Whither[†] SUSY?

G. Ross, IPPP, Durham, January 2012

† **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]

Little hierarchy problem $\Rightarrow$ definite SUSY structure

Fine Tuning measure:

$$\Delta(a_i) = \left| \frac{a_i}{M_Z} \frac{\partial M_Z}{\partial a_i} \right|,$$

$$\Delta_{\max} = Max_{a_i} \Delta(a_i)$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

MSSM: 105 +(19) Parameters

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

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

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

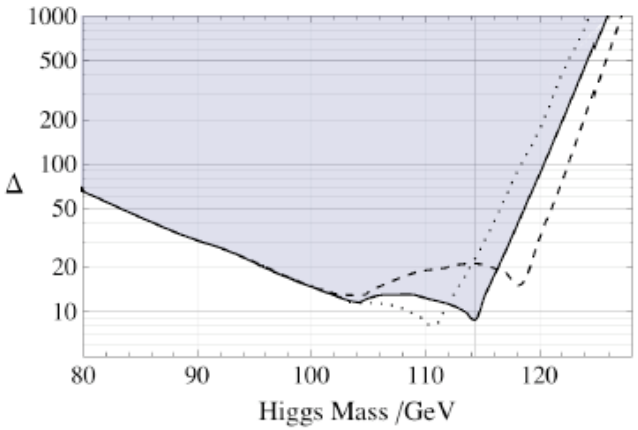
• The CMSSM

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

$$M_Z^2 = a_0 m_0^2 + a_{1/2} m_{1/2}^2 + a_\mu \mu^2 + .. \ll \tilde{m}_{q_i}^2, M_i^2$$

$$(= 0.6 m_{q_3}^2 (M_X) + 0.6 m_{U_3}^2 (M_X) + 3 M_3^2 (M_X) + 0.2 A_t^2 (M_X) - 2\mu^2 (M_X) + ...)$$

SPS1a



Constraints

SUSY particle masses

$3.20 < 10^4 \text{ Br}(b \to s\gamma) < 3.84$

$\text{Br}(b \to \mu\mu) < 1.8 \times 10^{-8}$

$\delta a_\mu < 292 \times 10^{-11}$

$-0.0007 < \delta\rho < 0.0012$

Radiative EW breaking

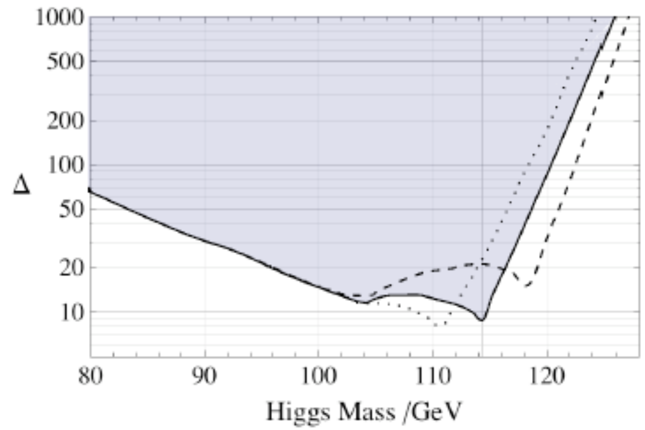
Relic density unrestricted

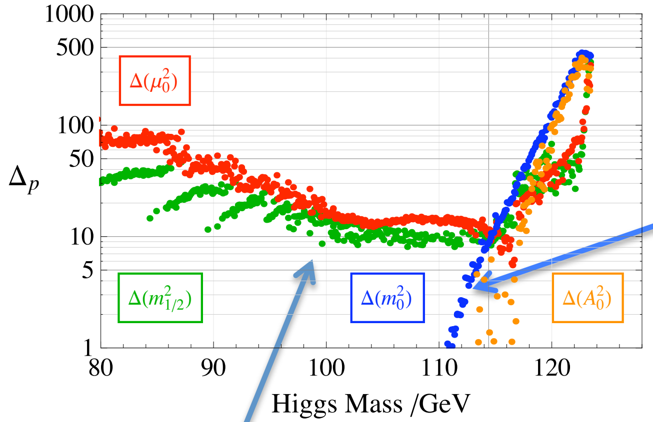
$$\Delta \equiv \max \left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

$$\boxed{\Delta_{Min} = 9, \quad m_h = 114 \pm 2 GeV}$$

(No Higgs bound applied)

The CMSSM





Limit of focus point

λ increases with M_H

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

Constraints

SUSY particle masses

$$3.20 < 10^4\ \mathrm{Br}(b \to s\gamma) < 3.84$$

$$\mathrm{Br}(b \to \mu\mu) < 1.8 \times 10^{-8}$$

$$\delta a_\mu < 292 \times 10^{-11}$$

$$-0.0007 < \delta\rho < 0.0012$$

Radiative EW breaking

Relic density unrestricted

S.Cassel, D.Ghilencea, GGR

Focus Point

$$2|y_t|^2(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2|a_t|^2$$

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3X_t - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2 \frac{d}{dt} m_{Q_3}^2 = X_t + X_b - \frac{32}{3}g_3^2|M_3|^2 - 6g_2^2|M_2|^2 - \frac{2}{15}g_1^2|M_1|^2$$

$$16\pi^2 \frac{d}{dt} m_{\bar{u}3}^2 = 2X_t - \frac{32}{3}g_3^2|M_3|^2 - \frac{32}{15}g_1^2|M_1|^2$$

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

$$\simeq -\frac{2}{3},\ Q^2 \simeq M_Z^2$$

Focus Point

$$2|y_t|^2 (m^2_{H_u} + m^2_{Q_3} + m^2_{\bar{u}3}) + 2|a_t|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{H_u} = 3X_t - 6g_2^2|M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{Q_3} = X_t + X_b - \frac{32}{3} g_3^2 |M_3|^2 - 6g_2^2|M_2|^2 - \frac{2}{15} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m^2_{\bar{u}3} = 2X_t - \frac{32}{3} g_3^2 |M_3|^2 - \frac{32}{15} g_1^2 |M_1|^2$$

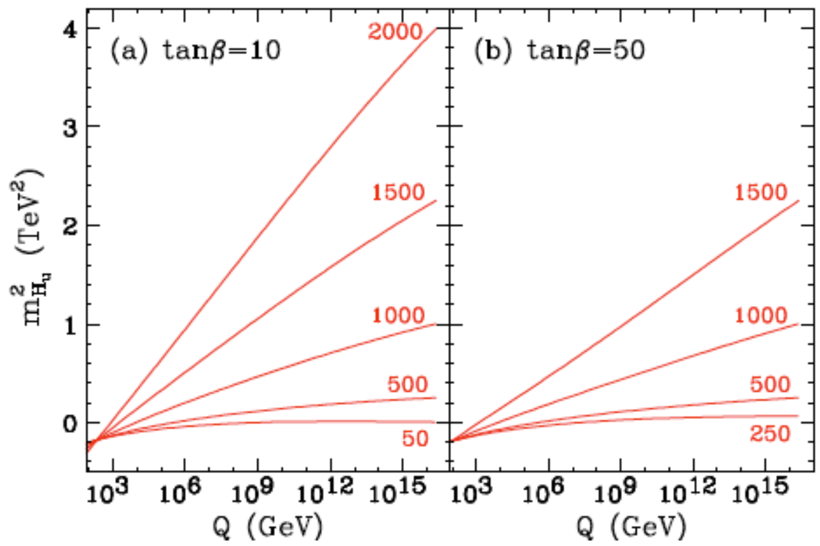
$$\boxed{m^2_{H_u}(Q^2) = m^2_{H_u}(M_P^2) + \frac{1}{2}\left(m^2_{H_u}(M_P^2) + m^2_{Q_3}(M_P^2) + m^2_{\bar{u}3}(M_P^2)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}} - 1\right]}$$

$$m_0^2 \qquad 3m_0^2 \qquad \simeq -\frac{2}{3},\ Q^2 \simeq M_Z^2$$

CMSSM: $\quad m^2_{H_u}(0) = m^2_{Q_3}(0) = m^2_{\bar{u}3}(0) \equiv m^2$

Natural choice

Focus Point



$$2|y_t|^2(m^2_{H_u}+m^2_{Q_3}+m^2_{\bar u_3})+2|a_t|^2$$

$$16\pi^2\frac{d}{dt}m^2_{H_u}=3X_t-6g_2^2|M_2|^2-\frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{Q_3}=X_t+X_b-\frac{32}{3}g_3^2|M_3|^2-6g_2^2|M_2|^2-\frac{2}{15}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{\bar u_3}=2X_t-\frac{32}{3}g_3^2|M_3|^2-\frac{32}{15}g_1^2|M_1|^2$$

$$\boxed{m^2_{H_u}(Q^2)=\underbrace{m^2_{H_u}(M_P^2)}_{m_0^2}+\frac{1}{2}\underbrace{\left(m^2_{H_u}(M_P^2)+m^2_{Q_3}(M_P^2)+m^2_{\bar u_3}(M_P^2)\right)}_{3m_0^2}\underbrace{\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}}-1\right]}_{\simeq-\frac{2}{3},\ Q^2\simeq M_Z^2}}$$

"Focus point": $m^2_{H_u}(0)=m^2_{Q_3}(0)=m^2_{\bar u_3}(0)\equiv m^2$

$$\boxed{m^2_{H_u}(Q^2)=a_0\,m^2+..,\ a_0\le 0.1}$$

$i.e.\ m^3_{Q_3},m^2_{\bar u_3}\gg M_Z^2$ possible

Feng, Matchev, Moroi
Chan, Chattopadhay, Nath
Barbieri, Giudice

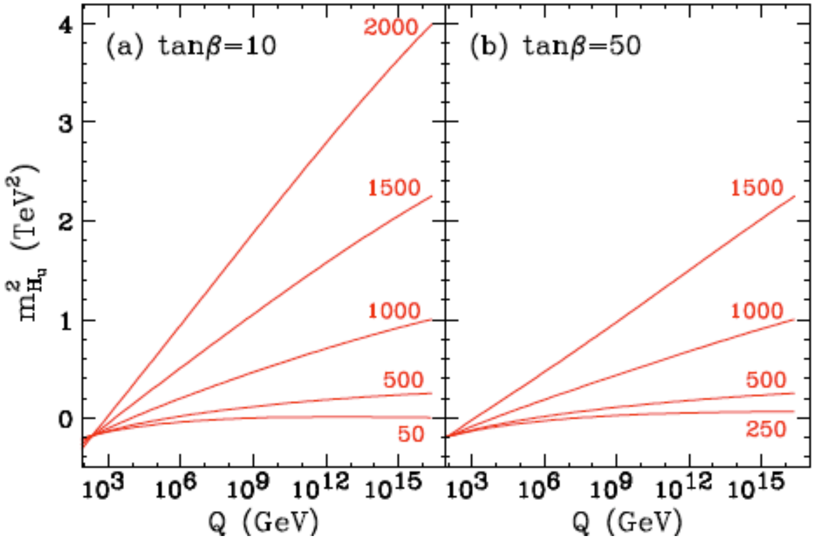
Focus Point

$$2|y_t|^2(m_{H_u}^2+m_{Q_3}^2+m_{\bar{u}3}^2)+2|a_t|^2$$

$$16\pi^2\frac{d}{dt}m_{H_u}^2=3X_t-6g_2^2|M_2|^2-\frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m_{Q_3}^2=X_t+X_b-\frac{32}{3}g_3^2|M_3|^2-6g_2^2|M_2|^2-\frac{2}{15}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m_{\bar{u}3}^2=2X_t-\frac{32}{3}g_3^2|M_3|^2-\frac{32}{15}g_1^2|M_1|^2$$

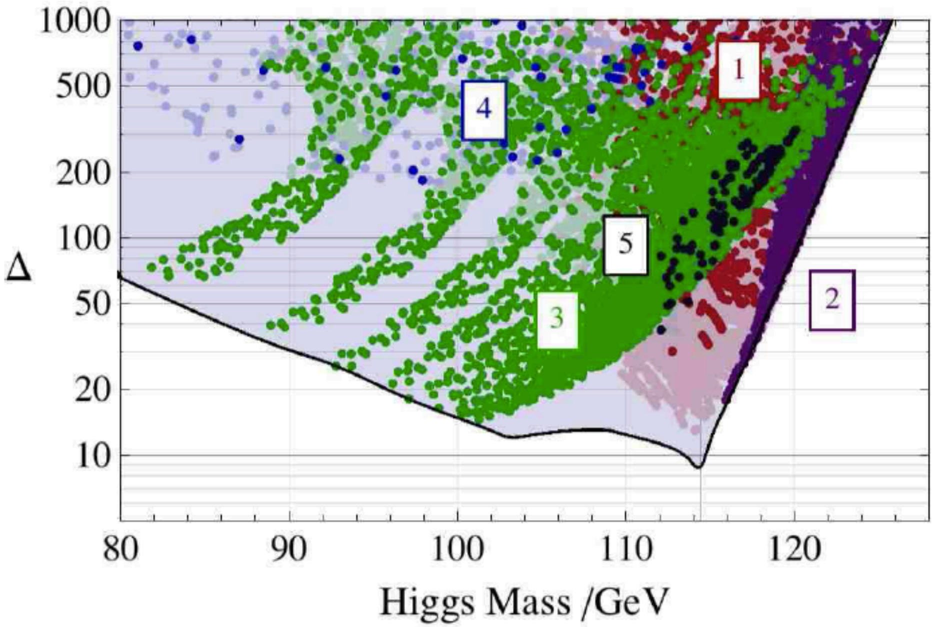


$$\boxed{m_{H_u}^2(Q^2)=m_{H_u}^2(M_P^2)+\frac{1}{2}\left(m_{H_u}^2(M_P^2)+m_{Q_3}^2(M_P^2)+m_{\bar{u}3}^2(M_P^2)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}}-1\right]}$$

$$\simeq-\frac{2}{3},\ Q^2\simeq M_Z^2$$

(Gauge mediation: $m_{H_u}^2(0)\neq m_{Q_3}^2(0)\neq m_{\bar{u}3}^2(0)$ no focus point-fine tuned)

CMSSM: Dark Matter structure



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

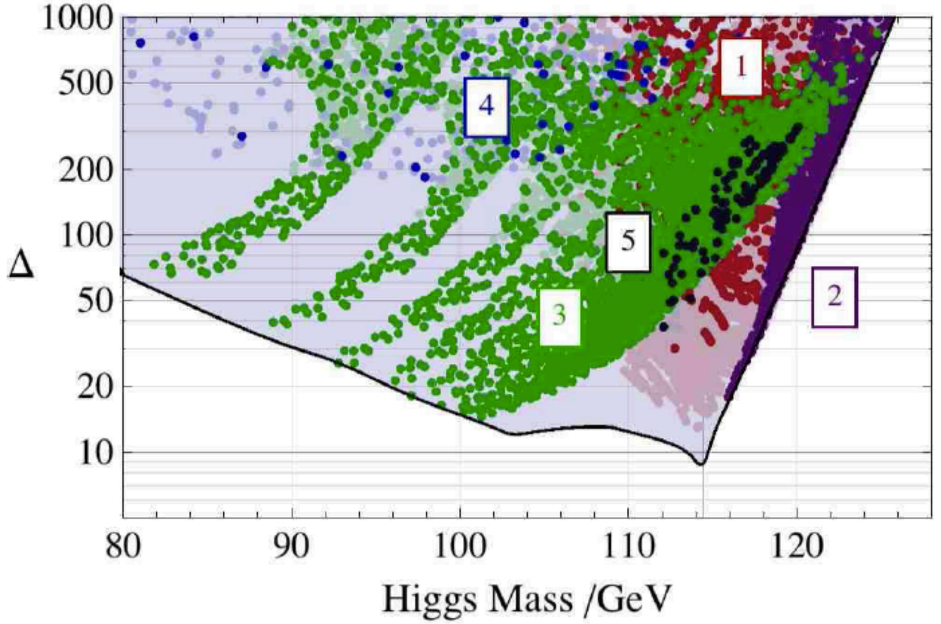
Within 3σ WMAP:

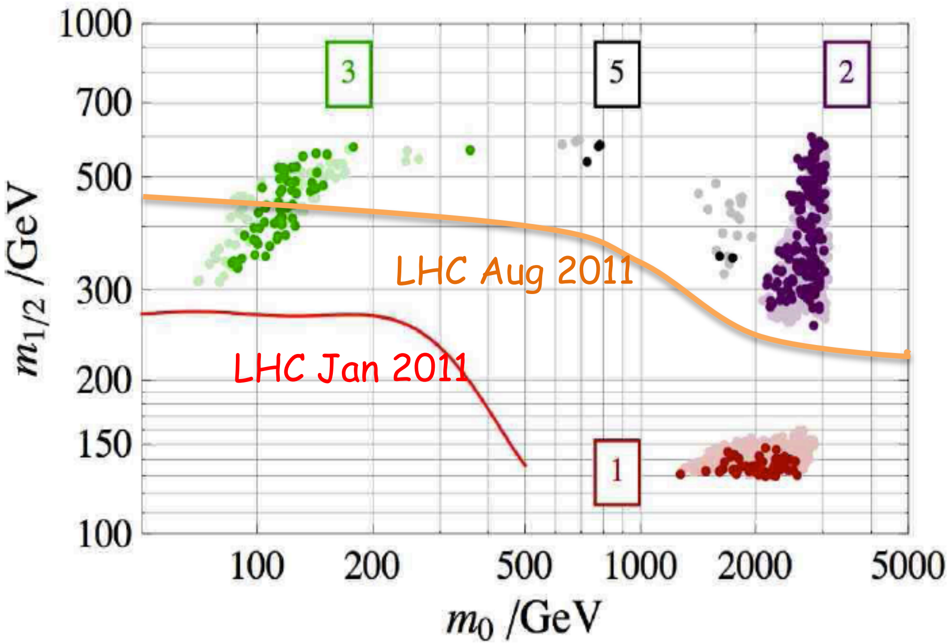
$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2GeV$

< 3σ WMAP:

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

Cassel, Ghilencea, GGR





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:

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

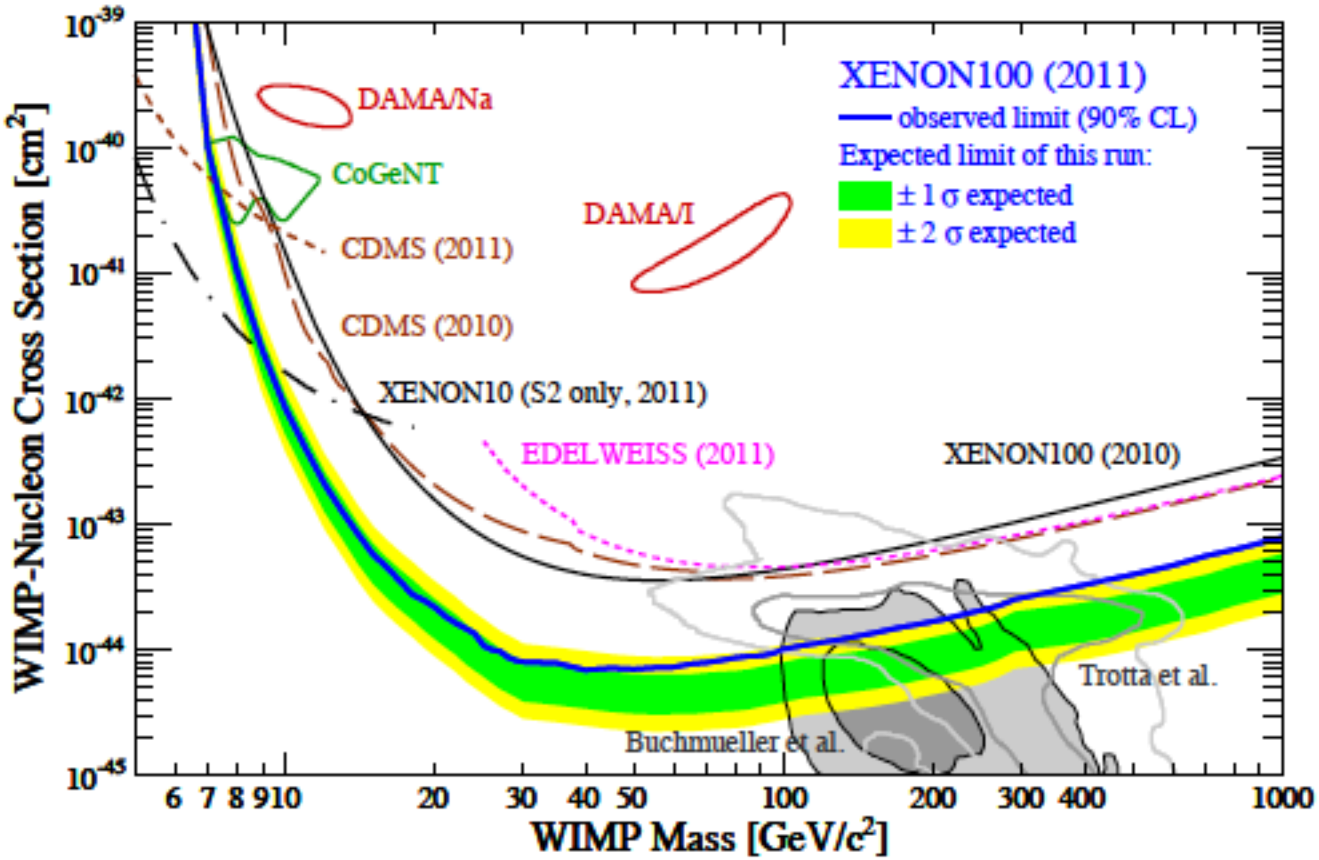
$< 3\sigma$ WMAP:

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

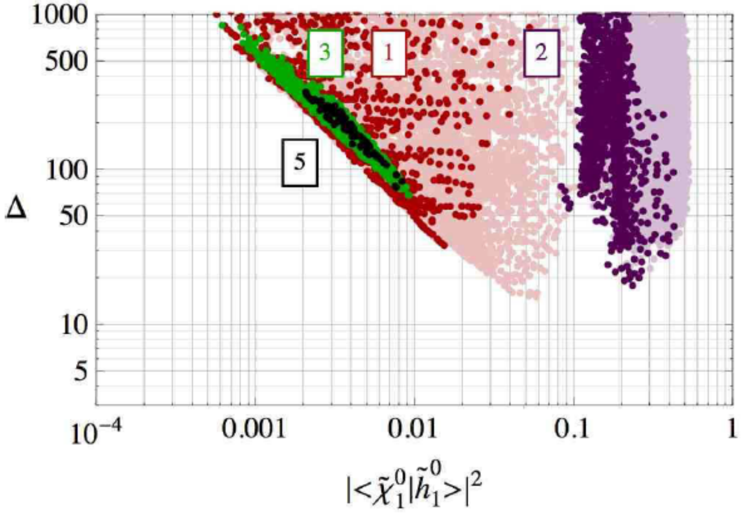
Cassel, Ghilencea, GGR

$$(\Delta < 100, m_h > 114.5\ GeV)$$

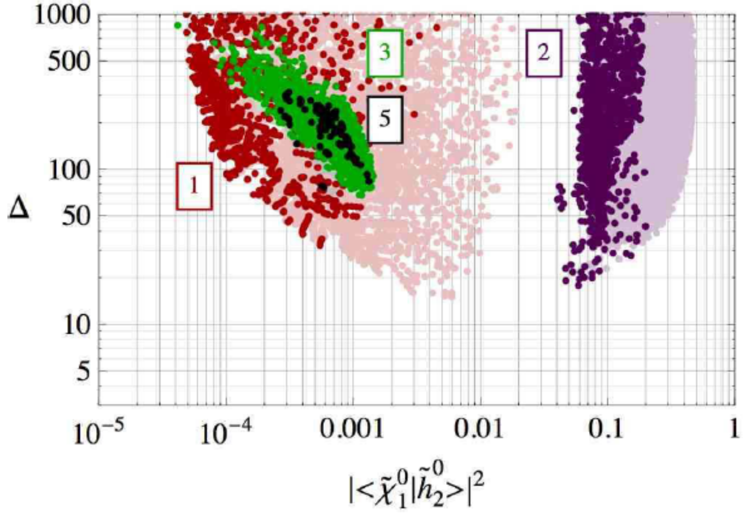
Direct dark matter searches: (spin independent)



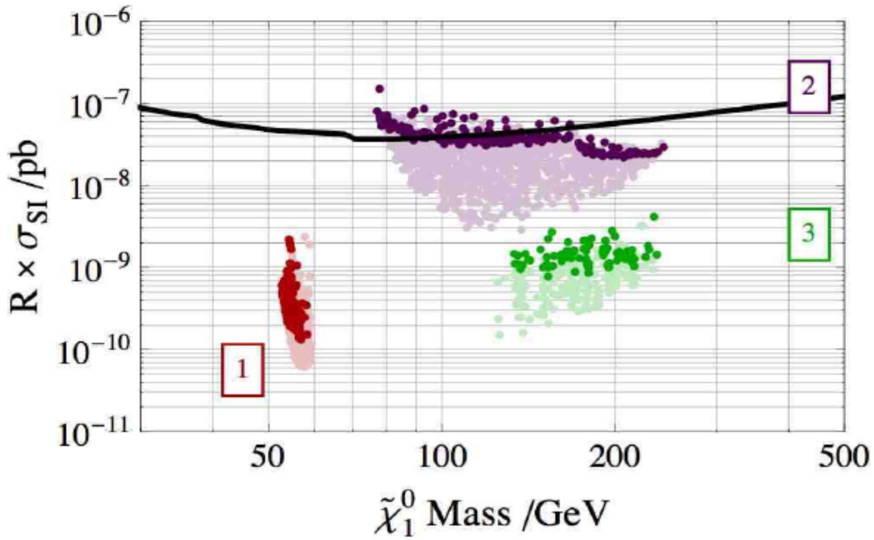
DM - Scaled spin independent cross section for LSP-proton scattering:



(a) LSP $\tilde{h}_1^0$ component

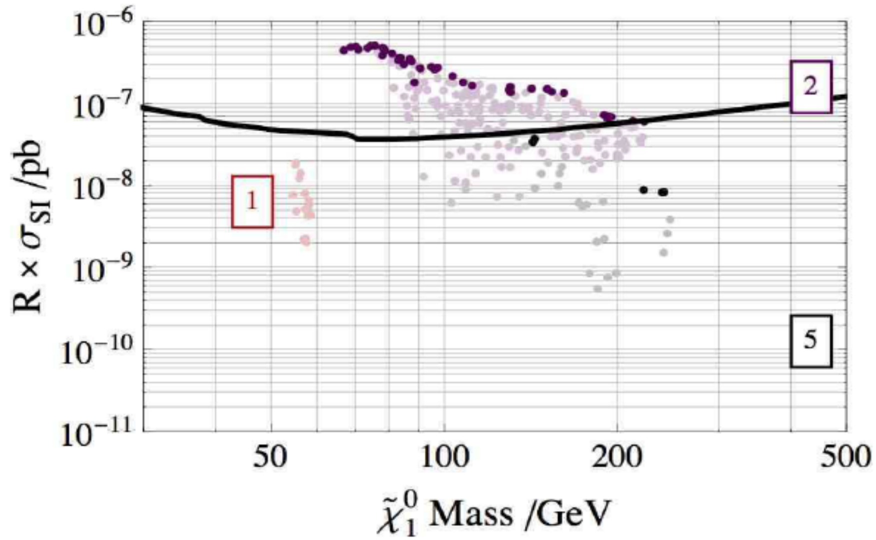


(b) LSP $\tilde{h}_2^0$ component



(a) $\tan\beta \leq 45$

$\Delta < 100, m_h > 114.5GeV$



(b) $50 \leq \tan\beta \leq 55$

$\Delta < 100, m_h > 114.5\ GeV$

Further reduction in fine tuning?

- New degrees of freedom e.g. singlet extensions

- New focus points?

Gauginos: $M_{\tilde{g},\widetilde{W},\tilde{B}}$ Non-universal gaugino correlations

Kane,King
Lebedev, Nilles, Ratz...
Horton, GGR
...

Scalars: M_0, A_0 correlations?

Feldman, Kane, Kuflik, Lu

$M_0, A_0, B_0 \gg \mu, m_a$ $\qquad m^2_{h_u^2}(t) = f_{M_0} M_0^2 - f_{A_0} A_0^2$

$f_{M_0} \sim f_{A_0} \sim 0.1 \quad + M_0 \sim A_0 \quad \Rightarrow \qquad m^2_{h_u} \sim 10^{-2} m^2_{3/2}$

$\Delta_{h_t} \sim 10^4, \quad M_0 \sim 10TeV$

Reduced fine tuning : singlet extensions

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

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

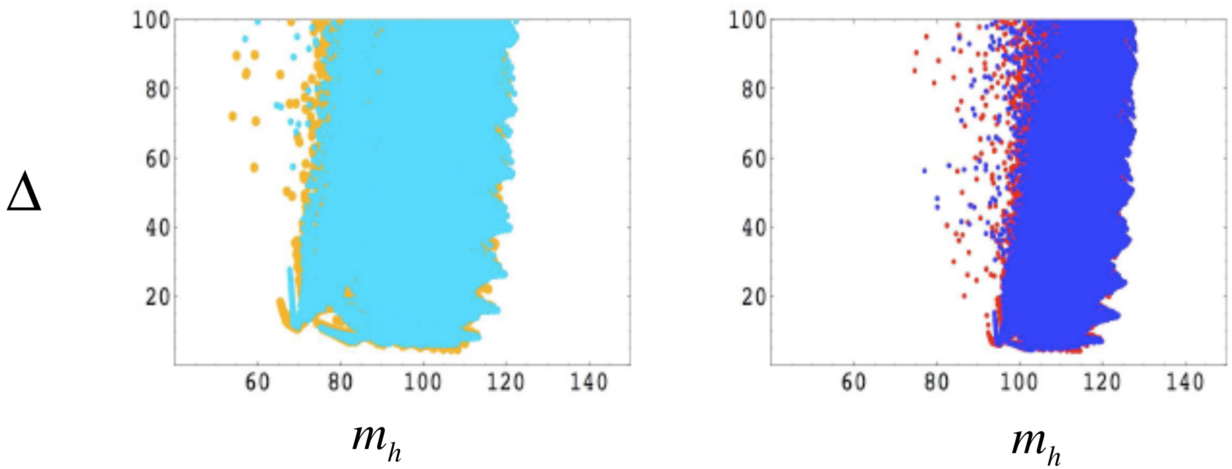
$\mu_S >> m_{3/2}$

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

$$\frac{\mu}{\mu_S}\left(\left|H_u\right|^2 + \left|H_d\right|^2\right) H_u H_d \longrightarrow \mathrm{v}^2 = -\frac{m^2}{\lambda}$$

Cassel, Ghilencea, GGR
Casas, Espinosa, Hidalgo
Dine, Seiberg, Thomas
Batra, Delgardo, Tait, Kaplan
Delgardo, Kolda, Puente
GGR,Schmidt Hoberg, Staub
Bastero-Gil, Hugonie,King…

Model independent analysis:



Reduced fine tuning in GNMSSM (but not so much in NMSSM)

Reduced fine tuning : singlet extensions

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

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

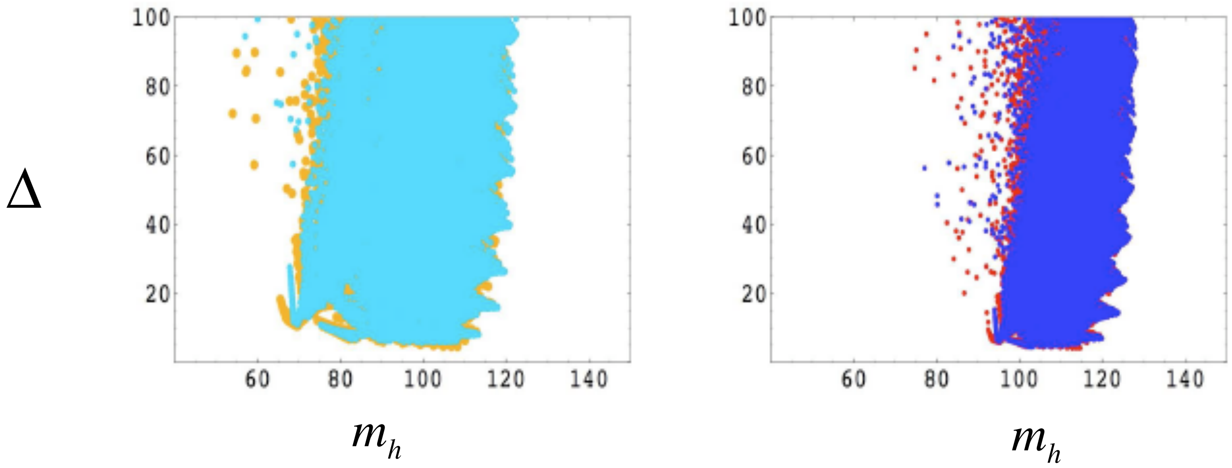
$\mu_S >> m_{3/2}$

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

$$\frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right) H_u H_d \longrightarrow \mathrm{v}^2 = -\frac{m^2}{\lambda}$$

Cassel, Ghilencea, GGR
Casas, Espinosa, Hidalgo
Dine, Seiberg, Thomas
Batra, Delgardo, Tait, Kaplan
Delgardo, Kolda, Puente
GGR,Schmidt Hoberg, Staub
Bastero-Gil, Hugonie,King…

Model independent analysis:



GNMSSM (NMSSM) unnatural? .....discrete R-symmetry.....

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange

Discrete R-symmetry and MSSM singlet extension

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

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

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

Discrete R-symmetry and MSSM singlet extension

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

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

R-symmetry ensures singlets light

D=5 operators

up and down Yukawas allowed

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

Weinberg operator

Discrete R-symmetry and MSSM singlet extension

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

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

R-symmetry ensures singlets light

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \quad \text{Mod N} \quad \Rightarrow \quad 3\mathrm{q}_{10} + q_{\bar{5}} = 0 \quad \text{Mod N} \quad \Rightarrow \quad \frac{1}{M}\cancel{QQQL} \quad \frac{1}{M}LLH_uH_u$$

Weinberg operator

SUSY breaking

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

$Z^R_{4,8} \rightarrow Z^R_2 \quad R-parity$

Domain walls and tadpoles safe   Abel

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

$$\boxed{\begin{aligned} W &= W_{MSSM} + \lambda S H_u H_d + \kappa S^3 + \Delta W \\ \Delta W_{Z_4^R} &\sim m_{3/2} H_u H_d + m_{3/2}^2 S + m_{3/2} S^2 \\ \Delta W_{Z_8^R} &\sim m_{3/2}^2 S \end{aligned}}$$

μ term and mass term

i.e. GNMSSM natural

GENERAL-NMSSM PHENOMENOLOGY

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

- SUSY structure

$\mu_s \gg \mu$ MSSM SUSY structure with reduced fine tuning $(\text{for } \mu_s < 5TeV)$

$\mu_s \sim \mu$ SUSY states can be heavier $(\text{v}^2 = m^2 / \lambda, \quad \lambda \text{ increase})$

- Higgs structure (h_u, h_d, s)

$\mu_s \gg \mu$ MSSM Higgs structure

$\mu_s, m_s, b_s \sim \mu$ Mixing between states $h_1 \simeq H_u + \varepsilon S, \quad h_2 = S - \varepsilon H_u$

$(M_{h_1} \ll M_{h_2}, \quad \varepsilon \ll 1)$

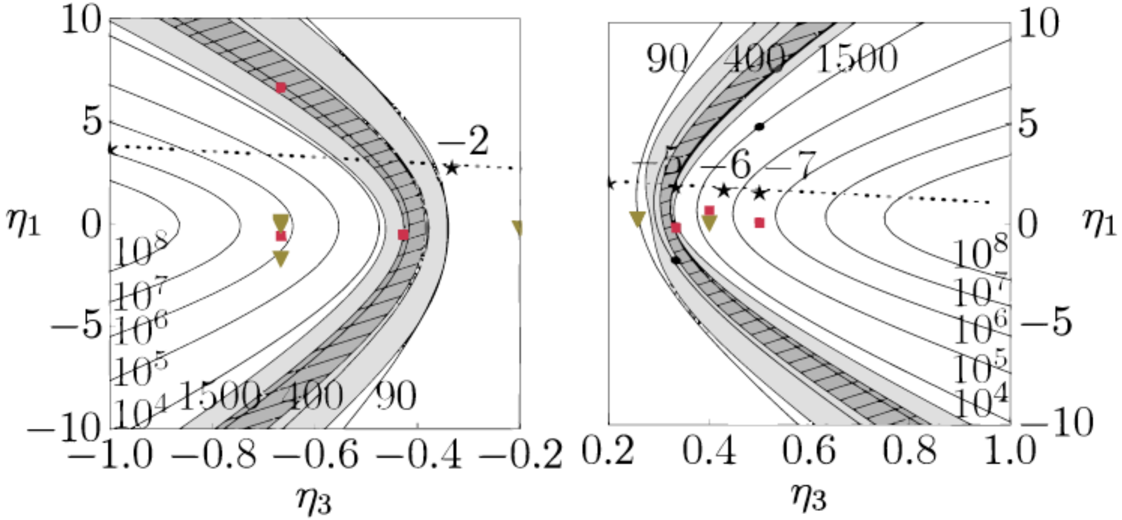
(Invisible Higgs decay $45\ GeV < m_{\tilde{S}} < 70\ GeV,\ BR\left(\frac{h_1 \to \tilde{S}\tilde{S}}{h_1 \to \gamma\gamma, b\bar{b}}\right) \gg 1)$

Reduced fine tuning : nonuniversal gaugino masses

Reduced fine tuning : nonuniversal gaugino masses

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

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



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

Reduced fine tuning : nonuniversal gaugino masses

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

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

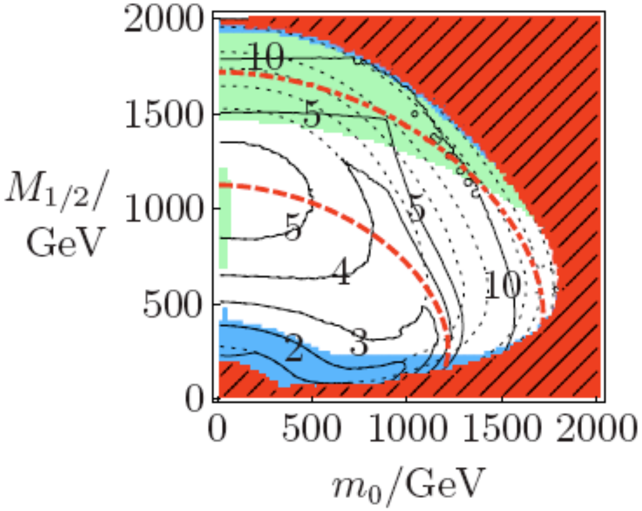
Natural ratios? e.g.:

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

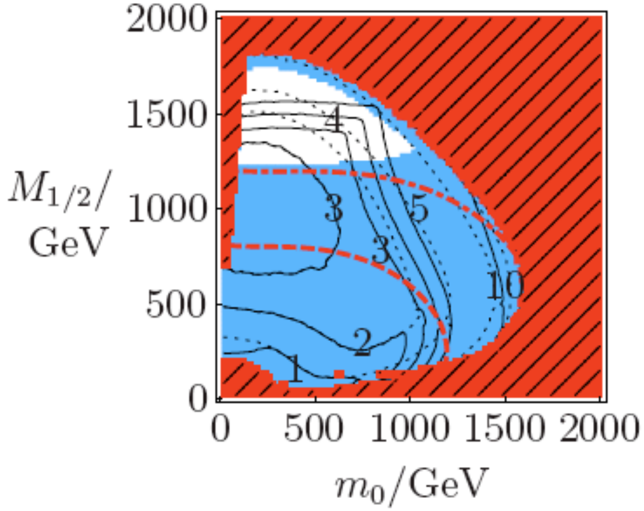
$\eta_3 : 1 : \eta_1$ $\qquad\qquad 2.7\eta_3 : 1 : 0.5\eta_1$

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

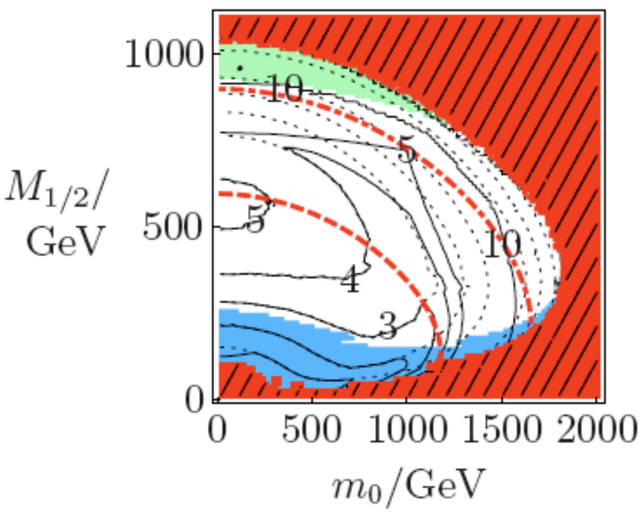
String: $(3+\delta_{GS}):(-1+\delta_{GS}):\left(-\frac{33}{5}+\delta_{GS}\right)$ (OII, also mixed moduli anomaly)



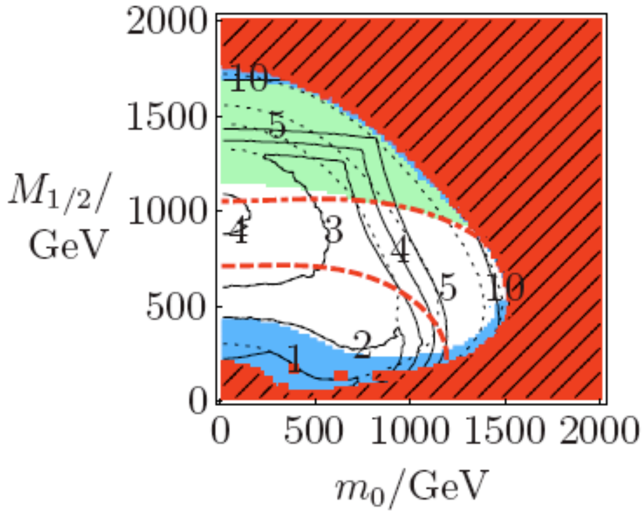
(a) 54



(b) 210



(c) 770



(d) O-II

Phenomenology

- Gaugino mass ratios

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

.... gauginos can be very heavy

- Light neutralino and 2 charginos nearly degenerate, $|M_1|, |M_2| \gg \mu$

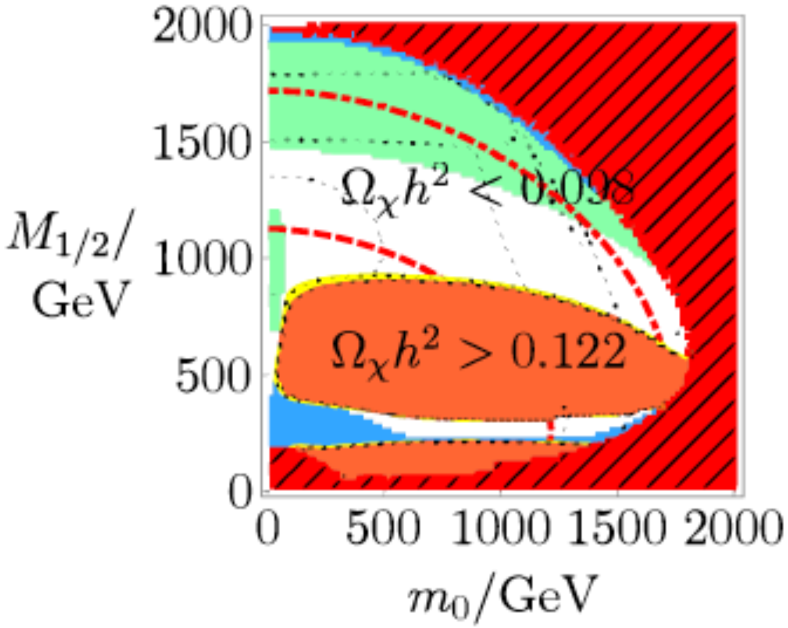
$$m_{\chi_2^0} - m_{\chi_1^0} = M_Z^2 \left(\frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) + \mathcal{O}(\frac{M_Z^3}{M_2^2})$$

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

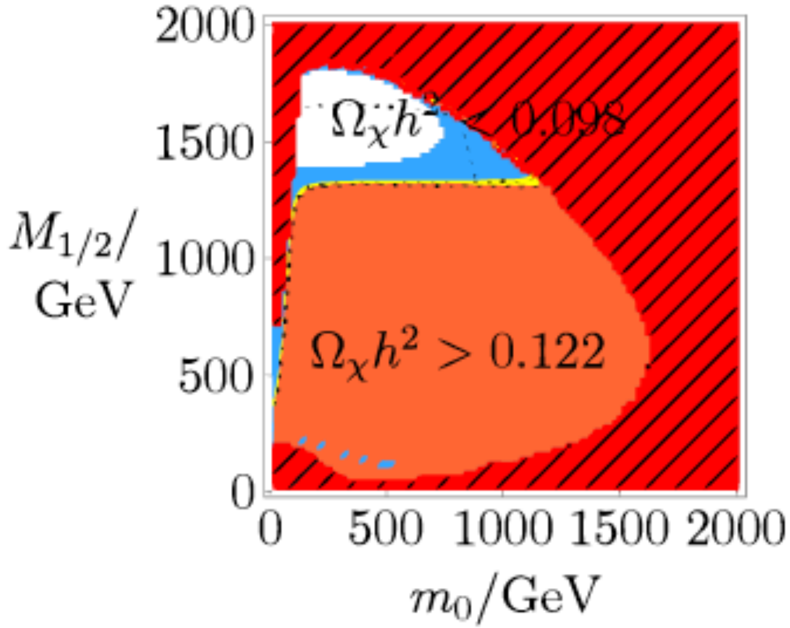
$+$ for $|M_1| < \mu$, Bino or Higgsino LSP candidate

Dark Matter

$\Delta < 5, 5 \le \Delta^{\Omega} \le 15$



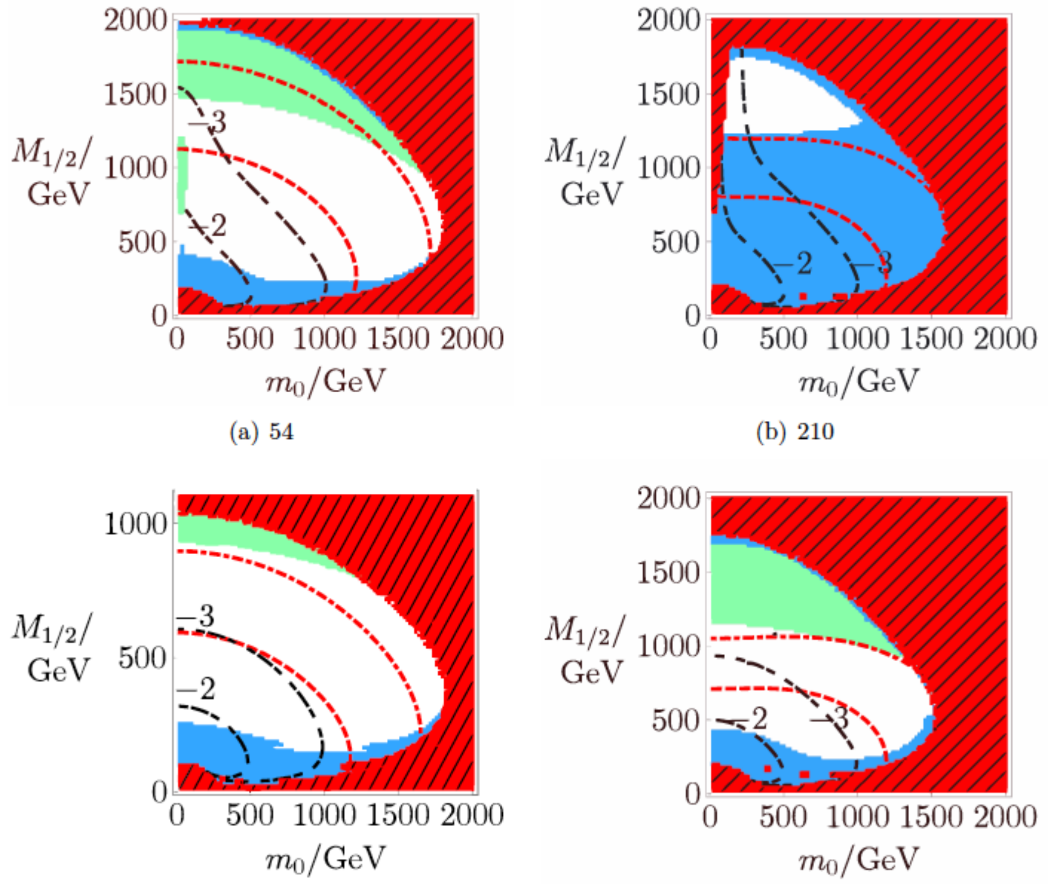
(a) 54, $\mu > 0$



(b) 210, $\mu < 0$

Figure 9: Contour plots of $\Omega_\chi h^2$ in the 54 and 210 models. These are for the hypersurface in parameter space with $\tan\beta = 10$ and $A_0 = 0$. The narrow, yellow region, which lies between the regions of over- and under- abundance, has a dark matter abundance that satisfies, within 3σ, the constraint given in Eq (47). The (red) dashed and (red) dot-dashed contours indicate where the Higgs mass, m_{h^0}, is 111 GeV and 114 GeV, respectively.

$g-2$

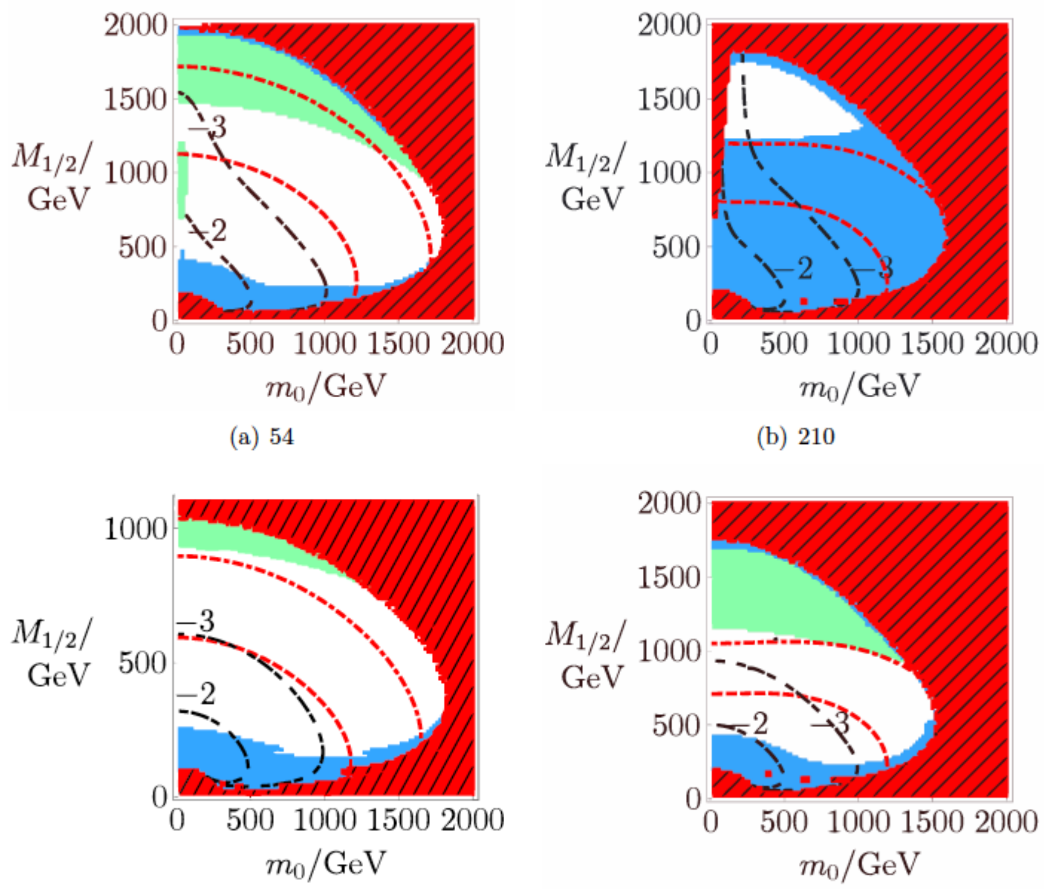


(a) 54 (b) 210

(c) 770 (d) O-II

Figure 7: Contour plots of δa_μ, in the m_0—$M_{1/2}$ plane. This is for the hypersurface in parameter space with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. Dashed (black, with alternating long and short dashing) contours are shown for $\delta a_\mu \times 10^{10} = 27.5 + n\sigma'$, where $n \in \mathbb{Z}$ and the error $\sigma' = 8.1$ combines all experimental and theoretical errors in quadrature. The (red) dashed and (red) dot-dashed contours indicate where the Higgs mass, m_{h^0}, is 111 GeV and 114 GeV, respectively, whilst the dotted contours correspond to the $|\Delta| = 5$ and $|\Delta| = 10$ contours from Fig 2.

$g-2$



(a) 54

(b) 210

(c) 770

(d) O-II

Figure 7: Contour plots of δa_μ, in the m_0—$M_{1/2}$ plane. This is for the hypersurface in parameter space with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. Dashed (black, with alternating long and short dashing) contours are shown for $\delta a_\mu \times 10^{10} = 27.5 + n\sigma'$, where $n \in \mathbb{Z}$ and the error $\sigma' = 8.1$ combines all experimental and theoretical errors in quadrature. The (red) dashed and (red) dot-dashed contours indicate where the Higgs mass, m_{h^0}, is 111 GeV and 114 GeV, respectively, whilst the dotted contours correspond to the $|\Delta| = 5$ and $|\Delta| = 10$ contours from Fig 2.

$\Longrightarrow$ GNMSSM+large tan β ?

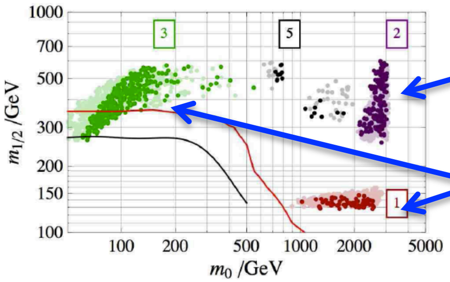
$$a_\mu^{\chi^\pm} \approx \frac{1}{32\pi^2}\frac{m_\mu^2}{M_{\mathrm{SUSY}}^2} g_2^2\, \mathrm{sgn}(\mu M_2) \tan\beta.$$

Summary

- Hierarchy problem $\Longrightarrow$ SUSY breaking structure and/or further states

- CMSSM $m_i = M_0$ $Max\left[\Delta_{EW}, \Delta_{\Omega}\right] = 15(29)$, $m_h = 114(116) \pm 2GeV$

  Complementary DM & LHC searches



(a) $m_h > 111$ GeV

DM $\Delta \leq 100$ Sensitivity $\times (10-100)$

LHC $\left(\text{Full region } LHC\ 14TeV\ 10\, fb^{-1}\right)$

(Gauge mediation $\Delta > 100$)

- NMSSM Reduced Δ $\Longrightarrow$ GNMSSM $\Longrightarrow$ Z_{4R}, Z_{8R}

  SUSY states can be (slightly)heavier

  $m_h \rightarrow 130GeV$

- Gaugino focus point $M_i = \eta_i M_{1/2}$

  Characteristic η_i

  Light $\chi^{0,\pm}$

  $\delta(b \rightarrow s\gamma)$ significant

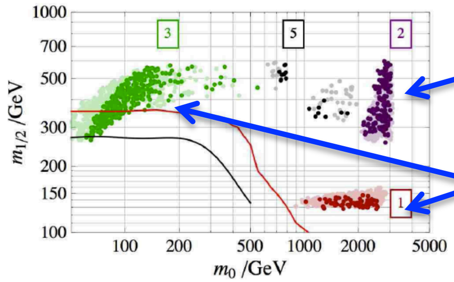
  $\delta(g-2)$ Small(?)

Summary

- Hierarchy problem $\Longrightarrow$ SUSY breaking structure and/or further states

- CMSSM $m_i = M_0 \quad Max\left[\Delta_{EW}, \Delta_{\Omega}\right] = 15(29), \quad m_h = 114(116) \pm 2GeV$

  Complementary DM & LHC searches



(a) $m_h > 111$ GeV

DM $\quad \Delta \leq 100 \quad$ Sensitivity $\times (10-100)$

LHC $\quad$ (Full region $LHC\ 14TeV\ 10\,fb^{-1}$)

- NMSSM $\quad$ Reduced Δ $\Longrightarrow$ GNMSSM $\Longrightarrow Z_{4R}, Z_{8R}$

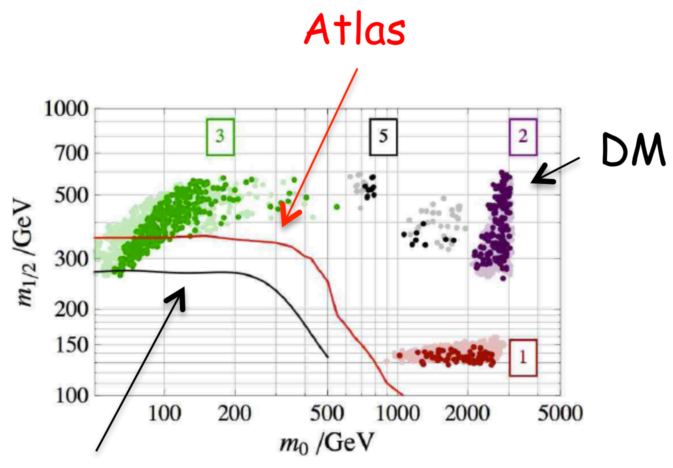
  †invisible Higgs a possibility

- Gaugino focus point

...Light Higgs search may† provide the first crucial test!

LHC – Regions of low fine tuning $\Delta < 100$:

	SUG0	SUG1	SUG2	SUG3	SUG5
m_0	1455	1508	2270	113	725
$m_{1/2}$	160	135	329	383	535
A_0	238	1492	30	-220	1138
$\tan\beta$	22.5	22.5	35	15	50
μ	191	433	187	529	581
$m_{\tilde{g}}$	482	414	900	898	1252
$m_{\tilde{u}_L}$	1469	1509	2331	826	1315
$m_{\tilde{t}_1}$	876	831	1423	602	1000
$m_{\tilde{\chi}_1^+}$	106	104	168	293	416
$m_{\tilde{\chi}_2^0}$	108	104	181	293	416
$m_{\tilde{\chi}_1^0}$	60	53	123	155	222
Δ	9	50	45	68	84
$\Omega_{\tilde{\chi}_1^0} h^2$	0.41	0.13	0.10	0.13	0.10
$\mathrm{BR}(b \to s\gamma) \times 10^4$	3.4	3.7	3.4	3.2	3.2
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9$	3.0	2.9	2.9	3.4	1.7
$\delta a_\mu \times 10^{10}$	4.5	3.2	3.2	22.5	16.6
$\sigma_{\chi p}^{\mathrm{SI}}$ (pb) $\times 10^{10}$	108	5	432	24	101
$\sigma^{(LO)}$(7 TeV) (pb)	8	12	0.9	0.4	0.02
$\sigma^{(LO)}$(14 TeV) (pb)	40	75	3	5	0.4

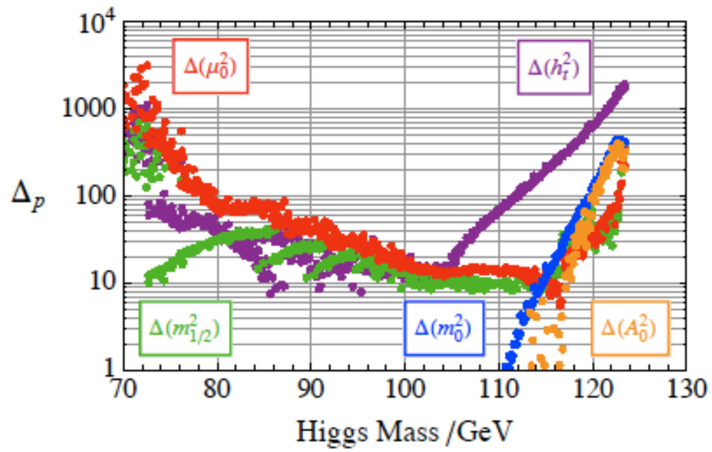


(a) $m_h > 111$ GeV

Effect of focus point limited by h_t :

Fine tuning for measured parameter :

$$\Delta'(h_t) \simeq \left| \frac{\Delta h_t}{M_Z} \frac{\partial M_Z}{\partial h_t} \right|$$



$\Delta(p)^{-1}$ is probability p lies in range $p, p+\delta p$

For measured parameter, probability p lies in range,

compatible with measured value is: $P \sim \frac{\delta p}{\sigma_p} = \Delta(p)^{-1} \frac{p}{\sigma_p}$

Ciafolini, Strumia
Romanino, Strumia

- (General) Gauge mediation in the MSSM

$$\boxed{\begin{aligned} M_{\tilde{\lambda}_i}(M_{mess}) &= k_i \frac{\alpha_i(M_{mess})}{4\pi} \Lambda_G \\ m_{\tilde{f}}^2(M_{mess}) &= 2\sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2 \end{aligned}}$$

No focus point

$$k_i = (\frac{5}{3}, 1, 1)$$

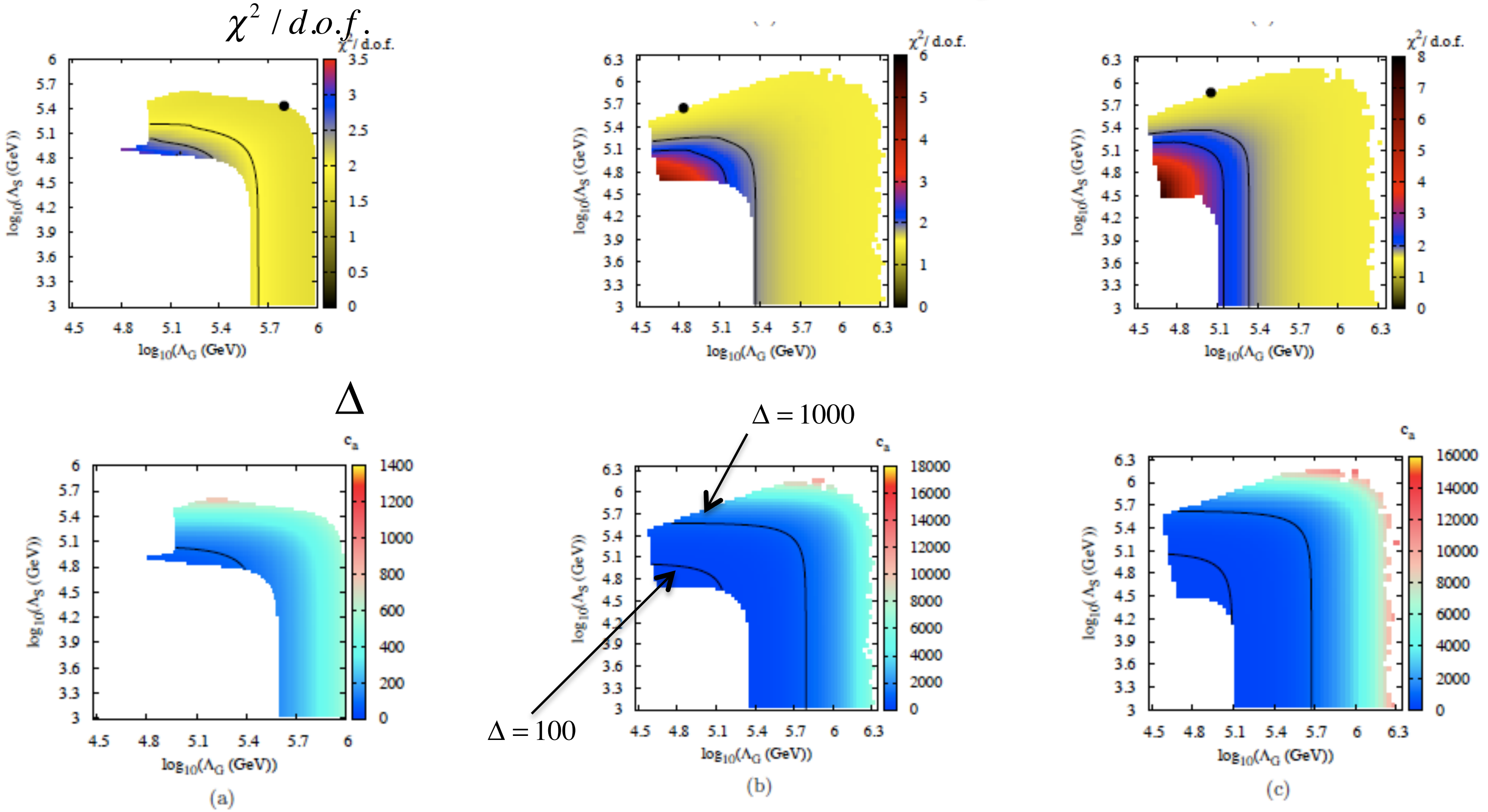
$$k_i \alpha_i \left(M_{GUT} \right) = 1, \quad i = 1,2,3$$

(Ordinary gauge mediation $\Lambda_G = \Lambda_S$)

Meade, Seiberg, Shih

Fine tuning in General Gauge Mediation

$B \to X_s\gamma, B \to \tau\mu, B \to \mu^+\mu^-, B \to D\tau\mu,$
$D_s \to \mu\nu, D_s \to \tau\nu, K \to \mu\nu / \pi \to \mu\nu, \Delta_{0-}$

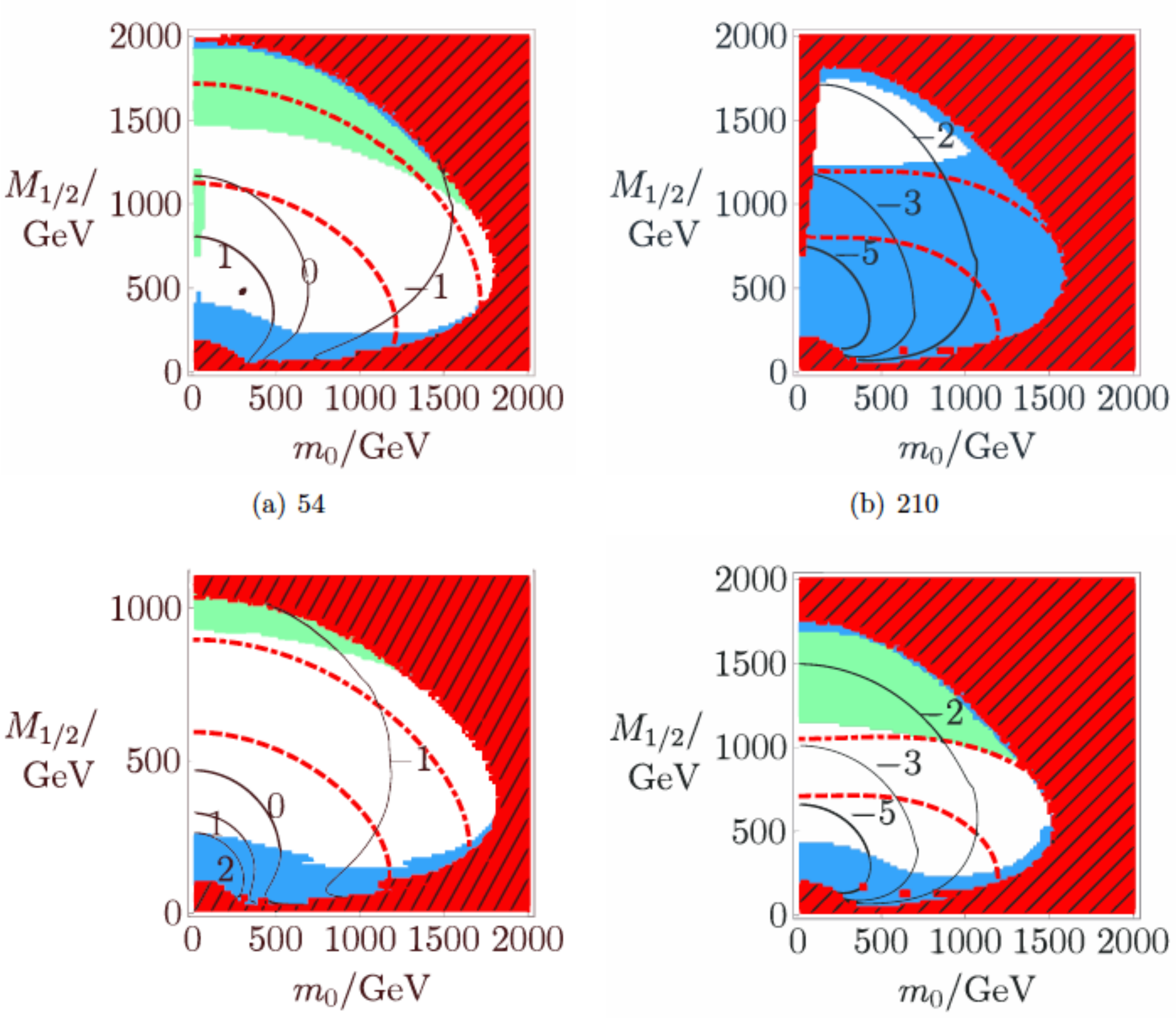


$M_{Messenger}$ $10^6\,GeV$ $10^{10}\,GeV$ $10^{14}\,GeV$

$\Delta > 100$ no focus point

Abel, Dolan, Jaeckel, Khoze
(Giusti, Romanino, Strumia)

$b \to s\gamma$



(a) 54

(b) 210

(c) 770

(d) O-II

Figure 5: Contour plots of the branching ratio $\mathrm{Br}(\overline{B} \to X_s\gamma)$ in the m_0—$M_{1/2}$ plane. This is for the hypersurface in parameter space with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. Solid (black) contours are shown for $\mathrm{Br}(\overline{B} \to X_s\gamma) \times 10^4 = 3.52 + n\sigma$, where $n \in \mathbb{Z}$ and the error $\sigma = 0.34$ combines all experimental and theoretical errors in quadrature. The (red) dashed and (red) dot-dashed contours indicate where the Higgs mass, m_{h^0}, is 111 GeV and 114 GeV, respectively, whilst the dotted contours correspond to the $|\Delta| = 5$ and $|\Delta| = 10$ contours from Fig 2.