Fine tuning in scale-invariant NMSSMs with and without extra matter

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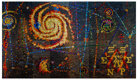


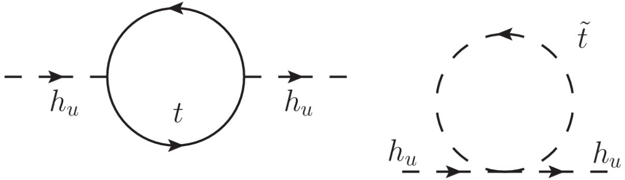
Outline

Fine tuning in the SM

- The Higgs potential in the SM,

$$V_H = \underbrace{m_H^2}_{-(90\text{GeV})^2} |H|^2 + \underbrace{\frac{\lambda}{2}}_{0.13} |H|^4$$

  - For a Higgs of 125 GeV, and a V.E.V of 174 GeV.
- To obtain this physical Higgs mass, the mass-squared parameter requires fine tuning of 1 part in 10^{30}.
- Supersymmetry solves this problem by introducing superpartners with ($Y_S = y_f^2$).



SUSY features

- Unique extension of the Poincare group.
- Solves the technical hierarchy problem.
- Unification of gauge couplings at the GUT scale.
- Dark Matter is naturally accommodated within SUSY (LSP is stable if R-parity is a symmetry).
- Electroweak symmetry breaking is radiatively generated.
- In the decoupling limit, predicts a SM-like Higgs boson.

The MSSM

- The MSSM superpotential:

$$W = y_u H_u Q \overline{u} - y_d H_d Q \overline{d} - y_e H_d L \overline{e} + \mu H_u H_d$$

  - Define $\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$
- One adds SUSY breaking terms to $\mathcal{L}$. The ones which do not reintroduce quadratic divergences (called *soft*) are:
  - Scalar masses: $m_Q^2, m_L^2, m_{H_u}^2, \ldots$
  - Gaugino masses: $M_{1,2,3}$
  - Trilinear couplings: $A_{u,d,e}$
  - Bilinear coupling: B_μ
- The potential V is composed of different F, D and *soft* contributions

$$V = V_D + V_F + V_{soft}$$

SUSY and fine tuning

- The mass of the Z boson is a derived quantity, e.g. in the MSSM (large $\tan\beta$) :

$$M_Z^2 = -2\left(\mu^2 + (m_{H_u}^2 + \delta m_{H_u}^2)\right)$$

- With:

$$\delta m_{H_u}^2 \sim -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{U_3}^2 + A_t^2) \ln\left(\frac{\Lambda}{M_{SUSY}}\right)$$

- Moreover, the mass of the physical Higgs is:

$$m_h^2 \approx M_Z^2 \cos 2\beta^2 + \delta m_h^2$$

SUSY and fine tuning

- With corrections:

$$\delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right]$$

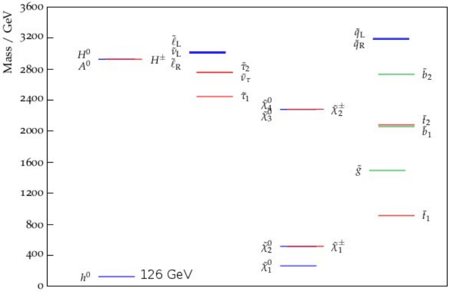
- $m_{\tilde{t}}^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$ and $X_t = A_t - \mu \cot \beta$.
- The little hierarchy problem represents the tension between requiring large loop corrections in order to obtain $125 GeV$ Higgs, and the requirement that $m_{H_u}^2 \sim \mathcal{O}(M_Z^2)$.

Measuring fine tuning

- Fine tuning:
  - Choose a framework (e.g. mSUGRA, GMSB, etc.)
  - Choose a set of fundamental parameters (e.g. GUT-scale parameters).
  - Compute:
    $$\Delta_a = \left| \frac{a}{M_Z} \frac{\partial M_Z}{\partial a} \right| .$$
  - Define: $\Delta \equiv \max(\{\Delta_a\})$.
- This allows comparing models and is commonly used as a guide by model-builders.

Fine tuning in the cMSSM

- Negative results from SUSY searches raise the question: "How natural SUSY models can be?"
- For example the CMSSM with $m_{1/2} = 0.6$ TeV, $m_0 = 3$ TeV, $A_0 = -2m_0$, $\tan\beta = 30$ (chosen to obtain a 126 GeV Higgs) has: $\Delta \sim 1250$ or 0.08% tuning in one of the parameters (used SOFTSUSY3.3.10+pySLHA).



Outline

Non-minimality

- Non-minimality amounts to:
  - Adding SUSY fields but keeping the gauge structure (e.g. NMSSM $\rightarrow$ F-term enhancement to m_h^{tree}).
  - Add another gauge group (e.g. E6SSM $\rightarrow$ F- and D-term enhancement to m_h^{tree}).
  - ...
- In the following, we consider NMSSM-type models with different matter content.

The NMSSM

- In the NMSSM, the μ parameter is replaced with a new singlet superfield S.
- The singlet couples to the Higgs ($\sim \lambda S H_u H_d$) and to itself ($\sim \kappa S^3$).
- It acquires a vev, and so dynamically produces the μ_{eff} term

$$\mu_{eff} = \lambda s.$$

- The NMSSM keeps all the good features of the MSSM, such as unification of gauge couplings, and radiative EWSB.

The NMSSM

- The Higgs sector of the NMSSM contains new Higgs fields (7 in total as apposed to 5 in the MSSM)
- Remarkably, the NMSSM allows for the increase of the tree-level Higgs mass

$$m_h^2 \approx M_z^2 cos^2 2\beta + \lambda^2 v^2 sin^2 2\beta + \delta m_h^2$$

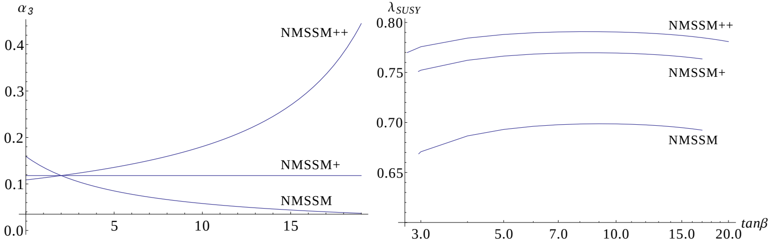
- However $\lambda_{\mathsf{SUSY}} < 0.7$ (GUT perturbativity bound).

The NMSSM with extra matter

- To increase the bound on λ_{SUSY}, we consider the NMSSM with additional $SU(5)$ vector-like states.
  - $$\text{NMSSM}+ \sim \text{NMSSM} + 3(5 + \overline{5})$$
  - $$\text{NMSSM}++ \sim \text{NMSSM} + 4(5 + \overline{5})$$
- Assume mass scale of the extra states of $\sim \mathcal{O}(\tilde{q})$.
- No Yukawa couplings with ordinary NMSSM states.

Effects of extra matter

- Since extra matter fields are charged under $\mathcal{G}_{\mathsf{SM}}$, the RGEs will be different:
  - $\alpha_3^+(M_{\mathsf{GUT}}) > \alpha_3(M_{\mathsf{GUT}})$
  - $h_t^+(M_{\mathsf{GUT}}) < h_t(M_{\mathsf{GUT}})$
  - $\lambda^+(M_{\mathsf{GUT}}) < \lambda(M_{\mathsf{GUT}})$



Outline

Constraints and framework

- NMSSMTools used for studying the parameter spaces of the models.
- In all our scans we require:
  - $123 < m_{h_{1,2}} < 127$ GeV,
  - $m_{\tilde{t}_1} \geq 700$ GeV,
  - $m_{\tilde{g}} > 1.2$ TeV
  - $\Delta_{max} < 2000$
- We choose a semi-constrained framework for all of the models:

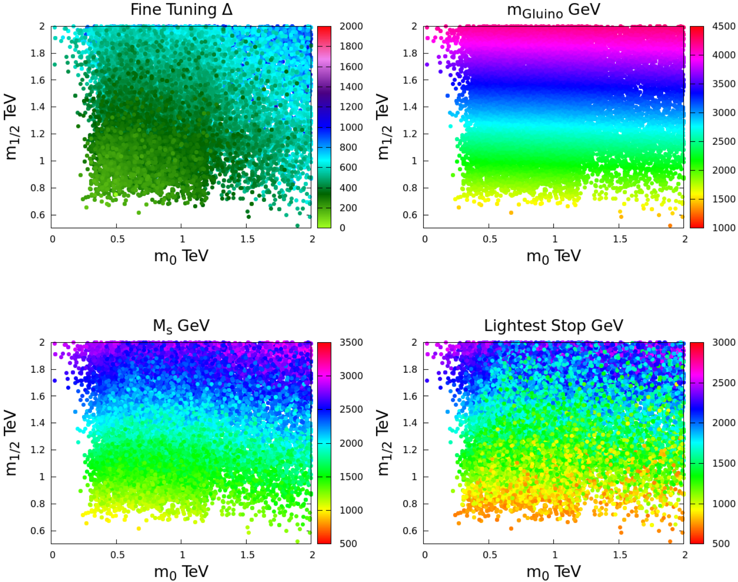
$$m_0, m_{1/2}, A_0, A_\lambda, A_\kappa, \lambda_{\text{SUSY}}, \kappa_{\text{SUSY}}, m_s$$

Scans

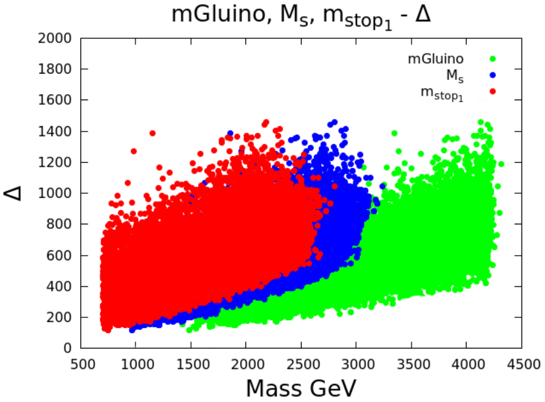
- Scan ranges:

$$100 < m_0 < 1000(2000, 7000)\ \text{GeV}$$
$$100 < m_{1/2} < 1000(2000, 7000)\ \text{GeV}$$
$$A_0 = -3, -1, 0, 1, 2, \ldots, 7\ \text{TeV}$$
$$-1.5(-3) < A_\lambda < 1.5(3)\ \text{TeV}$$
$$-1.5(-3) < A_\kappa < 1.5(3)\ \text{TeV}$$
$$0 < \tan\beta < 5$$
$$100 < \mu < 400\ \text{GeV}$$
$$0.5 < \lambda_{\text{SUSY}} < 1$$
$$10^{-4} < \kappa_{susy} < 0.6$$

NMSSM (m_{h_1} is SM-like)

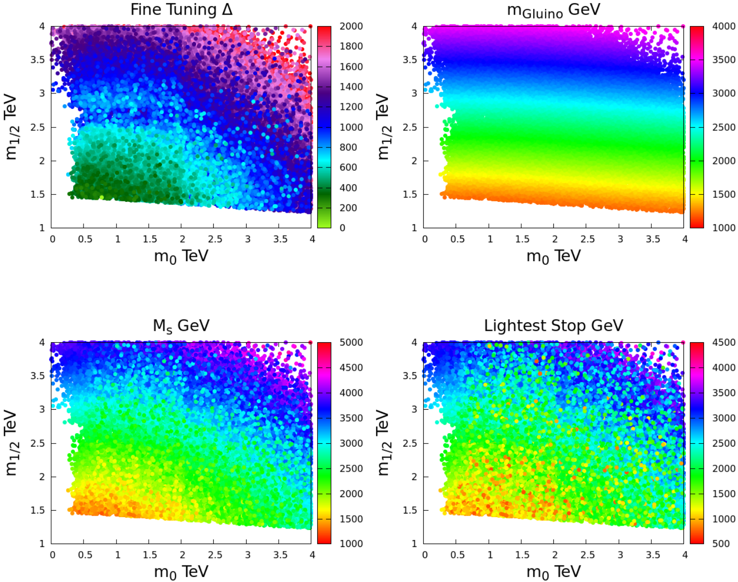


NMSSM (cont.)

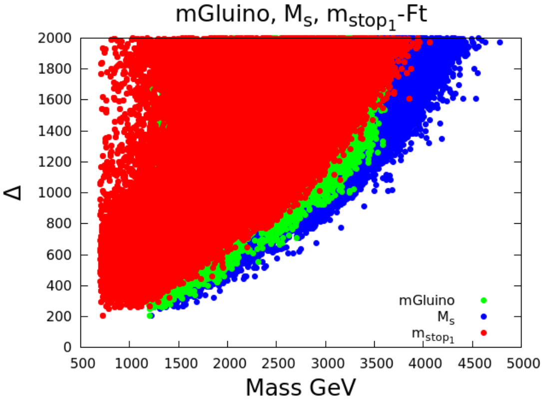


mGluino, M_S, m_{stop_1} - Δ
mGluino
M_S
m_{stop_1}
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Δ
500
1000
1500
2000
2500
3000
3500
4000
4500
Mass GeV

NMSSM+ (m_{h_1} is SM-like)

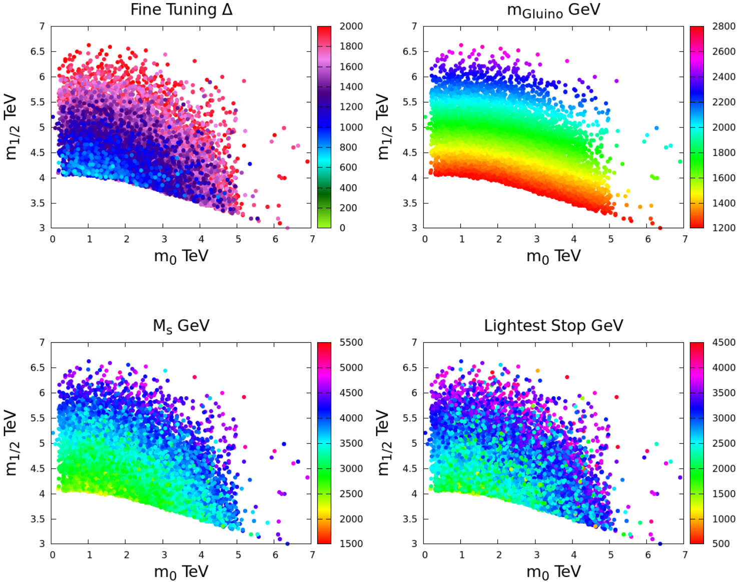


NMSSM+ (cont.)

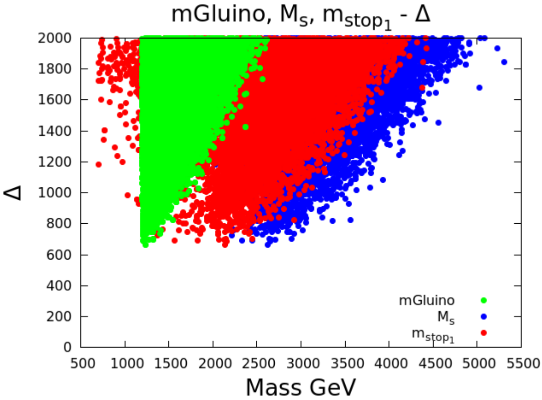


mGluino, M_s, m_{stop_1}-Ft
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Δ
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Mass GeV
mGluino
M_s
m_{stop_1}

NMSSM++ (m_{h_1} is SM-like)

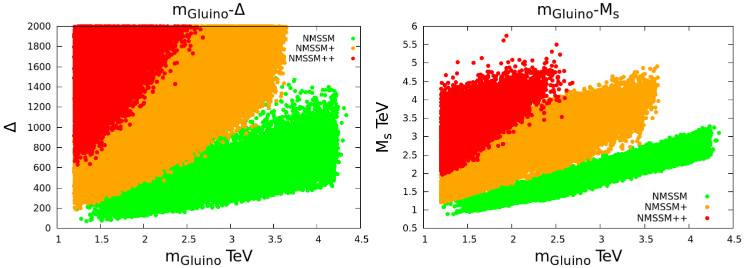


NMSSM++ (cont.)



mGluino, M_S, m_{stop_1} - Δ
Δ
2000
1800
1600
1400
1200
1000
800
600
400
200
0
500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500
Mass GeV
mGluino
M_S
m_{stop_1}

Comparison



m_{Gluino}-Δ
NMSSM
NMSSM+
NMSSM++
Δ
m_{Gluino} TeV
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
1.5
2
2.5
3
3.5
4
4.5
m_{Gluino}-M_S
M_S TeV
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5

Outline

Summary and Conclusions

- The EW sector of the cMSSM is fine tuned with $\Delta \sim 1000$.
- The NMSSM adds a tree-level F-term contribution to $m_h \propto \lambda_{\mathsf{SUSY}}$.
- Fine tuning in the NMSSM is around $\Delta \sim 100$.
- Extra matter allows λ_{SUSY} to be larger, hence aiding the Higgs mass at tree-level.
- However, gluino running in the plus-type models leads to larger-than-NMSSM physical stops.
- The NMSSM$+$ is fine tuned with $\Delta \sim 200$, while the NMSSM$++$ has $\Delta \sim 600$.
- Therefore, increasing the bound on λ_{SUSY} by adding such vector-like states does not help with the fine tuning (at least in this framework).