Montpellier, 10/10/2012

Natural SUSY

Intro

A] Why SUSY?

Hierarchy problem: $\delta m_h^2 \propto \Lambda^2$ (rad. corrections), Λ = cut-off theory

while for fermions $\delta m_f \propto \log \frac{\Lambda}{\mu}$

Idea: connect scalars & fermions with a symmetry → Supersymmetry (SUSY)

B] MSSM: $W = \mu H_u H_d + W_{Yukawa}$

Physical content:

	(F)		(S)
Matter	q_L	↔	$\tilde{q}_L$
	u_R	↔	$\tilde{u}_R$
	d_R	↔	$\tilde{d}_R$

	(V)		(F)
Gauge	W_μ^A	↔	$\tilde{W}^\pm$ $\tilde{W}_3$
	B_μ	↔	$\tilde{B}$
	G_μ	↔	$\tilde{g}$

	(S)		(F)
Higgs	H_u	↔	$\tilde{H}_u$
	H_d	↔	$\tilde{H}_d$

} $4 \times 2 = 8$ real dof $- 3$ NGB // 5 scalar particles

CP even h, H

CP odd A

charged

c] NMSSM : $W = \mu(S) H_u H_d + f(S) + W_{Yukawa}$

$\hookrightarrow \mu + \lambda S$

$S \to 2$ more scalar dof

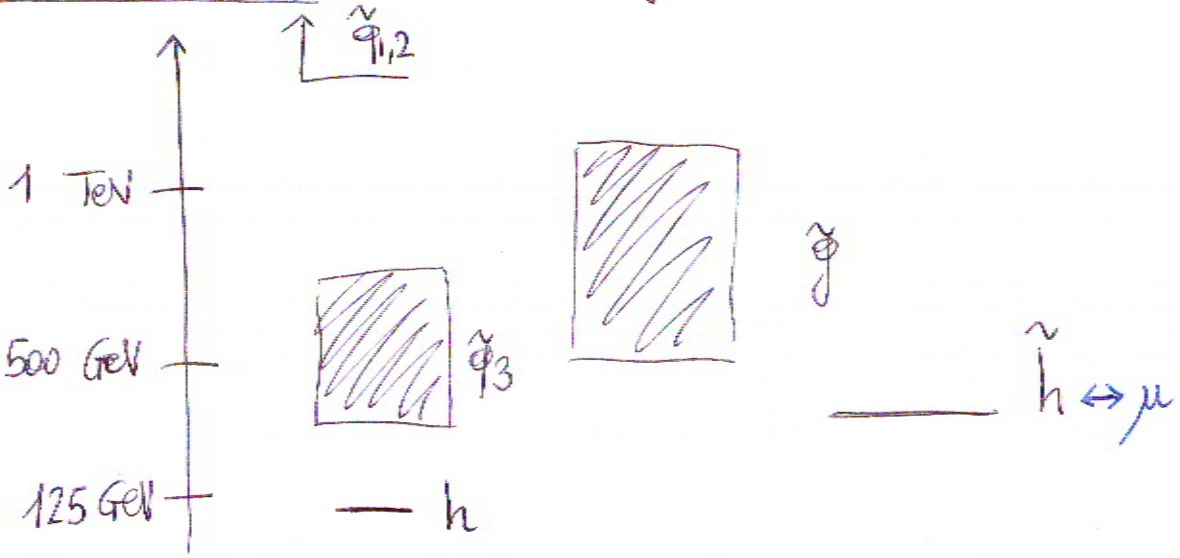
$\to 4 \times 2 + 2 = 10$ real dof -3 NGB $\Longrightarrow 7$ real dof

3 CP-even $S_{1,2,3}$

2 CP-odd $A_{1,2}$

1 charged $H^{\pm}$

1. Natural SUSY → how's defined?



2. Why is this "Natural" SUSY

Naturalness measure → $\dfrac{\partial \log m_h^2}{\partial \log a} < \Delta$, a = any parameter, $1/\Delta$ = fine-tuning

MSSM → when $\tan\beta \gtrsim 3$ $\quad \dfrac{m_h^2}{2} \approx -(m_{H_u}^2 + \mu^2)$

$$\Rightarrow \left[\begin{array}{l} \mu \lesssim 200 \text{ GeV} \left(\dfrac{m_h}{125 \text{ GeV}}\right) \sqrt{\dfrac{\Delta}{5}} \\ m_{\tilde{t}} \lesssim 600 \text{ GeV} \dfrac{\sin\beta}{\sqrt{1+X_t^2}} \sqrt{\dfrac{3}{\log \frac{\Lambda}{\text{TeV}}}} \left(\dfrac{m_h}{125 \text{ GeV}}\right) \sqrt{\dfrac{\Delta}{5}} \\ m_{\tilde{g}} \lesssim 900 \text{ GeV} \sin\beta \left(\dfrac{3}{\log \frac{\Lambda}{\text{TeV}}}\right) \left(\dfrac{m_h}{125 \text{ GeV}}\right) \sqrt{\dfrac{\Delta}{5}} \end{array} \right.$$

$X_t = \dfrac{A_t}{m_{\tilde{t}}}$ $\quad \left[\log \dfrac{\Lambda}{\text{TeV}} \approx 3 \text{ for } \Lambda \simeq 20 \text{ TeV} \right]$

(3) Experiments ?

(4) Heavy squarks → a connection to flavor

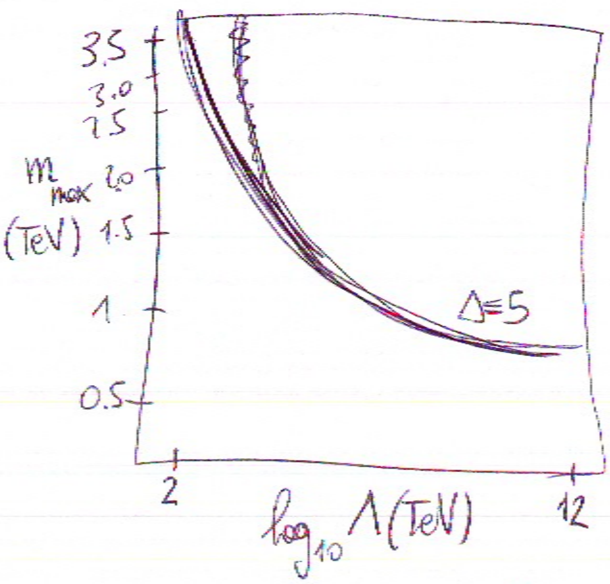
1) Degeneracy
2) Alignment
3) Hierarchy $m_{\tilde{q}_{1,2}} \gg m_{\tilde{q}_3}$

Roughly [see 0812.3610]

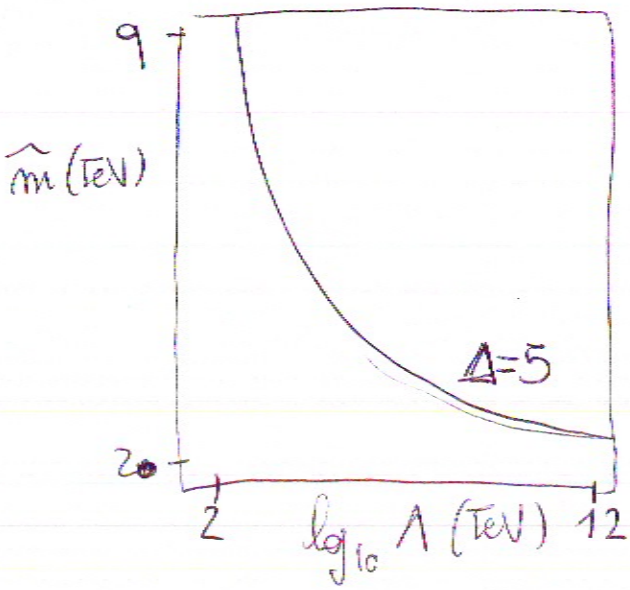
- no deg. nor alignment $m_{\tilde{q}_{1,2}} \gtrsim 700$ TeV
- deg & alignment $\mathcal{O}(\lambda_c)$ $m_{\tilde{q}_{1,2}} \gtrsim 10-20$ TeV

(5) Point is : $\tilde{q}_{1,2}$ heavy in principle compatible with naturalness :

BUT HOW HEAVY? → plots



No conditions @Λ
(1-loop)



Degeneracy @Λ
(2-loops)

(6) But if the resonance ~~at~~ 125 GeV [is] the supersymmetric Higgs boson, we need to raise its mass above m_Z somehow

RAD. ↑

MSSM → general problem: $m_h^2 \leqslant m_Z^2 \cos^2 2\beta + \delta m_i^2$

⇒ radiative corrections <u>MUST</u> be relevant

Largest contribution → stop system

↙ caracterized by 3 parameters: $m^2_{\tilde{Q}_3}$, $m^2_{\tilde{u}_3}$, A_t

- IF A_t small ⇒ $m_h \approx 125$ GeV ⟺ $m_{\tilde{t}_1, \tilde{t}_2} \simeq 4$–$5$
- IF A_t maximal ⇒ $m_h \approx 125$ GeV ⟺ one light stop + one heavy stop

→ heavy stops in conflict with naturalness!

- For A_t maximal, $\Delta = 100$ at least
- For A_t small, $\Delta \gg 100$

let's take this as our best chance: <u>FURTHER PROBLEM</u>

↙ CCB minima deeper than EW minima → non negligible probability to tunnel there

[old story, see 1208.1765 for recent considerations]

⑦ <u>IF</u> we really want to have natural SUSY → need to go beyond MSSM

How? If we don't have to rely on radiative corrections, the game is done (we can have light stops and 125 GeV Higgs)

⇒ increase m_h @ tree level → How? Remember $m_h \propto v\lambda$ ← increase quartic

m_h: mass of the scalar that takes vev: $h = c_\beta h_d + s_\beta h_u$

$$V = |F|^2 + \frac{1}{2} D^A D^A$$

- $|F|^2$: new interactions on $W \supset \lambda S H_u H_d$
- $\frac{1}{2} D^A D^A$: quartic, need for ~~new~~ additional gauge group

⑧ λSUSY framework ↔ NMSSM with large λ (~2)

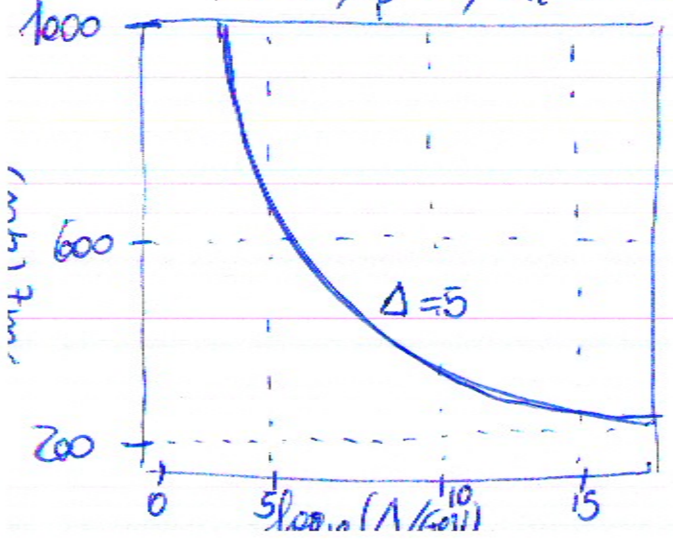
Effect → $m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

[Some papers: 0607332, 0710.5750, 1004.1271, 1004.2256, 1005.1070, 1105.5248, 1105.5389, 1112.2190]

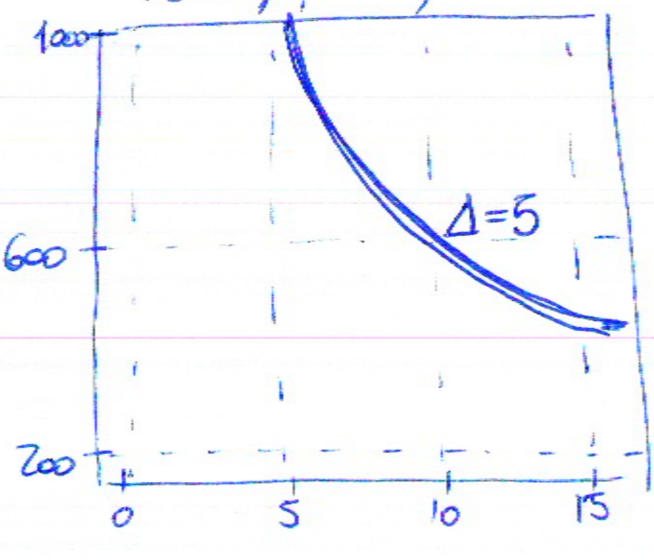
⑨ Effects on naturalness:

1) Stop system

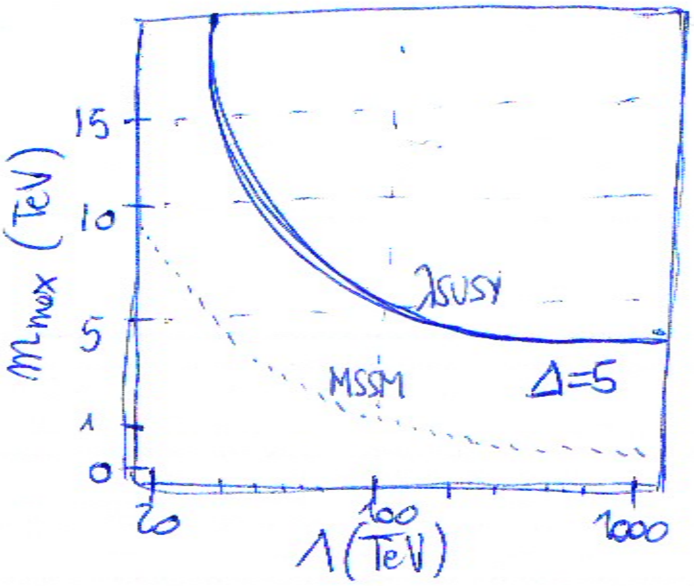
MSSM, $t_\beta = 10$, $m_h = 125$ GeV

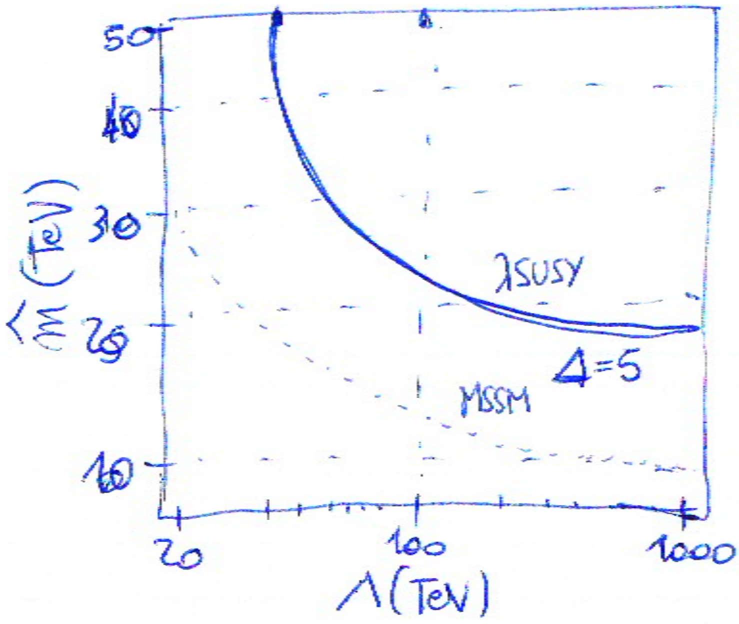


λSUSY, $t_\beta = 2.5$, $m_h = 250$ GeV



2) Squarks first two generations





Bounds from color conservation (~~the~~ heavy squarks of the first two generations tend to drive $m^2_{\tilde{Q}_3}$ & $m^2_{\tilde{u}_3}$ negative at EW scale) <u>are similar</u>

(10) What about the phenomenology of the Higgs boson in λSUSY?

3 states → h, H, S

- h-H mixing small for small t_β
- H-S mixing small for small t_β

⇒ H can be decoupled without introducing too much mixing

⇒ effective 2×2 system h-S

For small t_β & $\lambda \lesssim 2$ ⇒ $m_h \gtrsim 250$ GeV

⇒ need to rely on eigenvalues repulsion to bring one of the eigenvalues down to 125 GeV

→ usually, quite large singlet component in the 125 GeV state

⇒ in general, modification of all the production mode & decay width

[one way out is to lower λ and increase a bit t_β, i.e. $\lambda = 1.5$ & $t_\beta = 3.5$ ⇒ $m_h \approx 150$ GeV and is much simpler to have a SM-like Higgs at 125 GeV] → or to exit from Scale Invariant NMSSM, addition of explicit μ term helps

---

(1) Along these lines Schmidt-Hoberg / Staub [1208.1683]

→ lightest scalar state around 125 GeV, mostly SM-like

~~BUT~~ Focus on

$$W = (\mu + \lambda S) H_1 H_2 + \frac{1}{2}\mu_S S^2 + \frac{1}{3}\kappa S^3 + W_{MSSM}$$

There are regions in parameter space in which, for $\lambda = 1.5$, % singlet inside $s_1 \lesssim 10\%$ & $m_{s_1} \simeq 125$ GeV

2) Effects on phenomenology of s_1 (= lightest scalar)

1) σ_{prod} via glue-glue & VBF slightly reduced

2) $R_{WW} = \dfrac{\sigma BR(s_1 \to WW)}{\sigma BR(s_1 \to WW)_{SM}} \simeq 1$ in a region of parameter space because there is also a reduction of $\Gamma(s_1 \to b\bar{b})$ that increases BR(...)

(B) 3) $R_{\gamma\gamma}\ \frac{\sigma}{\sigma_{SM}} \simeq 2$ in the same region in which $\mu_{WW} \simeq 1$ because

a) reduction of $\Gamma(S_1 \to b\bar{b})$

b) Contributions to $S_1 \to \gamma\gamma$ enhanced because of contributions from light $H^\pm$ & $\chi^\pm$ whose coupling is proportional to λ:

$g_{hH^+H^-} \propto \lambda^2 \times$ (fraction of $h_{1,2}, S$ into S_1)

$g_{h\chi^+\chi^-} \propto \lambda \times$ (fraction of S into S_1)

13

Conclusions

- MSSM : $\frac{1}{\Delta} \lesssim 1\%$ because $m_h \simeq 125$ GeV requires heavy stops

  $\Rightarrow$ Naive natural SUSY is already in quite a bad shape

- Simple way to go beyond this:
  enhance m_h at <u>tree level</u> $\rightarrow$ increased naturalness

- λSUSY : $W = \mu(S) H_1 H_2 + f(S)$

  $$\lambda = \left.\frac{d\mu(S)}{dS}\right|_{S=0} \gtrsim 1.5$$

  Effects:

  ↳ naturalness improved

  ↳ lightest scalar pheno compatible with current data (apart from S, bb which is reduced):

  $\mu_W \simeq 1$

  $\mu_{\gamma\gamma} \simeq 2$

Relevant RGEs

$$\frac{dm_{H_u}^2}{d\log\mu} \sim \frac{3}{8\pi^2}\left[\lambda_t^2\left(m_{\tilde{Q}_3}^2 + m_{\tilde{u}_3}^2\right) + A_t^2\right] + \\ + \frac{1}{8\pi^4} g_s^2 m_{\tilde{g}} \left[2\lambda_t^2 m_{\tilde{g}} - \lambda_t^* A_t - \lambda_t A_t\right]$$

$$\frac{dm_{\tilde{Q}_3}^2}{d\log\mu} \sim \frac{dm_{\tilde{u}_3}^2}{d\log\mu} \sim -\frac{2}{3\pi^2} g_s^2 m_{\tilde{g}}^2$$

$$\frac{dA_t}{d\log\mu} \sim \frac{2}{3\pi^2} g_s^2 \lambda_t m_{\tilde{g}}$$

$$\frac{dm_{H_u}^2}{d\log\mu} = \frac{1}{16\pi^2} g'^2 \langle Y \tilde{m}^2 \rangle + \frac{48}{(16\pi^2)^2}\left(g^4 + \frac{5}{9} g'^4\right) \tilde{m}_{1,2}^2$$