A light SM-like natural Higgs in the NMSSM with a low cut-off

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Outline

SUperSYmmetry (SUSY)

- A Symmetry that relates fermions and bosons.

$$Q|Boson\rangle = |Fermion\rangle \ , \qquad Q|Fermion\rangle = |Boson\rangle$$

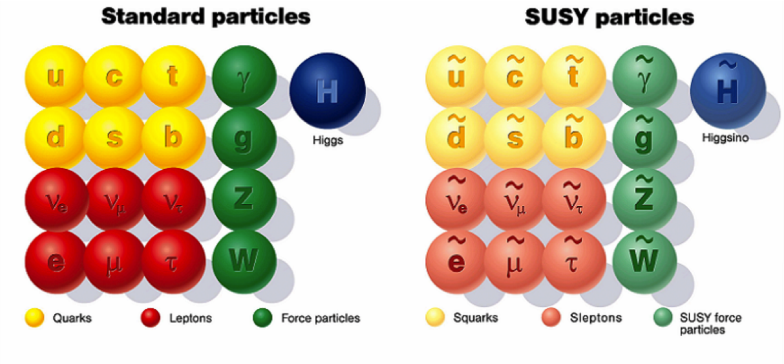
- Extends Special Relativity, evading the Coleman and Mandula "No-Go" theorem.
- The Super Poincaré Algebra:

$$\begin{aligned} \{Q^A_\alpha, \bar{Q}_{\dot\beta B}\} &= 2\sigma^\mu_{\alpha\dot\beta} P_\mu \\ \{Q^A_\alpha, \bar{Q}^B_\beta\} &= \{Q_{\dot\alpha A}, \bar{Q}_{\dot\beta B}\} = 0 \\ \left[P_\mu, Q^A_\alpha\right] &= \left[P_\mu, \bar{Q}_{\dot\alpha A}\right] = 0 \end{aligned}$$

- SUSY transformation= a translation in Superspace with coordinates, $z = (x_\mu, \theta^\alpha, \bar\theta_{\dot\alpha})$.

The Minimal Supersymmetric Standard Model (MSSM)

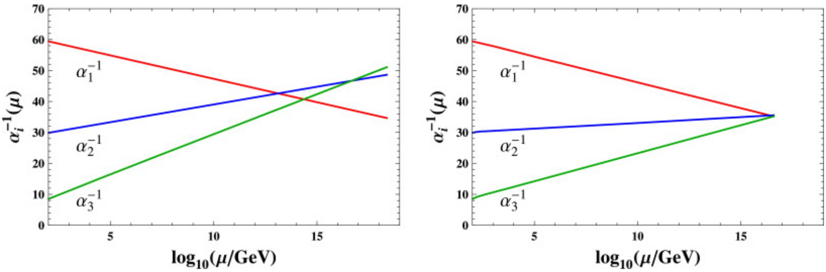
- The MSSM contains the minimal supersymmetric particle content compatible with the Standard Model (SM), $\mathcal{N} = 1$ SUSY (one SUSY charge generator).



Warning: Image not entirely accurate.

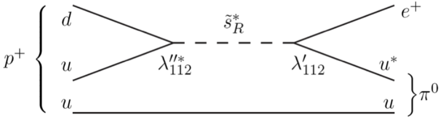
Gauge coupling Unification in the MSSM

- Gauge couplings unify in the MSSM $\Longrightarrow$ strong hint towards GUT theories.
- SM one-loop running on the left, and MSSM one-loop running on the right.



R-parity and Dark Matter

- Supersymmetric extensions of the SM typically contain baryon and lepton violating operators.
- There are strong constraints on L and B violating operators, strongest from non-observation of proton decay.



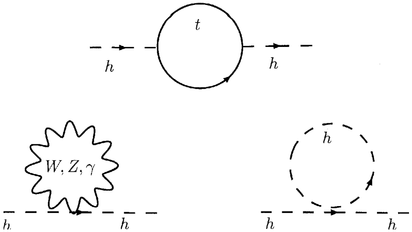
- One solution is to impose $R - parity$

$$P_R = (-1)^{3(B-L)+2S}$$

- All SM particles +Higgs boson: $P_R = +1$, all SUSY particles $P_R = -1 \Longrightarrow$ SUSY particles appear in even numbers
- Lightest Supersymmetric Particles (LSP) is stable $\Longrightarrow$ SUSY provides a natural Dark Matter (DM) candidate.

The Hierarchy Problem in the SM

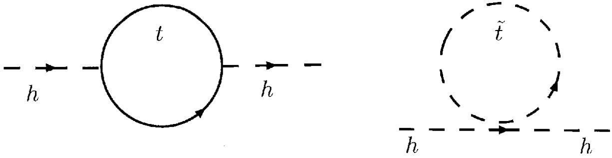
- One expects new physics at the Planck scale ($\Lambda_P \sim 10^{19}$ GeV).
- Higgs mass is sensitive to this scale ($m_h = \sqrt{2\lambda v^2} \sim \mathcal{O}(100)$ GeV).



- If the Higgs is a fundamental scalar (no protected by any symmetry), there is a quadratic sensitivity of the Higgs mass to the UV cut-off Λ_{UV}.

SUSY solution to the hierarchy problem

- $n_b = n_f$ bosonic and fermionic d.o.f.
- For example for the top-stop corrections:



$$m_h^2 = m_0^2 - \frac{\lambda_t^2}{8\pi^2}\left(\Lambda_{UV}^2 - \int_0^1 dx 2\Delta \log \frac{\Lambda_{UV}^2 + \Delta}{\Delta}\right)$$
$$+ \frac{\lambda_{\tilde{t}}}{16\pi^2}\left(2\Lambda_{UV}^2 - m_{\tilde{t}_1}^2 \log \frac{\Lambda_{UV}^2 + m_{\tilde{t}_1}^2}{m_{\tilde{t}_1}^2} - m_{\tilde{t}_2}^2 \log \frac{\Lambda_{UV}^2 + m_{\tilde{t}_2}^2}{m_{\tilde{t}_2}^2}\right)$$

- SUSY predicts $\lambda_{\tilde{t}} = \lambda_t^2$ and $m_{\tilde{t}} = m_t$.
- We've searched for these particles at colliders and haven't found them yet...therefore SUSY must be broken at low energies.
- Breaking must be such that the relation $\lambda_{\tilde{t}} = \lambda_t^2$ still holds $\Longrightarrow$ Soft SUSY breaking.
- Only logarithmic sensitivity to the cut-off $\Lambda_{UV} \Longrightarrow$ UV complete theory.

Higgs mass in the MSSM

- Tree-level Higgs mass in the MSSM satisfies:

$$m_h^2 \leq m_Z^2 \cos^2 2\beta$$

  Maximum tree-level mass in the large $\tan\beta \equiv v_u/v_d \gg 1$ regime but always less than m_Z (quartic coupling proportional to gauge couplings since it comes from D-terms in the Lagrangian).
- LEP put a lower bound on the SM Higgs mass of $m_h \geq 114$ GeV.
- Large loop corrections from the stop sector to the quartic coupling (of the order of the tree-level contribution) come to the rescue to raise the Higgs mass. In the large $\tan\beta$ region,

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}X_t + t\right]$$

  where $t = \log M_{SUSY}^2/m_t^2$ and,

$$X_t = \frac{2(A_t - \mu\cot\beta)^2}{M_{SUSY}^2}\left(1 - \frac{(A_t - \mu\cot\beta)^2}{12M_{SUSY}^2}\right)$$

Fine-tuning in the MSSM

- In the MSSM at tree level the minimization of the Higgs scalar sector potential implies the relation:

$$m_Z^2 = -m_{H_u}^2 - 2|\mu|^2 + \mathcal{O}\left(\frac{1}{\tan\beta}\right)$$

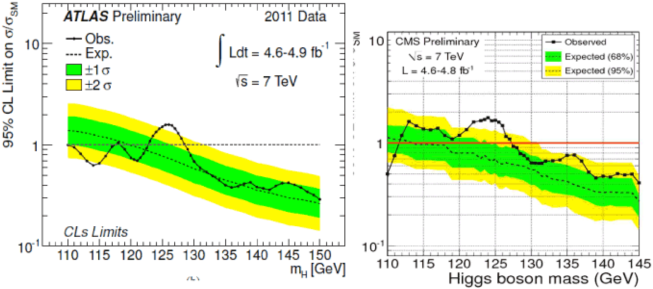
  Recall that the top quark-Yukawa coupling drives $m_{H_u}^2$ negative at low energies, thus triggering EWSB (radiatively EWSB).
- Stop sector also induces a correction to the up Higgs soft SUSY mass $m_{H_u}^2$ which can potentially destabilize the Electroweak scale $v = v_u^2 + v_d^2 = 174$ GeV.

$$\delta m_{H_u}^2 \approx \frac{3y_t^2}{16\pi^2}\left(\tilde{m}_{Q_3}^2 + \tilde{m}_{u_3}^2 + A_t^2\right)\log\frac{2\Lambda^2}{\tilde{m}_{Q_3}^2 + \tilde{m}_{u_3}^2}$$

- $\mu \sim \mathcal{O}(v)$ must be tuned to cancel the loop correction to $m_{H_u}^2 \Longrightarrow$ Little Hierarchy problem.
- Fine tuning in the MSSM at the percentage level.

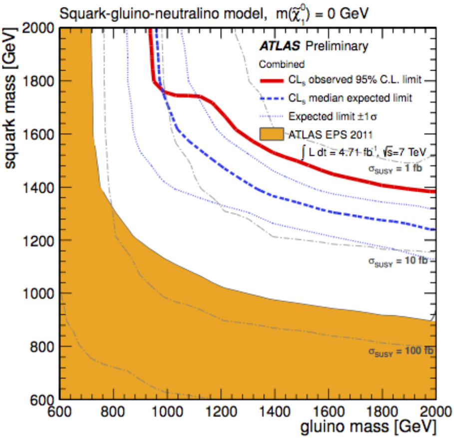
Latest Higgs results from ATLAS and CMS

- 2.2 σ significance at around $m_h \sim 125$ GeV in both experiments (ATLAS, CMS 2012).



Latest squark-gluino results from ATLAS

- Latest squark-gluino results from ATLAS (ATLAS 2012)



The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- Introduce a singlet chiral superfield S in addition to the MSSM particle content.
- NMSSM provides a simple solution to the μ-problem of the MSSM.
- Assuming a $\mathbb{Z}_3$ symmetry in the Higgs-singlet sector in the superpotential, no explicit μ term (or SUSY mass terms) can be written, the only new terms in the superpotential are:

$$W_{NMSSM} = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

- It can be seen inmediately that once S acquires a vacuum expectation value (vev) $\langle S \rangle = v_s \sim \mathcal{O}(v)$, a proper μ term can be generated for $\lambda \sim 1$.
- It also generates a tree-level contribution to the Higgs quartic coupling

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

Notice that the new contribution is largest for small $\tan\beta \sim 1$.

The NMSSM with a low UV cut-off

- If we assume that the cut-off of our theory is at $\Lambda_{UV} \approx M_{GUT} \approx 10^{16}$ GeV, then taking the maximum value for the coupling λ at the GUT scale, $\lambda^2(M_{GUT}) = 4\pi$ it turns out that $\lambda(M_{SUSY}) \sim 0.7$ from the RGE running.
- However by lowering the cut-off $\Lambda_{UV} \approx 10$ TeV $\Longrightarrow \lambda(M_{SUSY}) \sim 2$, thus increasing the tree-level Higgs mass contribution (Barbieri et al. 2007, Francheschini et al. 2011).
- Notice that also the $\delta m^2_{H_u}$ loop correction from the stop sector decreases with a lower cut-off.
- We take a minimalistic bottom-up approach and study the parameter space of the NMSSM decoupling the first and second generation squarks and sleptons, as well as the third generation sleptons, keeping only the necessary field content that allow us to obtain a "natural" light Higgs. We allow for the possibility of a low UV-cutoff as a mean to raise the Higgs mass.
- By decoupling all but third-generation squarks, higgsinos and gauginos, we satisfy most constraints coming from flavour physics.

The set up

- The scalar Higgs-singlet potential takes the form,

$$
\begin{aligned}
V &= (m_{H_d}^2 + \lambda^2 S^2)|H_d|^2 + (m_{H_u}^2 + \lambda^2 S^2)|H_u|^2 + \lambda^2 |H_d H_u|^2 + m_s^2 |S|^2 + \kappa^2 |S|^4 \\
&- [(a_\lambda S - \lambda\kappa S^2) H_d H_u + \frac{a_\kappa}{3} S^3 + h.c.] + \frac{(g_1^2 + g_2^2)}{8} (|H_u|^2 - |H_d|^2)^2 \\
&+ \frac{g_2^2}{8} |H_d^\dagger H_u|^2
\end{aligned}
$$

- The potential can be seen to always be stable for $\lambda \neq 0$ and $\kappa \neq 0$.
- The minima of the potential satisfies,

$$
\begin{aligned}
\lambda^2 v^2 &= 2\frac{(a_\lambda s - \lambda\kappa s^2)}{\sin(2\beta)} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 s^2 \\
m_Z^2 &= \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 s^2 \\
m_s^2 &+ \lambda\kappa v^2 \sin(2\beta) + 2\kappa^2 s^2 + \lambda^2 v^2 - \frac{a_\lambda v^2}{2s} \sin(2\beta) - a_\kappa s = 0
\end{aligned}
$$

where we only consider real solutions for CP-invariance.

Mass matrices

- Expanding the field around their vevs.

$$S = v_s + \frac{s + is^i}{\sqrt{2}}, \qquad H_d = v_d + \frac{h_d + ih_d^i}{\sqrt{2}}, \qquad H_u = v_u + \frac{h_u + ih_u^i}{\sqrt{2}}.$$

- Scalar sector consist of 3 neutral CP-even scalars (h_u,h_d and s), 2 neutral CP-odd pseudo scalars ($A = \sin\beta h_d^i + \cos\beta h_u^i$ and s^i) and two charged Higgs scalars $h^\pm$.
- 3×3 CP-even mass matrix and a 2×2 CP-odd mass matrix need to be diagonalized.
- As in the MSSM gauginos ($\tilde{B}$, $\tilde{W}^3$) and higgsinos ($\tilde{h}_d^0$, $\tilde{h}_d^0$) mix and also additional mixing between higgsinos and singlino ($\tilde{s}$) $\Longrightarrow 5 \times 5$ neutralino mass matrix.
- Chargino sector ($\tilde{W}^+$, $\tilde{H}_u^+$, $\tilde{W}^-$, $\tilde{H}_d^-$) mixes as in the MSSM with $\mu = \lambda s$.

Stop and sbottom sectors also mix as in the MSSM, with $\mu = \lambda s$,

$$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) m_Z^2 \cos 2\beta & m_t(A_t \sin\beta - \lambda s \cos\beta) \\ m_t(A_t \sin\beta - \lambda s \cos\beta) & m_{u_3}^2 + m_t^2 + \frac{2}{3}\sin^2\theta_W m_Z^2 \cos 2\beta \end{pmatrix}.$$

Electroweak Constraints

- We focus on the precision parameters S and T which take into account oblique corrections.

$$S = 4\cos^2\theta_W \sin^2\theta_W \left[\Pi'_{ZZ}(0) - \frac{\cos^2\theta_W - \sin^2\theta_W}{\sin\theta_W\cos\theta_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

$$T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}$$

- For a reference value $m_{h,ref} = 117$ GeV, the S and T parameters take the SM values $S_0 = 0.04 \pm 0.09$ and $T_0 = 0.07 \pm 0.08$ (PDG 2011) at 95 % C.L., and an ellipse angle $\cos\theta = 0.88$.
- There are 3 main contributions from new physics to the S and T parameters:
  1. Contribution from the singlet-Higgs scalar sector.
  2. Contribution from the stop-sbottom sector.
  3. Contribution from the neutralino-chargino sector.

Fine-tuning constraints

- Small variations in the dimensionful parameters ξ should imply small variations in the electroweak scale v.
- We demand that $\Sigma_\xi \equiv |d \log v^2/dlog\xi| < \Sigma$, where we want a fine-tuning better than 10 % ($\Sigma = 10$).
- In our analysis we consider the tree-level parameters in the Higgs-Singlet sector as well as the parameters from other sectors which give the largest loop-induced contributions to the Higgs-Singlet mass matrix, $\xi_1 = (m^2_{H_u}, m^2_{H_d}, a_\lambda, a_\kappa, m^2_s)$ and $\xi_2 = (m^2_{Q_3}, m^2_{u_3}, A_t, m^2_{d_3}, A_b, M_3)$.
- We took the 3 dependent variables $v^2(\xi)$, $s(\xi)$ and $\sin 2\beta(\xi)$ and we solve for $dv^2/d\xi$, $ds/d\xi$ and $d \sin 2\beta/d\xi$ in the linear system of equations that comes from differentiating the minimization Eqs. with respect to ξ

- Then we can write,

$$\Sigma_{\xi_1} = \left| \frac{\xi_1}{v^2} \times \frac{dv^2(\xi_1)}{d\xi_1} \right|$$

- We take into account the loop-corrections by looking at how "fine-tuned" the values ξ_1 obtained from the previous analysis really are:

$$\Sigma_{\xi_2} = \left| \frac{\xi_2}{v^2} \frac{dv^2}{d\xi_1} \frac{d\xi_1}{d\xi_2} \right| = \left| \frac{\xi_2}{\xi_1} \Sigma_{\xi_1} \frac{d\xi_1}{d\xi_2} \right| = \left| \Sigma_{\xi_1} \Sigma_{\xi_1(\xi_2)} \right|$$

- We demand that $\Sigma_{\xi_1} < \Sigma$ and that $\Sigma_{\xi_2} < \Sigma$ to constraint the fine-tuning in the EWSB scale and furthermore we constraint the fine-tuning in the parameters obtained from the previous constraint by demanding that $|\Sigma_{\xi_1(\xi_2)}| < \Sigma$.

Collider constraints and scanning range

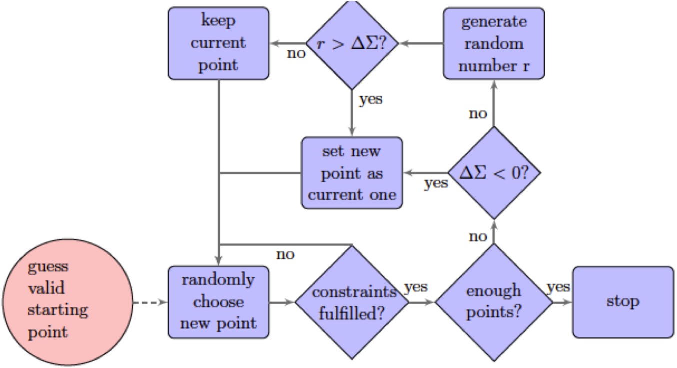
- We identify the Higgs with the mass state s_h that possess the largest H_u component and we concentrate on Higgs masses in the range not yet excluded by ATLAS, CMS and the Tevatron experiments, $120 < m_h < 130$.
- Since our theory can have a low UV cut-off, we allow for the possibility of low $\tan\beta \gtrsim 0.5$.
- We consider $0 < \lambda(M_{SUSY}) < 2$ and $0 < \kappa(M_{SUSY}) < 1.3$.
- We restrict the scanning to values $M_{SUSY} > 200$ GeV, $M_{1,2} > 0$.
- Current stop and gluino searches at the LHC and Tevatron $\Longrightarrow M_3 > 900$ GeV and $m_{\tilde{t},\tilde{b}} > 100$ GeV.
- No $Z \to \tilde{\chi}_1\tilde{\chi}_1$ and $h \to a_1 a_1 \Longrightarrow m_{\tilde{\chi}_1} > m_Z/2$ and $m_{a_1} > m_h/2$.
- $m_{\tilde{\chi}^\pm} > 103$ GeV and $m_{H^\pm} > 79$ GeV.
- We find that there is a large region of parameter space where $H_\pm$ and $\tilde{\chi}^\pm$ can be "light" and thus $b \to s\gamma$ could potentially constrain such region.
- Since LHC Higgs searches seem to be pointing to a close to SM-like Higgs, we concentrate primarily in a Higgs produced as in the SM $\Longrightarrow R_{s_h u\bar{u}} \equiv g_{s_h u\bar{u}}/g_{hu\bar{u}}$, $R_{s_h ZZ} \equiv g_{s_h ZZ}/g_{hZZ}$ and $R_{s_h W^+W^-} \equiv g_{s_h W^+W^-}/g_{hW^+W^-}$ such that $|R_{s_h u\bar{u}} - 1| < 0.05$, $|R_{s_h ZZ} - 1| < 0.05$ and $|R_{s_h W^+W^-} - 1| < 0.05$

Cosmological constraints and Dark Matter

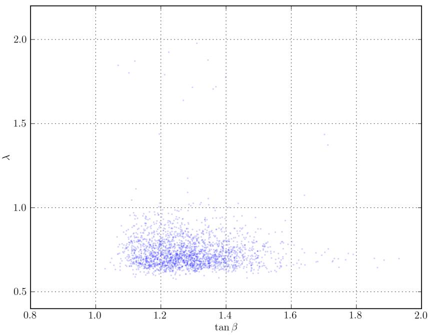
- Lightest SUSY particle (LSP) is the lightest neutralino.
- If LSP is thermally produced $\Longrightarrow$ relic density must not overclose the Universe.
- If LSP is mostly higgsino or Wino $\Longrightarrow$ strong annihilation $\Longrightarrow$ small relic density cannot account for DM but doesn't overclose the Universe.
- More interesting cases: LSP mostly Bino or LSP with a large Singlino component.
  1. If LSP mostly Bino we expect to be able to obtain the correct relic density since this case reduces to the MSSM.
  2. If LSP with large Singlino component at small values of $\tan\beta \sim 1.3$ the correct relic density can be accommodated.

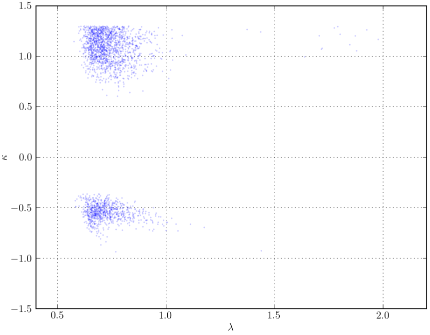
Scan algorithm

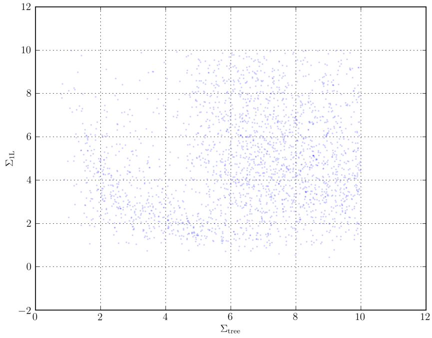
- We fixed the cutoff scale $\Lambda_{UV} = 10$ TeV and $\Lambda_{UV} = 100$ TeV, and varied the parameters.
- The variation is done using a random walk where the fine-tuning is used to determine the next step:

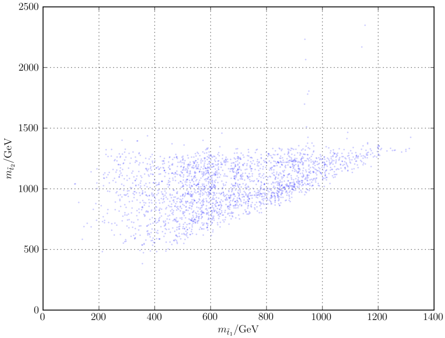


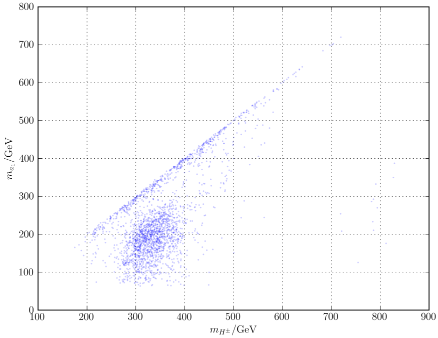
Results

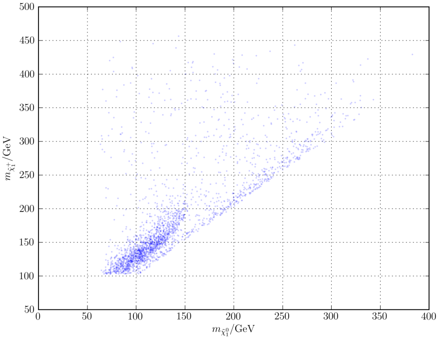

2.0
1.5
λ
1.0
0.5
0.8
1.0
1.2
1.4
1.6
1.8
2.0
tan β

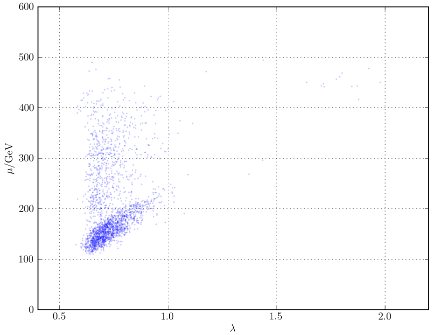

1.5
1.0
0.5
κ
0.0
−0.5
−1.0
−1.5
0.5
1.0
1.5
2.0
λ

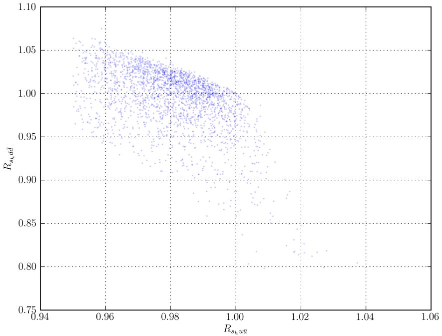

12
10
8
6
4
2
0
−2
0
2
4
6
8
10
12
Σ_{1L}
$\Sigma_{\rm tree}$


2500
2000
1500
1000
500
0
0
200
400
600
800
1000
1200
1400
$m_{\tilde{t}_2}$/GeV
$m_{\tilde{t}_1}$/GeV


800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
m_{a_1}/GeV
$m_{H^\pm}$/GeV


500
450
400
350
300
250
200
150
100
50
0
50
100
150
200
250
300
350
400
$m_{\tilde{\chi}_1^+}$/GeV
$m_{\tilde{\chi}_1^0}$/GeV


600
500
400
300
200
100
0
μ/GeV
0.5
1.0
1.5
2.0
λ


1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.94
0.96
0.98
1.00
1.02
1.04
1.06

Conclusions

- A SM-like Higgs with a mass $m_h \approx 125$ GeV and small amount of fine tuning can be accomplished in the NMSSM with a low UV cutoff.
- A μ term ranging 100 GeV $< \mu <$ 500 GeV is naturally generated by the singlet vev.
- Third generation squarks can be relatively heavy $m_{\tilde{t},\tilde{b}} \sim 1.3$ TeV without introducing extra fine-tuning.
- Excess in the two photon Higgs discovery channel could be explained by a smaller coupling to down-type quarks than in the SM.
- Though small values of tan β are preferred, larger values of tan β are allowed that in the case of EW gaugino decoupling.
- Light SUSY states predicted are charginos and neutralinos.