Symmetries and the nature of the Higgs.

G.G.Ross, CERN, May 2011

Hierarchy problem $\mu, \not{B}, \not{L}$	}	SUSY +further symmetry	$\Rightarrow$	Higgs structure

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\not{L}) \right)$$

R-parity: Z_2

$H_u, H_d \quad +1$

$L, \overline{E}, Q, \overline{D}, \overline{U}, \quad \theta \quad -1$

SUSY states odd

Weinberg, Sakai

SUSY extensions of the Standard Model

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R-parity: Z_2

SUSY states odd

Weinberg, Sakai

Baryon "parity": Z_3

$Q \quad 1$

$\overline{D}, H_u \quad \alpha$

$L, \overline{E}, \overline{U}, H_d \quad \alpha^2$

LSP unstable

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + \ldots (\not{L}) \right)$$

μ term, GUTs?

R-parity: Z_2 — SUSY states odd

Baryon "parity": Z_3 — LSP unstable

Proton hexality: $Z_6 = Z_2^R \times Z_3^B$ — LSP stable

$\frac{1}{M} L L H_u H_u$

Dreiner, Luhn, Thormeier

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
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Proton hexality: $Z_6 = Z_2^R \times Z_3^B$ — LSP stable

Z_N^R R-symmetry — N=4,6,8,12,24 — LSP stable

$\frac{1}{M} L L H_u H_u$

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange
Babu, Gogoladze,Wang

A unique solution : discrete R symmetry

c.f.Hyun Min Lee's talk

MSSM spectrum

No perturbative μ term

Commutes with SO(10)

Anomaly cancellation

$$A_{G-G-\mathbb{Z}_N} = \rho \mod \eta$$

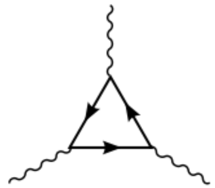
Green Schwarz term (→ ρ)

η: N, N odd; N/2, N even

$$A_{\mathrm{SU}(3)-\mathrm{SU}(3)-\mathbb{Z}_N} = \frac{1}{2}\sum_i \left[3\cdot q_{\mathbf{10}_i} + q_{\overline{\mathbf{5}}_i} - 4R\right] + 3R$$

$$A_{\mathrm{SU}(2)-\mathrm{SU}(2)-\mathbb{Z}_N} = \frac{1}{2}\sum_{3} \left[3\cdot q_{\mathbf{10}_i} + q_{\overline{\mathbf{5}}_i} - 4R\right] + 2R + \frac{1}{2}\left(q_H + q_{\bar{H}} - 2R\right)$$

$$A_{\mathrm{U}(1)_Y\text{-}\mathrm{U}(1)_Y\text{-}\mathbb{Z}_N^R} = \frac{1}{2}\sum_{g=1}^{3}\left(3q_{10}^g + q_{\overline{5}}^g\right) + \frac{3}{5}\left[\frac{1}{2}\left(q_{H_u} + q_{H_d}\right) - 11\right] \qquad (R=1)$$



No D=4 $\not{B}$, $\not{L}$

$$A_3 - A_2 \Rightarrow \quad (q_H + q_{\bar{H}}) = 4R \mod 2\eta$$

$$A_3 - A_1 \Rightarrow \quad \frac{3}{5}\left[\frac{1}{2}\left(q_{H_u} + q_{H_d}\right) - 6\right] = 0 \mod \eta$$

$$\Rightarrow N = 3,4,6,8,12,24$$

M	q_{10}	$q_{\overline{5}}$	q_{H_u}	q_{H_d}	$q_{H_u}^{\mathrm{sh}}$	$q_{H_d}^{\mathrm{sh}}$	ρ
4	1	1	0	0	16	16	1
6	5	3	4	0	28	24	0
8	1	5	0	4	24	28	1
12	5	9	4	0	28	24	3
24	5	9	16	12	88	84	9

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

Z_{4R} Phenomenology

M	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	$q_{H_u}^{\rm sh}$	$q_{H_d}^{\rm sh}$	ρ
4	1	1	0	0	16	16	1
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24	5	9	16	12	88	84	9

MSSM spectrum
No perturbative μ term
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Anomaly cancellation

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \mod M \Rightarrow 3q_{10} + q_{\bar{5}} = 0 \mod M \Rightarrow \frac{1}{M}\cancel{QQ}QL \quad \frac{1}{M}LLH_uH_u$$

Weinberg operator

SUSY breaking

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

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

Domain walls safe

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

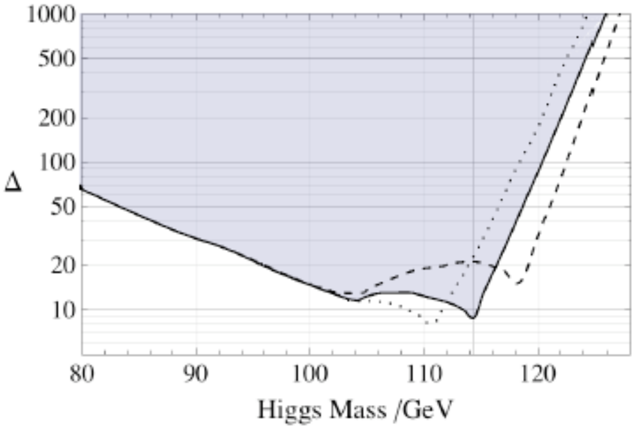
$M_{higgs} \approx M_{SUSY}$ Residual fine tuning?

$\mu, \not{B}, \not{L}$

The CMSSM

$$\lambda v^2 = -\mu^2 + 0.34(m_{\tilde{Q}}^2 + m_{\tilde{U}}^2) + 1.86 M_3^2 - 0.22 M_2^2 + \ldots$$ SPS1a

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



Relic density unrestricted

SUSY particle masses

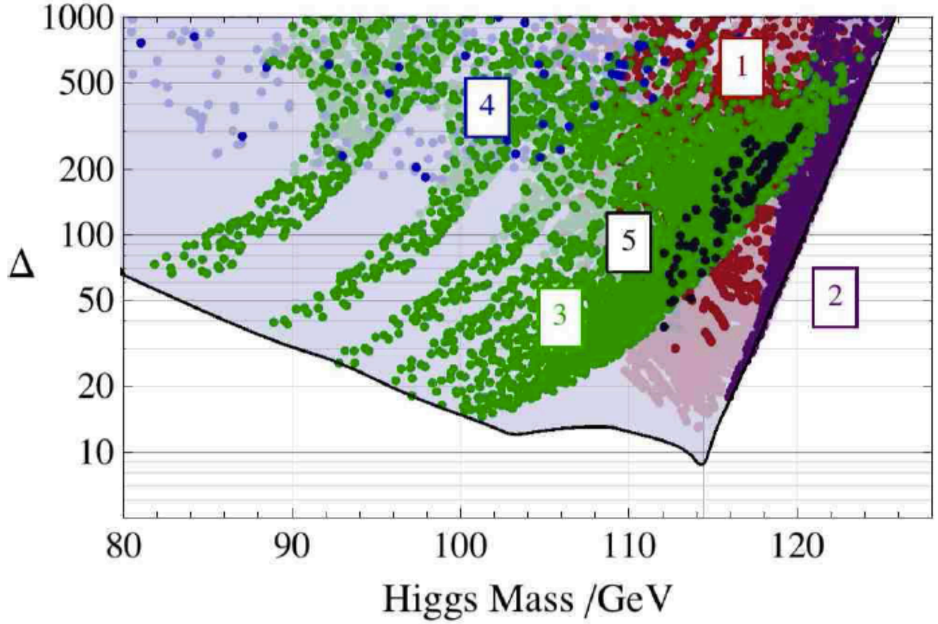
$3.20 < 10^4 \,\mathrm{Br}(b \to s\gamma) < 3.84$

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

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

$-0.0007 < \delta\rho < 0.0012$

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



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:

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

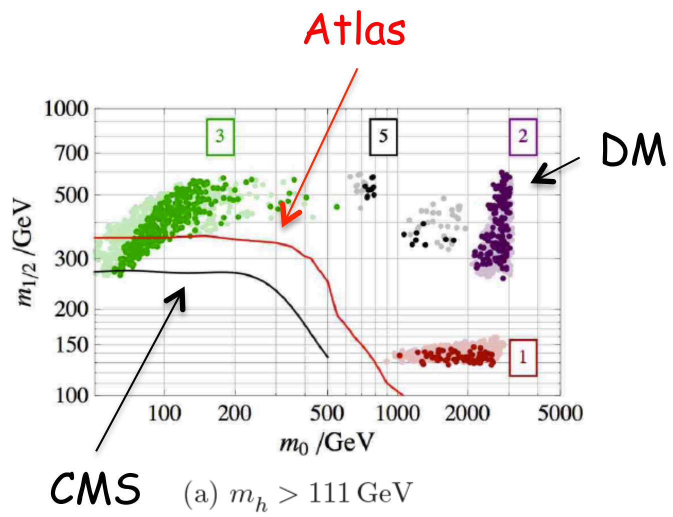
$< 3\sigma$ WMAP:

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

Cassel, Ghilencea, Kraml,Lessa,GGR

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

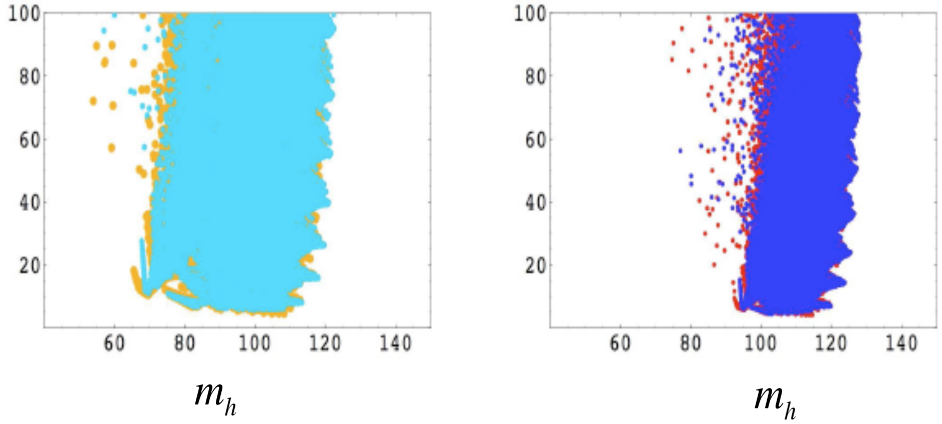
	SUG0	SUG1	SUG2	SUG3	SUG5
m_0	1455	1508	2270	113	725
$m_{1/2}$	160	135	329	383	535
A_0	238	1492	30	-220	1138
$\tan\beta$	22.5	22.5	35	15	50
μ	191	433	187	529	581
$m_{\tilde{g}}$	482	414	900	898	1252
$m_{\tilde{u}_L}$	1469	1509	2331	826	1315
$m_{\tilde{t}_1}$	876	831	1423	602	1000
$m_{\tilde{\chi}_1^+}$	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
$\sigma^{(LO)}(7\ \mathrm{TeV})$ (pb)	8	12	0.9	0.4	0.02
$\sigma^{(LO)}(14\ \mathrm{TeV})$ (pb)	40	75	3	5	0.4



(a) $m_h > 111$ GeV

Reduced fine tuning - singlet extensions

Δ



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

$$\varsigma_1 2 \frac{\mu_0}{M_*}\left(|h_1|^2 + |h_2|^2\right) h_1 h_2 \quad \rightarrow \quad v^2 = -\frac{m^2}{\lambda}$$

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

Cassel, Ghilencea, GGR
Dine, Seiberg, Thomas
Bastero-Gill, Hugonie, King, Roy, Vempati
Delgado, Kolda, Olson, Puente

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

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

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

Singlet extensions with R-symmetry

$$W = W_{NMSSM} + \Delta W$$

$$\begin{aligned} \Delta \mathscr{W}_{\mathbb{Z}_4^R} &= Y + Y^2 N + Y\,N^2 + Y\,H_u\,H_d \\ &\sim m_{3/2}\,M_{\mathrm{P}}^2 + m_{3/2}^2\,N + m_{3/2}\,N^2 + m_{3/2}\,H_u\,H_d \end{aligned}$$

M	q_{10}	$q_{\overline{5}}$	q_{H_u}	q_{H_d}	q_N
4	1	1	0	0	2

$$\begin{aligned} \Delta \mathscr{W}_{\mathbb{Z}_8^R} &= Y + Y^2\left(N + Y\,N^2 + Y\,H_u\,H_d\right) \\ &\sim m_{3/2}\,M_{\mathrm{P}}^2 + m_{3/2}^2\,N + \frac{m_{3/2}^3}{M_{\mathrm{P}}^2}\,N^2 + \frac{m_{3/2}^3}{M_{\mathrm{P}}^2}\,H_u\,H_d \end{aligned}$$

M	q_{10}	$q_{\overline{5}}$	q_{H_u}	q_{H_d}	q_N
8	1	5	0	4	6

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

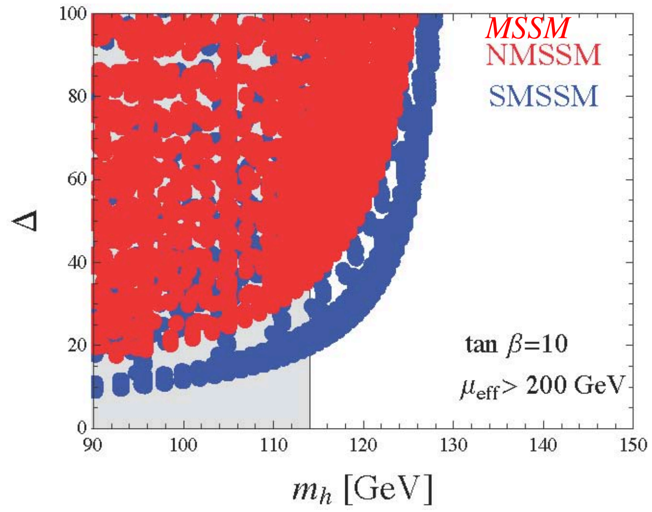
R-symmetry guarantees tadpoles under control

Abel

General-NMSSM phenomenology

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

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



GGR, Schmidt-Hoberg (preliminary)

SUSY phenomenology

$\mu_s \gg \mu$ MSSM SUSY structure

General-NMSSM phenomenology

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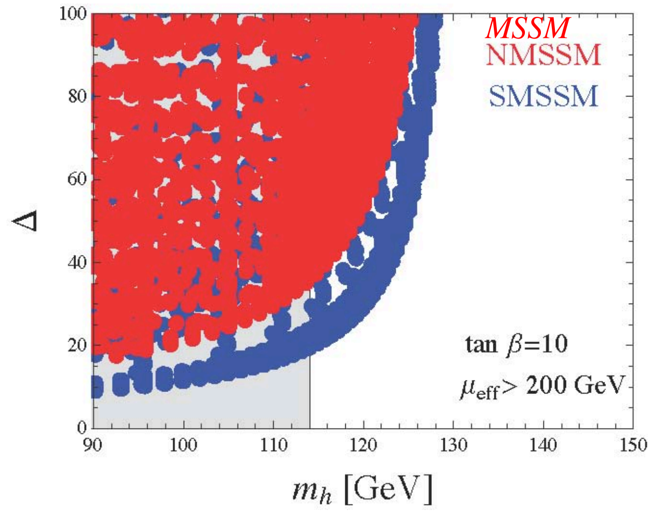
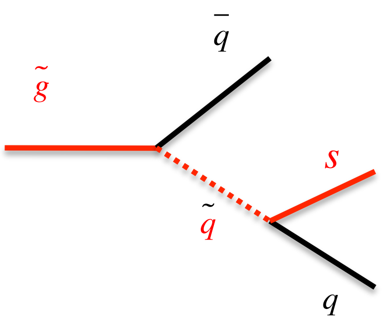


GGR, Schmidt-Hoberg (preliminary)

SUSY phenomenology

$\mu_s \gg \mu$ MSSM SUSY structure

$\mu_s \sim \mu$ $\tilde{S}$ can be LSP



$q = t, b$

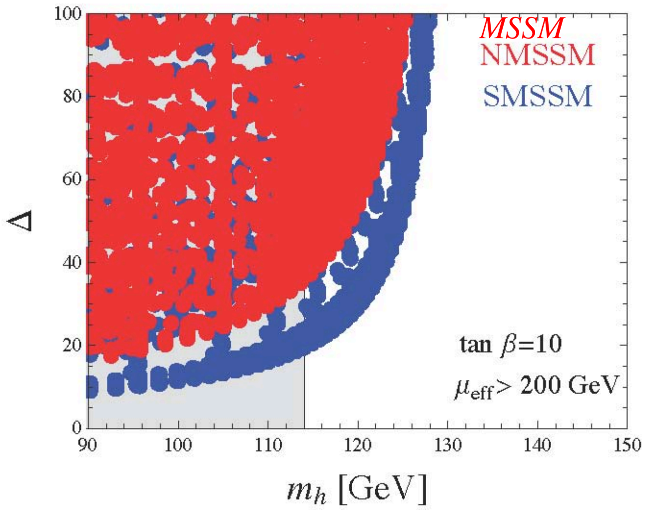
$\left(\tilde{B}, \widetilde{W}^0, \widetilde{H}^0_d, \widetilde{H}^0_u, \tilde{S}\right)$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu & -\lambda v s_\beta \\ M_Z s_W s_\beta & -M_Z s_W s_\beta & -\mu & 0 & -\lambda v c_\beta \\ 0 & 0 & -\lambda v s_\beta & -\lambda v c_\beta & \mu_s \end{pmatrix}$$

General-NMSSM phenomenology

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

$$V_{\text{soft}} = m_s^2 |s|^2 + m_{h_u}^2 |h_u|^2 + m_{h_d}^2 |h_d|^2 + \left(\lambda A_\lambda s h_u h_d + \frac{1}{3} \kappa A_\kappa s^3 + \frac{1}{2} b_s s^2 + h.c. \right)$$

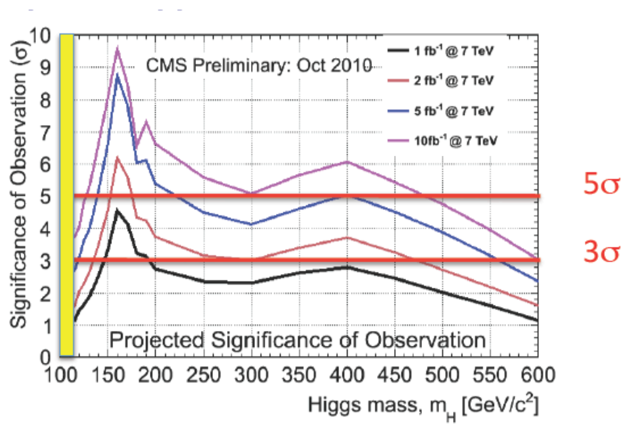


GGR, Schmidt-Hoberg (preliminary)

Higgs structure (h_u, h_d, s)

$\mu_s \gg \mu$ MSSM Higgs structure

Δ significantly reduced even for $\mu_s \sim 5TeV$



General-NMSSM phenomenology

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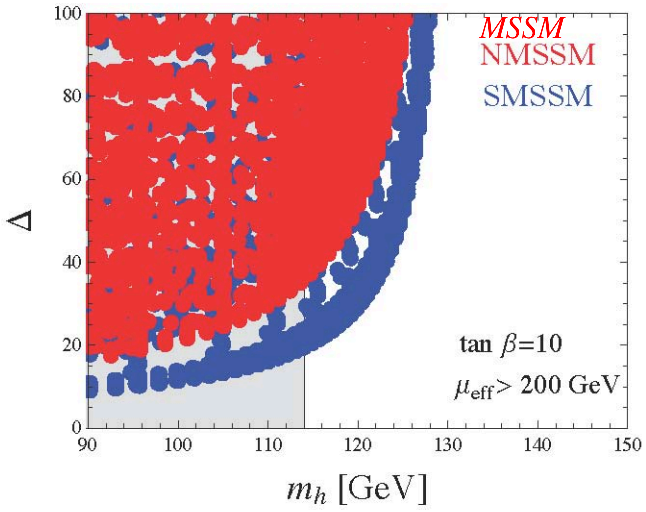
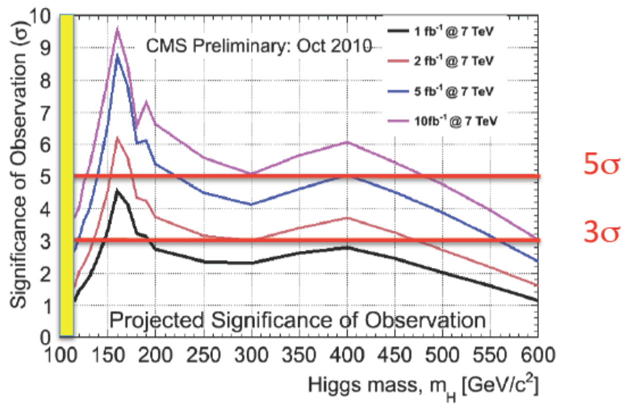


GGR, Schmidt-Hoberg (preliminary)

Higgs structure (h_u, h_d, s)

$\mu_s \gg \mu$ MSSM SUSY structure

$\mu_s, m_s, b_s \sim \mu$ h, s mixing, reduced production cross section



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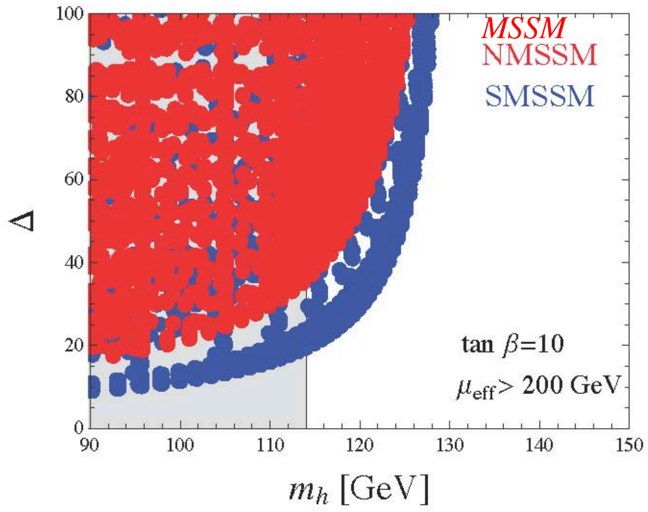


GGR, Schmidt-Hoberg (preliminary)

Higgs structure (h_u, h_d, s)

$\mu_s \gg \mu$ MSSM SUSY structure

$\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_u + \varepsilon S, \quad h_2 = S - \varepsilon H_u$ $M_{h_1} \ll M_{h_2}, \quad \varepsilon \ll 1$

$$BR\left(\frac{h_1 \to \tilde{S}\tilde{S}}{h_1 \to \gamma\gamma, b\bar{b}} \right) \gg 1$$

Invisible Higgs decay

LEP: invisible Higgs searches $e^+e^- \to h^0 Z$

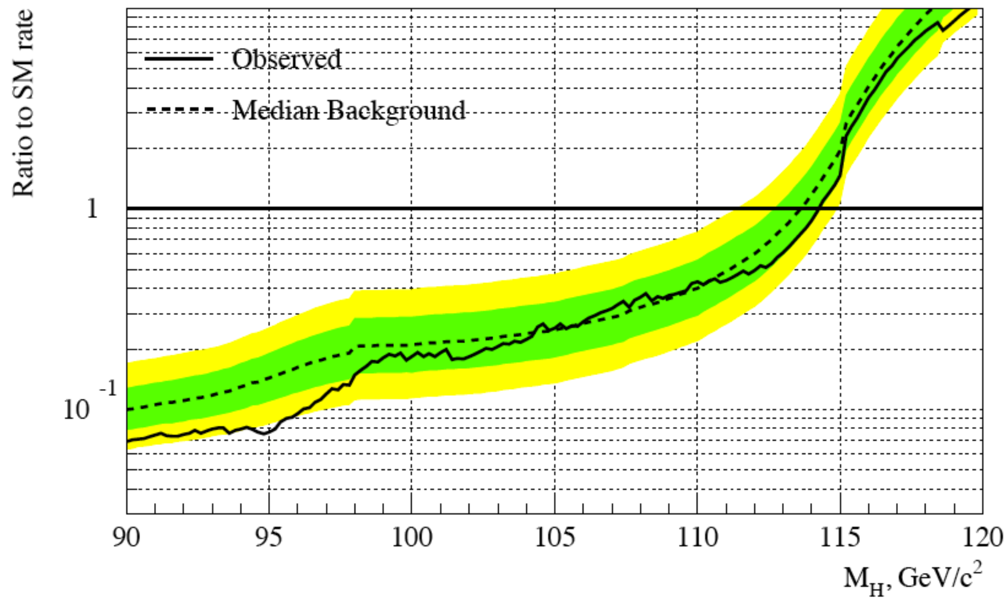
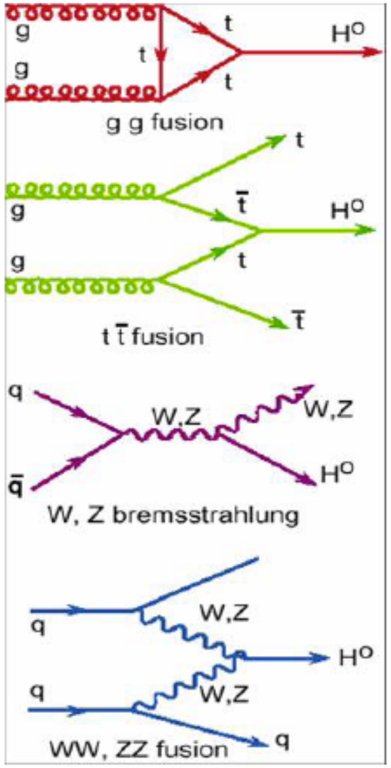
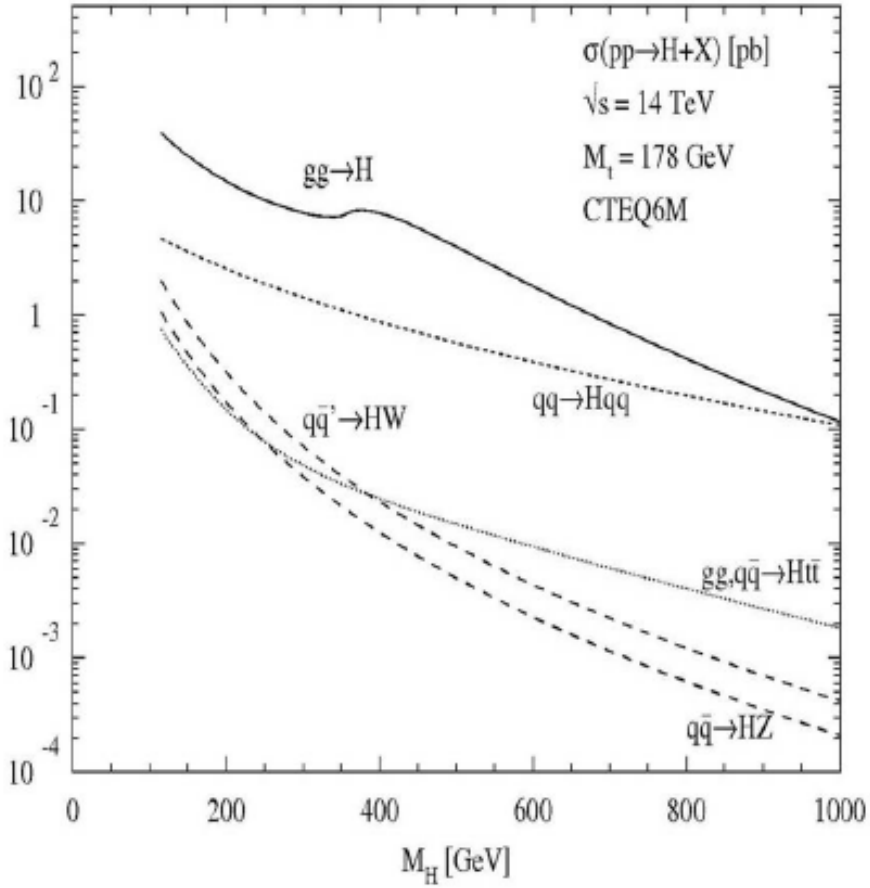


Figure 4: *The region excluded by the combined LEP results in the $h^0 \to$ invisible search. The 95% CL upper limit on, ξ^2, the production rate as a fraction of the Standard Model total rate, is shown, together with the expected range assuming there is no signal.*

Aleph, Delphi, L3 and Opal combined

LHC:





$gg \to h^0$ forward-backward jets

$q\bar{q} \to h^0 Z$ X 10^{-1}

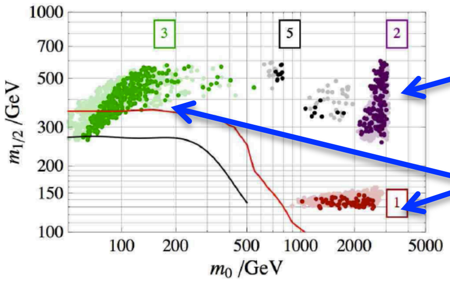
....no invisible Higgs LHC sensitivity reported yet

Summary

- Hierarchy problem $\Longrightarrow$ Low-energy SUSY + further symmetry

  Z_{4R} : μ, $\not{B}$, $\not{L}$

- CMSSM Complementary DM & LHC searches



(a) $m_h > 111$ GeV

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

LHC $\Delta \leq 100$ $\sim LHC\ 7TeV\ 1 fb^{-1}$

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

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

  SUSY states can be heavier

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

General-NMSSM phenomenology

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

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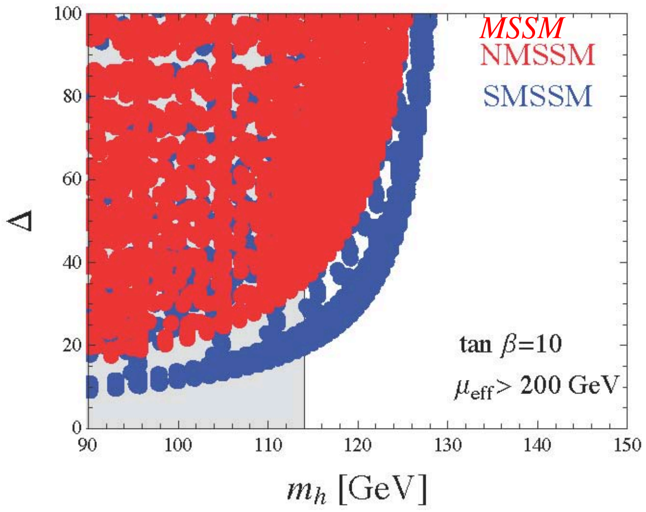

GGR, Schmidt-Hoberg (preliminary)

Higgs structure

(h_u, h_d, s)

$\mu_s \gg \mu$ MSSM SUSY structure

$\mu_s, m_s, b_s \sim \mu$

$h_1 \simeq H_u + \varepsilon S, \quad h_2 = S - \varepsilon H_u$

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

$$BR\left(\frac{h_1 \to \tilde{S}\tilde{S}}{h_1 \to \gamma\gamma, b\bar{b}} \right) \gg 1$$

$$M_{11}^2 = \cot(\beta)(\lambda(v_s(A_\lambda + v_s\kappa + \mu_s) + \xi) + b\mu) + M_Z^2 \sin^2(\beta)(1+\delta)$$
$$M_{22}^2 = \tan(\beta)(\lambda(v_s(A_\lambda + v_s\kappa + \mu_s) + \xi) + b\mu) + M_Z^2 \cos^2(\beta)$$
$$M_{33}^2 = v_s\kappa(A_\kappa + 4v_s\kappa + 3\mu_s) + \frac{1}{2v_s}\left(v^2\lambda(A_\lambda + \mu_s)\sin(2\beta) - 2v^2\lambda\mu - 2\mu_s\xi\right)$$
$$M_{12}^2 = -\lambda(v_s(A_\lambda + v_s\kappa + \mu_s) + \xi) - b\mu + (v^2\lambda^2 - M_Z^2/2)\sin(2\beta)$$
$$M_{13}^2 = v\lambda(2\sin(\beta)(v_s\lambda + \mu) - \cos(\beta)(A_\lambda + 2v_s\kappa + \mu_s))$$
$$M_{23}^2 = v\lambda(2(v_s\lambda + \mu)\cos(\beta) - (A_\lambda + 2\kappa v_s + \mu_s)\sin(\beta))$$

Invisible Higgs decay