

Whither[†] SUSY?

G. Ross, Birmingham, January 2013



†

whither *Archaic or poetic*
adv

1. to what place?
2. to what end or purpose?

conj

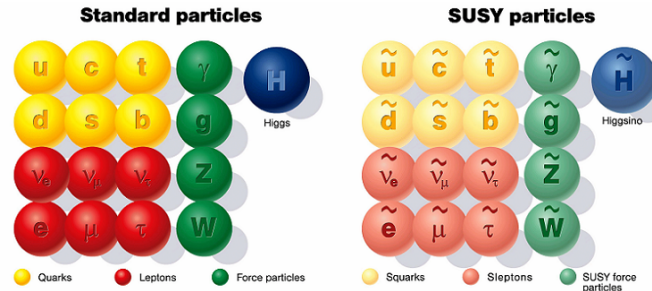
to whatever place, purpose, etc.

[Old English *hwider*, *hwæder*; related to Gothic *hvadrē*; modern English form influenced by HITHER]

Low energy

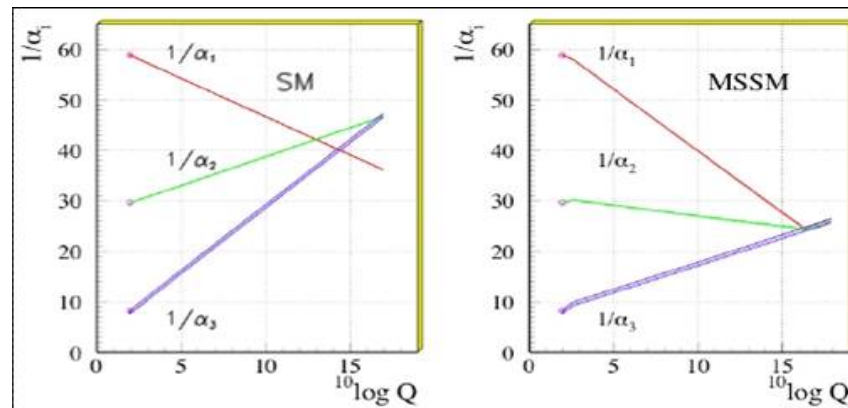
SUSY - to what end or purpose?

^



Unification:

SU(5), SO(10),...



✓

The hierarchy problem:

$$M_{Higgs}, M_{W,Z} \ll M_{Planck}, M_{GUT}, \dots$$

✓

(?)

ATLAS

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)

Search Category	Search Description	Lower Limit	Notes
Inclusive searches	MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-033]	1.40 TeV $\tilde{q} = \tilde{g}$ mass
	MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-041]	1.20 TeV $\tilde{q} = \tilde{g}$ mass
	MSUGRA/CMSSM : 0 lep + multijets + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1206.1760]	840 GeV \tilde{g} mass (large m_0)
	Pheno model : 0 lep + j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-033]	1.38 TeV \tilde{q} mass ($m(\tilde{g}) < 2 \text{ TeV}$, light $\tilde{\chi}_1^0$)
	Pheno model : 0 lep + j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-033]	940 GeV \tilde{g} mass ($m(\tilde{g}) < 2 \text{ TeV}$, light $\tilde{\chi}_1^0$)
	Gluino med. $\tilde{\chi}^\pm (\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}^\pm)$: 1 lep + j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-041]	900 GeV \tilde{g} mass ($m(\tilde{\chi}_1^0) < 200 \text{ GeV}$, $m(\tilde{\chi}^\pm) = \frac{1}{2}(m(\tilde{\chi}_1^0) + m(\tilde{g}))$)
	GMSB : 2 lep OSSF + $E_{T,miss}$	$L=1.0 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2011-156]	810 GeV \tilde{g} mass ($\tan\beta < 35$)
	GMSB : 1- τ + j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1204.3852]	920 GeV \tilde{g} mass ($\tan\beta > 20$)
	GMSB : 2- τ + j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1203.6580]	990 GeV \tilde{g} mass
	GGM : $\gamma\gamma$ + $E_{T,miss}$	$L=4.8 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-072]	1.07 TeV \tilde{g} mass
3rd gen. squarks gluino mediated	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ (virtual \tilde{b}) : 0 lep + 1/2 b-j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1203.6193]	900 GeV \tilde{g} mass
	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ (virtual \tilde{b}) : 0 lep + 3 b-j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-058]	1.02 TeV \tilde{g} mass
	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ (real \tilde{b}) : 0 lep + 3 b-j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-058]	1.00 TeV \tilde{g} mass
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ (virtual \tilde{t}) : 1 lep + 1/2 b-j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1203.6193]	710 GeV \tilde{g} mass
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ (virtual \tilde{t}) : 2 lep (SS) + j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1203.5763]	650 GeV \tilde{g} mass
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ (virtual \tilde{t}) : 0 lep + multi-j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1206.1760]	870 GeV \tilde{g} mass
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ (virtual \tilde{t}) : 0 lep + 3 b-j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-058]	940 GeV \tilde{g} mass
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$ (real \tilde{t}) : 0 lep + 3 b-j's + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-058]	820 GeV \tilde{g} mass
	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$ (real \tilde{b}) : 0 lep + 3 b-j's + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1112.3832]	390 GeV \tilde{b} mass ($m(\tilde{\chi}_1^0) = 0 \text{ GeV}$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (very light) : 2 lep + b-jet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-059]	135 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 45 \text{ GeV}$)
3rd gen. squarks direct production	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (heavy) : 1/2 lep + b-jet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-070]	120-173 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 45 \text{ GeV}$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (heavy) : 0 lep + b-jet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-074]	380-465 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 0$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (heavy) : 1 lep + b-jet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-073]	230-440 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 0$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (heavy) : 2 lep + b-jet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-071]	298-305 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 0$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$ (GMSB) : Z($\rightarrow ll$) + b-jet + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1204.6736]	310 GeV \tilde{t} mass ($115 < m(\tilde{\chi}_1^0) < 230 \text{ GeV}$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$: 2 lep + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-076]	93-180 GeV \tilde{t} mass ($m(\tilde{\chi}_1^0) = 0$)
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$: 2 lep + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-076]	120-330 GeV \tilde{t} mass
	$\tilde{t} \rightarrow b\tilde{t}\tilde{\chi}_1^0$: 3 lep + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-077]	118 GeV \tilde{t} mass
	AMS \tilde{b} : long-lived $\tilde{\chi}_1^0$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [CONF-2012-034]	118 GeV $\tilde{\chi}_1^0$ mass
	Stable \tilde{g} R-hadrons : Full detector	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-075]	
Long-lived particles	Stable \tilde{b} R-hadrons : Full detector	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-075]	
	Stable \tilde{t} R-hadrons : Full detector	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-075]	
	Metastable \tilde{g} R-hadrons : Pixel det. only	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-075]	
	GMSB : stable $\tilde{\tau}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-075]	310 GeV $\tilde{\tau}$ mass ($5 < \tan\beta < 10$)
	RPV : high-mass $e\mu$	$L=1.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [1109.3089]	1.32 TeV $\tilde{\nu}_\tau$ mass ($\lambda_{311}=0.10, \lambda_{312}=0.05$)
RPV	Bilinear RPV : 1 lep + j's + $E_{T,miss}$	$L=1.0 \text{ fb}^{-1}, 7 \text{ TeV}$ [1109.6606]	760 GeV $\tilde{q} = \tilde{g}$ mass ($c\tau_{LSP} < 15 \text{ mm}$)
	BC1 RPV : 4 lep + $E_{T,miss}$	$L=2.1 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-035]	1.7 TeV \tilde{g} mass
Other	Hypercolour scalar gluons : 4 jets, $m_g = m_{kl}$	$L=34 \text{ pb}^{-1}, 7 \text{ TeV}$ [1110.2693]	100-185 GeV scalar mass (not excluded, $m_g = 140 \pm 3 \text{ GeV}$)
	Spin dep. WIMP interaction : monojet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-084]	709 GeV M^* scale ($m_\chi < 100 \text{ GeV}$, vector D5, Dirac χ)
	Spin indep. WIMP interaction : monojet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CONF-2012-084]	548 GeV M^* scale ($m_\chi < 100 \text{ GeV}$, tensor D9, Dirac χ)

$\int L dt = (0.03 - 4.8) \text{ fb}^{-1}$
 $\sqrt{s} = 7 \text{ TeV}$

ATLAS
Preliminary

Limit 1 TeV strong interacting particles

Limit 300-400 GeV stop particles

And limits on WEAK INTERACTIONS

Mass scale [TeV]

*Only a selection of the available searches

SUSY - to what place?

Little hierarchy problem

MSSM: 105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q}, \tilde{l}} a_i \tilde{m}_i^2 + \sum_{\tilde{g}, \tilde{W}, \tilde{B}} \tilde{M}_i^2 + \dots$$

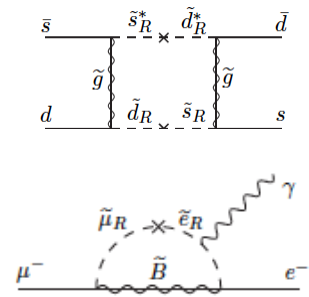
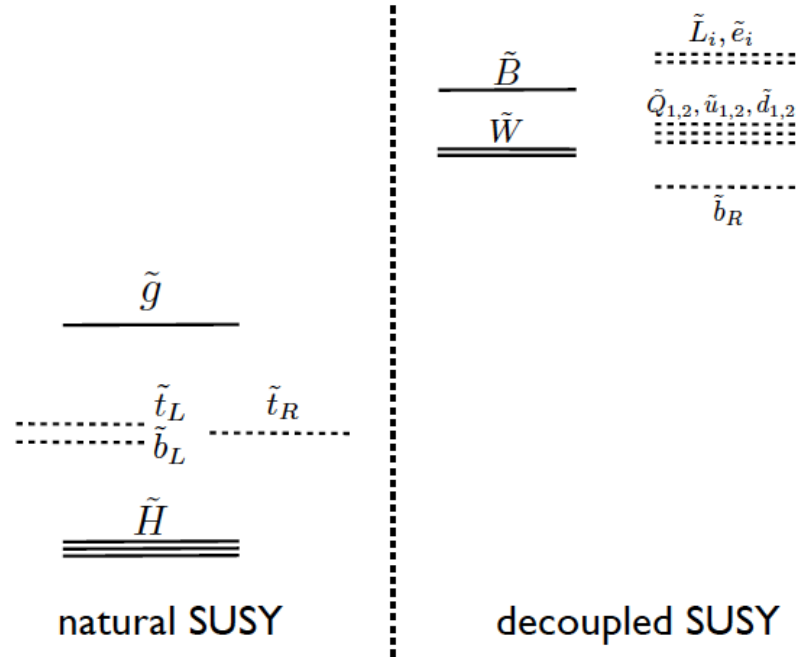
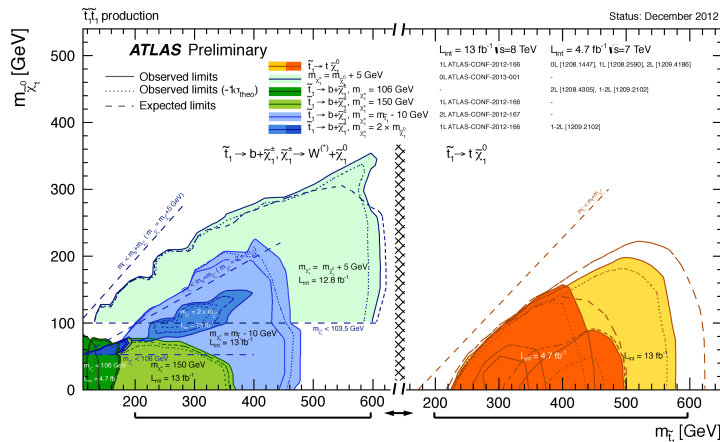
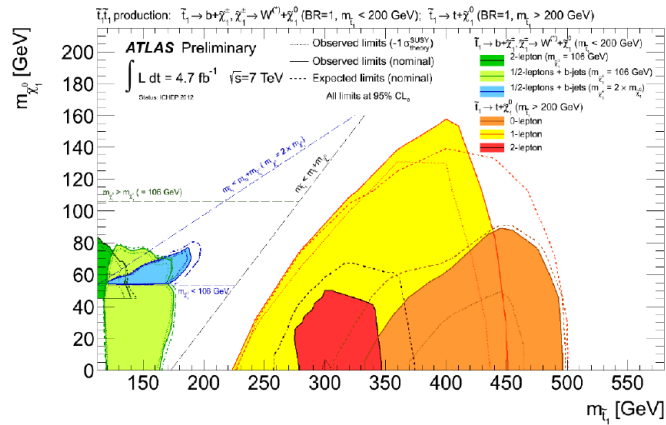
$$m_{\tilde{q}} > 0.6 - 1 \text{TeV} \Rightarrow \Delta > a \frac{\tilde{m}^2}{M_Z^2} \sim 100$$

An exception: "Natural" SUSY

light stop $m_{\tilde{t},LHC} > 250 \text{ GeV}$

FCNC: 1,2 sgenerations heavy

Hierarchy problem: 3rd sgeneration light

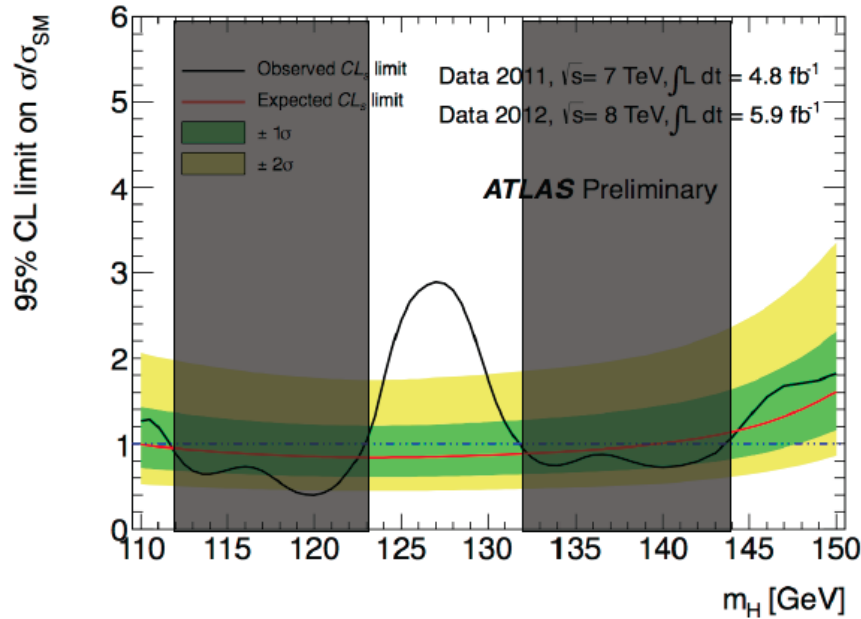


The Higgs mass in SUSY ?

$$M_S^2 = m_{q_3} m_{U_3} \geq (900 \text{ GeV})^2$$

$$M_{h^0}^2 = M_Z^2 \cos^2 2\beta + \frac{3M_t^2 h_t^2}{4\pi^2} \left(\ln\left(\frac{M_S^2}{M_t^2}\right) + \delta_t \right) + \dots \approx 125 \text{ GeV (LHC)}$$

Atlas

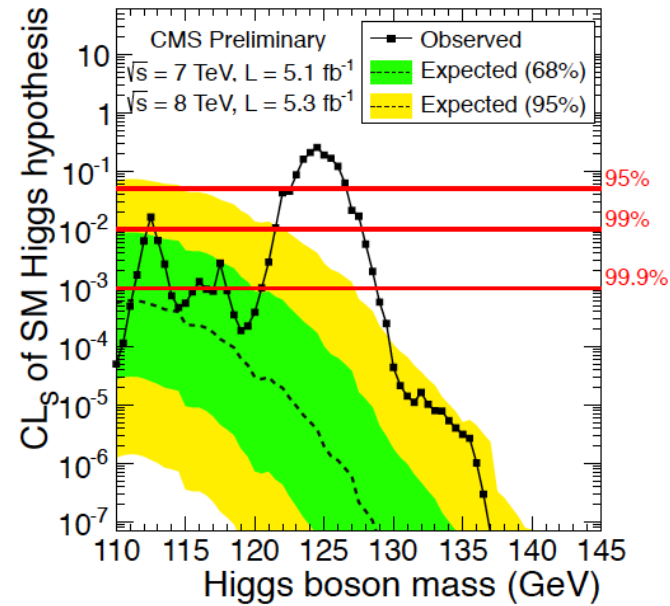


$126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst) GeV}$
at
5σ significance

CMS

- LHC July 2012

Zoomed mass range



125.3 ± 0.6 GeV
at
4.9σ significance!

SUSY - to what place?

Little hierarchy problem \Rightarrow definite SUSY structure ^{breaking}
^

MSSM: 105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q}, \tilde{l}} a_i \tilde{m}_i^2 + \sum_{\tilde{g}, \tilde{W}, \tilde{B}} \tilde{M}_i^2 + \dots$$

$$m_{\tilde{q}} > 0.6 - 1 \text{TeV} \Rightarrow \Delta > a \frac{\tilde{m}^2}{M_Z^2} \sim 100$$

\Rightarrow Correlations between SUSY breaking parameters
and/or additional low-scale states

SUSY searches - significance

SUSY parameters

$$L(\text{data}|\gamma_i^0) = \frac{1}{\Delta_q} L(\text{data}|\gamma_i; v_0, \beta, \tilde{y}_t(\beta), \tilde{y}_b(\beta)) \Big|_{\beta=\beta_0(\gamma_i); \gamma_i=\gamma_i^0}$$

Likelihood

$$\delta \left(v_0 - \left(-\frac{m^2(\gamma_i)}{\lambda(\gamma_i)} \right)^{1/2} \right)$$

Ghilencea, GGr

$$\Delta_q = \left(\sum_i \left| \frac{\gamma_i}{M_Z} \frac{\partial M_Z}{\partial \gamma_i} \right|^2 \right)^{1/2}$$

Fine tuning measure

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

$$\Delta_q = 100, \quad \delta\chi^2 \sim 9, \quad \delta\chi^2 / d.o.f. \sim 1$$

Outline

I. The CMSSM

Scalar focus point

II. Reduced fine tuning

(G)NMSSM

Gaugino focus point

Natural SUSY

R-parity breaking

Supersoft SUSY breaking

Compressed spectrum

III. Implications of 125 GeV Higgs

I. The CMSSM

$$\mu_0, m_0, m_{1/2}, A_0, B_0$$

assume correlation between SUSY breaking parameters

$$\Delta \equiv \max |\Delta_p|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \quad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

$$v^2 = \frac{m^2}{\lambda}$$

Couplings and masses evaluated to two loop (leading log) order

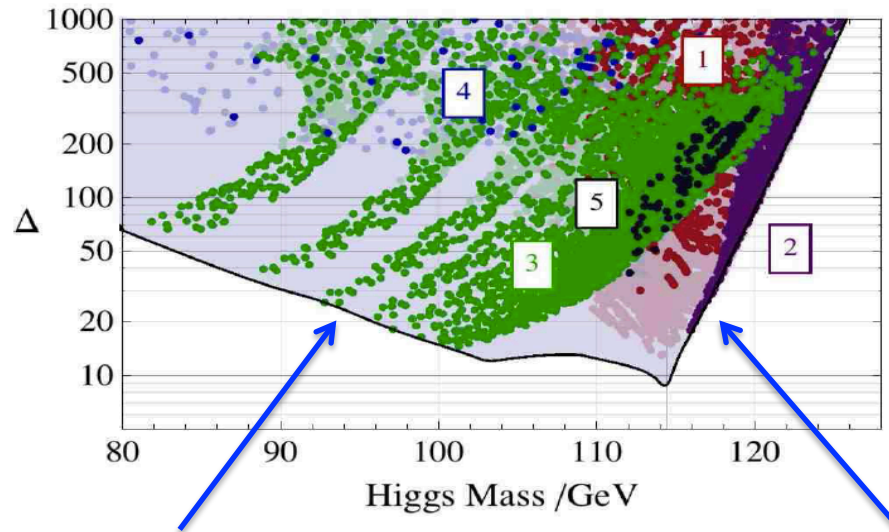
...enhanced sensitivity due to small tree-level $\lambda = \frac{1}{8}(g_1^2 + g_2^2)\cos^2 2\beta$

Cassel, Ghilencea, GGR
c.f. earlier work : Dimopoulos, Giudice
Chankowski, Ellis, Olechowski, Pokorski

e.g. CMSSM

$$\gamma_i \equiv \mu_0, m_0, m_{1/2}, A_0, B_0$$

Pre-LHC



Relic density restricted

- 1 h^0 resonant annihilation
- 2 \tilde{h} t-channel exchange
- 3 $\tilde{\tau}$ co-annihilation
- 4 \tilde{t} co-annihilation
- 5 A^0 / H^0 resonant annihilation

Within 3σ WMAP:

$$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$$

< 3σ WMAP:

$$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$$

Cassel, Ghilencea, GGR

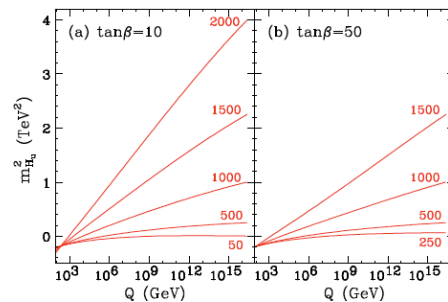
λ increases with m_H

$$v^2 = \frac{m^2}{\lambda}$$

Limit of RGE focus point

-natural cancellation of terms for

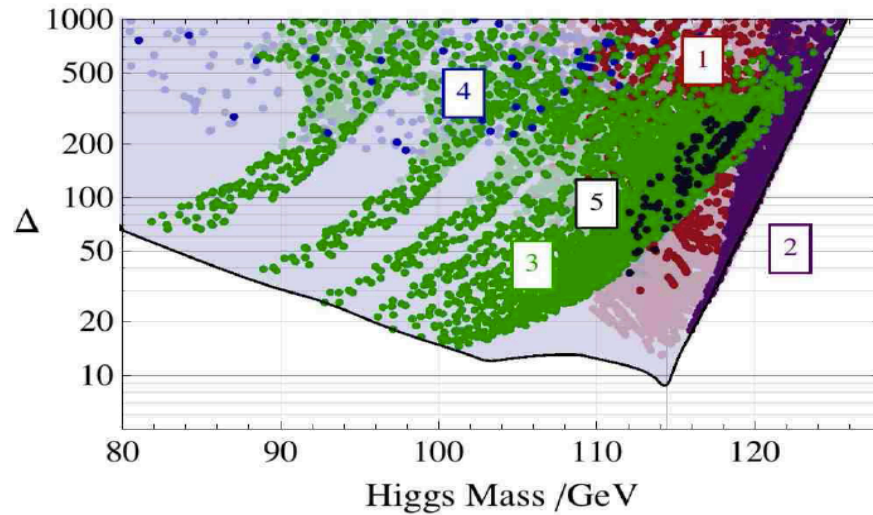
$$m_{H_u}^2(M_X) = m_{\tilde{t}_R}^2(M_X) = m_{\tilde{t}_L}^2(M_X) = m_0$$



$$m_{H_u}^2(Q^2) = m_{H_u}^2(M_P^2) + \frac{1}{2} \left(m_{H_u}^2(M_P^2) + m_{Q_3}^2(M_P^2) + m_{u_3}^2(M_P^2) \right) \left[\left(\frac{Q^2}{M_P^2} \right)^{\frac{3y_t^2}{4\pi^2}} - 1 \right]$$

e.g. CMSSM

$$\gamma_i \equiv \mu_0, m_0, m_{1/2}, A_0, B_0$$



Relic density restricted

- 1 h^0 resonant annihilation
- 2 \tilde{h} t-channel exchange
- 3 $\tilde{\tau}$ co-annihilation
- 4 \tilde{t} co-annihilation
- 5 A^0 / H^0 resonant annihilation

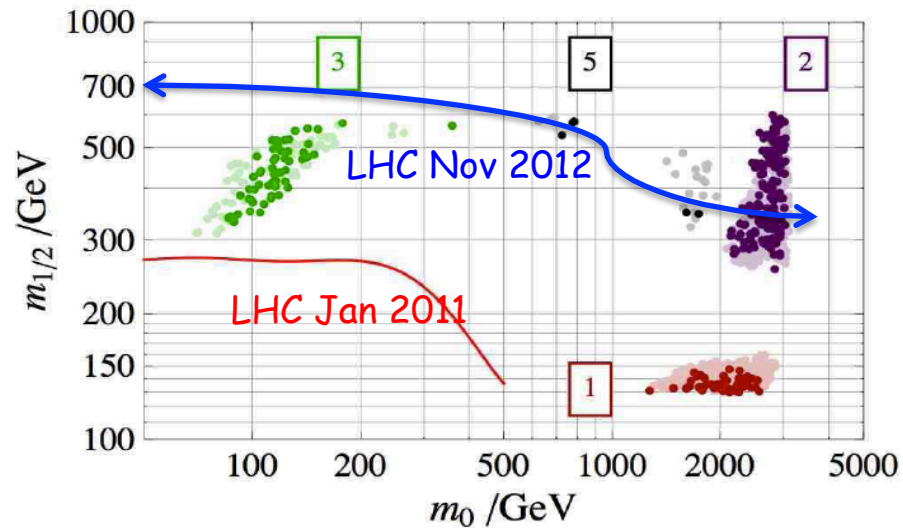
Within 3σ WMAP:

$$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$$

< 3σ WMAP:

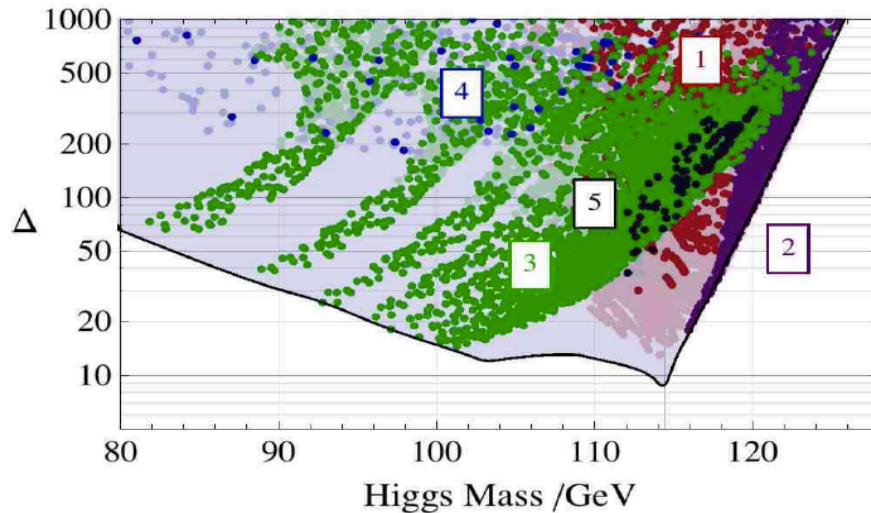
$$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$$

Direct SUSY searches:



e.g. CMSSM

$$\gamma_i \equiv \mu_0, m_0, m_{1/2}, A_0, B_0$$



Relic density restricted

- 1 h^0 resonant annihilation
- 2 \tilde{h} t-channel exchange
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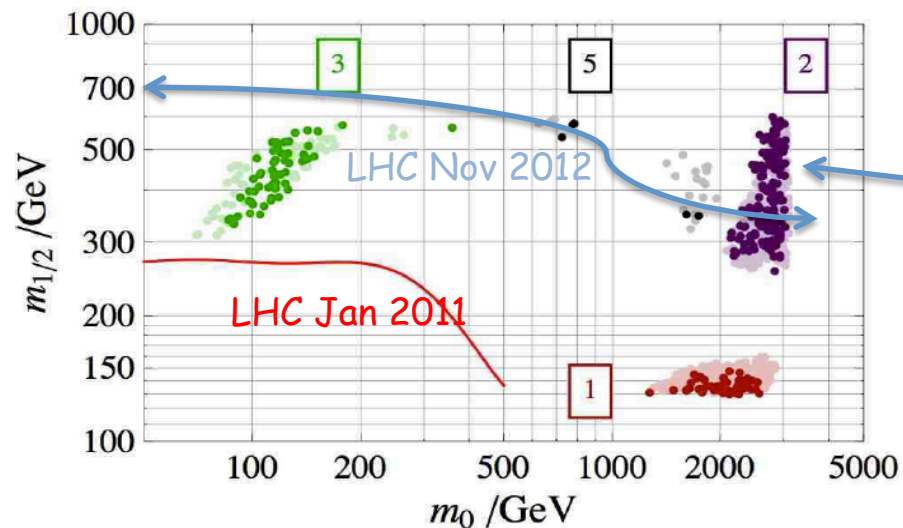
Within 3σ WMAP:

$$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$$

< 3σ WMAP:

$$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$$

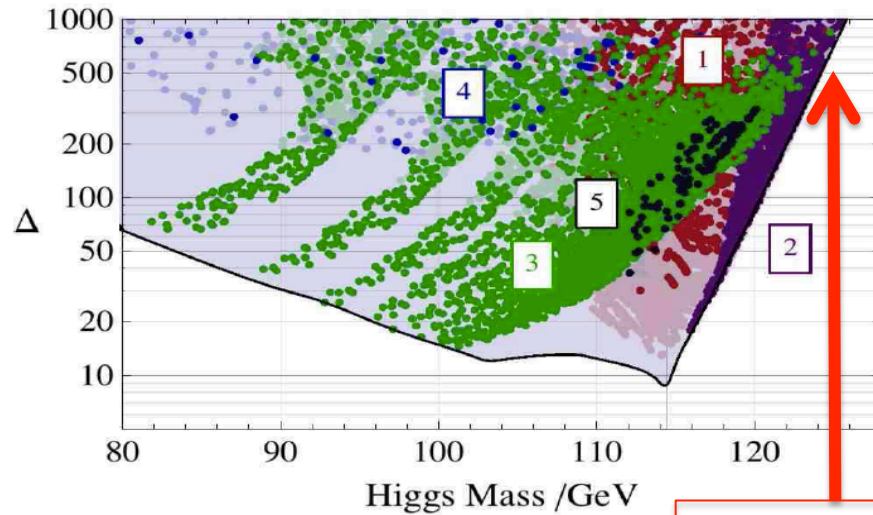
Direct SUSY searches:



Significant Higgsino LSP component
-now excluded by XENON 100

e.g. CMSSM

$$\gamma_i \equiv \mu_0, m_0, m_{1/2}, A_0, B_0$$



$$m_H > 125 \text{ GeV}$$

$$\Delta > 300$$

Relic density restricted

- 1 h^0 resonant annihilation
- 2 \tilde{h} t-channel exchange
- 3 $\tilde{\tau}$ co-annihilation
- 4 \tilde{t} co-annihilation
- 5 A^0 / H^0 resonant annihilation

Within 3σ WMAP:

$$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 \text{ GeV}$$

$< 3\sigma$ WMAP:

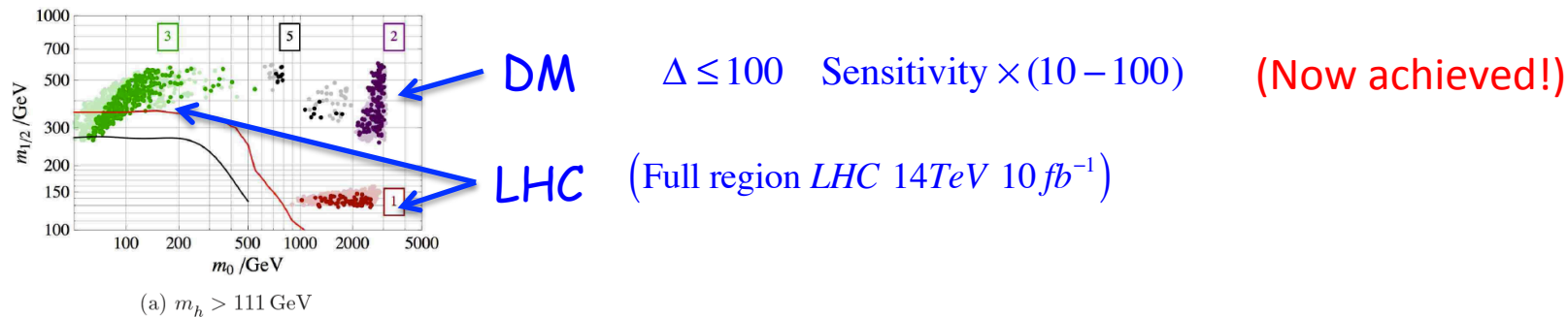
$$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 \text{ GeV}$$

CMSSM summary:

- Minimises MSSM fine tuning (focus point) (c.f. gauge mediation $\Delta \gg \Delta_{CMSSM}$)

$$\text{Max}[\Delta_{EW}, \Delta_{\Omega}] = 15(29), \quad m_h = 114(116) \pm 2 \text{ GeV}$$

- Complementary DM & LHC searches



- **BUT** $\Delta > 300$ for $m_H = 126 \text{ GeV}$

(If give up on unification of soft parameters fine tuning reduced by factor ~ 10)

II. Reduced fine tuning :

...more correlations between parameters...later

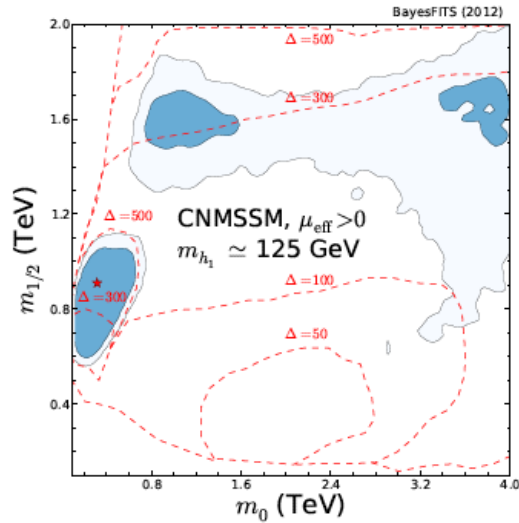
...beyond the MSSM

e.g. singlet extensions - the NMSSM

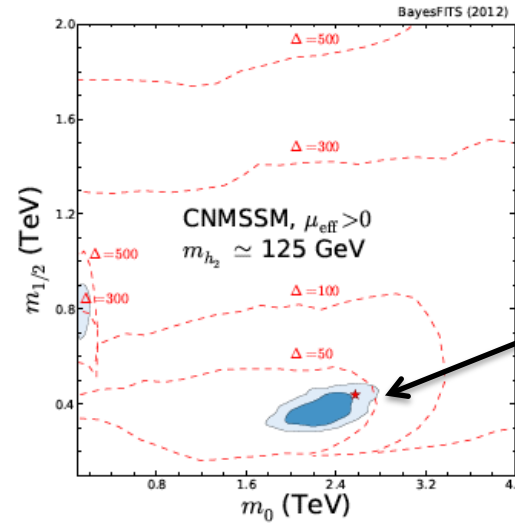
$$W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

Additional quartic interaction $\delta V = |\lambda H_u H_d|^2$

Fine tuning in the NMSSM $(\lambda \leq 0.7^\dagger)$

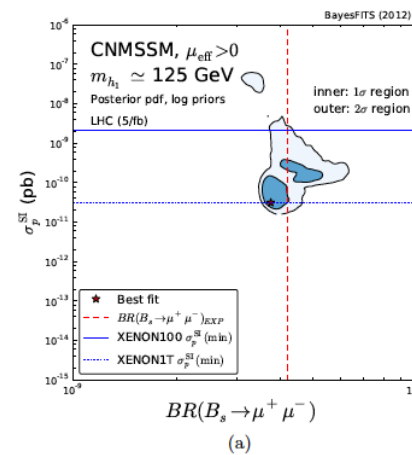
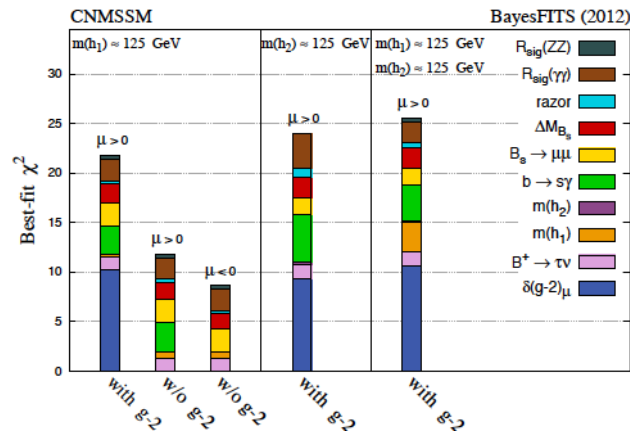


(a)

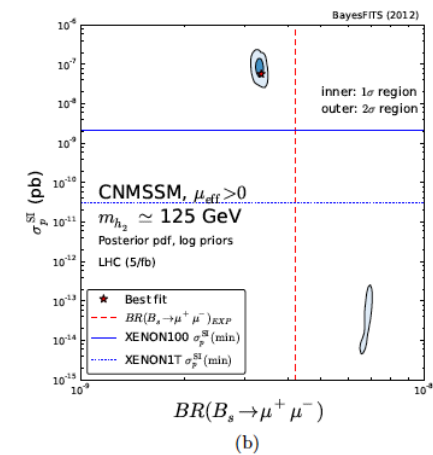


(b)

(Δ_{h_i} not included)



(a)

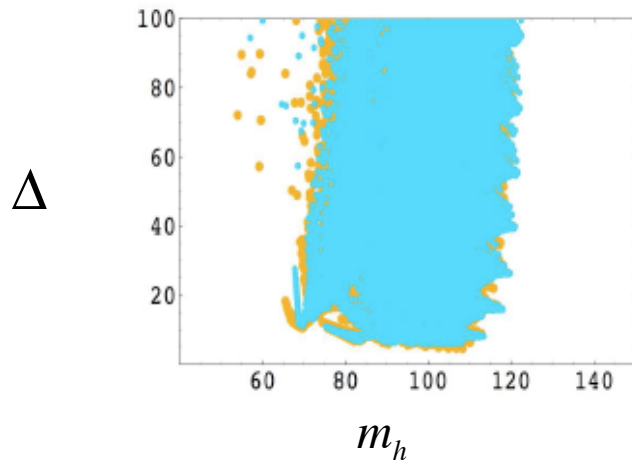


(b)

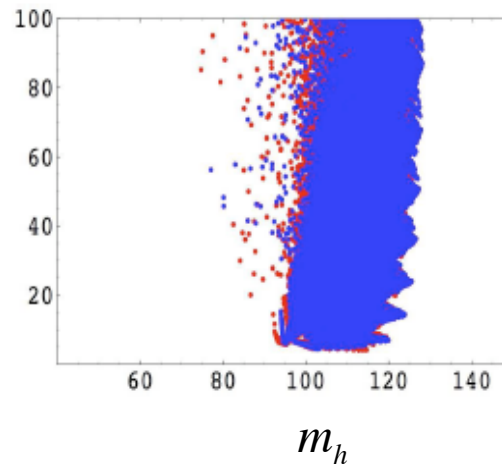
Reduced fine tuning : BMSSM - General Operator analysis

$$\delta L = \int d^2\theta \frac{1}{M_*} (\mu_0 + c_0 S) (H_1 H_2)^2, \quad S = m_0 \theta\theta \quad \text{Dimension 5}$$

$$\delta V = \varsigma_1 (|h_1|^2 + |h_2|^2) h_1 h_2 + \varsigma_2 (h_1 h_2)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \quad \varsigma_2 = \frac{c_0 m_0}{M_*}$$



MSSM



+ dim 5 operators

Cassel, Ghilencea, GGR
 Casas, Espinosa, Hidalgo
 Dine, Seiberg, Thomas
 Batra, Delgado, Tait
 Kaplan,

...effect mainly comes from $\varsigma_1 |h_1|^2 h_1 h_2$ term ... origin?

Reduced fine tuning : singlet extensions

$$W = W_{\text{Yukawa}} + (\mu + \lambda S)H_u H_d + \frac{\mu S}{2}S^2 + \frac{\kappa}{3}S^3 + \xi S \quad \text{GNMSSM}$$

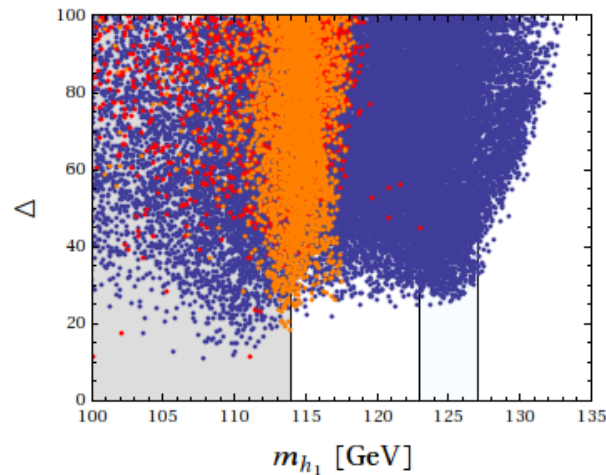
$$\mu_s \gg m_{3/2}$$

$$\text{c.f. } W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3}S^3 \quad \text{NMSSM}$$

$$W_{\text{eff}}^{\text{GNMSSM}} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$$

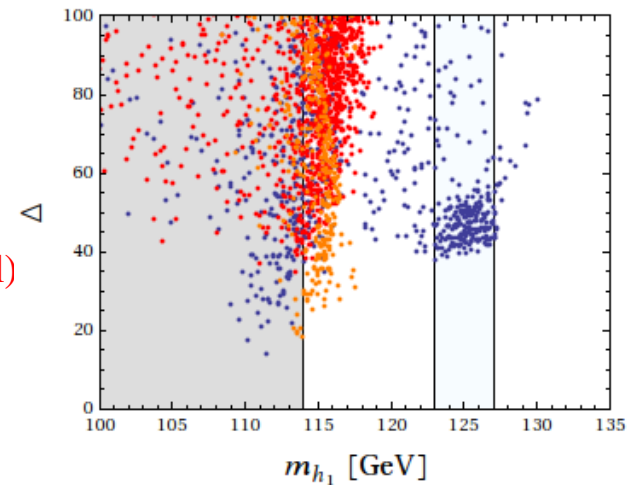
$$\frac{\mu}{\mu_s} (|H_u|^2 + |H_d|^2) H_u H_d \quad \rightarrow \quad v^2 = -\frac{m^2}{\lambda}$$

Reduced fine tuning mainly for GNMSSM



- CMSSM
- CGNMSSM
- CNMSSM
(Higgs not universal)

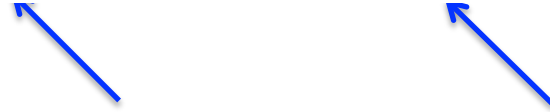
LHC constraints
applied



LHC + DM constraints
applied

GNMSSM

$$W = W_{\text{Yukawa}} + (\mu + \lambda S)H_u H_d + \frac{\mu S}{2}S^2 + \frac{\kappa}{3}S^3 + \xi S$$



R-symmetry ensures Singlet extensions natural

GNMSSM

$$W = W_{\text{Yukawa}} + (\mu + \lambda S)H_u H_d + \frac{\mu S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$$

NMSSM spectrum
 No perturbative μ term
 Commutes with $SO(10)$
 Anomaly cancellation

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_S
4	1	1	0	0	2
8	1	5	0	4	6

R-symmetry ensures singlets light

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \pmod{N} \Rightarrow 3q_{10} + q_{\bar{5}} = 0 \pmod{N} \Rightarrow \frac{1}{M} \cancel{QQQL} \quad \frac{1}{M} LLH_u H_u$$

Weinberg operator

SUSY breaking

$\langle W \rangle, \langle \lambda \lambda \rangle$ R=2 non-perturbative breaking

$$Z_{4,8}^R \rightarrow Z_2^R \quad R\text{-parity}$$

Domain walls and tadpoles safe Abel

$$\mu \sim m_{3/2}, \quad O\left(\frac{m_{3/2}}{M^2} QQQL\right)$$

$$W = W_{MSSM} + \lambda S H_u H_d + \kappa S^3 + \Delta W$$

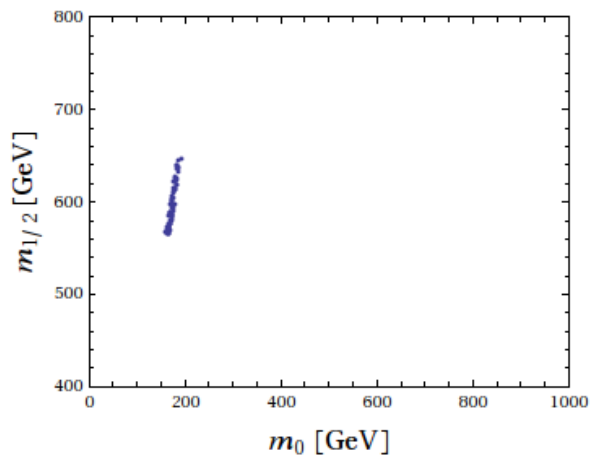
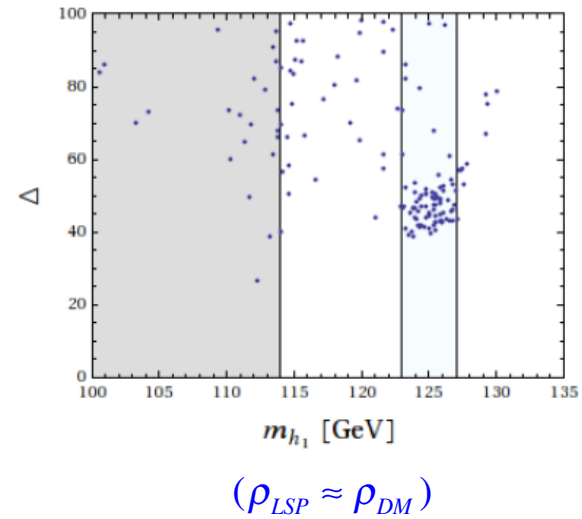
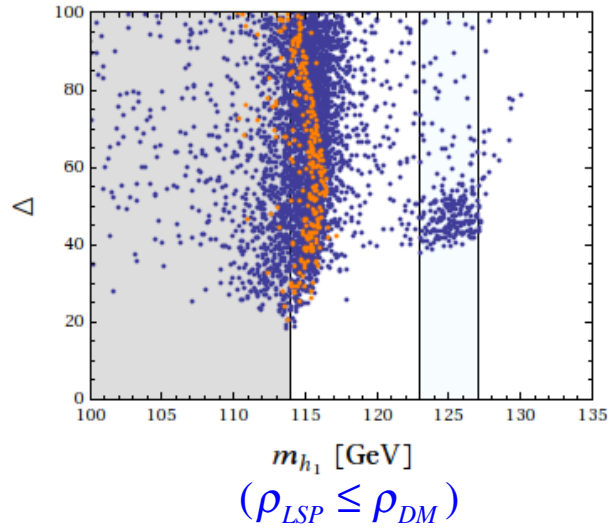
$$\Delta W_{Z_4^R} \sim m_{3/2} H_u H_d + m_{3/2}^2 S + m_{3/2} S^2$$

$$\Delta W_{Z_8^R} \sim m_{3/2}^2 S$$

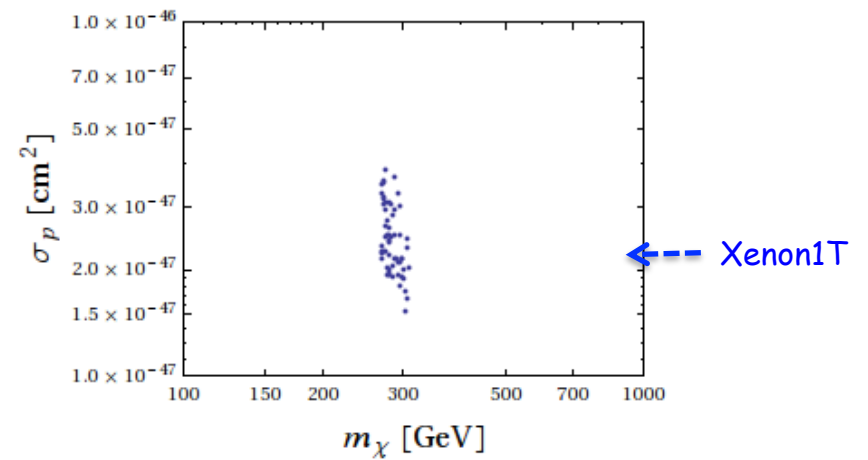
← μ term and mass terms “natural”
 GNMSSM (c.f. NMSSM)

GENERAL-NMSSM PHENOMENOLOGY

Dark Matter structure



Stau co-annihilation



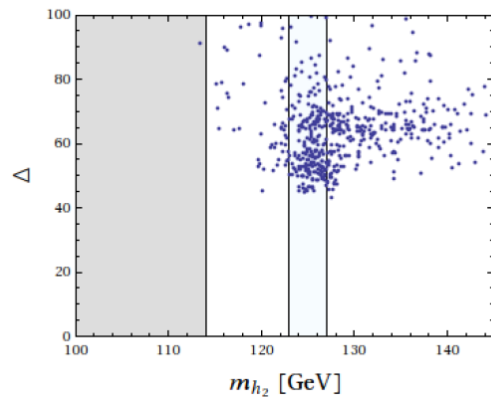
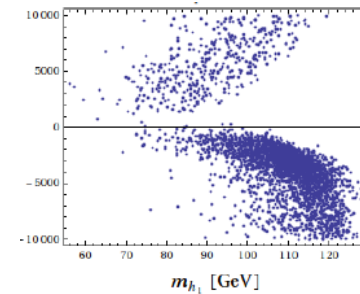
DM searches insensitive

GENERAL-NMSSM PHENOMENOLOGY

Higgs structure (h_u, h_d, s)

- $\mu_s \gg \mu$ MSSM SUSY structure with heavy Higgs
- $\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_{u,d} + \epsilon S, \quad h_2 = S - \epsilon H_{u,d}$

... h_2 may be lighter than LEP bound



$m_{h_1} \ll \Delta$ for the case $m_{h_2} < m_{h_1}$

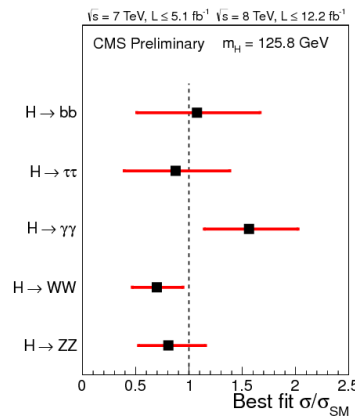
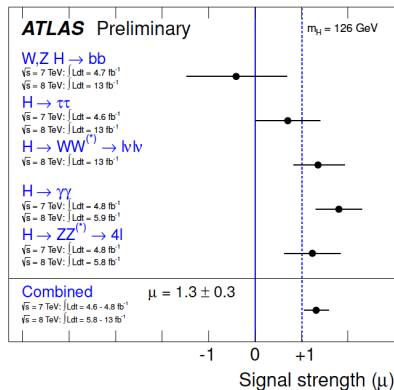
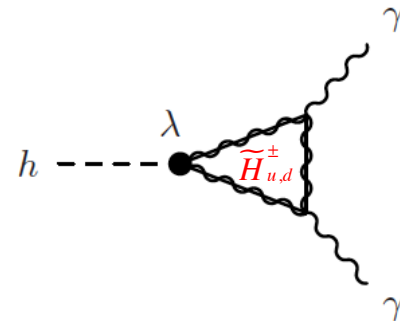
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... h_1 may have enhanced $\gamma\gamma$ rate



GENERAL-NMSSM PHENOMENOLOGY

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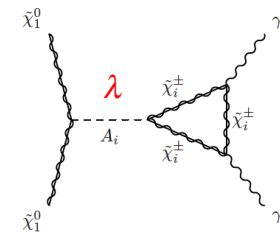
... h_2 may be lighter than LEP bound

... h_1 may have enhanced $\gamma\gamma$ rate

... h_1 may have enhanced LSP annihilation rate to photons..?

$$\langle\sigma v\rangle_{\gamma\gamma} \simeq (6 \cdot 10^{-28} \text{ cm}^3 \text{ s}^{-1}) \cdot \lambda^2 \kappa^2 \left(\frac{(100 \text{ GeV})^2}{4 m_{\tilde{\chi}_1^0}^2 - m_{A_1}^2} \right)^2 \left(\frac{m_{\tilde{\chi}_1^0}}{130 \text{ GeV}} \right)^2$$

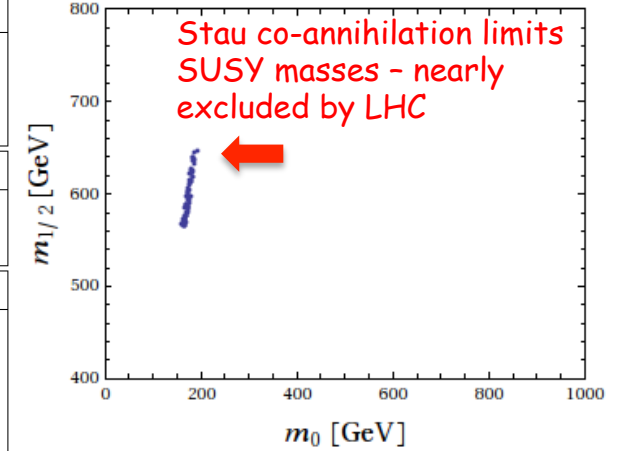
Fermi 135GeV line : $\lambda, \kappa \leq 1, \quad m_{A_1} \simeq 240 - 280 \text{ GeV}$



Input			
$\tan\beta$	1.2	v_s [GeV]	-4.0
λ	0.74	A_λ [GeV]	0
κ	1.4	A_κ [GeV]	0
μ_s [GeV]	103.0	b_s [GeV ²]	$3.356 \cdot 10^5$
μ [GeV]	208.0	$b\mu$ [GeV ²]	$2.4 \cdot 10^5$
M_1 [GeV]	1500.0	M_2 [GeV]	193.0
M_3 [GeV]	1500.0	m_{scalar} [GeV]	1500.0
$A_{top}Y_{top}$ [GeV]	1500.0	ξ_S [GeV ³]	0.0
CP even Higgs sector			
m_{h_1} [GeV]	125.7	down fraction h_1	41.5%
m_{h_2} [GeV]	690.1	up fraction h_1	57.8%
m_{h_3} [GeV]	786.8	singlet fraction h_1	0.7%
CP odd Higgs sector			
m_{A_1} [GeV]	247.5	singlet fraction A_1	99.9%
m_{A_2} [GeV]	691.9	up and down fraction A_1	0.1%
Neutralino sector			
$\tilde{\chi}_1^0$ [GeV]	130.0	bino fraction $\tilde{\chi}_1^0$	<0.1%
$\tilde{\chi}_2^0$ [GeV]	156.4	wino fraction $\tilde{\chi}_1^0$	5.1%
$\tilde{\chi}_3^0$ [GeV]	316.2	down-higgsino fraction $\tilde{\chi}_1^0$	0.3%
$\tilde{\chi}_4^0$ [GeV]	331.6	up-higgsino fraction $\tilde{\chi}_1^0$	10.0%
$\tilde{\chi}_5^0$ [GeV]	1497.4	singlet fraction $\tilde{\chi}_1^0$	84.5%
Chargino sector			
$\tilde{\chi}_1^+$ [GeV]	154.8	wino fraction $\tilde{\chi}_1^+$	70.6%
$\tilde{\chi}_2^+$ [GeV]	332.6	higgsino fraction $\tilde{\chi}_1^+$	29.4%
Electroweak observables			
$R_{\gamma\gamma}$	1.2	$R_{b\bar{b}}$	1.0
R_{ZZ}	1.0	$R_{\tau\bar{\tau}}$	1.0
$\text{Br}(b \rightarrow s\gamma)$	$3.4 \cdot 10^{-4}$	$\text{Br}(B_s \rightarrow \mu\mu)$	$3.7 \cdot 10^{-9}$
Δa_μ	$-1.2 \cdot 10^{-11}$	$\delta\rho$	$4.5 \cdot 10^{-5}$
Dark matter			
Ωh^2	0.1	X_{FO}	24.9
σ_p^{SI} [cm ²]	$2.2 \cdot 10^{-45}$	σ_p^{SD} [cm ²]	$3.8 \cdot 10^{-40}$
$\langle\sigma v\rangle_{\gamma\gamma}$ [cm ³ /s]	$0.83 \cdot 10^{-27}$	$\langle\sigma v\rangle_{\gamma Z}$ [cm ³ /s]	$0.79 \cdot 10^{-27}$

GNMSSM benchmark point

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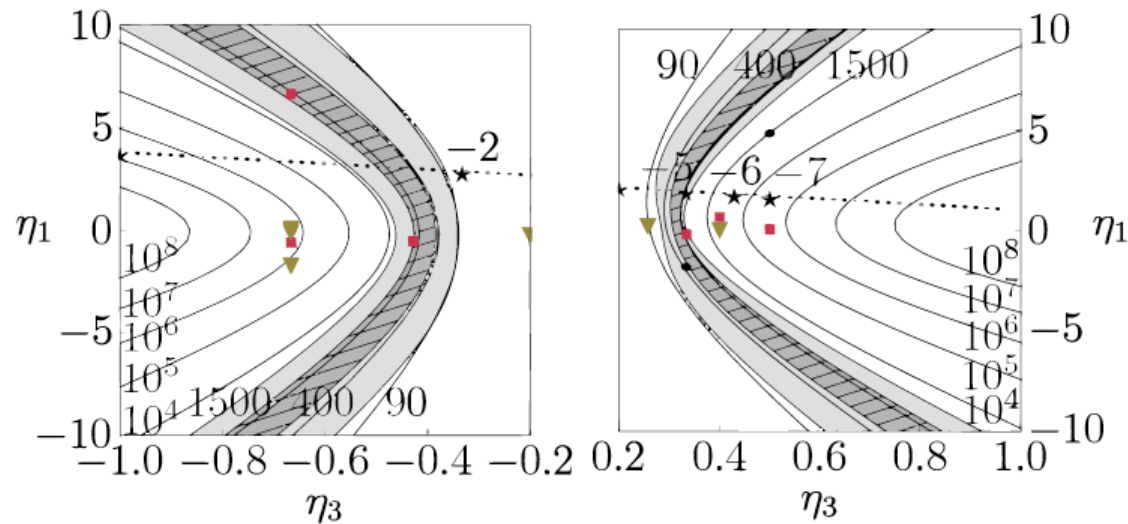


GNMSSM benchmark point

Reduced fine tuning: nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3 \left(2 |y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{u_3}^2) + 2 |a_t|^2 \right) - 6g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}



$$M_3 : M_2 : M_1 = \eta_3 : 1 : \eta_1$$

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Natural ratios? e.g.:

GUT: $SU(5): \Phi^N \subset (24 \times 24)_{\text{symm}} = 1 + 24 + 75 + 200; \quad SO(10): (45 \times 45)_{\text{symm}} = 1 + 54 + 210 + 770$

	$\eta_3 : 1 : \eta_1$	$2.7\eta_3 : 1 : 0.5\eta_1$
Representation	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

String: $(3 + \delta_{GS}) : (-1 + \delta_{GS}) : \left(-\frac{33}{5} + \delta_{GS} \right)$ (OII, also mixed moduli anomaly)

Gaugino focus point - Phenomenology

- Gaugino mass ratios

$$\frac{M_i(Q)}{M_{1/2}} = \eta_i \frac{\alpha_i(Q)}{\alpha_i(M_X)} \Rightarrow \begin{aligned} \frac{M_1(Q)}{M_2(Q)} &\approx 0.5\eta_1 \\ M_2(Q) &\approx 0.8M_{1/2} \\ \frac{M_3(Q)}{M_2(Q)} &\approx 2.7\eta_3 \end{aligned}$$

.... gauginos can be very heavy

- Light neutralino and 2 charginos nearly degenerate

$$\begin{aligned} m_{\chi_2^0} - m_{\chi_1^0} &= M_Z^2 \left(\frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) + \mathcal{O}\left(\frac{M_Z^3}{M_2^2}\right) \\ m_{\chi_1^\pm} - m_{\chi_1^0} &= \frac{1}{2}M_Z^2 \left(\frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) + \frac{1}{2}M_Z^2 \left(\frac{s_W^2}{M_1} - \frac{c_W^2}{M_2} \right) \epsilon \sin 2\beta + \mathcal{O}\left(\frac{M_Z^3}{M_2^2}\right) \end{aligned}$$

+ for $|M_1| < \mu$, Bino or Higgsino LSP candidate

Summary

- CMSSM (and other MSSMs) highly fine tuned

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- BCMSSM: more correlations or BMSSM

-(G) NMSSM Reduced $\Delta \implies$ GNMSSM $\implies Z_{4R}, Z_{8R}$
SUSY states can be (slightly) heavier
 $m_h \rightarrow 130 \text{ GeV}$

LHC bounds already severe with conventional cosmology

Summary

- CMSSM (and other MSSMs) highly fine tuned
- BCMSSM: more correlations or BMSSM
 - GNMSSM + gaugino focus point; SUSY states heavier
 - Still room for natural SUSY!
- Indirect hints... $g-2$, $h \rightarrow \gamma \gamma$, Fermi

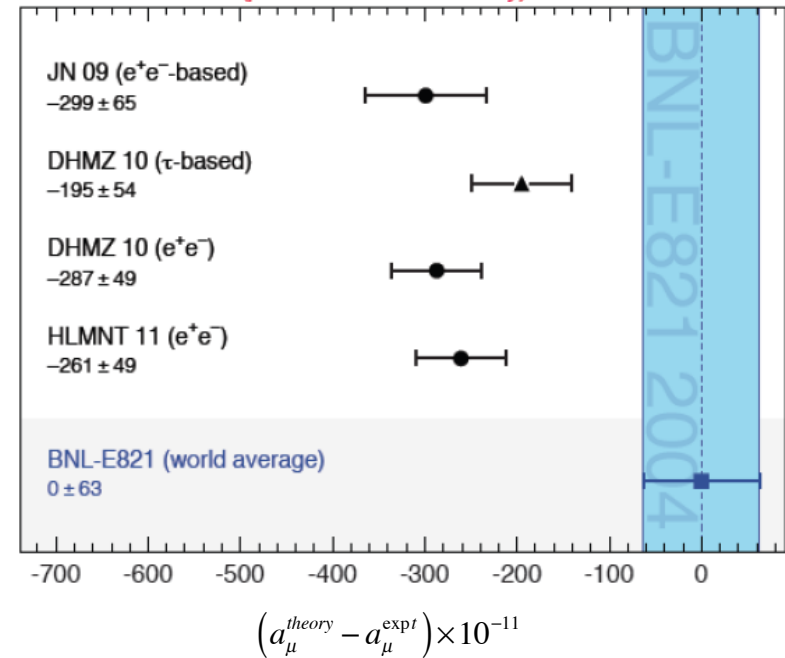
Muon $g-2$

$$a_{\mu}^{theory} - a_{\mu}^{expt} = -(28.7 \pm 8.0) \times 10^{-10}$$

Theory error from hadronic contribution:

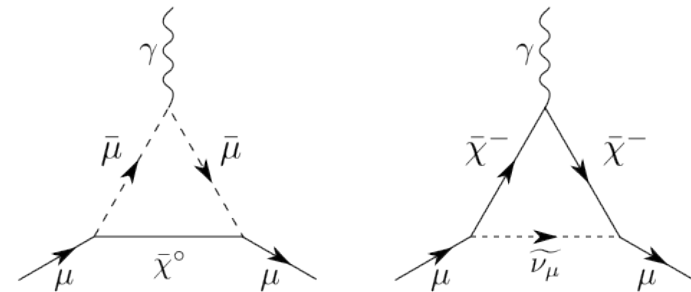
$$\delta a_{\mu}^{e^+e^-} = 3.6 \sigma$$

$$\delta a_{\mu}^{\tau} = 2.4 \sigma$$



SUSY

$$\delta a_{\mu}^{SUSY} = -13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{SUSY}} \right)^2 \tan \beta$$



Needs light sleptons - anomaly/mirage spectrum?

With slepton universality - $h \rightarrow \gamma \gamma$ plausibly correct!

Summary

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 - GNMSSM + gaugino focus point; SUSY states heavier
 - Still room for natural SUSY!
- Indirect hints... $g-2$, $h \rightarrow \gamma \gamma$, Fermi
- Hidden SUSY
 - Natural SUSY
 - R-parity breaking
 - Supersoft SUSY breaking
 - Compressed spectrum

Summary

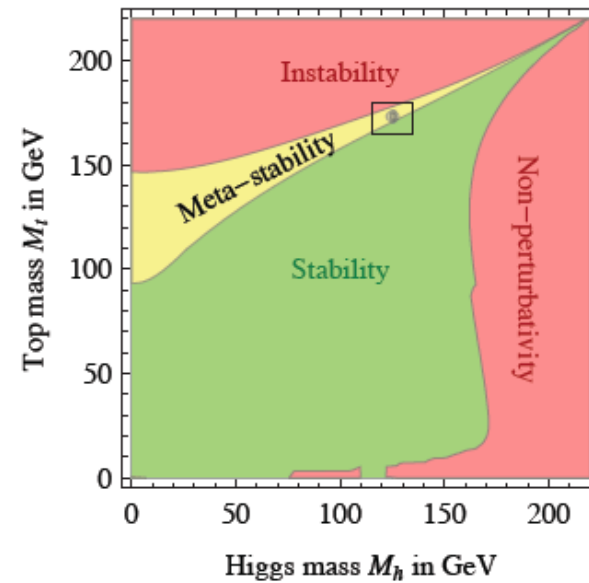
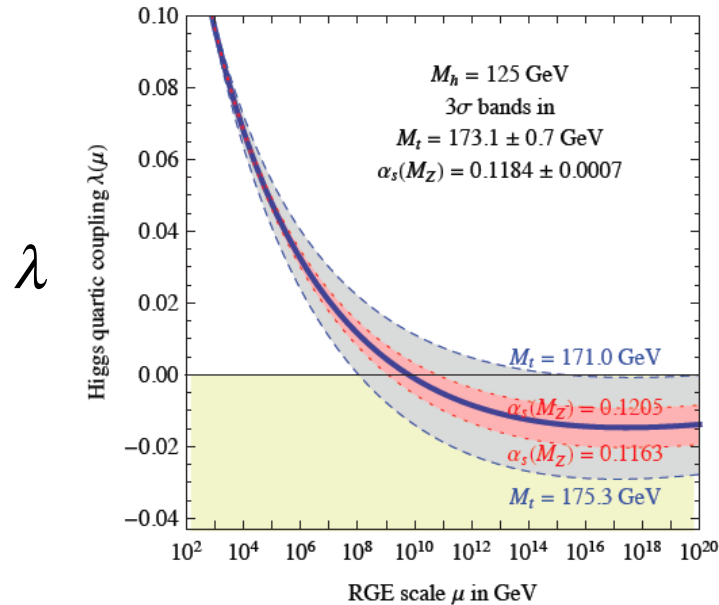
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- Hidden SUSY
- Intriguing implications of 125GeV pure SM Higgs
 - IRFP?, Higgs inflation?...

Implications of 125 GeV Higgs - vacuum instability

$$V(H) = -\frac{1}{2} M_H^2 |H|^2 + \frac{\lambda}{4} |H|^4$$

$$\text{Tunneling probability: } p = \max_R \frac{V_U}{R^4} \exp \left[-\frac{8\pi^2}{3|\lambda(\mu)|} - \Delta S \right]$$

Isidori, Ridolfi, Strumia



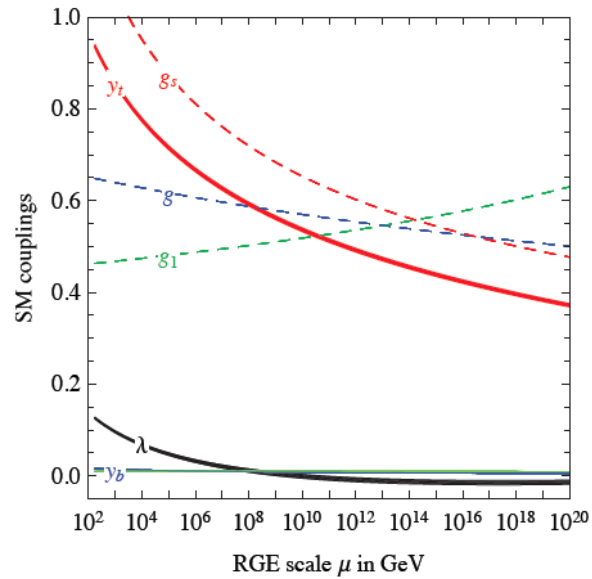
$$M_h \text{ [GeV]} > 129.4 + 1.4 \left(\frac{M_t \text{ [GeV]} - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$

$$M_h > 129.4 \pm 1.8 \text{ GeV.}$$

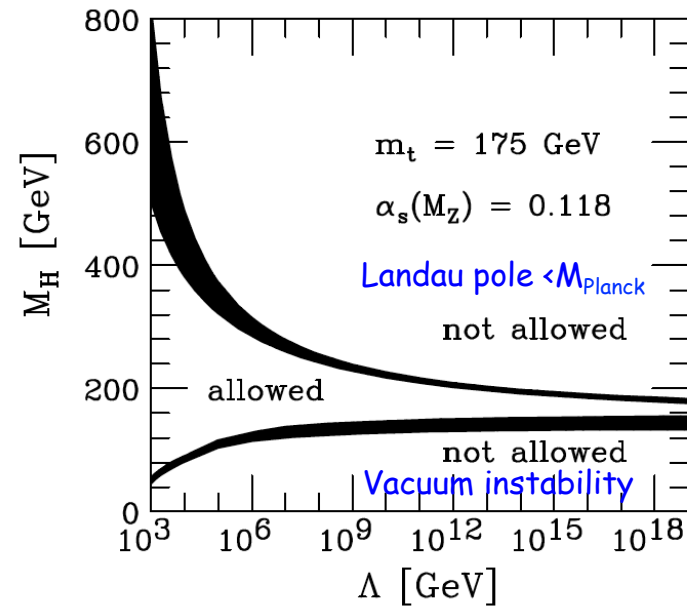
2σ away from stability

De Grassi et al

III. Implications of 125 GeV Higgs



RGE - just the Standard Model



Higgs coupling small

