higgs boson mass (MSSM).
- New sources of CP violation.
- New sources of flavor violation.
- Proton decay.

The models

The Minimal Supersymmetric Standard Model

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)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
sleptons,leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$
(×3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgses, Higgsinos	H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)$
	H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

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

At the EW scale | Much above the EW scale

Single scale SUSY

Chiral supermultiplets

Name	Symbol	spin 0	spin 1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks,quarks (×3 families)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
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At the EW scale | **Much above the EW scale**

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)	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$
(×3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
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Higgs mechanism in the MSSM

- Tree level Higgs scalar potential for the neutral components ($m_u^2 = m_{H_u}^2 + |\mu|^2$ and $m_d^2 = m_{H_d}^2 + |\mu|^2$)

$$V_0 = m_u^2 \left|H_u^0\right|^2 + m_d^2 \left|H_d^0\right|^2 + B_\mu (H_d^0 H_u^0 + \text{h.c.}) + \frac{g^2 + g'^2}{8} \left(\left|H_d^0\right|^2 - \left|H_u^0\right|^2\right)^2$$

- The two Higgs doublet are supposed to acquire a v.e.v. different from zero
- Decomposition of the fields

$$H_u^0 = \frac{1}{\sqrt{2}}(v_u + S_u + iP_u), \quad H_d^0 = \frac{1}{\sqrt{2}}(v_d + S_d + iP_d)$$

- Diagonalization of the pseudoscalar mass matrix (rotation angle β) give a would-be Goldstone boson eaten by the Z and a pseudoscalar state with a mass

$$m_A^2 = \frac{B_\mu}{\cos\beta \sin\beta}$$

- Same diagonalization angle for the charged Higgs matrix
- Pseudoscalar couplings to quarks and leptons are given by

$$g_{Auu} = \cot\beta \frac{m_u}{v}, \quad g_{Add,Aee} = \tan\beta \frac{m_{d,e}}{v}$$

Higgs mechanism in the MSSM

- Mass matrix for the scalar sector (m_u^2 and m_d^2 replaced by a combination of m_A^2 and $\tan\beta$)

$$\mathcal{M}_0 = \begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_A^2 \cos^2\beta + m_Z^2 \sin^2\beta \end{pmatrix}$$

- Diagonalization angle α. $m_h^2 \leq m_Z^2 \cos^2(2\beta)$ at tree level.

$$\tan 2\alpha = \left(\frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}\right)\tan 2\beta$$

-

$$m_{h,H} = \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_Z^2 m_A^2 \sin^2(2\beta)}\right)$$

- Scalar coupling to the gauge bosons: $g_{hVV} = \frac{2m_V^2}{v}\sin(\beta-\alpha), \quad g_{HVV} = \frac{2m_V^2}{v}\cos(\beta-\alpha)$
- Scalar couplings to the quarks and leptons are given by

$$g_{huu} = \frac{\cos\alpha}{\sin\beta}\frac{m_u}{v}, \quad g_{hdd,hee} = -\frac{\sin\alpha}{\cos\beta}\frac{m_{d,e}}{v}$$

$$g_{Huu} = \frac{\sin\alpha}{\sin\beta}\frac{m_u}{v}, \quad g_{Hdd,hee} = \frac{\cos\alpha}{\cos\beta}\frac{m_{d,e}}{v}$$

Higher order corrections to the Higgs mass

One can compute the Higgs mass by computing the complex zero of the inverse propagator matrix.

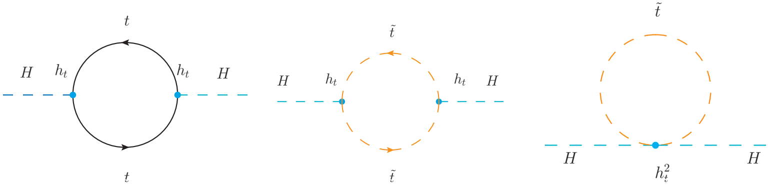
For the CP-even sector

$$M^2_{hH}(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{hH}(q^2) \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

where $\hat{\Sigma}_{ij}(q^2)$ $(i,j = h,H)$ are the renormalized self-energies; m_H^2 and m_h^2 the tree level masses.

One then computes the complex roots of $\det(M^2_{hH}(q^2)) = 0$, $\mathcal{M}_i$ and from those extracts the mass and width: $\mathcal{M}_i^2 = M_i^2 - iM_i\Gamma_i$.

Higher order corrections to the Higgs mass



Considering radiative corrections to the self-energies then all MSSM particles contributes.

- $\hat{\Sigma}_{ij}(q^2) = \hat{\Sigma}^1_{ij}(q^2) + \hat{\Sigma}^2_{ij}(q^2) + \dots$

Structure of radiative corrections

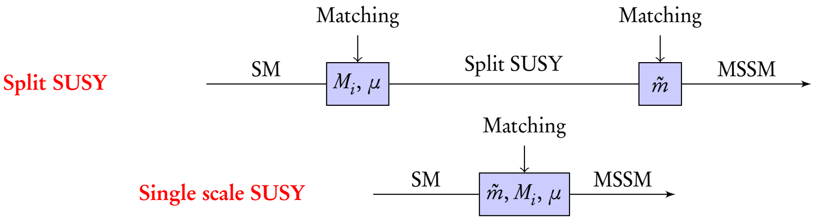
Only stop-top sector for simplicity

1. At one loop: $\Delta(M_h^{(1)})^2 = m_t^4[L + C^{(1)}]$ with $L = \log\left(\frac{m_{\tilde{t}}}{m_t}\right)$
2. At two loop: $\Delta(M_h^{(2)})^2 = m_t^2\left[m_t^2\alpha_s\left(L^2 + L + C^{(2)}\right) + m_t^4\left(L^2 + L + D^{(2)}\right)\right]$

In this case the problem of this approach is that, if directly applied to the High-scale SUSY/Split SUSY lead to large $\log(M_S/Q_{EW})$.

A tower of effective theories

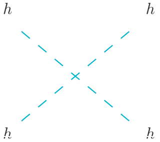
- Problem: mass gap in the physical spectrum makes large logs of the ratio $m_{\text{ew}}/\tilde{m}$ appears in the perturbative expressions.
- Solution: For a proper computation these logs have to be resummed.
- Method: define a tower of effective field theories, where the heavy particles are integrated out, and match them at a proper scale. Use RGE to resum the large logarithms.



Tree level matching

- Matching conditions with the MSSM at the scale $\tilde{m}$.
  - Higgs quartic coupling.

$$\lambda(\tilde{m}) = \frac{1}{4}\left[g_2^2(\tilde{m}) + \frac{3}{5}\,g_1^2(\tilde{m})\right]\cos^2 2\beta$$



  - Higgs-higgsino-gaugino effective couplings

$$\tilde{g}_{2u}(\tilde{m}) = g_2(\tilde{m})\sin\beta\,, \qquad \tilde{g}_{1u}(\tilde{m}) = \sqrt{3/5}\,g_1(\tilde{m})\sin\beta\,,$$
$$\tilde{g}_{2d}(\tilde{m}) = g_2(\tilde{m})\cos\beta\,, \qquad \tilde{g}_{1d}(\tilde{m}) = \sqrt{3/5}\,g_1(\tilde{m})\cos\beta$$

- Note that $\tan\beta$ is **not** a parameter of the low-energy theory.

Threshold corrections

All corrections computed with the following assumptions:

1. Limit of unbroken EW symmetry ($v^2/\tilde{m}^2 \to 0$).
2. Limit of zero external momenta.
3. Limit of zero mass for the light particles.
4. Neglect all Yukawa couplings aside g_t.

For the couplings relevant for the Higgs boson mass computation we have:

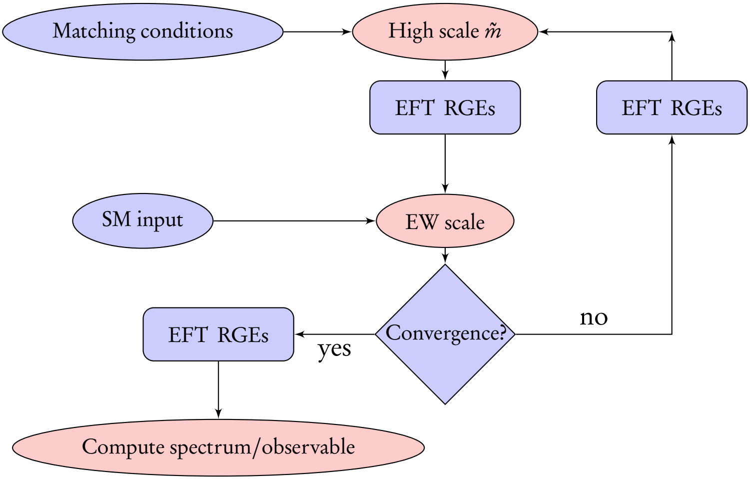
- One loop threshold to the Higgs quartic coupling.

$$\lambda(\tilde{m}) = \frac{1}{4}\left[g_2^2(\tilde{m}) + \frac{3}{5}g_1^2(\tilde{m})\right]\cos^2 2\beta + \Delta\lambda^{1\ell,\mathrm{reg}} + \Delta\lambda^{1\ell,\phi} + \Delta\lambda^{1\ell,\chi^1} + \Delta\lambda^{1\ell,\chi^2} + \Delta\lambda^{2\ell}$$

- One loop threshold to the Higgs-higgsino-gauge coupling.

$$\tilde{g}_{2u}(\tilde{m}) = g_2(\tilde{m})\sin\beta\left[1+\Delta_{\tilde{g}_{2u}}\right], \qquad \tilde{g}_{1u}(\tilde{m}) = \sqrt{3/5}\,g_1(\tilde{m})\sin\beta\left[1+\Delta_{\tilde{g}_{1u}}\right],$$
$$\tilde{g}_{2d}(\tilde{m}) = g_2(\tilde{m})\cos\beta\left[1+\Delta_{\tilde{g}_{2d}}\right], \qquad \tilde{g}_{1d}(\tilde{m}) = \sqrt{3/5}\,g_1(\tilde{m})\cos\beta\left[1+\Delta_{\tilde{g}_{1d}}\right]$$

Algorithm implementation



Higgs mass prediction

- The Higgs mass is predicted in the low-energy theory, at the weak scale, using the relation between the λ quartic coupling and the physical Higgs boson mass.
- At tree level

$$m_H^2(Q) = 2\lambda(Q)v^2 = \frac{\lambda(Q)}{\sqrt{2}G_F}$$

- At one- and with two-loop $\mathcal{O}(g_t^4 g_3^2)$ and $\mathcal{O}(g_t^6)$

$$\begin{aligned} M_H^2 = {} & m_H^2(Q)\left[1+\delta_{1l}^{\mathrm{SM}}+\delta_{1l}^{\mathrm{Split}}\right] \\ & + \frac{g_t^4 v^2}{128\pi^4}\left[16 g_3^2\left(3l_t^2+l_t\right)-3g_t^2\left(9l_t^2-3l_t+2+\frac{\pi^2}{3}\right)\right] \end{aligned}$$

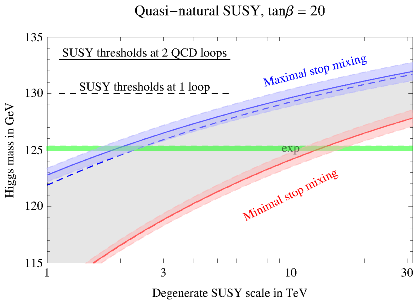
Phenomenological predictions

Quasi-natural SUSY

- All superparticles have masses in the range between a few to tens TeV.

- Minimal stop mixing in the vicinity of $X_t = 0$.
- Maximal stop mixing close to $X_t = \sqrt{6}\tilde{m}$.
- Colored bands are due to the parametric uncertainty due to M_t and $\alpha_s(M_z)$.
- Two-loop corrections vanish for zero mixing and degenerate SUSY masses.

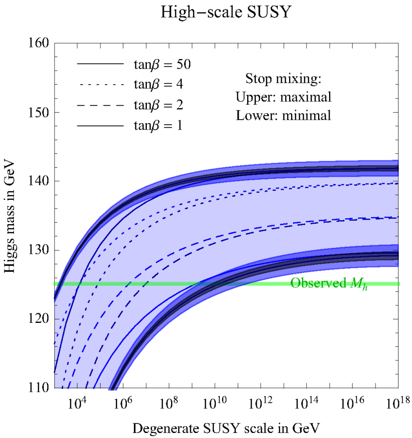
$$\text{SM in } \overline{\text{MS}} \;\; g_{1,2,3}, g_t, \lambda \quad \longleftrightarrow \quad \text{MSSM in } \overline{\text{DR}} \;\; g_{1,2,3}, y_t$$



High-scale SUSY

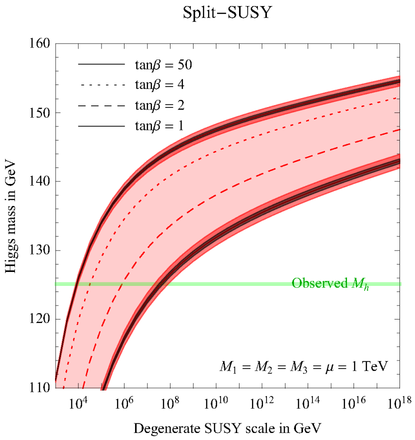
- All SUSY particles lie around the same scale $\tilde{m}$, which can be much higher than the weak scale.

- Thinner gray band due to 1σ variation of $\alpha_s(M_Z)$.
- Larger colored) due to 1σ variation of M_t.



Split-SUSY

- $M_1 = M_2 = M_3 = \mu = 1$ TeV.
- All scalars degenerate at scale $\tilde{m}$.
- $A_t = 0$ (In Split-SUSY $A_t/\tilde{m} \ll 1$).



- Thinner gray band due to 1σ $\alpha_s(M_Z)$.
- Larger colored band due to M_t variation.

Conclusions

- Negative results from LHC searches for BSM states or for possible deviations from the SM predictions point to the possibility that the scale of BSM physics can be much higher than the electroweak scale.
- In this scenario, for models that offer a prediction for the Higgs mass, the latter can be the only handle to BSM physics coming from the LHC.

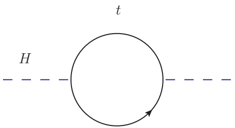
Future outlook

- New data from the LHC will improve the precision of the experimental measurements, need to reduce the theoretical uncertainty.
- Include new threshold corrections to the matching of λ.
- Improved uncertainty estimation of the Higgs mass prediction, especially for the intermediate mass-range (EFT uncertainty).
- Extend precision study to more complex mass hierarchies (e.g. intermediate pseudoscalar).

Backup slides

Fine-tuning

- Naturalness has been the guiding principle to try to design BSM models.
- New physics should appear at a scale not much higher than EW one.
- From a theoretical point of view, the problem of the tuning of the Higgs mass is similar to the cosmological constant problem (it implies new dynamic at 10^{-3} eV).
- Anthropic solution? A non-problem?



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \cdots$$

The MSSM Lagrangian

- Gauge part of the Lagrangian and fermion-scalar-gaugino interactions.
- Superpotential $W = h_e H_d L \bar{e} + h_d H_d Q \bar{d} + h_u Q H_u U^c - \mu H_u H_d$
- Soft SUSY-breaking mass and interaction terms for MSSM scalars

$$\begin{aligned}\mathscr{L}_{\text{soft-breaking}} = {} & m^2_{H_u} H_u^\dagger H_u + m^2_{H_d} H_d^\dagger H_d + m^2_Q Q^\dagger Q + m^2_L L^\dagger L \\ & + m^2_u \tilde{u}^*_R \tilde{u}_R + m^2_d \tilde{d}^*_R \tilde{d}_R + m^2_e \tilde{e}^*_R \tilde{e}_R \\ & + \left(T_e H_d L \tilde{e}^*_R + T_d H_d Q \tilde{d}^*_R + T_u Q H_u \tilde{u}^*_R + B_\mu H_u H_d + h.c. \right)\end{aligned}$$

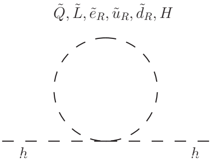
- SUSY-soft-breaking gauginos masses

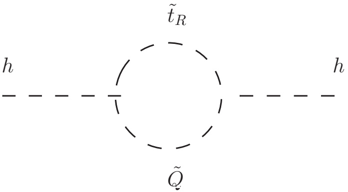
$$\mathscr{L}_G = \frac{1}{2} \left(M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right) + h.c.$$

One loop corrections to the quartic coupling

$$\lambda(\tilde{m}) = \frac{1}{4}\left[g_2^2(\tilde{m}) + \frac{3}{5}g_1^2(\tilde{m})\right]\cos^2 2\beta + \Delta\lambda^{1\ell,\mathrm{reg}} + \Delta\lambda^{1\ell,\phi} + \Delta\lambda^{1\ell,\chi^1} + \Delta\lambda^{1\ell,\chi^2}$$

- $\Delta\lambda^{1\ell,\phi}$ contains the threshold corrections from diagrams involving scalars.
- Needed in all models.





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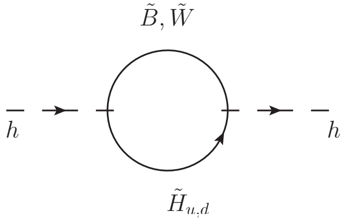
- $\Delta\lambda^{1\ell,\chi^1}$ contains the proper threshold corrections from SUSY fermions.



- Needed for single scale SUSY.
- In Split SUSY either introduced at the matching threshold with the SM or not present as a threshold (enters the relation between the quartic and the Higgs mass).

One loop corrections to the quartic coupling

$$\lambda(\tilde{m}) = \frac{1}{4}\left[g_2^2(\tilde{m}) + \frac{3}{5}g_1^2(\tilde{m})\right]\cos^2 2\beta \;+\; \Delta\lambda^{1\ell,\,\mathrm{reg}} \;+\; \Delta\lambda^{1\ell,\phi} \;+\; \Delta\lambda^{1\ell,\chi^1} \;+\; \Delta\lambda^{1\ell,\chi^2}$$

- $\Delta\lambda^{1\ell,\,\mathrm{reg}}$ contains term due to the fact that we are expressing the matching in terms of the low-energy effective theory in the $\overline{\mathrm{MS}}$ scheme.
- $\Delta\lambda^{1\ell,\chi^2}$ contains the terms that are needed in single scale SUSY due to the fact that the tree level matching for λ is expressed in terms of the SM gauge couplings.

Two loop matching

- Two loop $\mathcal{O}(g_3^2 g_t^4)$ corrections to λ computed with EP techniques from the results of Slavich et al.

$$\Delta\lambda^{2\ell} = \frac{1}{2}\frac{\partial^4 \Delta V^{2l,\tilde{t}}}{\partial^2 H^\dagger \partial^2 H} + \Delta\lambda^{2l,\text{shift}}$$

- Two-loop diagrams involving strong gauge interaction of the stop squarks

$$\begin{aligned}\Delta V^{2\ell,\tilde{t}} \quad = \quad & \frac{g_3^2}{64\,\pi^4}\Big\{2\,m_{\tilde{t}_1}^2\, I(m_{\tilde{t}_1}^2, m_{\tilde{t}_1}^2, 0) + 2\,L(m_{\tilde{t}_1}^2, M_3^2, m_t^2) - 4\,m_t\,M_3\,s_{2\theta}\,I(m_{\tilde{t}_1}^2, M_3^2, m_t^2) \\ & + \left(1 - \frac{s_{2\theta}^2}{2}\right) J(m_{\tilde{t}_1}^2, m_{\tilde{t}_1}^2) + \frac{s_{2\theta}^2}{2} J(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) + \left[m_{\tilde{t}_1} \leftrightarrow m_{\tilde{t}_2}\,,\, s_{2\theta} \to -s_{2\theta}\right]\Big\}\end{aligned}$$

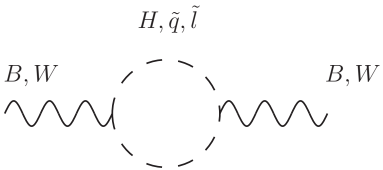
- $\Delta\lambda^{2l,\text{shift}}$ contains one-loop renormalization term for the top Yukawa.

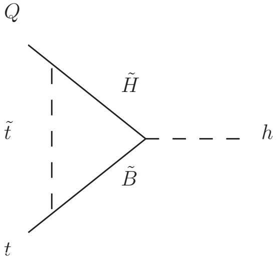
Other threshold corrections

- Not needed for the computation of the Higgs mass but required to study the behavior at high energy (e.g. unification).

$$\hat{g}_1(\tilde{m}) = g_1(\tilde{m}) + \Delta g_1$$
$$\hat{g}_2(\tilde{m}) = g_2(\tilde{m}) + \Delta g_2$$
$$\hat{g}_3(\tilde{m}) = g_3(\tilde{m}) + \Delta g_3$$

$$\hat{y} = \frac{g_t(\tilde{m})}{\sin\beta}\left(1 + \Delta g_t^{\phi} + \Delta g_t^{\chi}\right)$$





Computation of the spectrum and of the parameters/couplings

In Split SUSY two possibilities:

1. Bagnaschi et al [arXiv 1407.4081]

$$\begin{array}{c}\text{SM in }\overline{\text{MS}}\\ g_{1,2,3}, g_t, \lambda\end{array} \longleftrightarrow \begin{array}{c}\text{Split-SUSY in }\overline{\text{MS}}\\ g_{1,2,3}, g_t, \lambda, \tilde{g}_{1\text{d}}, \tilde{g}_{1\text{u}}, \tilde{g}_{2\text{d}}, \tilde{g}_{2\text{u}}\end{array} \overset{\tilde{m}}{\longleftrightarrow} \begin{array}{c}\text{MSSM in }\overline{\text{DR}}\\ g_{1,2,3}, y_t\end{array}$$

2. Bernal et al [arXiv 0705.1496v3]

$$\begin{array}{c}\text{Split-SUSY in }\overline{\text{MS}}\\ g_{1,2,3}, g_t, \lambda, \tilde{g}_{1\text{d}}, \tilde{g}_{1\text{u}}, \tilde{g}_{2\text{d}}, \tilde{g}_{2\text{u}}\end{array} \overset{\tilde{m}}{\longleftrightarrow} \begin{array}{c}\text{MSSM in }\overline{\text{DR}}\\ g_{1,2,3}, y_t\end{array}$$

- According to the scheme chosen, the corresponding threshold corrections have to be used. In theory one should define as many thresholds as needed by the mass spectrum.

The renormalization of the mixing angle

- It is not useful to relate β to the ratio of the vacuum expectation value of H_u and H_d.
- β should be interpreted as the fine-tuned mixing angle that rotates the two original doublets into one heavy doublet A and a light one H.
- The divergent part of the CT for β is required to cancel the divergence of the anti-symmetric part of the WFR matrix

$$\delta\beta^{\mathrm{div}} = \frac{1}{2}\frac{\Pi^{\mathrm{div}}_{HA}(m_H^2) - \Pi^{\mathrm{div}}_{HA}hA(m_A^2)}{m_H^2 - m_A^2}$$

- Finite part of the CT is arbitrary and defines the renormalization scheme. In our case it cancels exactly the off-diagonal WFR contributions from the matching conditions of the effective couplings

$$\delta\beta^{\mathrm{fin}} = \frac{\Pi^{\mathrm{fin}}_{HA}(m_H^2)}{m_H^2 - m_A^2}$$

- It is the angle that diagonalized the radiatively corrected Higgs mass matrices at $p^2 = m_H^2$.

Algorithm implementation

- SM input parameters: $\alpha_s(M_Z)$, $\alpha(M_Z)$, G_F, M_Z, $m_b(m_b)$, M_τ.
- SUSY parameters: $\mu(M_Z)$, $M_1(M_Z)$, $M_2(M_Z)$, $M_3(M_Z)$, $\tilde{m}$, $\tan\beta(\tilde{m})$, $A_t(\tilde{m})$, plus all the soft-susy breaking mass terms for the scalars.
- The running parameters are extracted with two loop precision.
- SM RGEs at three loop, Split SUSY RGEs at two loop.

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 Mathematica code.
- Available at https://flexiblesusy.hepforge.org/

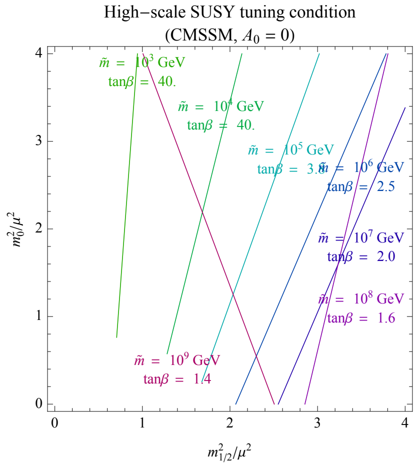
```
FSModelName = "THDM";
FSEigenstates = SARAH`EWSB;
AutomaticInputAtMSUSY = False;
FSDefaultSARAHModel = "THDM-II";
MINPAR = {
    {3, TanBeta}
};
EXTPAR =
    {0, MSUSY},{1, MEWSB},
    {2, MuInput},{6, MAInput},
    {7, AtInput},{8, AbInput},
    {9, AtauInput},{100, LambdaLoopOrder}
};
EWSBOutputParameters = { 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),
[...]
```

Uncertainty of the Higgs mass prediction

- ± 0.2 GeV are estimated to come from missing higher orders in the SM RGEs and in the relation between physical observables and running parameters in the SM.
- ± 0.5 GeV from the missing higher orders in the SUSY threshold corrections (estimated by varying by a factor of two $\tilde{m}$ – expected not to be much larger than the $\mathcal{O}(g_3^2 g_t^4)$ corrections that are at most 0.4 GeV for large stop mixing and $\tilde{m} = 10$ TeV.
- The other uncertainties are suppressed by $v^2/\tilde{m}^2$, it should be already irrelevant for a scale $\tilde{m} = 10$ TeV.

EW Tuning in High-scale SUSY

- Tuning condition: $\tan^2\beta = \left.\frac{m_{H_d}^2 + \mu^2}{m_{H_u}^2 + \mu^2}\right|_{\tilde{m}}$
- SUSY breaking pattern: common gaugino mass $m_{1/2}$, common scalar mass m_0, Higgsino μ and $A_0 = 0$.
- For any given value for $m_{1/2}/\mu$ and m_0/mu, the measured Higgs mass and the EW tuning conditions determines $\tan\beta$ and $\tilde{m}$.
- New focus point for $\tilde{m} \simeq 10^8$ GeV and low $\tan\beta$.



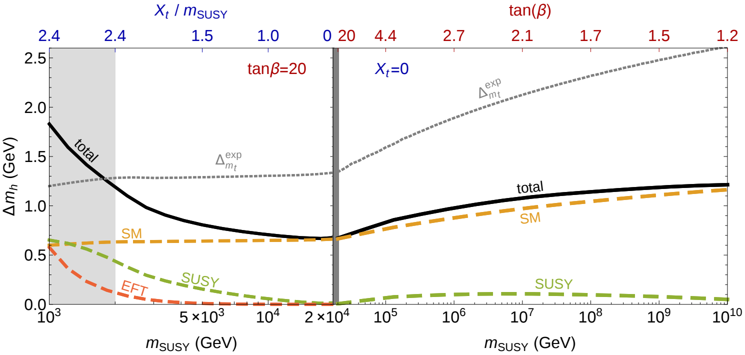
Uncertainty of the Higgs mass prediction

There are different sources of uncertainty

- Missing higher order corrections in the translation from the physical measured data and the running parameters used in the iterative procedure.
- Missing higher terms in the RGEs.
- Power suppressed terms $1/(4\pi)^2 v^2/\tilde{m}^2$ in the above two computations.
- Higher order corrections to the SUSY thresholds.
- $v^2/\tilde{m}^2$ terms due to the fact that we neglect EWSB when matching the MSSM with the low-energy effective theory.

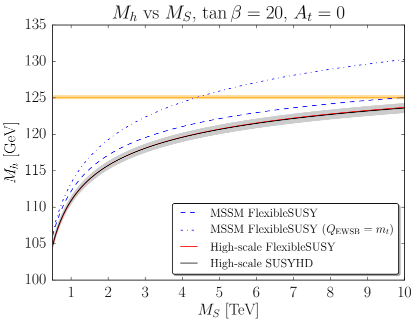
The procedure is valid only if there is a definite hierarchy between the particles.

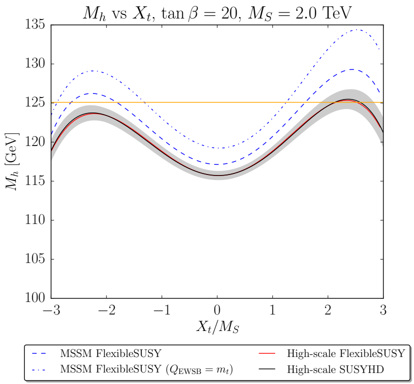
SUSYHD uncertainty estimation



- Villadoro and Pardo-Vega: [1504.05200]

Uncertainty in the Higgs mass prediction





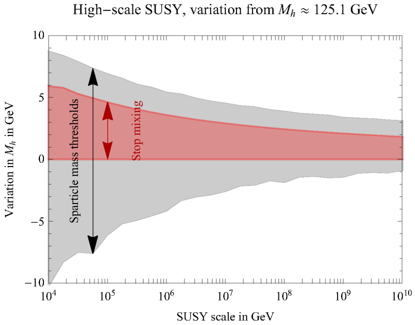
- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

[SusyHD 1504.05200] [FlexibleSUSY WIP] [FeynHiggs 1312.4937]

High-scale SUSY

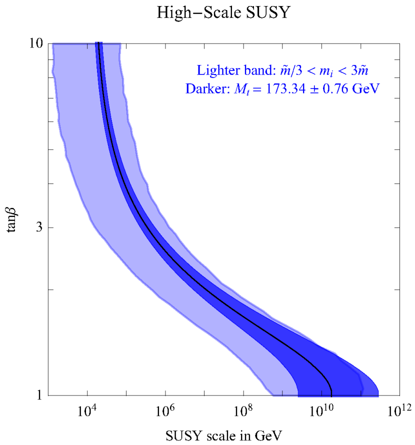
- The darker (red) region denotes the effect of varying only A_t, in the range allowed by vacuum stability.
- Larger (gray) band due to random scanning of each SUSY particle mass parameters ($M_1, M_2, M_3, m_{Q_i}, m_{U_i}, m_{D_i}, m_{E_i}, m_{L_i}$, distinguishing the third generation from the other two), up to a factor of 3 (1/3) above (below) the SUSY scale $\tilde{m}$.

Variation of M_h around the value obtained with $\tan\beta$ and A_t in such a way that $X_t = 0$ and $M_h = 125.15$ GeV, for a given mass scale $\tilde{m}$.



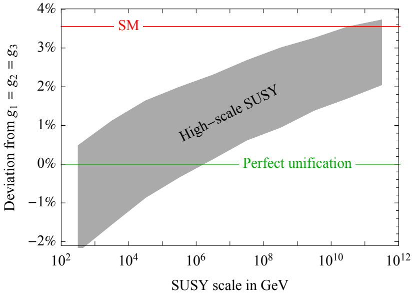
High-scale SUSY

- For $\tan\beta \lesssim 2$ dominant uncertainty from the top mass value (dependence of M_h on $\tilde{m}$ rather flat).
- For $\tan\beta \gtrsim 2$ larger sensibility to SUSY-threshold effects, with no strong dependence on $\tilde{m}$). This is due to two competing effects: flatness of the M_h dependence on $\tilde{m}$ vs smallness of the SUSY thresholds at large $\tilde{m}$.
- Perturbativity of the top Yukawa satisfied ($\tilde{m} > 10^7$ GeV for $\tan\beta = 1$).



Unification in High-scale SUSY

- Use on the full one loop threshold corrections to the MSSM couplings $\hat{g}_1, \hat{g}_2, \hat{g}_3, \hat{g}_t$.
- Two-loop MSSM RGEs.
- The gray band is obtained by scanning the SUSY mass parameters by up of a factor 3 (1/3) above (below) $\tilde{m}$.
- $\tan\beta$ in the scan is tuned to reproduce the observed Higgs mass.
- A_t in the range allowed by vacuum stability.



Vacuum stability in High-scale SUSY

- All the scans respect the vacuum stability constraints.
- Eliminates corrections that could reduce the Higgs mass when $\tilde{X}_t = (A_t - \mu \cot\beta)^2 / m_{Q_3} m_{U_3} \gtrsim 12$.

Scalar potential for the stop-Higgs system

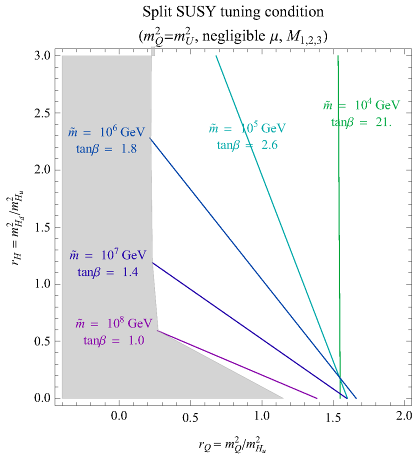
$$\begin{aligned} V \quad &= \quad m_{Q_3}^2 |\tilde{Q}_3|^2 + m_{U_3}^2 |\tilde{U}_3|^2 + \frac{g_t}{\sin\beta}\left(A_t H_u \tilde{Q}_3 \tilde{U}_3 + \mu H_d^* \tilde{Q}_3 \tilde{U}_3 + \text{h.c.}\right) \\ &+ \quad \frac{g_t^2}{\sin^2\beta}\left(|H_u \tilde{Q}_3|^2 + |H_u \tilde{U}_3|^2 + |\tilde{Q}_3 \tilde{U}_3|^2\right) + \text{Higgs-mass terms} + D\text{-terms} \end{aligned}$$

- Requiring that the color-breaking minimum is not deeper than the EW one implies

$$\tilde{X}_t = \frac{(A_t - \mu\cot\beta)^2}{m_{Q_3} m_{U_3}} < \left(4 - \frac{1}{\sin^2\beta}\right)\left(\frac{m_{Q_3}}{m_{U_3}} + \frac{m_{U_3}}{m_{Q_3}}\right)$$

Tuning conditions

- Less parameter at $\tilde{m}$ than high-scale SUSY.
- Tuning condition: $\tan^2\beta = \left.\frac{m^2_{H_d}}{m^2_{H_u}}\right|_{\tilde{m}}$.
- Assuming $SU(5)$ unification relations for the scalar, the tuning condition can be expressed in term of $r_H = \left.\frac{m^2_{H_d}}{m^2_{H_u}}\right|_{M_{\rm GUT}}$ and $r_Q = \left.\frac{m^2_Q}{m^2_{H_u}}\right|_{M_{\rm GUT}}$.
- Solutions in a region close to universality ($r_H \sim r_Q \sim \mathcal{O}(1)$).



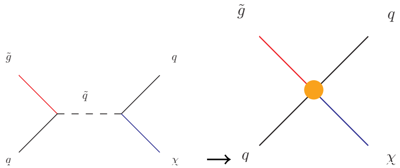
Collider signatures: gluino decay

- Gluino lifetime (decay length) from the determination of $\tilde{m}$ due to the Higgs mass prediction.

$$c\tau_{\tilde{g}} = \left(\frac{2\text{TeV}}{M_{\tilde{g}}}\right)^2 \left(\frac{\tilde{m}}{10^7\text{GeV}}\right)^4 0.4 \text{ m}$$

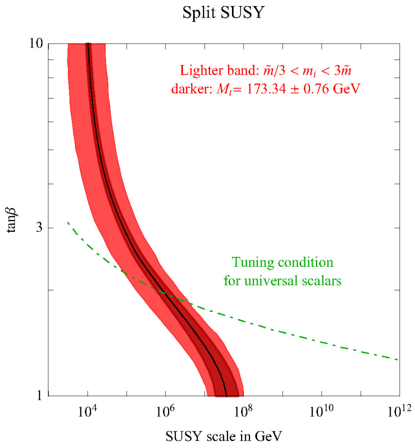
- Need EFT computation to resum large logs.
  Gambino et al [hep-ph/0506214]

- $\tan\beta \approx 1 \;\; \rightarrow \;\; c\tau_{\tilde{g}} \gtrsim 10\text{m}$ (out of detector decay).
- $1 < \tan\beta < 2 \;\; \rightarrow \;\; c\tau_{\tilde{g}} \gtrsim 50\mu\text{m}$ (displaced vertex).
- $\tan\beta > 2 \;\; \rightarrow$ prompt decay.



Split-SUSY

- For $\tan\beta \lesssim 2$ dominant uncertainty from the top mass value.
- For $\tan\beta \gtrsim 2$ dominant uncertainty from SUSY threshold effects.
- Smallness of A_t and μ implies small stop threshold corrections (smaller effect than in high-scale SUSY).
- Less sensitivity to M_t (in respect to high-scale SUSY).

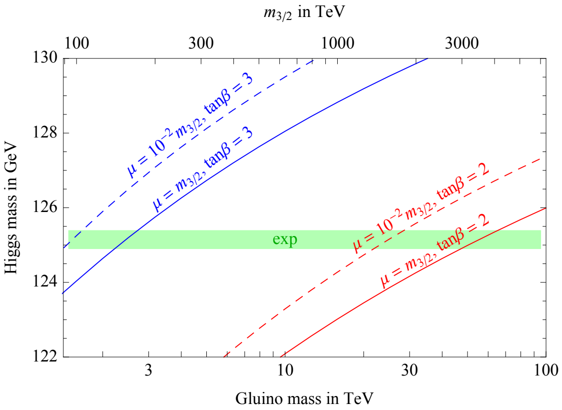


Mini-split SUSY

1. Simplest Split SUSY model emerging from anomaly mediation.
2. Theory characterized by four parameters: $\tilde{m}$, $m_{3/2}$, μ and $\tan\beta$.
3. One parameter fixed by the Higgs mass.
4. If gravity is the only mediator of SUSY breaking, $\tilde{m} \sim m_{3/2}$.
5. If μ and B_μ are generated from the same operator, then $\tan\beta$ is fixed.

Higgs mass in mini-split

- Soft scalar masses assumed to be all equal to $m_{3/2}$.
- $2 \lesssim tan\beta \lesssim 3$ to get the correct Higgs mass.
- Mild dependence on the value of μ.



Gaugino masses in mini-split SUSY

Anomaly mediation yields precise prediction for the gaugino masses.

$$M_{\tilde{B}} = \quad M_1(Q)\left[1+\frac{C_\mu}{11}+\frac{g_1^2}{80\pi^2}\left(-\frac{41}{2}\ln\frac{Q^2}{M_1^2}-\frac{1}{2}\ln\frac{\mu^2}{M_1^2}+\ln\frac{m_A^2}{M_1^2}+11\ln\frac{m_{\tilde{q}}^2}{M_1^2}+9\ln\frac{m_{\tilde{\ell}}^2}{M_1^2}\right)+\frac{g_3^2}{6\pi^2}-\frac{13g_t^2}{264\pi^2\sin^2\beta}\right]$$

$$M_{\widetilde{W}} = \quad M_2(Q)\left[1+C_\mu+\frac{g_2^2}{16\pi^2}\left(\frac{19}{6}\ln\frac{Q^2}{M_2^2}-\frac{1}{6}\ln\frac{\mu^2}{M_2^2}+\frac{1}{3}\ln\frac{m_A^2}{M_2^2}+3\ln\frac{m_{\tilde{q}}^2}{M_2^2}+\ln\frac{m_{\tilde{\ell}}^2}{M_2^2}\right)+\frac{3g_3^2}{2\pi^2}-\frac{3g_t^2}{8\pi^2\sin^2\beta}\right]$$

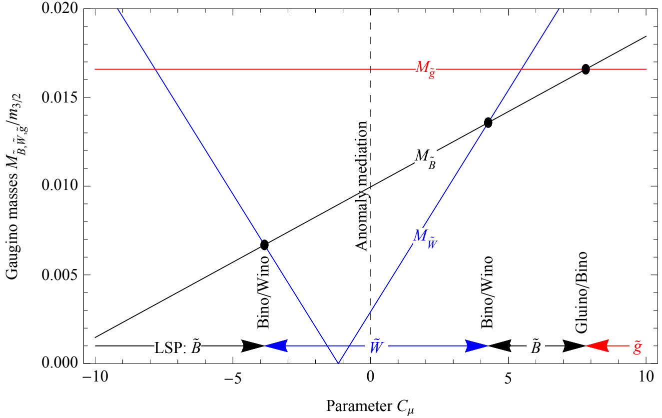
where

$$M_1(Q) = \frac{33\,g_1^2(Q)}{80\pi^2}\,m_{3/2}\,, \qquad M_2(Q) = \frac{g_2^2(Q)}{16\pi^2}\,m_{3/2}\,,$$

$g_i(Q)$ are the gauge couplings of the SM renormalized in the $\overline{\text{MS}}$ scheme at a generic scale Q, and

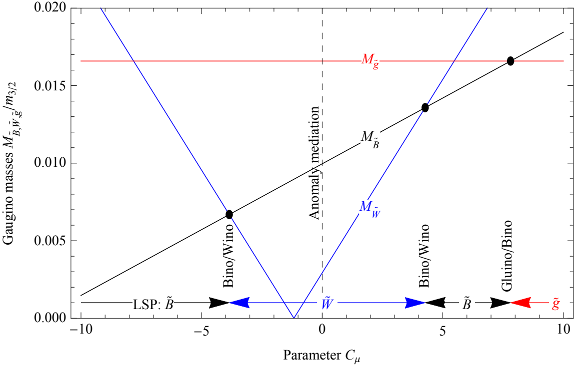
Dark matter in mini-split SUSY

- Rich phenomenology as μ is allowed to vary.
- Nature of LSP defined by $C_\mu = \frac{\mu}{m_{3/2}} \frac{m_A^2 \sin 2\beta}{m_A^2 - \mu^2} \ln \frac{m_A^2}{\mu^2}$.



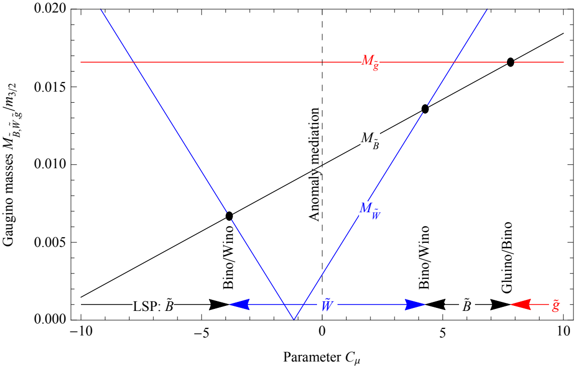
Dark matter in mini-split SUSY

- $|C_\mu| \lesssim 4$ the LSP is the Wino (this is also the case of the usual Split SUSY with μ at the EW scale).
- $M_{\widetilde{W}} = 2.7$ TeV if the Wino is a DM thermal relic.
- Most favorable case $M_{\tilde{g}} = 1.2 \times 2.7 = 3.24$ TeV $\rightarrow$ out of the LHC reach.



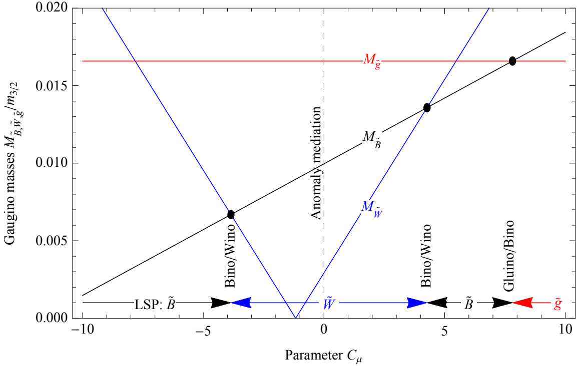
Dark matter in mini-split SUSY

- $C_\mu < 3.9$ and $4.1 < C_\mu < 7.8$ the LSP is the Bino.
- Thermal relic abundance would overclose the universe (need late entropy injection/low reheat temperature).
- In the range $4.1 < C_\mu < 7.8$ compressed gaugino mass spectrum.



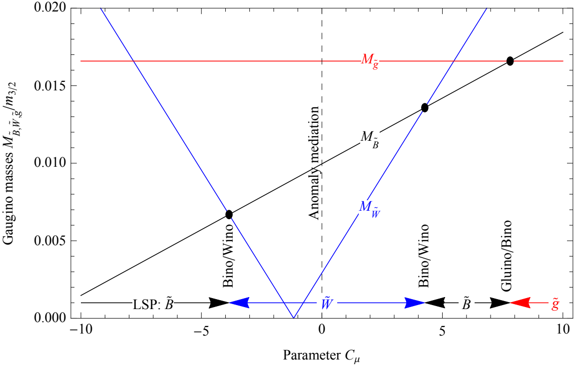
Dark matter in mini-split SUSY

- $C_\mu < 7.8$ the LSP is the gluino.
- Not acceptable for DM but interesting for collider phenomenology.
- Cosmological constraints evaded with R-violating effective interactions.



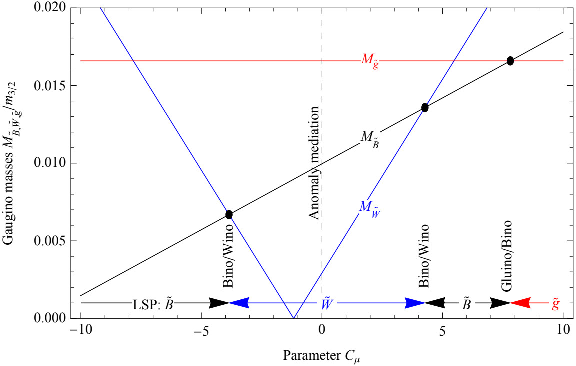
Dark matter in mini-split SUSY

- For $|C_\mu| \approx 4$, the LSP can be a well-tempered Bino-Wino.
- For 10% mass splittings, the mass can be in the range of hundreds of GeV.
- $M_{\tilde{g}}/M_{\tilde{W}} = 2.4$ (for $C_\mu \approx -4$) and $M_{\tilde{g}}/M_{\tilde{W}} = 1.2$ (for $C_\mu \approx 4$).
- Case particularly favorable for the LHC.



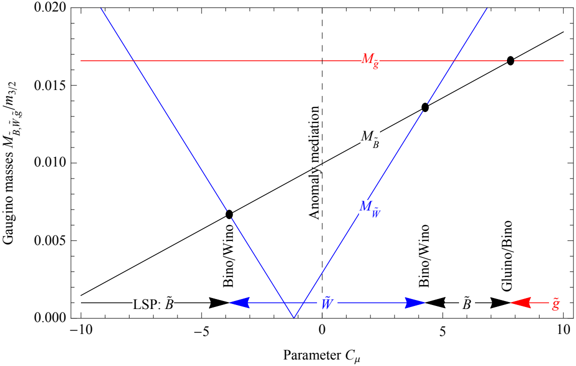
Dark matter in mini-split SUSY

- For $C_\mu \approx 0$, the LSP can be a mixture of higgsino and wino.
- large annihilation cross section, not much gained in terms of relic abundance.
- Detection at DM experiments can be sizable due to Higgs boson exchange.



Dark matter in mini-split SUSY

- For $C_\mu \approx 7.8$, allows for an unusual co-annihilation between gluino and bino.
- For splittings in 100-150 GeV range, the bino can be a thermal relic DM and the gluino withing reach of the LHC.
- However difficult detection at the LHC due to soft decay products.



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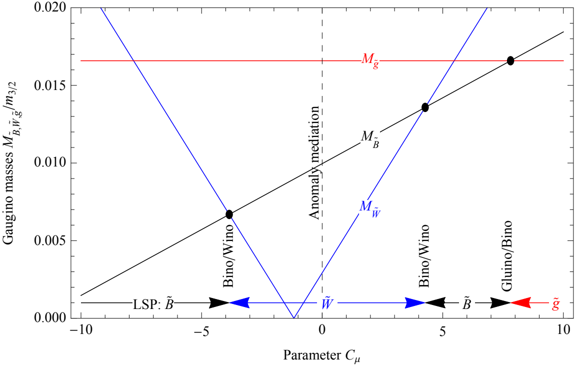
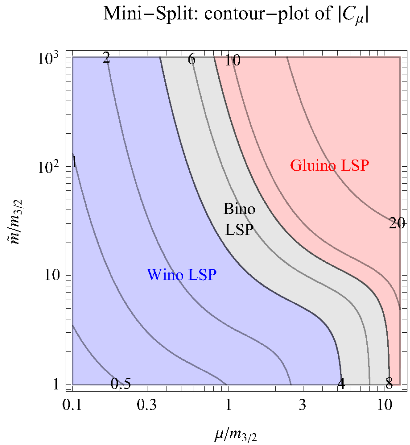


Dark matter in mini-split SUSY

$$C_\mu = \frac{2\mu\tan\beta}{m_{3/2}} \frac{\tilde{m}^2+\mu^2}{(\tan^2\beta+1)\tilde{m}^2+\mu^2} \ln\left[(1+\tan^{-2}\beta)\left(1+\frac{\tilde{m}^2}{\mu^2}\right)\right]$$

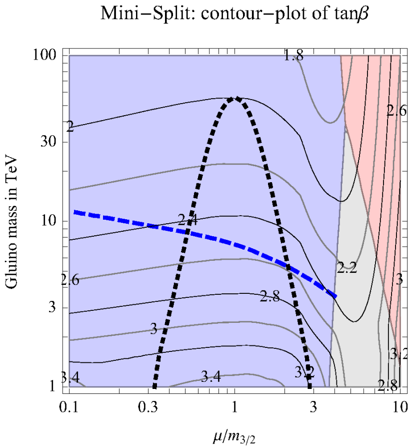
- We can express C_μ in terms of the original parameter of the model.
- The 1-10 range can be easily obtained for natural choices of the parameters.



Dark matter in mini-split SUSY

Wino LSP – Bino LSP – Gluino/Bino LSP (depends on the sign of μ).

- Assumed exact universality of the scalar masses $\tilde{m} = m_{3/2}$.
- Contours of $\tan\beta$ as extracted from the Higgs mass measurements (mild dependence on μ).
- Dashed blue line is where Wino DM abundance reproduces the observed DM density.
- Dash black line if $m_{H_d}^2 = \tilde{m}^2 = m_{3/2}^2$ is assumed.



Mini-split SUSY

- Spectrum characterized by:
  1. SUSY scalars at the mass scale $\tilde{m}$. Tipical size related to the gravitino mass $\tilde{m} \simeq (M_{PL}/M_*)m_{3/2}$ where M_* is the mediation scale.
  2. Anomaly mediation gives precise predictions for the physical size of the gauginos in terms of $m_{3/2}$.
  3. μ is expected to be of $\mathcal{O}(m_{3/2})$ if there is no suppression related to PQ breaking. Otherwise μ is a free parameter between $m_{3/2}$ and the EW scale.
  4. B_μ is of order $\tilde{m}^2$
  5. $\tan\beta$ can assume any value, unless μ and B_μ are generated by the same operator.

Heavy SUSY matched to a THDM

- Enrich the phenomenology by considering the possibility of a THDM for the scalar sector of low-energy EFT.
- First detailed in Haber & Hempfling ([hep-ph/9307301]).
- Matching performed recently by Lenz et al ([1203.0238]), however in the context of studying B meson mixing.
- First recent study focused on the Higgs mass by Lee & Wagner ([1508.00576]).
- Bagnaschi et al ([1512.07761]) studied vacuum stability with GUT study.

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)	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$
(×3 families)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
sleptons,leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$
(×3 families)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgses, Higgsinos	H_u	(H_u^+, H_u^0)	$(\widetilde{H}_u^+, \widetilde{H}_u^0)$	$\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)$
	H_d	(H_d^0, H_d^-)	$(\widetilde{H}_d^0, \widetilde{H}_d^-)$	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

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 + 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)	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons,leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\bar{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
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

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

Matching to a THDM

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \left(m_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right) + V_4\,,$$
$$V_4 = \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \left(\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \lambda_6 (H_1^\dagger H_2)(H_1^\dagger H_1) + \lambda_7 (H_1^\dagger H_2)(H_2^\dagger H_2) + \text{h.c.}\right).$$

- More complex scalar sector, requires computation of the thresholds for each λ_i.

$$\lambda_1 = \frac{1}{4}\left(g^2 + g'^2\right), \lambda_2 = \frac{1}{4}\left(g^2 + g'^2\right),$$
$$\lambda_3 = \frac{1}{4}\left(g^2 - g'^2\right), \lambda_4 = -\frac{1}{2}g^2, \lambda_5 = \lambda_6 = \lambda_7 = 0$$

Matching to a THDM

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

- "Wrong" yukawas $\tilde{\gamma}_i = \tilde{\eta}_j = 0$ at tree level.
- Ignored for now for simplicity, EFT is then a type II THDM. They will be included in a upcoming study.

The hMSSM approach

- Based on using the observed Higgs mass (and not the un-observed spectrum) as an input.
- Higgs sector of the MSSM described only in terms of m_A,$\tan\beta$ and m_h (which is now an input).
- Predictive power in the heavy Higgs mass and the mixing angle α

$$\mathcal{M}^2_\Phi = \mathcal{M}^2_{\text{tree}} + \begin{pmatrix} \Delta\mathcal{M}^2_{11} & \Delta\mathcal{M}^2_{12} \\ \Delta\mathcal{M}^2_{12} & \Delta\mathcal{M}^2_{22} \end{pmatrix}$$

$$\tan\alpha = -\frac{(m_Z^2+m_A^2)\cos\beta\sin\beta}{m_Z^2\cos^2\beta + m_A^2\sin^2\beta - m_h^2}$$

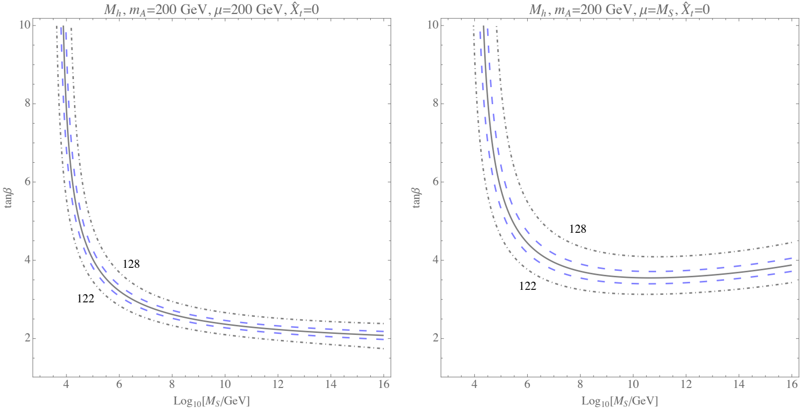
$$m_H^2 = \frac{(m_A^2+m_Z^2-m_h^2)(m_Z^2\cos^2\beta+m_A^2\sin^2\beta) - m_A^2\, m_Z^2\cos^2 2\beta}{m_Z^2\cos^2\beta + m_A^2\sin^2\beta - m_h^2}$$

It depends on the following assumptions

- The neglected stop-top corrections in $\Delta\mathcal{M}^2_{11}$,$\Delta\mathcal{M}^2_{12}$ scale as $\mu X_t/m^2_{\text{SUSY}}$
- SUSY sparticles do not affect the Higgs besides the effect in mass matrix (satisfied in the low-$\tan\beta$ scenarios).
- Proper approach is EFT (Lee and Wagner, Bagnaschi et al)

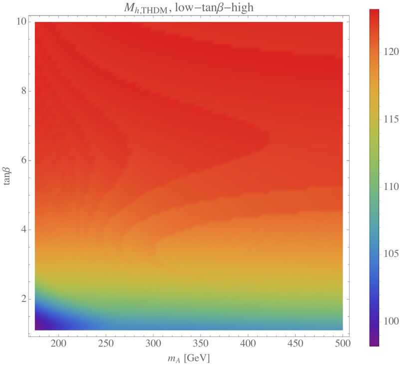
[1305.2172,1307.5205,1502.05653,LHCHXSWG-2015-002]

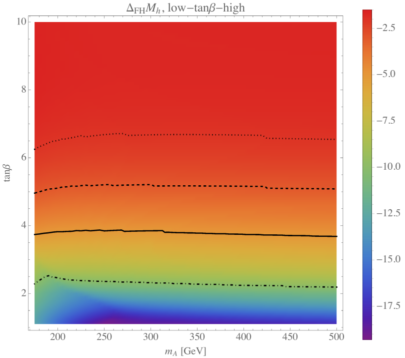
Results



- Lee and Wagner, ref. [1508.00576]
- Code will be available shortly.

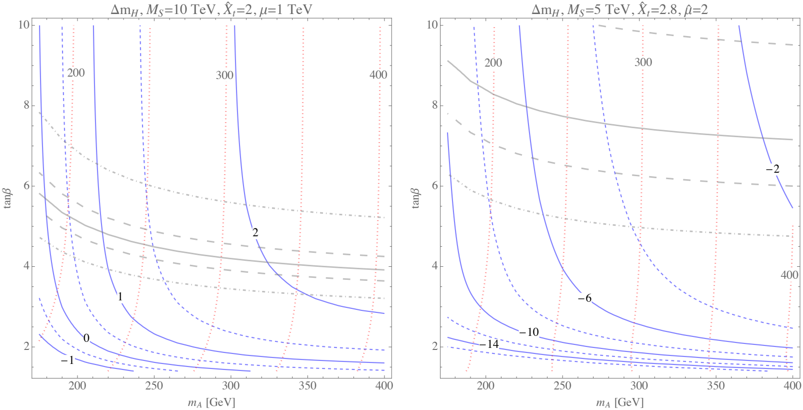
Comparison with FeynHiggs





- Comparison with `FeynHiggs` in the `low-tb-high` scenario ([1508.00576]).

Results and comparison with the hMSSM



- m_H comparison with the `hMSSM` ([1508.00576]).

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

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

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

Metastability

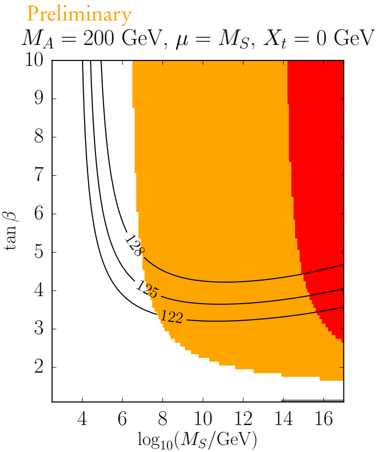
- Derive a metastability bound from the λ^4 potential at tree level.
- Choose a gauge and field basis such that the problem become one-dimensional.

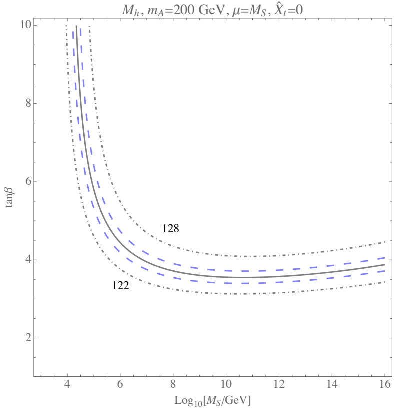
$$\lambda(\mu_r) \gtrsim -\frac{2.82}{41.1 + \log_{10}\frac{\mu_r}{\mathrm{GeV}}}$$

with

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

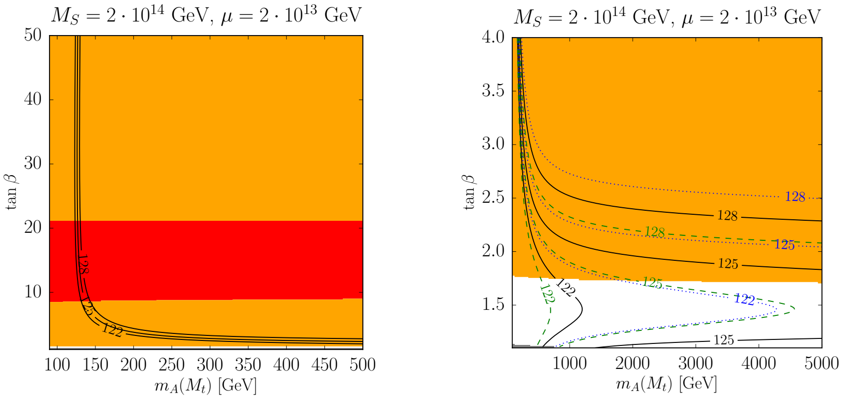
Comparison with Wagner et al





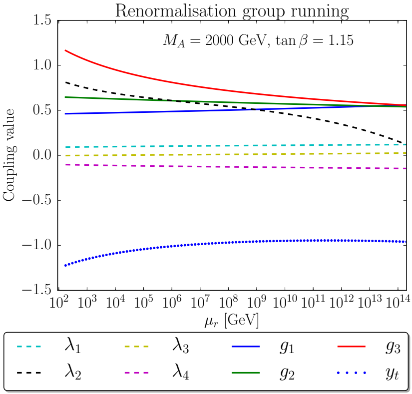
- Good qualitative agreement for the THDM. Looking forward for a more thorough comparison of the implementations.

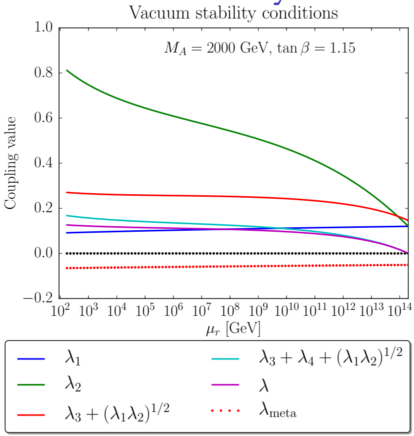
THDM with GUT-scale SUSY



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

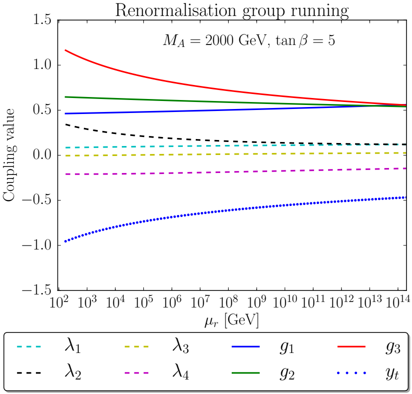
RG running and vacuum stability

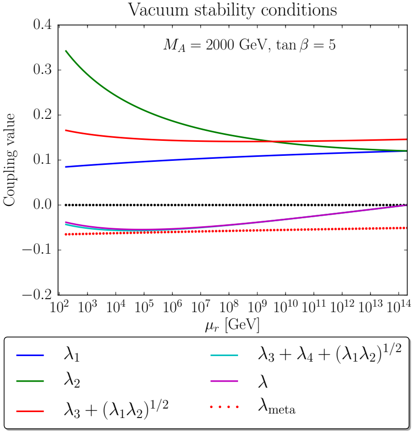




- At low $\tan\beta$, the large top Yukawa at the low scale drives high λ_2 to high values in the IR.
- At the high scale, gauge couplings approximately unify; λ_4 negative.
- $\lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2} > 0$.

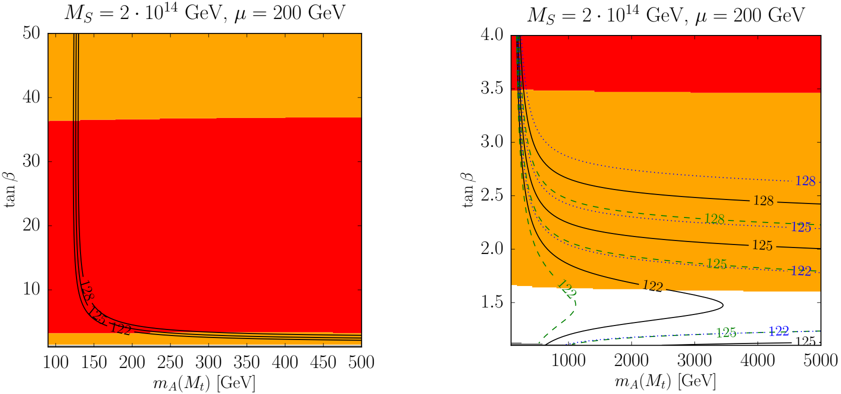
RG running and vacuum stability





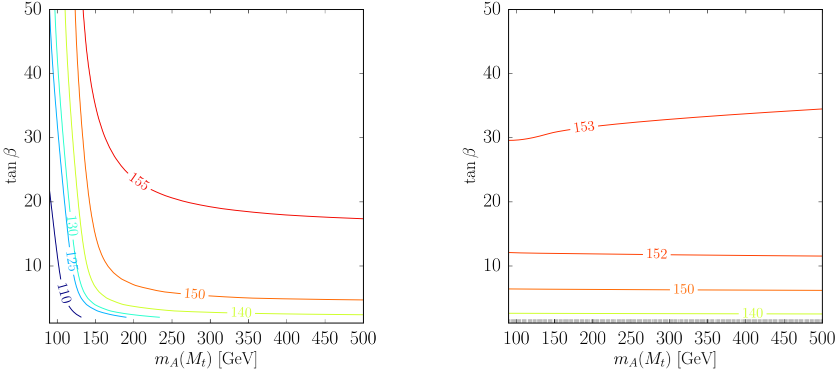
- If $\tan\beta$ is large enough, the top Yukawa is unable to push λ_2

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 light Higgs mass, impossible agreement with the measured value.