SUSY without the Little Hierarchy

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based on a collaboration with

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MSSM and the Little Hierarchy

- The mass parameters in the Higgs potential are determined by soft SUSY-breaking parameters m_s

$$m_Z^2 = \sum_i \alpha_i m_{s_i}^2$$

- LEP negative search pushes m_s up
- A very efficient cancellation ?

MSSM

- $m_h^2|_{tree-level} < m_Z^2 \Rightarrow$ Large radiative corrections

$$\delta\lambda \simeq (3/4\pi^2) m_t^4/v^2 \log\left(m_s^2/m_t^2\right) \Rightarrow m_h^2|_{tree-level} + 2v^2\delta\lambda$$

$$\delta m_{Hu}^2 = -\,(3y_t^2/8\pi^2) m_s^2 \ln\left(\Lambda^2/m_s^2\right)$$

- $m_h^2 > 115$ GeV $\Rightarrow m_s \gtrsim 1\,\mathrm{TeV} \Rightarrow \Delta = \frac{|\delta m_H^2|}{m_h^2/2} \to FT < 1\%$

Possible solutions

$$\delta m_{Hu}^2 = -(3y_t^2/8\pi^2) m_s^2 \log\left(\Lambda^2/m_s^2\right)$$

1. Lower the Log
   - 1A Lower Λ (e.g. NMSSM, $\kappa = 2 \Rightarrow \Lambda = 20$ TeV)
   - 1B Replace Λ with an effective lower scale $f \sim 1$ TeV (e.g. Little Higgs)
2. Raise up the tree-level Higgs mass, $\Rightarrow m_s^2 (\downarrow)$
   - 2A From F-terms (e.g NMSSM)
   - 2B From D-terms (i.e. extending the gauge structure)
3. 1B+2B= this model: a Super Little Higgs with enhanced quartic

The model: preliminary

Why SUSY+LH?

- $SM \longrightarrow \delta m_H^2 \sim \Lambda^2$
- $SUSY \longrightarrow \delta m_H^2 \sim m_s^2 \log \Lambda$
- $LH \longrightarrow \delta m_H^2 \sim f^2 \log \Lambda$

SUSY+LH

The marriage between SUSY and LH enforce a "double protection" from SUSY and a global symmetry under which the Higgs is a *PseudoGoldstone* boson

$$SUSY + LH \longrightarrow \delta m_H^2 \sim 3 m_s^2 / 8\pi^2 \log f$$

Berezhiani, Chankowky, Falkowski, Pokorski, Wagner '04, '05
Csaki, Strumia, Marandella, Shirman '05
Birkedal, Chacko, Gaillard '04

Roy, Schmaltz '06

THE MODEL: $SU(3)_W \times U(1)_X$

The easiest way to embed the LH in a SUSY theory is via the "simplest little Higgs"

$$SU(2)_W \times U(1)_Y \rightarrow SU(3)_W \times U(1)_X$$

The Higgs doublets are promoted to triplets

$$H_{u,d} \rightarrow \mathcal{H}_{u,d} = (H_{u,d}, S_{u,d}) = 3, \bar{3}$$

and cloned in exact copies $\Phi_{u,d} = 3, \bar{3}$

$$\mathcal{W} = \mathcal{W}_\Phi + \mathcal{W}_\mathcal{H}$$

As far as $\mathcal{H}$ and Φ don't talk each other the Higgs sector has a $SU(3)_1 \times SU(3)_2 \supset SU(3)_W$

The model: down to the SM

$$\langle \Phi_{u,d} \rangle = (0, 0, F \sim 10\,\mathrm{TeV}) \Rightarrow SU(3)_1 \times SU(3)_2 \to SU(2)_1 \times SU(3)_2$$

$$\langle |\mathcal{H}_{u,d}| \rangle = f_{u,d} \sim 1\,\mathrm{TeV} \Rightarrow SU(2)_1 \times SU(3)_2 \to SU(2)_1 \times SU(2)_2$$

$$16 - 3 - 3 - 5 = 5 = 4 + 1$$

These 4 degrees form a doublet under $SU(2)_W$ and indeed are the SM Higgs doublet H

It controls the direction of $SU(2)_2$ with respect to $SU(2)_W$

$$\mathcal{H}_u = (H^T, \sqrt{f^2 - |H|^2}) \sin\beta \quad \mathcal{H}_d = (H, \sqrt{f^2 - |H|^2}) \cos\beta$$

If $v = 0$ there is no EWSB $\Rightarrow SU(2)_W \times U(1)_Y$ is unbroken

Higgs as a PseudoGoldstone boson

H is a pseudoGoldstone: integrating out the heavy modes Φ we generate a potential

$$V_{\mathcal{H}} = V_F^{SU(3)} + V_D \simeq V_F^{SU(3)} + V_D^{SU(2)} + \left(\frac{m^2}{F^2}\right) \sum_{\hat{T}} \hat{D}^2$$

$\hat{D}$ are the D-terms corresponding to the broken generators
m is the soft breaking parameter for Φ.

Physical Higgs potential

- $m^2/F^2 \gg 1 \Rightarrow V_H = m_0^2|H|^2 + \lambda_0|H|^4$
- $m^2/F^2 \ll 1 \Rightarrow V_H = \lambda_0|H|^4$

SUSY+global symmetry $\Rightarrow$ only a quartic is generated at tree-level

Matter content

The minimal matter content with anomaly cancellation and generation-universal (*Csaki, Marandella, Strumia and Shirman '05*)

	$SU(3)_c$	$SU(3)_W$	$U(1)_x$	$U(1)_{em}$
Q	3	3	0	$(+2/3, -1/3, -1/3)$
U	$\bar{3}$	1	$-2/3$	$-2/3$
$2 \times D$	$\bar{3}$	1	$+1/3$	$1/3$
Q'	$\bar{3}$	3	$-1/3$	$(1/3, -2/3, -2/3)$
$\bar{Q}'$	3	$\bar{3}$	$+1/3$	$(-1/3, +2/3, +2/3)$
$2 \times L$	1	$\bar{3}$	$-1/3$	$(-1, 0, 0)$
E	1	$\bar{3}$	$+2/3$	$(0, +1, +1)$

- 2 extra heavy fermionic *little-partner* of Top (and Bottom)
- 2 extra heavy leptons and two (almost) sterile neutrinos

Radiative corrections

$$\mathcal{W}_{top} = m_{Q'}\bar{Q}'Q' + y_1\bar{Q}'\mathcal{H}_u U + y_2 Q\mathcal{H}_u Q' + \tilde{y}_1\bar{Q}'\Phi_u U + \tilde{y}_2 Q\Phi_u Q'\,.$$

generates 1-loop correction to the Higgs potential once that $\langle\Phi\rangle = (0,0,F)$.

top/stop loops

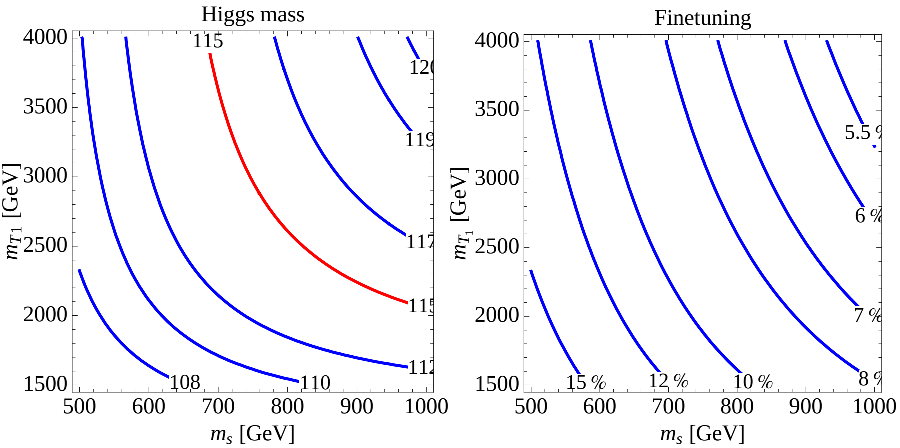
$$V_H = \delta m_H^2 |H|^2 + (\lambda_0 + \delta\lambda)|H|^4$$

$$\delta m_H^2 \simeq -\frac{3y_t^2\sin^2\beta}{8\pi^2}\left[m_s^2\ln\left(\frac{m_{T_1}^2+m_s^2}{m_s^2}\right) + m_{T_1}^2\ln\left(\frac{m_{T_1}^2+m_s^2}{m_{T3}^2}\right)\right]$$

$$\delta\lambda \simeq \frac{3y_t^4\sin^4\beta}{16\pi^2}\left[\ln\left(\frac{m_s^2}{m_t^2}\right) + \ln\left(\frac{m_{T_1}^2}{m_s^2+m_{T_1}^2}\right) + \frac{2m_s^2}{m_{T_1}^2}\ln\left(\frac{m_s^2}{m_s^2+m_{T_1}^2}\right)\right]$$

Higgs mass and Tuning

Finetuning around $5 \div 7\%$ with $m_h \sim 115 \div 120$ GeV.



Bellazzini, Pokorski, Rychkov and Varagnolo '08

Doping the quartic

- "Double protection" works for δm_H^2 but the quartic is still too small
- How enhance the quartic and retain the "double protection" ?

The idea is to enlarge the gauge structure and break SUSY in a way that the low-energy D-terms rensemble the structure of SUSY D-terms but bigger.

	$SU(3)_W$	$U(1)_x$	$U(1)_z$
$\mathcal{H}_{u,d}$	$3,\ \bar{3}$	$\pm 1/3$	$\pm q'$
$\Phi_{u,d}$	$3,\ \bar{3}$	$\pm 1/3$	$\pm q$
$\Psi_{u,d}$	1	0	q_Ψ

- $\langle \Psi \rangle = \Omega \approx 10$ TeV
- $m_\Psi / \Omega \sim 1$ and $m/F \ll 1$
- $q' = q$

The effective D-terms

$$V_D \simeq V_D^{SU(2)_W} + \left(\frac{m^2}{F^2}\right) \sum_{\hat{T} \neq T^8} \hat{D}^2 + D^2_{8,x,y,z}$$

$$D_x = D_z\,, \quad D_y = \frac{1}{\sqrt{3}} D_8 + \frac{2}{3} D_x = |H_u|^2 - |H_d^2|$$

$$D^2_{8,x,y,z} = a D_y^2 + b D_y D_x + c D_x^2$$

$$V_D = \left(V_D^{SU(2)_W} + a D_y^2\right) + b D_y D_x + c D_x^2$$

1. $q = q' \Rightarrow b = c = 0$
2. $a = \frac{g_y^2}{8}\left[1 + a_1 \frac{m_\Psi^2}{\Omega^2}\right] > a^{SM} \Rightarrow m_h^2|_{tree-level} > m_Z^2 \cos^2 2\beta$

The effective D-terms

- SUSY limit $m_\Psi/\Omega \to 0$

$$\Rightarrow V_D = D^2_{MSSM} = \left(V_D^{SU(2)_W} + \frac{g_y^2}{8} D_y^2 \right)$$

$$a = a^{sm}(1 + a_1 m_\Psi^2/\Omega^2)\,, \quad b = b_1 m_\Psi^2/\Omega^2\,, \quad c = c_1 m_\Psi^2/\Omega^2$$

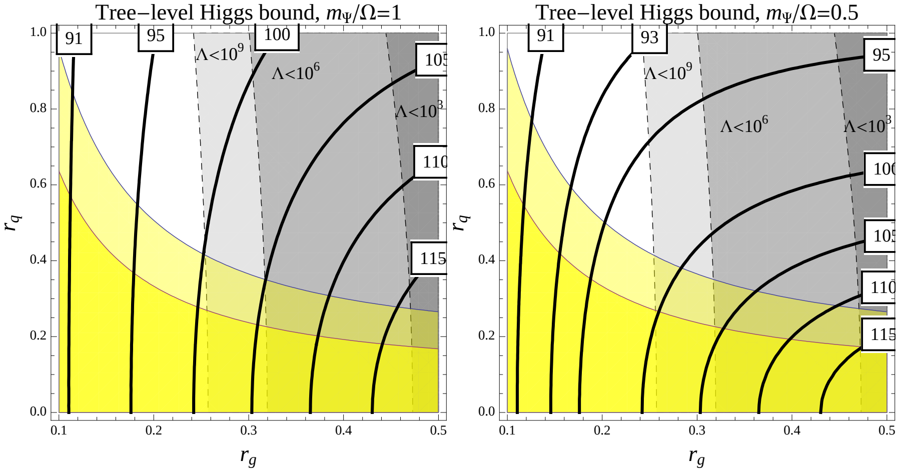
- Hard breaking $m_\Psi/\Omega \to \infty$

$$\Rightarrow Y\,,\ \tilde{Y} = T^8/\sqrt{3} + Z/3q \quad \text{conserved} \Rightarrow \mathrm{D}^2_{8,x,y,z} = \mathrm{D}^2_{y} + \mathrm{D}^2_{\tilde{y}}$$

$$YH_{u,d} \propto \tilde{Y} H_{u,d} \Rightarrow D^2_{\tilde{y}} \propto D^2_y \Rightarrow b = c = 0$$

$$V_D = V_D^{SU(2)_W} + \left(1 + a_1 \frac{m_\Psi^2}{\Omega^2}\right) D_y^2$$

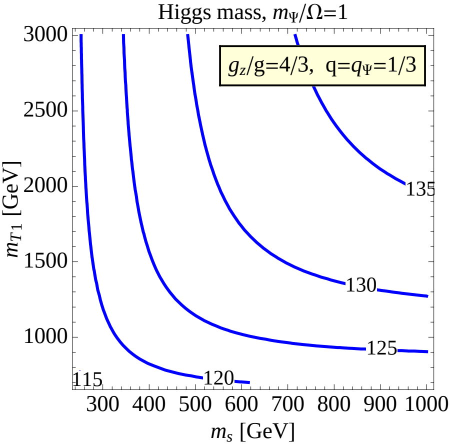
THE TREE-LEVEL HIGG MASS

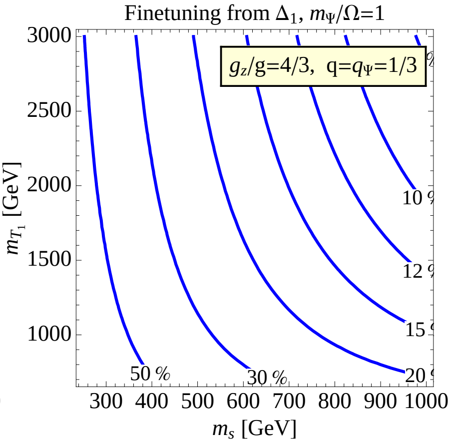


Constraints: Z' and $\Lambda_{Landau} = 10^3\,, 10^6\,, 10^9$ TeV

$r_g = qg_z/g,\ r_q = q_\psi/3q$

Higgs mass and Tuning I

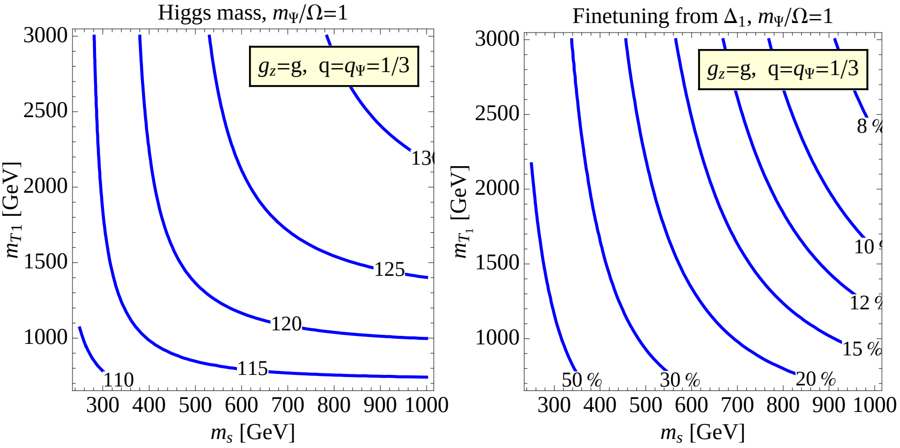




$\Lambda_{Landau} = 10^3$ TeV $\quad m_{stop} \approx 400$ GeV $\quad m_{T_1} \gtrsim 700 \div 1000$ GeV

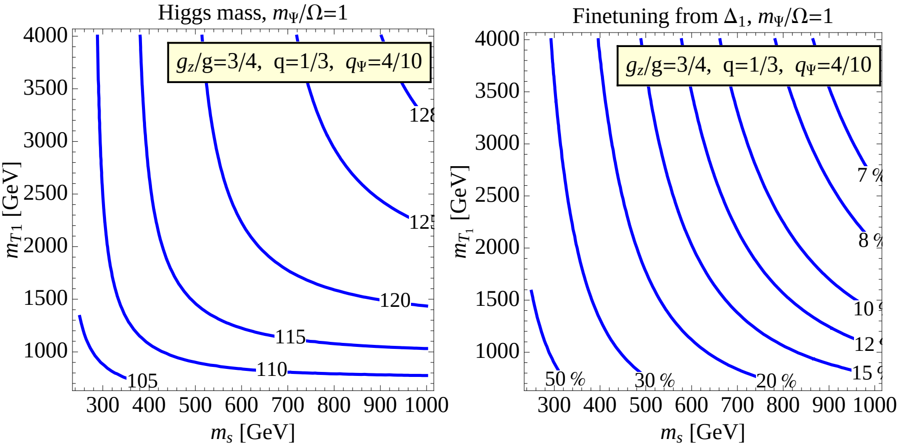
Bellazzini, Csaki, Delgado, Weiler '09

Higgs mass and Tuning II



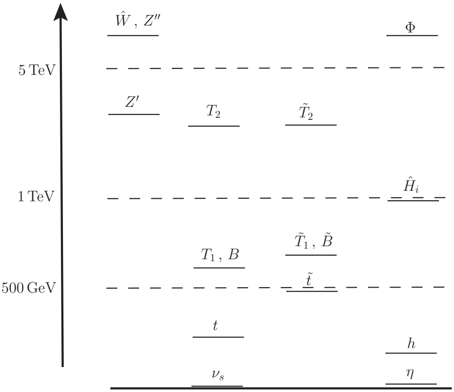
$\Lambda_{Landau} = 10^6$ TeV

Higgs mass and Tuning III



$\Lambda_{Landau} = 10^9$ TeV

CONCLUSIONS



- SUSY+LH $\Rightarrow$ "double protection"
- non decoupling D-terms $\Rightarrow$ quartic enhancement
- no tuning

- fermionic "little" partner T_1 of top at 700 GeV
- Z' at 3.5 TeV or more
- sterile neutrinos at $\sim$ KeV.