Implications of a SM like Higgs for a natural NMSSM with low cutoff

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in collaboration with T. Gherghetta, B. v. Harling, A. Medina [to appear soon]

Outline

Introduction/Motivation

2 Framework

3 Results

4 Conclusions

Outline

Introduction/Motivation

Low-energy Supersymmetry – MSSM



gauge coupling unification



solution to hierarchy problem



$$\Delta m_{H}^{2} = \frac{\lambda_{s}}{16\pi^{2}} \left[\Lambda_{UV}^{2} - 2m_{s}^{2} \ln \frac{\Lambda_{UV}}{m_{s}} + \dots \right]$$
$$\Delta m_{H}^{2} = -\frac{|\lambda_{f}|^{2}}{16\pi^{2}} \left[\Lambda_{UV}^{2} + \dots \right]$$

DM candidate



Higgs mass prediction At tree level

 $m_{h^0} < m_Z |\cos 2\beta|$

LHC constraints

		ATLAS SUSY Searches* - 95% CL Lower Limits (Status: March 2012)			
dusive searches	MSUGRA/CMSSM : 0-lep + j's + E _{T,miss}	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-033] 1.40 TeV $\widetilde{q} = \widetilde{g}$ mass			
	MSUGRA/CMSSM : 1-lep + j's + E _{T,miss}	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-041] 1.20 TeV q = g mass			
	MSUGRA/CMSSM : multijets + ET, miss	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-037] 850 GeV g mass (large m ₀)			
	Pheno model : 0-lep + j's + E _{T.miss}	L=4.7 (b ⁻¹ (2011) [ATLAS-CONF-2012-033] 1.38 TeV q mass (m(g) < 2 TeV, light χ_{-}^{0}) ATLAS			
	Pheno model : 0-lep + j's + E _{T,miss}	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-033] 940 GeV \tilde{g} mass $(m(\tilde{q}) < 2$ TeV, light $\tilde{\chi}_{1}^{0}$) Preliminary			
	Gluino med. $\overline{\chi}^* (\tilde{g} \rightarrow q \overline{q} \chi^*)$: 1-lep + j's + $E_{T miss}$	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-041] 900 GeV \widetilde{g} mass $(m(\chi^0) < 200 \text{ GeV}, m(\chi^0) = \frac{1}{2}(m(\chi^0) + m(\widetilde{g}))$			
	GMSB : 2-lep OS _{SF} + E _{T.miss}	L=1.0 (b ⁻¹ (2011) [ATLAS-CONF-2011-156] 810 GeV g mass (tan β < 35)			
d,	GMSB : $1-\tau + j's + E_{T.miss}$	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-005] 920 GeV g mass (tanβ > 20)			
Third generation	GMSB : $2-\tau + j's + E_{T miss}$	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-002] 990 GeV g mass (tanβ > 20)			
	$GGM: \gamma\gamma + E_{T,miss}$	L=1.1 (b ⁻¹ (2011) (1111.4116) 805 GeV g mass (m(\chi ⁰) > 50 GeV)			
	Gluino med. b̃ (ğ→bb¯ ⁰ _Z) : 0-lep + b-j's + E _{T.miss}	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-003] 900 GeV g mass (m($\chi_{\star}^{-0})$ < 300 GeV)			
	Gluino med. \tilde{t} ($\tilde{g} \rightarrow t \bar{t} \chi_{i}^{0}$) : 1-lep + b-j's + $E_{T miss}$	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-003] 710 GeV g mass (m($\chi_{-}^{0})$ < 150 GeV)			
	Gluino med. t (g→tt ⁻⁰ ₂) : 2-lep (SS) + j's + E _{T,miss}	L=2.1 (b ⁻¹ (2011) [ATLAS-CONF-2012-004] 650 GeV g mass (m(x ₁ ⁰) < 210 GeV)			
	Gluino med. t̃ (ğ→tt ⁻⁰) : multi-j's + E _{T.miss}	L=4.7 fb ⁻¹ (2011) [ATLAS-CONF-2012-037] 830 GeV g mass (m(\chi ⁰) < 200 GeV)			
	Direct \widetilde{bb} $(\widetilde{b}_1 \rightarrow b\chi^{-b})$: 2 b-jets + $E_{T,miss}$	L=2.1 (b ⁻¹ (2011) [1112.3832] 390 GeV Ď mass (m(∑ ⁰) < 60 GeV)			
	Direct ît (GMSB) : Z(→II) + b-jet + E	L=2.1 (b ⁻¹ (2011) [ATLAS-CONF-2012-036] 310 GeV T mass (115 < m(χ_1^{-0}) < 230 GeV)			
G	Direct gaugino $(\overline{\chi}_{1}^{*}\overline{\chi}_{2}^{0} \rightarrow 3I\overline{\chi}_{1}^{0})$: 2-lep SS + $E_{T,miss}$	L=1.0 (b ⁻¹ (2011) [1110.6189] 170 GeV $\overline{\chi}_1^n$ mass $((m(\overline{\chi}_1^0) < 40 \text{ GeV}, \overline{\chi}_1^0, m(\overline{\chi}_1^n) = m(\overline{\chi}_2^0), m(\overline{l}, \overline{v}) = \frac{1}{2}(m(\overline{\chi}_1^0) + m(\overline{\chi}_2^0)))$			
0	Direct gaugino $(\overline{\chi}_{1}^{*}\overline{\chi}_{2}^{0} \rightarrow 3I \overline{\chi}_{1}^{0})$: 3-lep + $E_{T,miss}$	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-023] 250 GeV χ_{1}^{*} mass ($m(\chi_{1}^{0}) < 170$ GeV, and as above)			
Se	AMSB : long-lived 2	$\sum_{k=4.7 \text{ (b)}^3} (2011) [CF-2012-254]^{118 \text{ GeV}} \widetilde{\chi}_1^* \text{ mass } (1 < \tau(\widetilde{\chi}_1^*) < 2 \text{ ns}, 90 \text{ GeV limit in } [0.2,90] \text{ ns})$			
r fic/	Stable massive particles (SMP) : R-hadrons	L=34 pb ⁻¹ (2010) [1103:1984] 562 GeV g mass			
d pa	SMP : R-hadrons	L=34 pb ⁻¹ (2010) [1103.1984] 294 GeV b mass			
mg-livec	SMP : R-hadrons	4=34 pb ⁻¹ (2010) [1103:1984] 309 GeV T mass			
	SMP : R-hadrons (Pixel det. only)	L=2.1 fb ⁻¹ (2011) [ATLAS-CONF-2012-022] 810 GeV ĝ mass			
- F	GMSB : stable ∓	L=37 pb ⁻¹ (2010) [1108.4495] 136 GeV T mass			
	RPV : high-mass eµ	L=1.1 fb ⁻¹ (2011) [1103.3089] 1.32 TeV ν _τ mass (λ ₃₁₁ =0.10, λ ₃₁₂ =0.05)			
ЧH	Bilinear RPV : 1-lep + j's + E _{T,miss}	L=1.0 fb ⁻¹ (2011) [1108.6606] 760 GeV q = g mass (cr _{LSP} < 15 mm)			
	MSUGRA/CMSSM - BC1 RPV : 4-lepton + E _{T,miss}	L=2.1 (b ⁻¹ (2011) [ATLAS-CONF-2012-035] 1.77 TeV g mass			
	Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$	L=34 pb ⁻¹ (2010) [1110.2003] 185 GeV sgluon mass (excl: m _{pg} < 100 GeV, m _{sg} ~ 140 ± 3 GeV)			
		10 ⁻ 1 10			
		Mass scale [TeV			

* Only a selection of the available mass limits on new states or phenomena shown

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Status of low-energy supersymmetry

- strong limits on squark and gluino masses (mostly in CMSSM/simplified models)
- relatively large Higgs mass
- ightarrow large loop correction to Higgs mass needed
- \rightarrow fine tuning
- ⇒ Simplest SUSY models in bad shape

Barbieri-Giudice fine-tuning measure

[Barbieri/Giudice (1988)]

$$\Sigma_{\xi}^{\nu} \equiv \left| rac{d\log m_Z^2}{d\log \xi}
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measures the sensitivity of the weak scale (or m_Z) to the dimensionful parameters ξ of the theory



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 - Extend MSSM to modify Higgs mass prediction, more specifically raise Higgs mass
- \rightarrow e.g. at tree level in NMSSM: introduce gauge singlet S

Literature: NMSSM and 125 GeV

"A Natural SUSY Higgs Near 126 GeV" L. J. Hall, D. Pinner and J. T. Ruderman. arXiv:1112.2703 [hep-ph] JHEP 1204, 131 (2012) "Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale" U. Ellwanger and C. Hugonie. arXiv:1203.5048 [hep-ph] "The 125 GeV Higgs in the NMSSM in light of LHC results and astrophysics constraints" D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson and C. Wymant, arXiv:1203.3446 [hep-ph] <u>"A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM"</u> J. Cao, Z. Heng, J. M. Yang, Y. Zhang and J. Zhu. arXiv:1202.5821 [hep-ph] JHEP 1203, 086 (2012) "NMSSM Higgs Benchmarks Near 125 GeV" S. F. King, M. Muhlleitner and R. Nevzorov. arXiv:1201.2671 [hep-ph] Nucl. Phys. B 860, 207 (2012) "The Constrained NMSSM and Higgs near 125 GeV" J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1201.0982 [hep-ph] Phys. Lett. B 710, 454 (2012) "A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM" U. Ellwanger. arXiv:1112.3548 [hep-ph] JHEP 1203, 044 (2012) "The fine-tuning of the generalised NMSSM" G. G. Ross and K. Schmidt-Hoberg. arXiv:1108.1284 [hep-ph] "The generalised NMSSM at one loop: fine tuning and phenomenology" G. G. Ross, K. Schmidt-Hoberg and F. Staub. arXiv:1205.1509 [hep-ph]

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2 Framework

Superpotential

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



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$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_s^2 |S|^2 - (a_\lambda S H_d H_u + rac{a_\kappa}{3} S^3 + h.c.)$$

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Bound on lightest Higgs mass m_h

$$m_h^2 \leq m_Z^2 \cos^2 2eta + \lambda^2 v^2 \sin^2 2eta
ightarrow \left\{ egin{array}{c} m_Z^2 \cos^2 2eta & ext{large tan} \ \lambda^2 v^2 \sin^2 2eta & ext{small tan} \ \lambda^2 v^2 \sin^2 2eta & ext{small tan} \ eta \end{array}
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- No gain for large tan β compared to MSSM
- ullet small tan oldsymboleta o large $\lambda\gtrsim$ 0.7 or additional stop loop contribution
- ightarrow Landau pole below GUT scale ightarrow low cutoff required

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or Fat Higgs

[Harnik, Kribs, Larson, Murayama; Chang, Kilic, Mahbubani; Delgado, Tait; Birkedal, Chacko, Nomura]

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Our Study

- Aim: Find the "Golden Region" of small fine-tuning (better 10%), i.e. the natural region of parameter space in the NMSSM
- assuming "SM-like" Higgs with $m_h pprox$ 125 GeV [(124 126) GeV]

Our Study

Assumptions

- Cutoff $\Lambda = 10 \text{ TeV}$
- no CP violation
- First two generations of squarks and all sleptons decoupled
- impose LEP bounds on particle masses
- Neutralino LSP (EW gauginos not decoupled)
- no invisible Higgs decays

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Analysis

- Markov-Chain Monte-Carlo (MCMC)
- with modified version of NMHDECAY[Ellwanger, Gunion, Hugonie]
- No Landau pole below the cutoff scale $\Lambda=10\,{
 m TeV}$
- Electroweak precision test: S and T taking into account
 - Neutralino-Chargino sector
 - Higgs sector
 - T in stop-sbottom sector (S is small [Barbieri, Hall, Nomura, Rychkov])

Analysis

Input values are specified at

$$M_{SUSY}^2 = \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + m_{\tilde{b}_1}^2 + m_{\tilde{b}_2}^2}{4}$$

range of input values:

 $0 \text{ TeV} < M_1, M_2 < 3 \text{ TeV}$ $700 \text{ GeV} < M_3 < 3 \text{ TeV}$ $0 \text{ TeV} < m_{Q_3}, m_{u_3}, m_{d_3} < 3 \text{ TeV}$ $-3 \text{ TeV} < A_{\lambda}, A_{\kappa}, A_t, A_b < 3 \text{ TeV}$ $\lambda > 0$ $a_{\kappa} = \kappa A_{\kappa} \ge 0$ $\tan \beta > 0.5$

Loop corrected Minimisation Conditions

$$v_{u}(Q) \left(m_{H_{u}}^{2} + \mu_{eff}^{2} + \lambda^{2} v_{d}(Q)^{2} + \frac{g_{1}^{2} + g_{2}^{2}}{4} \left(v_{u}(Q)^{2} - v_{d}(Q)^{2} \right) \right) = v_{d}(Q) \mu_{eff} B_{eff} - \frac{1}{2} \frac{\partial \Delta V_{eff}}{\partial v_{u}(Q)} \\ v_{d}(Q) \left(m_{H_{d}}^{2} + \mu_{eff}^{2} + \lambda^{2} v_{u}(Q)^{2} + \frac{g_{1}^{2} + g_{2}^{2}}{4} \left(v_{d}(Q)^{2} - v_{u}(Q)^{2} \right) \right) = v_{u}(Q) \mu_{eff} B_{eff} - \frac{1}{2} \frac{\partial \Delta V_{eff}}{\partial v_{d}(Q)} \\ s(Q) \left(m_{S}^{2} + \kappa A_{\kappa} s(Q) + 2\kappa^{2} s^{2}(Q) + \lambda^{2} (v_{u}^{2}(Q) + v_{d}^{2}(Q) - 2\lambda \kappa v_{u}(Q) v_{d}(Q) \right) = \lambda A_{\lambda} v_{u}(Q) v_{d}(Q) - \frac{1}{2} \frac{\partial \Delta V_{eff}}{\partial s(Q)}$$

with $\mu_{eff} = \lambda s(Q)$, $B_{eff} = A_\lambda + \kappa s(Q)$ and

$$v_{\boldsymbol{u}}(\boldsymbol{Q}) = v_{\boldsymbol{u}}/\sqrt{Z_{\boldsymbol{H}_{\boldsymbol{u}}}}$$
 $v_{\boldsymbol{d}}(\boldsymbol{Q}) = v_{\boldsymbol{d}}/\sqrt{Z_{\boldsymbol{H}_{\boldsymbol{d}}}}$ $s(\boldsymbol{Q}) = s/\sqrt{Z_{\boldsymbol{s}}}$

• Three minimisation conditions result in linear system of equations for $\frac{dv^2}{d\xi}$, $\frac{d\tan\beta}{d\xi}$ and $\frac{ds}{d\xi}$.

• which determines the usual fine-tuning: $\Sigma_{\xi}^{\nu} \equiv \left| \frac{\xi^2}{v^2} \frac{dv^2}{d\xi^2} \right| < \Sigma$

• Are the parameters at the SUSY scale fine-tuned?

Quantum Corrections between SUSY scale and cutoff Λ

For example stop contribution to m_{H_u} :

$$\delta m_{H_u}^2 pprox rac{3}{16\pi^2} \left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2
ight) \log\left[rac{\Lambda^2}{M_{SUSY}^2}
ight]$$

Are the parameters at the SUSY scale fine-tuned?Consider fine-tuning measure for each dimensionful coupling

e.g.
$$\Sigma_{m_{Q_3}^2}^{m_{H_u}^2} \equiv \frac{m_{Q_3}^2}{m_{H_u}^2} \frac{d\delta m_{H_u}^2}{dm_{Q_3}^2}$$

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Fine-tuning of EW scale with respect to m²_{Q3}:

$$\left| \Sigma_{m_{\mathbf{Q}_3}^{\nu}}^{\nu} \right| \approx \left| \Sigma_{m_{\mathbf{Q}_3}^{\nu}}^{\nu,MC} + \sum_{i} \frac{m_{\mathbf{Q}_3}^2}{\nu^2} \frac{d\nu^2}{d\xi_i} \frac{d\delta\xi_i}{dm_{\mathbf{Q}_3}^2} \right| = \left| \Sigma_{m_{\mathbf{Q}_3}^{\nu,MC}}^{\nu,MC} + \sum_{i} \Sigma_{m_{\mathbf{Q}_3}^{\xi_i}}^{\xi_i} \Sigma_{\xi_i}^{\nu,MC} \right| < \Sigma$$

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Hence, the overall fine-tuning of the EW scale is given by
$$\Sigma^{\nu} = max_i \left| \Sigma_{i}^{\nu} \right|$$

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Higgs mass



large Higgs mass m_h requires large λ and small tan β
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In the following

- 124 GeV $< m_h <$ 126 GeV
- "SM-like" Higgs: $|R_{ZZh} 1| < 0.05$ and $|R_{u\bar{u}h} 1| < 0.05$

Higgs couplings



 $\lambda - \kappa$





- 0.6 $\lesssim \lambda \lesssim$ 2.3 • $\lambda \sim \kappa$
- running of κ stronger than $\lambda \Rightarrow \max \kappa < \max \lambda$
- $\tan \beta$ bounded due to contribution to T parameter

Neutralinos and T parameter

Neutralinos

(M_1	0	$-\cos\beta\sin\theta_W m_Z$	$\sineta\sin heta_W m_Z$	0)
		M_2	$\coseta\cos heta_W m_Z$	$-\sineta\cos\theta_W m_Z$	0
			0	$-\mu$	$-\lambda v \sin eta$
			$-\mu$	0	$-\lambda v \cos eta$
					$-2\frac{\kappa}{\lambda}\mu$ /

in gauge-eigenbasis $\psi^0 = (\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$

• $\tan \beta \lesssim 5$ limited by stop contribution to T [Barbieri, Hall, Nomura, Rychkov] \rightarrow Higgsino-Singlino mixing restricted $A_{\lambda} - A_{\kappa}$



• small A terms: $A_\kappa \lesssim A_\lambda < 1\,{
m TeV}$

stop masses



- $m_{ ilde{t}_2} \lesssim 2.4 \, {
 m TeV}$
- natural region with no light stops
- consistent with results obtained for $W_{NMSSM} = \lambda SH_uH_d + \hat{\mu}H_uH_d + \frac{M}{2}S^2$ [Hall, Pinner, Ruderman (2011)]

What is light? – Higgs sector



- one CP odd Higgs < 500 GeV</p>
- ullet at least one CP even Higgs $\lesssim 1\,{
 m TeV}$
- $b
 ightarrow s \gamma$ will constrain light charged Higgs mass, but it is already mostly above 400 GeV

What is light? – Neutralino-Chargino sector



several light neutralinos (< 1 TeV)
 lightest chargino m_{\chi_1}[±] < 700 GeV

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- ⇒ Testing the whole parameter space of natural SUSY at the LHC not easy

Thank you very much for your attention.