Higgs mass and unnatural supersymmetry

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[1407.4081,1512.xxxxx, ...]

Talk structure

Introduction and motivations

Unnatural SUSY

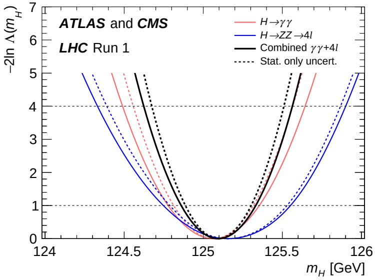
EFT definitions and matching

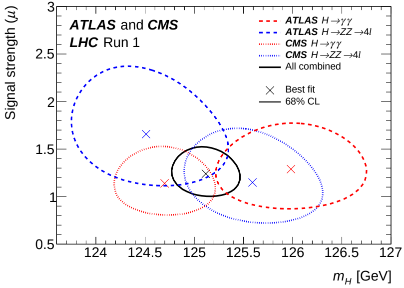
Predictions and phenomenological signatures

Conclusions

Physical motivations

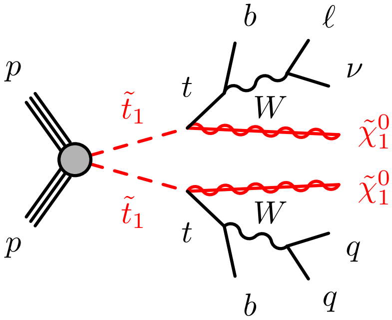
- Most important results from LHC run 1 is the discovery a SM-like Higgs boson.
- Mass measured with high-accuracy (e.g. [hep-ex/1503.07589]).





Physical motivations

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

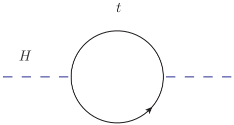


Moreover light scalars particle could imply the following issues:

- In general quite light Higgs boson mass.
- New sources of CP violation.
- New sources of flavor violation.
- Fast proton decay.

Physical motivations

- For a long time the hierarchy problem has been the guiding principle to try to understand what kind of Physics lies beyond the SM.
- It implies new physics at energy scales close to the TeV.



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

- 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).
- To justify this fine tuning an anthropic selection principle based on a large number of metastable vacua has been invoked.
- We could think of using an analogous explanation for the hierarchy problem.

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)	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
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	$(\mathbf{1}, \mathbf{1}, 0)$

Physical motivations

Various possible models:

1. Large masses for the scalar superpartners, much above the weak scale, violate naturalness, however supersymmetric fermions at a low scale are sufficient for DM and gauge coupling unification.

   Split-SUSY

2. Both supersymmetric fermions and scalars are at the same scale, higher than the EW scale.

   Quasi natural SUSY
   High scale SUSY

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	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$
(×3 families)	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
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	H_d	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	$\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$

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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

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)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$
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

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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

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

Higgs mechanism in the MSSM

- Tree level Higgs scalar potential ($m_u^2 = m_{H_u}^2 + |\mu|^2$ 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. $m_h \leq m_Z^2 \cos^2(2\beta)$ at tree level.

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

-

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

- 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 in the MSSM

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

For the CP-even sector

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

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

One then computes the complex roots of $\det(M^2_{hH}(q^2))$, $\mathcal{M}_i$ 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 in the MSSM

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

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

Structure of radiative corrections

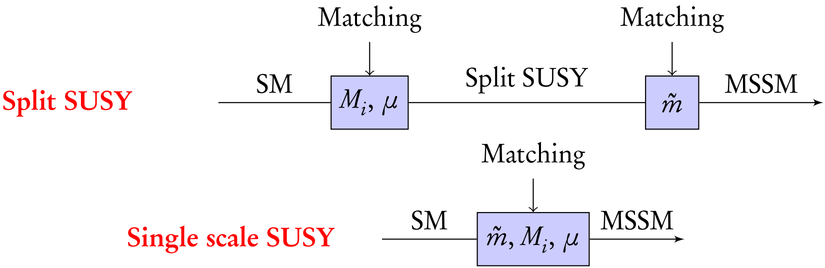
Only stop-top sector for simplicity

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



The Split-SUSY effective Lagrangian

- The Split-SUSY effective Lagrangian is obtained from the MSSM Lagrangian after the integration of the scalar supersymmetric partners and of an heavy Higgs doublet (A).

$$\mathscr{L}^{\text{split}} \supset -\frac{M_3}{2}\tilde{g}^A\tilde{g}^A - \frac{M_2}{2}\tilde{W}^a\tilde{W}^a - \frac{M_1}{2}\tilde{B}\tilde{B} - \mu\tilde{H}_u^T\epsilon\tilde{H}_d + \\ -\frac{H^\dagger}{\sqrt{2}}\left(\tilde{g}_{2u}\sigma^a\tilde{W}^a + \tilde{g}_{1u}\tilde{B}\right)\tilde{H}_u - \frac{H^T\epsilon}{\sqrt{2}}\left(-\tilde{g}_{2d}\sigma^a\tilde{W}^a + \tilde{g}_{1d}\tilde{B}\right)\tilde{H}_d + \text{h.c.} + \mathcal{O}(\frac{1}{\tilde{m}^2})$$

- The other Higgs doublet (H) is finely tuned to be light.

$$\begin{pmatrix} H \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} -\epsilon H_d^* \\ H_u \end{pmatrix}$$

$$H = -\cos\beta\epsilon H_d^* + \sin\beta H_u$$

- $V(H) = m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2$ as in the SM.

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.

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

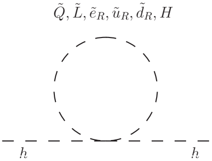
- One loop threshold to the Higgs-higgsino-gauge coupling.

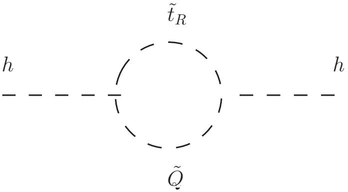
$$\tilde{g}_{2u}(\tilde{m}) = g_2(\tilde{m})\sin\beta\left[1+\Delta_{\tilde{g}_{2u}}\right], \qquad \tilde{g}_{1u}(\tilde{m}) = \sqrt{3/5}\,g_1(\tilde{m})\sin\beta\left[1+\Delta_{\tilde{g}_{1u}}\right],$$
$$\tilde{g}_{2d}(\tilde{m}) = g_2(\tilde{m})\cos\beta\left[1+\Delta_{\tilde{g}_{2d}}\right], \qquad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

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.

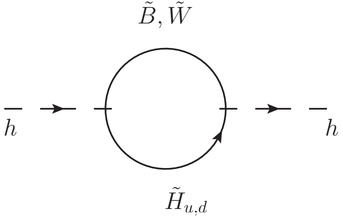




One loop corrections to the quartic coupling

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

- $\Delta\lambda^{1\ell,\chi^1}$ 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).

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

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

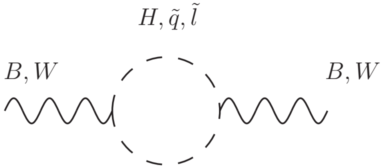
- $\Delta\lambda^{2l,\text{shift}}$ contains one-loop renormalization term for the top Yukawa.

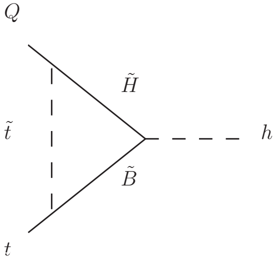
Other threshold corrections

- 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]

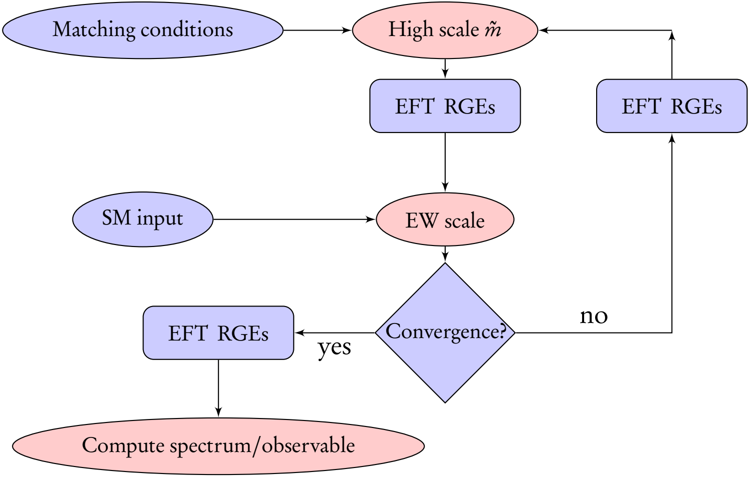
$$\begin{array}{ccccc} \text{SM in }\overline{\text{MS}} & \longleftrightarrow & \text{Split-SUSY in }\overline{\text{MS}} & \overset{\tilde{m}}{\longleftrightarrow} & \text{MSSM in }\overline{\text{DR}} \\ g_{1,2,3}, g_t, \lambda & & g_{1,2,3}, g_t, \lambda, \tilde{g}_{1\text{d}}, \tilde{g}_{1\text{u}},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

2. Bernal et al [arXiv 0705.1496v3]

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

- 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.

Algorithm implementation



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.

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 $\mathcal{O}(g_t^6)$

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

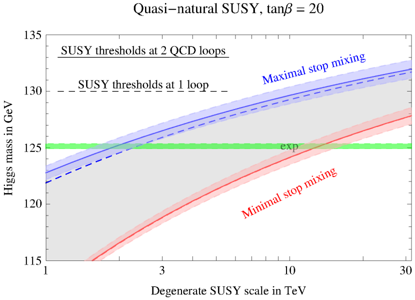
Phenomenological predictions

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.

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



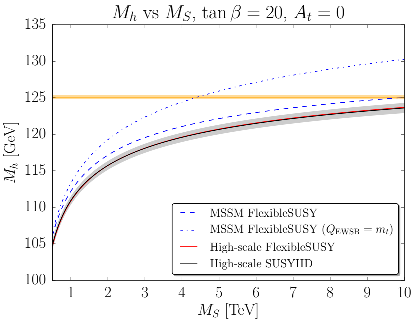
Uncertainty in the Higgs mass prediction

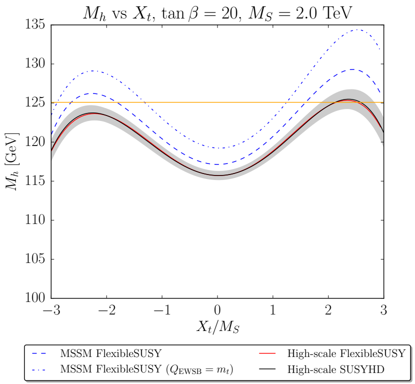
There are different sources of uncertainty

- 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.

Uncertainty in the Higgs mass prediction



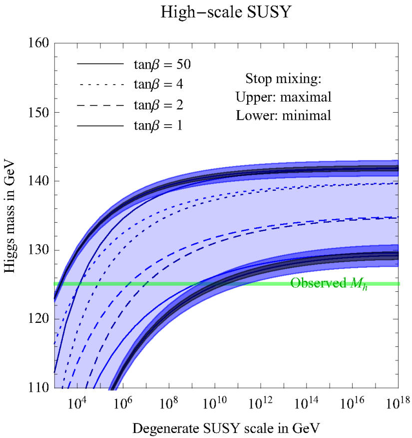


- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

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

High-scale SUSY

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

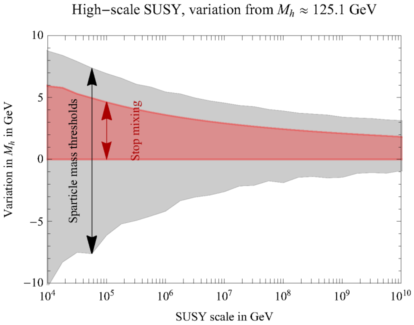


- Thinner gray band due to 1σ variation of $\alpha_s(M_Z)$.
- Larger colored) due to 1σ variation of M_t.

High-scale SUSY

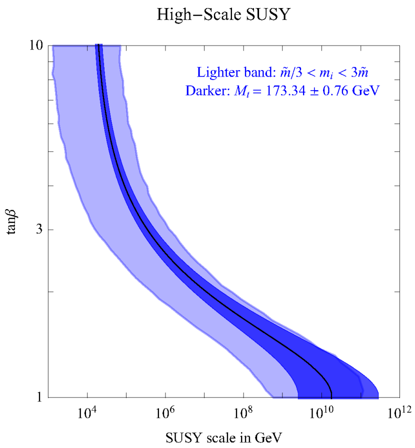
- The darker (red) region denotes the effect of varying only A_t, in the range allowed by vacuum stability.
- Larger (gray) band due to random scanning of each SUSY particle mass parameters (M_1, M_2, M_3, m_{Q_i}, m_{U_i}, m_{D_i}, m_{E_i}, m_{L_i}, distinguishing the third generation from the other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



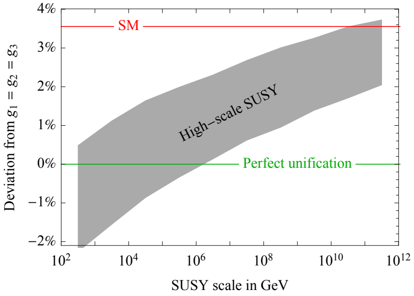
High-scale SUSY

- 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 $\tan\beta = 1$).



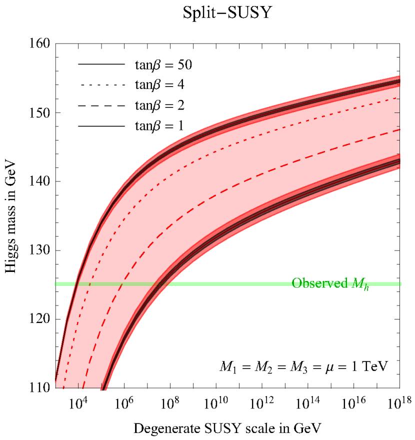
Unification in High-scale SUSY

- 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.



Split-SUSY

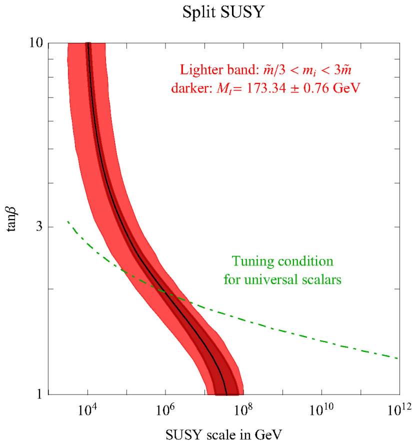
- $M_1 = M_2 = M_3 = \mu = 1$ TeV.
- All scalars degenerate at scale $\tilde{m}$.
- $A_t = 0$ (In Split-SUSY $A_t/\tilde{m} \ll 1$).



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

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).



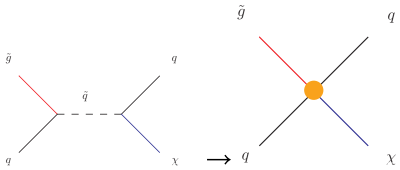
Collider signatures: gluino decay

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

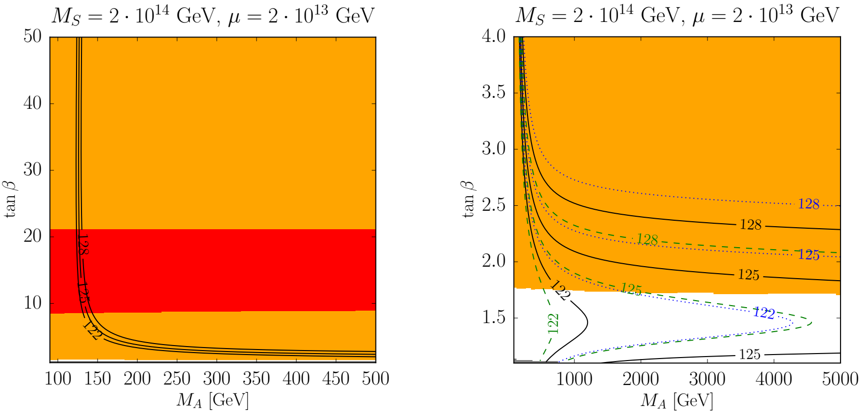
$$c\tau_{\tilde{g}} = \left(\frac{2\mathrm{TeV}}{M_{\tilde{g}}}\right)^2 \left(\frac{\tilde{m}}{10^7\mathrm{GeV}}\right)^4 0.4\ \mathrm{m}$$

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

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



THDM



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

Conclusions

- Due to the negative results of SUSY particle searches at the LHC, models with an unnatural spectrum are becoming more interesting.
- The Higgs mass represents the prime observable to probe these models.
- These models, like mini-split SUSY, have also interesting predictions for DM.

Future outlook

- Due to the importance of the Higgs mass prediction, it is important to improve the accuracy of the prediction by computing higher order corrections.
- Combination of the results with the Feynman diagrammatic approach.
- Extension to other spectrum-splitting configuration and/or other models.

Backup slides

One loop corrections to the quartic coupling

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

- $\Delta\lambda^{1\ell,\text{reg}}$ contains term due to the fact that we are expressing the matching in terms of the low-energy effective theory in the $\overline{\text{MS}}$ 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.

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

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

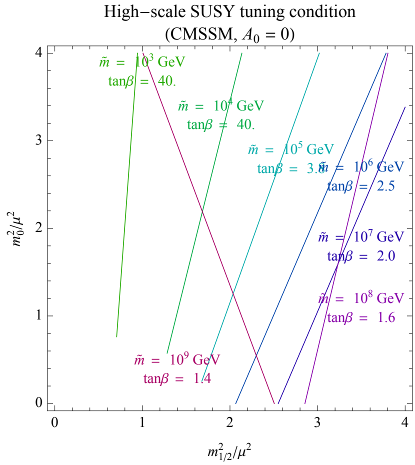
- Finite part of the CT is arbitrary and defines the renormalization scheme. In our case it cancels exactly the off-diagonal WFR contributions from the matching conditions of the effective couplings

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

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

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 $\tan\beta$.



Vacuum stability in High-scale SUSY

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

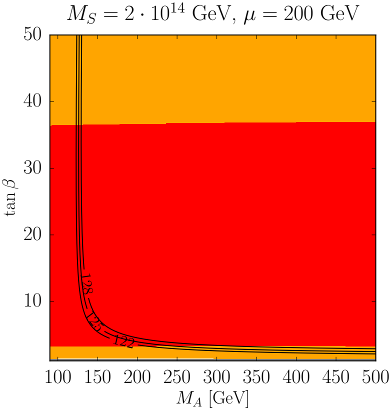
Scalar potential for the stop-Higgs system

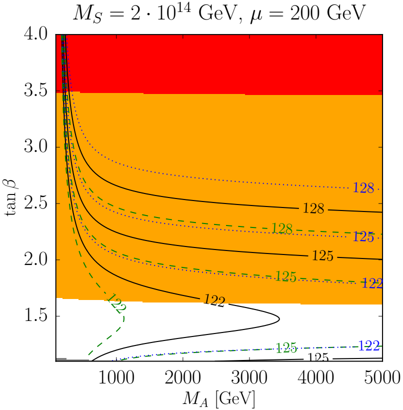
$$\begin{aligned} V &= m_{Q_3}^2 |\tilde{Q}_3|^2 + m_{U_3}^2 |\tilde{U}_3|^2 + \frac{g_t}{\sin\beta}\left(A_t H_u \tilde{Q}_3 \tilde{U}_3 + \mu H_d^* \tilde{Q}_3 \tilde{U}_3 + \text{h.c.}\right) \\ &+ \frac{g_t^2}{\sin^2\beta}\left(|H_u \tilde{Q}_3|^2 + |H_u \tilde{U}_3|^2 + |\tilde{Q}_3 \tilde{U}_3|^2\right)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

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

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

THDM+Higgsinos





THDM+Split SUSY